SWACHHATA HI SEVA 2024
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Swabhav Swachhata - Sanskaar Swachhata

सत्यमेव जयते
Ministry of Housing and Urban Affairs
Government of India

स्वच्छ भारत
एक कदम स्वच्छता की ओर

# OUR COLLECTIVE CONTRIBUTION TOWARDS SWACHHATA

## A Repository of Publications

## Part B : Journals

**TITLE**
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# Message

As we proudly celebrate the 10th anniversary of the Swachh Bharat Mission (SBM), it is with great honour that I introduce this knowledge repository—a comprehensive compilation of published journal papers and articles focused on sanitation and waste management.

This repository comprises a range of reports, anecdotal experiences, and field-based learning that shall aid in developing a deep understanding of the impacts of the SBM at the ground level. By encapsulating a decade of SBM's progress, it showcases a wealth of topics, including sustainable sanitation strategies, community engagement, and the essential role of women in sanitation efforts.

This repository documents the Mission's impact across India, highlighting the efforts made towards building a Swachh nation. By leveraging the insights collated in this document, we aim to inspire cities to adopt sustainable sanitation practices.

Together, let us continue our commitment to building a Swachh Bharat, striving for a clean and sustainable future for all.

Debolina Kundu

Dr. Debolina Kundu
Director
National Institute of Urban Affairs

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## Part B: Journal Papers

# Inferences

The Swachh Bharat Mission - Urban (SBM-U) launched on 2 October 2014, aims to eradicate open defecation and ensure scientific management of municipal solid waste in 4,041 statutory towns across India. The second phase, SBM-U 2.0, began on 1 October 2021, with a five-year plan to achieve “Garbage Free” status for all cities by 2026. This mission has significantly enhanced public health, contributing to a cultural shift towards cleanliness and hygiene, and fostering community-led initiatives essential for maintaining sanitation practices.

The document provides extensive insights into various aspects of sanitation and waste management, including inclusive sanitation, solid waste challenges post-pandemic, technological advancements and the health and safety of sanitation workers. It highlights SBM’s impact on public health, estimating that it has potentially averted 60,000 to 70,000 infant deaths annually by improving sanitation access and eliminating open defecation, thereby reducing waterborne diseases.

The document emphasizes the critical role of waste management in public health and socio-economic development, identifying household plastic waste as a major environmental pollution source. It advocates for tailored waste management solutions that consider seasonal variations, promoting a circular economy that enhances resource efficiency through reuse, recycling, and recovery of materials relevant for economic recovery post-COVID-19 and aligns with several UN Sustainable Development Goals.

Waste management solutions such as bio-methanation and composting were identified as suitable waste treatment technologies in Guwahati. Co-composting faecal sludge (FS) is presented as a viable alternative to traditional fertilizers, with 90% of farmers reporting increased yields and 80% noting improved soil quality due to enhanced nutrient content. This method not only sanitizes sludge for safe agricultural use but also addresses both productivity and food safety. The potential of advanced technologies, like computer vision for electronic waste recycling, and improved logistics modelling for healthcare waste management, has also been discussed. By adopting a data-driven digital transformation, medical waste management efficiency and regulatory compliance can be significantly enhanced.

The importance of community engagement in effective waste management is emphasized, showcasing how civic activism in Bengaluru influenced waste management policies. Successful sanitation requires building trust through transparent communication and active resident participation. Gender-sensitive approaches improved access to sanitation for women, underscoring the need for inclusive solutions.

The document concludes that sustained investments in sanitation infrastructure, robust regulatory frameworks, and community-driven initiatives are crucial for achieving “Garbage Free” status by 2026. Collaborative efforts among stakeholders will solidify the path towards sustainable sanitation and waste management, contributing to healthier communities and a cleaner environment.

# Part B

# JOURNALS

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Scope
Volume 14 Number 1 March 2024

# Empowering Indian Women Sanitary Workers: A Need for Awarness About Breast Cancer among Them

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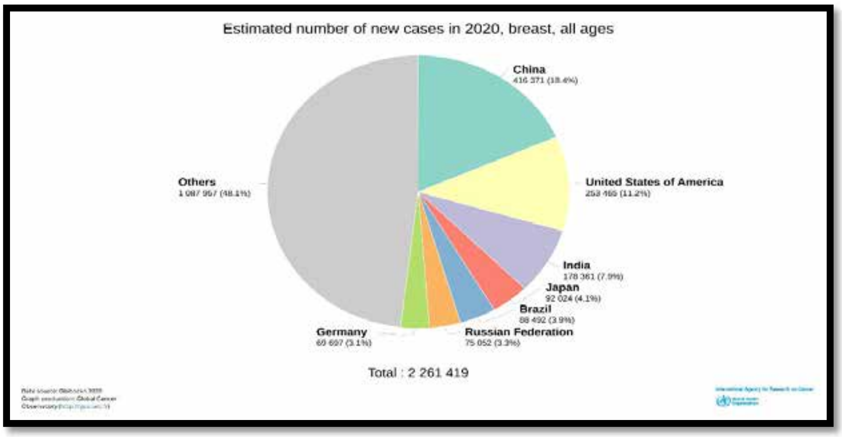
**Abstract:**

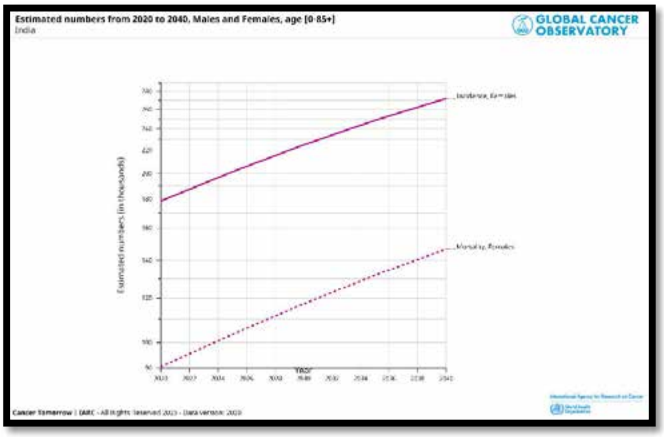
Breast cancer (BC) poses a global health challenge, demanding proactive measures for prevention and early detection. While developed nations have made strides in reducing bc mortality, the same cannot be definitively claimed for developing countries like india. This article explores the heightened breast cancer risk among female sanitation workers, a predominantly affected workforce in hazardous conditions. Factors such as gender, age, obesity, and night shift work contribute to their increased vulnerability to breast cancer. Examining India's bc landscape reveals a 50% incidence surge over two decades, with a projected substantial increase in new cases. A concerning shift from cervical to breast cancer prevalence is noted, coupled with lower survival rates due to delayed treatment. The study elucidates bc detection methods, emphasizing breast self-examination's potential in resource-limited settings. Given limited infrastructure, the article underscores the need for comprehensive awareness programs tailored to sanitation workers.**Introduction:** In developed countries, breast cancer (BC) mortality has been significantly decreasing due contributions from developed treatment strategies, yet the incidence of the disease has been found to increase. Although this increase can be accounted by improvements in diagnostic technologies it can also be stated that there is a failure in implication of existing BC prevention maneuvers(1)(2). Despite being the leading cancer-related disease burden among women, it is also stated as a fact that bc will affect 1 in every 8 women by 85 years in high-GDP nations. It is a well-known fact that prevention is better than cure and in order to apply that into practise for bc we must make sure the awareness about the disease among women is in an adequate level. Bc development is influenced by both genetic and non-genetic factors. When compared, the non-genetic factors are easier to be kept in check to exercise maximum prevention for, let alone bc but, any disease. The non-genetic factors for bc are age, exposure to radiation, personal history of breast pathologies, high Body-mass index (BMI), exogenous usage of female hormones, alcohol, reproductive factors (shortened breast-feeding periods, low parity, late menopause and early menarche) and exposure to hazardous(carcinogenic) chemicals(3)(4)(5). The 4'd's that describe the work of a sanitation worker are dangerous, dirty, drudgery and dehumanizing. In India, there are almost five million people whose work come under this category. These workers are exposed to various hazardous chemicals and toxic gases from the waste they handle despite having safety equipment that have a questionable quality(6). This is indicated by higher death rates among sanitation workers (9 in every 1000) when compared to general population (7 in every 1000) (7). Women sanitation workers are at a greater risk of exposure, when compared to men, since most of them are engaged in collection and waste segregation(8). The stats discussed about breast cancer were taken from studies conducted in developed countries. India being a developing country it would require much more efforts in prevention strategies than those of the developed countries. The fact that India is one of the leading countries in population should be taken into consideration when discussing the amount of waste handled by sanitation workers. It is found that most women in sanitation work environments are non-literate (9). This would mean that these people would fall short in the awareness level when it comes to a disease like breast cancer. Hence this article aims to emphasise the need for executing prevention and awareness programs about breast cancer among women sanitation workers.

**Keywords:** Breast cancer, Sanitary workers, Awareness programs ,Risk factors.

**Status of breast cancer in India**

The incidence of bc in india had increased by 50% during a 20-yearperiod (1965-1985) (10). A higher proportion of bc occurs in younger Indian women when compared to the western countries[(11)].The 2020 globacon data[fig.1]estimates that india will account for 7.9% (178,361) of new bc cases globally only behind china (18.4%) and the United States of America (11.2%). It also shows there will be gradual increase in the number of new cases from 180,000(2020) to 270,000(2040) within a period of 20 years[fig.2]




In the 1990s, cervical cancer (cc) was a bigger burden than bc across India with only a few exceptions like Mumbai (24.1% bc vs 16.0% cc). The registries of Bangalore, Delhi, Chennai and Bhopal had higher incidence of cervical cancer when compared to bc. However, this scenario had changed in the early 2000s when bc overtook cc in almost all registries except the rural registry of barshi (16.9% bc vs 36.38 cc)[(12)].

The survival rates in different stages of cancer decreases gradually from stage i to stage iii(95%, 92%, 72%) but a drastic drop can be observed when the cancer reaches stage iv (21%)(13). The survival rates are low in india when compared to the western countries mainly due to the early onset, late stage of disease when consulting the physician and delayed treatment[(14)].

According to the international agency for research on cancer(IARC), the best and most effective intervention to control bc is earlier detection of disease and thus rapid treatment. In order to achieve that, there is a need for a good knowledge, attitude and practices among women of all ages and occupation in the prevention of bc.

**Risk factors associated with sanitation workers**

***Gender:***

As obvious as it seems, bc has higher incidence among women than in men due to the differences in the levels of female hormones. This can be accounted by the fact that only 1% of all breast cancer cases were men(15). While the exact statistical data for gender destitution among sanitary workers in india is unavailable, a significant number of women are engaged in door-door waste collection, waste segregation, street sweeping and other such sanitary activities. Many studies done with sanitary workers in india have shown that the weightage of women among sanitary workers are not much different than men and in fact similar to that of men(16)(17)(18).

***Age:***

Following gender, age is considered one of the most important known risk factors for bc. As age increases, the incidence rate of the disease also increases and reaches its peak at the menopausal period(19). A study conducted among sanitation workers in india during the covid 19 lockdown had participants with a mean age of 37.5 years(20). While the small sample size of the study may seem as a limitation, due to the lack of statistical evidences in large scale, this study can be used to interpret that the majority of women in sanitary works are in their pre-menopausal age.

***Obesity:***

In adipose tissue, the conversion rates of androgenic precursors to oestrogen through peripheral aromatization is higher. This results in an increased incidence of breast cancer among women who are obese (Bmi≥ 25.00). Additionally, the increased levels of insulin and insulin-like factors in an obese person are found to spur the growth of cancer cells(21). In a study conducted among 311 sanitary workers, it was found that around 51.5% were obese and 21.5% were overweight(22).

***Night work:***

Working in night hours causes an individual an exposure to artificial light. This exposure, at a time when melatonin levels are supposed to be at its peak, causes a decrease in melatonin production(23). This reduction in melatonin production causes an increase in reproductive hormones such as oestrogen, which is responsible for the hormone-sensitive breast tumours(24). A meta-analysis done to assess the relationship between night work and breast cancer found a 48% increase in the risk of breast cancer(25). A study published in the indian journal of applied economics and business shows that sanitary workers are made to work on irregular shift basis without proper resting intervals for 12 hours which includes both morning and night shifts(26).

## Breast cancer detection & screeningtechniques

***Mammography:***

This is a medical imaging technique that uses x-rays to detect changes in the breast tissues. It has a sensitivity that varies from 34%-90% and a specificity up to 32%-93% (27). Indian women are found to have dense breasts and adding to this the fact that there is a lack of adequate mammography machines and lesser trained professionals to perform the diagnostic technique might lead to false positives(11). Advancements in technology has given rise to digital mammography which uses computer aided detection software resulting in better detection at the cost of an increased price.

***Ultrasonography:***

The ultrasonography uses high pitched sound waves to image the breast tissues. It has a sensitivity ranging from 53%-67% with specificity of 89%-99%[28]. This can be highly useful in detection among younger women aging from 40-49 years but the hurdle in this technique is the availability of trained professional.

***Breast self-examination:***

The breast self-examination is a technique that requires an individual to assess or examine their breast themselves to feel and detect any abnormalities or changes in the breasts. It is not accepted as an early detection technique but when used with proficiency and meticulously it is considered a useful auxiliary to make women aware of their normal breast[29].

**Need for awareness assessment programs among sanitary women**

Early detection followed by immediate institutional therapy is considered the best course of management in bc to decrease the morbidity/ mortality rates and thus improve the long-termsurvival of bc patients. This can be achieved by regular diagnostic procedures. However it is not feasible to implement such methods in a developing country due to the lesser availability of infrastructure and limited trained professionals [29].

Breast self-examination (BSE) is considered as a simple and inexpensive method in early detection of breast lumps[30].When a study assessed the awareness levels about the bc risk factors and BSEpractices, it was found that health care professionals (hcp) had a better awareness level about cancer than women of other socio-economic status. Although this might seem as an obvious observation, around 10% of those hcp did not consider age of menarche & menopause and age at first child birth as a risk factor while those are actually one of the key risk factors when looking into bc[31]. If that's the case of educated and trained professionals, we can say the levels of awareness among lesser educated sanitary workers would be comparatively lesser as well. This calls for a nation- and state-wide awareness assessment and promotion programs.

**Conclusion:**

Thisstudy discusses about the risk factors of breast cancer and how those risk factors correlate with the lives of sanitary workers, the current breast cancer status in india and the available detection techniques. Upon discussion on the above topic, it was found that really not many, if not none of the, studies assessed the awareness levels and the prevention practices among sanitary women. This article calls for research institutions and organisations to promote studies that assess the awareness levels and prevention practices of breast cancer among sanitary women at various levels to achieve a better understanding and promote healthy life practices among sanitary workers and thus a better society.

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# Toilet construction under the Swachh Bharat Mission and infant mortality in India

Suman Chakrabarti[1], Soyra Gune[2], Tim A. Bruckner[3], Julie Strominger[4] & Parvati Singh[4]✉

**Improvement of water and sanitation conditions may reduce infant mortality, particularly in countries like India where open defecation is highly prevalent. We conducted a quasi-experimental study to investigate the association between the Swachh Bharat Mission (SBM)—a national sanitation program initiated in 2014—and infant (IMR) and under five mortality rates (U5MR) in India. We analyzed data from thirty-five Indian states and 640 districts spanning 10 years (2011–2020), with IMR and U5MR per thousand live births as the outcomes. Our main exposure was the district-level annual percentage of households that received a constructed toilet under SBM. We mapped changes in IMR and U5MR and toilet access at the district level over time. We fit two-way fixed effects regression models controlling for sociodemographic, wealth, and healthcare-related confounders at the district-level to estimate the association between toilets constructed and child mortality. Toilet access and child mortality have a historically robust inverse association in India. Toilets constructed increased dramatically across India following the implementation of SBM in 2014. Results from panel data regression models show that districts with > 30% toilets constructed under SBM corresponds with 5.3 lower IMR ($p < 0.05$), and 6.8 lower U5MR ($p < 0.05$). Placebo, falsification tests and robustness checks support our main findings. The post-SBM period in India exhibited accelerated reductions in infant and child mortality compared to the pre-SBM years. Based on our regression estimates, the provision of toilets at-scale may have contributed to averting approximately 60,000–70,000 infant deaths annually. Our findings show that the implementation of transformative sanitation programs can deliver population health benefits in low- and middle-income countries.**

Investments and global commitments to population health have facilitated a remarkable improvement in child survival in low- and middle-income countries (LMICs)[1]. India accounts for one-fifth of the 5.4 million under-five deaths globally[2]. Therefore, reducing infant and child mortality in India is crucial for efforts to reduce the overall global burden. Much of the literature on child survival focuses on access to preventive and curative antenatal and postnatal care[3]. Growing evidence finds that analyses of infant and child mortality should focus on subnational variations in antenatal and postnatal intervention coverage to provide a better understanding of the largest gaps in child survival[4]. However, scant literature examines the effectiveness of large-scale investments, such as in sanitation, to address infant and child mortality.

Prior research documents disproportionately higher growth faltering in early childhood resulting in child stunting (low height for age) rates in India, despite rapid economic progress, relative to other LMICs[5]. This phenomenon, also referred to as the "Asian Enigma", presumably arises from the widespread practice of open defecation. Open defecation carries a substantial negative externality with respect to infant and child health[6]. Proposed mechanisms include repeated infections through the fecal–oral route resulting in dehydration and malabsorption of nutrients following chronic inflammation of the small intestine (tropical enteropathy)[7]. Historically, lack of access to toilets has served as a major driver of open defecation, particularly in rural India. For this reason, expansion of access to sanitation facilities may reduce open defecation which, in turn, may improve infant and child health[6,8,9].

Infant and child mortality due to fecal pathogen-based infections (diarrhea, in particular) and malabsorption of nutrients may decline following improved access to toilets and elimination of open defecation[7,10]. Scholars view sanitation as one of the most important public health interventions of the past century, with dramatic declines

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in infant mortality rate (IMR) following improved sanitation in the United States and other western countries in the early 1900s[11]. Given India's high burden of infant mortality, we would expect large-scale national sanitation programs in the twenty-first century to precede declines in infant and child mortality.

Contrary to theoretical expectations, however, conventional strategies for improving water and sanitation services do not always correspond with sizable improvements in infant and child health. Basic low-cost interventions insufficiently address the multiple pathways through which infants and children are repeatedly exposed to enteric pathogens, especially in highly contaminated settings[12]. Many researchers view the lack of evidence from randomized trials in low open defecation prevalence countries as confirmation of the need for more comprehensive interventions[13]. Given the time and resources needed to implement large-scale interventions experimentally, sole reliance on randomized trials presents feasibility constraints[13]. Examination of evidence from current, large-scale public health programs could offer evidence to inform the design of new interventions.

In this paper, we study one of the world's largest sanitation programs ever undertaken, the Swachh Bharat Mission (SBM) or Clean India Mission. From 2014 to 2020, the government of India constructed over 100 million household toilets and, as a result, declared more than 600,000 villages as free of open defecation[6]. SBM was launched by Prime Minister Narendra Modi on October 2nd, 2014, as a "Jan Andolan" (people's movement) and adopted an intensive, multi-pronged approach to national sanitation[14]. For the period spanning 2015–2020, SBM averaged an annual budget of approximately 1.25 billion USD and comprised the following key components[15–18]:

(a) The SBM aimed to provide subsidized toilets to eliminate open defecation. By 2020, approximately 109 million individual household latrines (IHHLs) were built under the program. Over the same period there was a twofold increase in toilet availability and a decline in open defecation from 60 to 19% in the first 5 years of the campaign[15–18].
(b) SBM's "people's movement" approach included Information, Education and Communication (IEC) campaigns to raise awareness about sanitation and hygiene. With a funding of around $375 million, these campaigns reached rural Indians with an average of 50 messages per month over 5 years[15–18].
(c) SBM invested in capacity building and training programs for government officials, frontline workers, volunteers, and communities to enhance sanitation practices[15–18].
(d) SBM established waste segregation, collection, transportation, and disposal systems, along with treatment plants and recycling centers for effective waste management[15–18].
(e) The SBM introduced mobile and web applications for citizen engagement and monitoring. The National Annual Rural Sanitation Survey (NARSS) was conducted bi-annually to assess progress and provided targeted approaches for underserved regions. Findings were used for delivery augmentation[15–18].

SBM's approach of combining toilet construction with substantial investments in IEC and community engagement differ markedly from prior sanitation efforts in India[18,19]. However, despite the increase in household toilet availability and government reports of considerable reduction in open defecation post implementation of SBM, concerns regarding actual utilization of toilets, sustained behavior change and overreporting of Open Defecation Free (ODF) status of Indian regions remain[20]. We contend that if the 109 million toilets constucted under the SBM program are being utilized, it may be reasonable to expect an associated marked improvement in health and mortality outcomes, particularly among young children. Indeed, recent studies find a significant influence of the program on improving growth and immune-sensitive responses among children[6,9,21,22]. We build upon prior work and examine SBM's relationship with infant and child mortality. In the present study, we exploit spatiotemporal variation from over 600 districts in India across a span of 10 years to estimate the extent to which an increase in district-level household toilet availability post 2014 precedes reductions in infant and child mortality.

## Methods
### Data
India has two national data sources that provide subnational estimates of infant and under five mortality rates. The vital registration system of the Indian Census Bureau (VRS) provides infant mortality estimates at the state-level (n = 36 states and union territories); whereas the District Level Household Surveys (DLHS) (waves two and three), and the National Family Health Surveys (NFHS) (waves four and five) allow estimation of infant mortality at the district-level (n = 640 districts) between[23–27].

Graphical analysis of long-term association between toilet coverage and infant mortality: The DLHS and NFHS are large national household surveys sampled to be representative at the district level. NFHS/DLHS follow a multi-stage design based on village size, with households randomly chosen in each selected village for rural areas. In urban areas, a similar approach was used with Census Enumeration Blocks, randomly selecting households per block. The DLHS corresponds to the years 2002–2004 and 2008–2009, while the NFHS corresponds to 2015–2016 and 2019–2021. We calculate infant and under five mortality rates at the district-level, along with estimates of the coverage of toilets and other covariates for all districts across the surveys. The district-level estimates are subsequently used for analyses.

SBM coverage data: For measuring SBM rollout we use district-level data from the Ministry of Drinking Water and Sanitation, Swachh Bharat Mission Target versus Achievement database[28]. This government database provides data on the number of toilets built from 2014 to 2021 under the SBM for all districts in India, except for nine urban districts. To standardize this indicator, we divided the number of toilets built by the total number of households in each district, as per the Indian 2011 census, resulting in an annual SBM coverage indicator at the district-level expressed as a percentage[29].

Data for primary analysis: We merge SBM coverage data with NFHS data by birth-year of the child and district of residence. We matched birth-years with SBM years to investigate the association between toilets built under

SBM each year and the infant deaths in the same year. Thus, we exploit variation from 6 years of SBM data for 640 Indian districts for estimating the main coefficients of interest.

Data for robustness checks: The VRS provides annual estimates of infant mortality for years 2000–2019 which are considered the most reliable subnational estimates of infant mortality in India. We use the VRS panel data for longitudinal analyses at the state-level.

All datasets used in this study have been made publicly available by the Government of India.

## Outcome

Our primary outcomes comprise (1) infant mortality rate (IMR), defined as the number of children dying before reaching the age of 1 year out of the total number of live births (per thousand), and (2) under five mortaltiy rate (U5MR), defined as the number of children dying before reaching the age of 5 years out of the total number of children born alive (per thousand). The VRS directly provides state-year estimates of the infant mortality. DLHS and NFHS provide complete birth history data, including the month and year of birth and death of the children, reported retrospectively by mothers[4]. These data allow for the calculation of the IMR and U5MR for each year at the district-level. We validated estimates from DLHS and NFHS using the VRS data, ensuring that the state-level means obtained from DLHS and NFHS correspond closely with estimates from the VRS. This ensured that the district-level estimates concur with patterns at the state and national levels.

Other outcomes include child height-for-age (HAZ) and weight for age-z-scores (WAZ) estimated using the WHO growth standards, and episodes of diarrhea and acute respiratory infection (ARI) reported in the 15 days prior to the survey[30,31]. These outcomes are indicators of child health and nutrition.

## Graphical analysis

We employ graphical and regression methods to quantify the relation between SBM and mortality. First, we map the prevalence of IMR and coverage of toilets across Indian districts in 2002–2004, 2007–2008, 2015–2016, and 2019–2021 to gauge spatiotemporal changes. Second, for the same years, we generate scatterplots to visualize the district-level cross-sectional association between IMR and toilet coverage, as well as the association between the annualized change in IMR and toilet coverage. Third, we map the cumulative coverage of toilets built under SBM across districts from 2015 to 2020 to illustrate geographic variation in program exposure over time.

## Exposure and covariates for panel data analyses

For district-level econometric analyses, given the ecological, negative externalities of open defecation and poor sanitation practices, we define our exposure as percentage of households that received a toilet under SBM at the district-level by birth cohort. This served as the continuous treatment variable. We additional constructed a categorical treatment variable to measure the intensity of coverage. For the categorical variable, we binned the SBM coverage by birth cohort at the district-level into the following categories: 0%, > 0 to < 10%, 10 to < 20%, 20 to < 30%, and 30 to ≤ 60% coverage. In any given birth cohort year, no district had more than 60% of households receiving toilets under SBM.

Covariates include the percentage of the population residing in urban areas, caste, religion, and wealth at the district-level. We created a district-wealth variable using a principal component analysis of household ownership and utilization of 33 assets and ammenities (including drinking water, cooking fuel)[32]. Subsequently, the wealth variable was collapsed at the district-level to provide a weighted estimated of district wealth. This wealth variable controls for the possibility of poorer districts being targeted for toilet construction under SBM. We further include health seeking and behavioural factors including the mean number of antenatal care visits provided by a skilled health professional during pregnancy (which could independently reduce IMR and U5MR), as well as percent of hospital births, and BCG vaccination coverage, child birthorder, maternal education, access to health insurance, piped water, and clean cooking fuel. Covariates serve as standard control variables to account for confounding and to explain variation in IMR and U5MR at the district-level over time[33].

## Two-way fixed effects econometric specification

For econometric analysis we merged district-year specific SBM coverage data with NFHS4 and NFHS5 data by district and birth-year. For example, if a child was born in district x in year y, then they would be assigned an SBM coverage level as the percentage of households that received a toilet under SBM in year y in district x.

In our primary specification we fit a two-way fixed effects (TWFE) model using district-level data with the following form:

$$IMR/U5MR_{d,t} = SBM_{d,t}\alpha + X_{d,t}\theta + D_d + BY_t + \varepsilon_{d,t}\ldots \quad (1)$$

Here $SBM_{d,t}$ is the variable of interest that measures SBM toilet coverage or the intensity of SBM coverage by birth cohort at the district-level. $X_{d,t}$ is the full set of covariates, $D_d$ is district fixed-effects that controls for all unobserved district-specific time invariant factors and $BY_t$ are birth year dummies that account for birth cohort specific differences in exposure to SBM that are common across districts. $\alpha$ measures the association of SBM with child mortality and is similar to a difference-in-difference (DID) estimate of SBM toilet coverage coefficient comparing the pre-SBM period to the post-SBM period. Put another way, the parameter $\alpha$ estimates the "net association" between change in SBM-related toilet construction and change in IMR or U5MR. TWFE estimators control for all common time trends and any place-specific characteristics that could otherwise confound results[34]. Standard errors are robust and were clustered at the district-level.

## Placebo and falsification tests

Our TWFE models assume that negative trends in IMR and U5MR were absent in districts eventually treated by SBM. This hypothesis is an extension of the parallel trends assumption that underlies any TWFE model. Since this assumption cannot be directly tested with out data, we conduct three types of tests to support the primary model.

Firstly, we conducted a randomization inference test for the primary model using the RITEST Stata module. This test utilizes the district-level SBM coverage data and randomly assigns it across districts and birth cohort years in our analysis sample. Thereafter, our primary TWFE model with IMR and U5MR as the outcomes is executed, and estimates are derived. This process is repeated for the number of iterations specified in the command. We set this number to a thousand. The test provides an estimate of the probability that our main result was obtained purely by chance.

Secondly, we conducted a fake treatment test using the DLHS and NFHS. The DLHS2, DLHS3, and NFHS4 surveys provide us with a cohort of children born between 1998 and 2014 who were born prior to implementation of SBM. To ensure that there were no differential trends in districts that were later exposed to SBM pre-treatment, we assigned SBM coverage at the district-level by birth year between 2015 and 2018 to the same districts between 2011 and 2014. For instance, 2015 coverage was assigned to 2011. We then re-fit our primary model and estimated coefficients with continuous and categorical treatments. These tests indicate whether sanitation investments made after SBM, align with patterns of mortality reduction in the earlier period.

Thirdly, we applied our primary specification using the NFHS4 and NFHS5 data to a set of placebo outcomes: ≥4 antenatal care (ANC) visits during pregnancy, receipt of services from the Integrated Child Development Services Program (ICDS) during pregnancy, lactation, and childhood, maternal education, alcohol consumption, and clean cooking fuel. ANC and ICDS were used as indicators of exposure to national early childhood programs that can influence IMR and U5MR. Maternal education is a crucial underlying determinant of mortality. Alcohol consumption was chosen as a pure placebo outcome which theoretically should have no association with SBM rollout. Finally, clean cooking fuel served as a surrogate for coverage of the Pradhan Mantri Ujjwalak Yojana (PMJY) which was introduced in 2016.

## Exploring the effects on child health outcomes and interaction effects with contextual factors

To test for potential mechanisms through which SBM can be linked with child mortality and to explore effects on other health and nutrition outcomes, we estimated Eq. 1 with other outcomes including HAZ, WAZ, diarrhea and ARI using the NFHS4 and NFHS5 data at the individual-level.

The mechanism of improved sanitation measures may vary based on availability of healthcare access. We hypoethsized that any potential relationship between SBM and mortality might be more muted in districts with high healthcare access. To further explore this hypothesis, we created dummy variables for districts with high (above the median) versus low (below the median) levels of coverage of BCG vaccinations. Districts with higher coverage of BCG above the median indicate areas with lower disease incidence and consequently lower mortality. We then interacted SBM coverage with this dummy to test if it attenuates SBM effects using Eq. 2 using the NFHS4 and NFHS5 data at district-birth year level.

$$IMR/U5MR_{d,t} = SBM_{d,t}\alpha + SBM_{d,t}BCG_{d,t}\beta + X_{d,t}\theta + D_d + BY_t + \varepsilon_{d,t}\ldots \quad (2)$$

Here, $\alpha$ represents the effects of SBM coverage at low levels of BCG coverage, while $\beta$ estimates the additional effects of SBM coverage at high levels of BCG coverage in the district.

Similarly, given that household water supply may be a necessity for families to use the newly constructed toilets, the results from our models might depend on the quality of water facilities in the districts. To consider the influence of piped water on SBM, we employed an interaction model of SBM coverage with piped water access using Eq. 3.

$$IMR/U5MR_{d,t} = SBM_{d,t}\alpha + SBM_{d,t}Piped_{d,t}\beta + X_{d,t}\theta + D_d + BY_t + \varepsilon_{d,t}\ldots \quad (3)$$

## Robustness check 1: state-level analysis with VRS data

Lastly, using state-year data from the VRS we visualized the deviation in the IMR trend post-SBM (2015–2019) from the predicted trend using pre-SBM data (2000–2014). The predicted trend is estimated using a mixed effects regression model with linear time and its square as fixed effects; and nested random effects for states (intercepts) and state-years (slopes). We fit an interrupted time series (ITS) model with state-year data from 2000 to 2019 using the following equation for state s in year t:

$$LogIMR_{s,t} = Trend_t\alpha + SBM_t\beta + Trend_t \text{ X } SBM_t\pi + S_s + \varepsilon_{s,t}\ldots \quad (4)$$

Here Log IMR is the natural logarithm of IMR to account for its non-linear movement over time. $Trend_t$ is a discrete variable that indexes the years 2000 to 2019. $SBM_t$ is a dummy variable that takes the value 1 for 2015–2019 and zero otherwise. $Trend_t \times SBM_t$ is an interaction term of Trend and SBM that tests for change in the trend of log IMR comparing the pre-SBM to the post-SBM period. $S$ is state fixed-effects that controls for all unobserved state-specific time invariant factors. Broadly, this model produces a within state ITS estimate of the average effect of the SBM on IMR assuming that the pre-SBM trend within states provides a reasonable counterfactual estimate for what would have happened in the absence of the program[35]. We correct standard error estimates for clustering at the state-level. Centering the trend variable at 2015 allows us to interpret the intercept as the value of log IMR at the start of SBM. We fit an additional ITS model excluding the variable $SBM_t$ in senstivity analyses.

### Robustness check 2: individual-level analysis

There are three reasons for using districts as the level of analysis in our study. Firstly, mortality rates are typically calculated for specific geographical areas such as countries, states, and local areas. Since the DHS surveys are sampled to be representative at the district level, this is the smallest area for which we can obtain stable estimates of mortality from the data. Secondly, the DHS surveys do not capture direct individual-level covariates for children who died. For instance, we lack information on whether the mother received care during pregnancy for children who died. Therefore, at the individual level, we are unable to directly adjust for such confounders. By aggregating variables to the district level, we can adjust for a range of child-specific confounders at the district level, although this does mean that inference is made at the district level rather than for individual children. Thirdly, sanitation effects are known to have positive externalities that extend beyond individual households. It is common practice to use sanitation as an ecological-level exposure aggregated to a level above the household (such as communities or districts) to account for these positive effects. Therefore, our preferred estimates are at the district level. However as a robustness check, to complement the district level analysis, we also perform child-level analyses using Eq. 1.

### Robustness check 3: assessing the relationship between cumulative exposure to SBM and mortality

In Eq. 1, our treatment exposure is the percentage of households who received toilets under SBM in a given birth year. As robustness check, we reestimate Eq. 1 using the cumulative percentage of households who received toilets under SBM since the start of the program in a given birth year as the treatment exposure. We hypothesize that particularly in the case of under five mortality, cumulative exposure to the SBM program over multiple years might have a larger association with mortality reductions compared to exposure in a single year. We categorized the continuous cumulative exposure variable into the following bins for our analysis: no coverage of SBM, < 25%, 25 to < 50%, and 50% or above coverage.

## Results

Figure 1 (panels a–d) show a secular decline in infant mortality in India from 2003 to 2020. Initially (2003), the majority of districts had an infant mortality rate (IMR) exceeding 60 per 1000 live births, with a mean of 48.9. However, by 2020, most districts had achieved an IMR below 30, with a district mean of 23.5. Notably, the central and Indo-Gangetic plains regions had the highest burden of IMR in 2020. Panels e–h of Fig. 1 depict the changes in household access to toilets. In 2003, toilet coverage remained relatively low across districts, with less than 40% coverage on average (mean of 46.7%). This coverage showed minimal improvement from 2003 to 2008, and

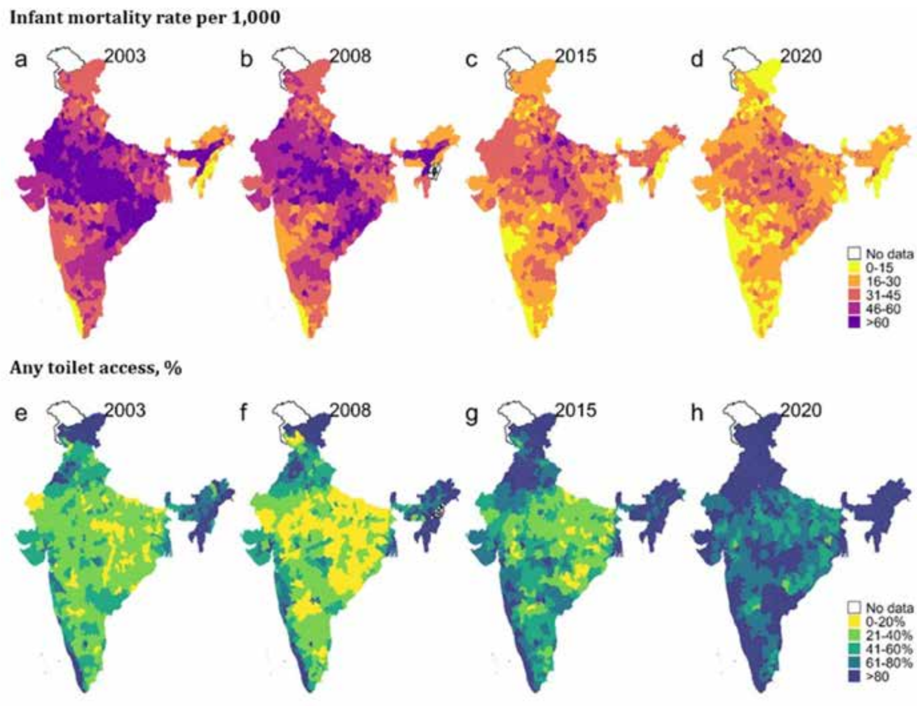


**Fig. 1.** Changes in district-level infant mortality and toilet access in India, 2003–2020.

some districts even witnessed a decline in access. However, by 2015, toilet coverage had substantially improved nationwide. In 2020, the majority of districts boasted toilet coverage exceeding 60% (mean of 81.2%). Figure 2 (panels a and b) demonstrates an inverse correlation between district-level toilet coverage and IMR both in cross-sectional analysis and after accounting for first differences. Whereas a cross-sectional association may indicate the presence of a link in the long run, the first difference plots show that IMR responds to short term changes in toilet access. Table S1 details the temporal distribution of key district-level characteristics from 2002 to 2021.

Figure 3 shows the expansion of SBM coverage between 2015 and 2020. The maps show that SBM coverage across district-years varies from less than 5% to > 90%, suggesting substantial yearly variation in toilet construction across India. Table 1 shows the distribution of outcomes and covariates used in the regression models, stratified by periods before and during SBM. Infant and child mortality was lower in the SBM period compared to the pre-SBM period. SBM coverage was 23% across districts, on average. There were improvements in maternal education, ANC, hospital births, health insurance, and clean cooking fuel. Examination of potential key correlates of SBM shows that SBM coverage varies positively with the availability of piped water (Table S2). Higher SBM coverage also co-occurs with higher utilization of health and nutrition programs, including ANC and institutional deliveries. SBM coverage varies inversely with household size. Together, these results suggest that districts scaled up other health services in concurrence with SBM coverage. However, states where the average household size was higher were slower to scale up SBM, likely reflecting a higher population burden and a greater requirement for toilets.

Figure 4 shows that trends in IMR and U5MR by birth cohort experienced a secular 10 point decline during SBM. Figure 5 shows results from the two-way fixed effects linear regression analyses using categorical SBM exposures at increasing levels. SBM coverage greater than 30% in a district corresponds with with 5.3 fewer infant and 6.7 fewer child deaths per 1000 ($p < 0.05$). Figure 6 presents the predicted IMR and U5MR with SBM formulated as a continuous exposure (percentage of toilet coverage per district). Fixed effects regression analyses indicate a decline in predicted IMR (− 0.09 per 1000 per 1% increase in SBM) and U5MR (− 0.11 per 1000 per 1% increase in SBM) with increased SBM coverage for both outcomes (Table 2).

## Placebo and falsification tests

In Table S3, randomization inference tests show that the probability that our main estimate of reduction in IMR and U5MR in relation to SBM being obtained purely by chance ranges from 0.02 to 0.07 (i.e. very low chance) across our four model specifications. Table S4 shows that re-estimation of the association between our exposure and outcome using a placebo treatment variable does not detect a relation between placebo treatment and IMR and U5MR indicating that birth cohorts that pre-dated SBM did not experience a reduction in IMR and U5MR in district eventually exposed to SBM. In Table S5, application of our primary exposure specification to a set of

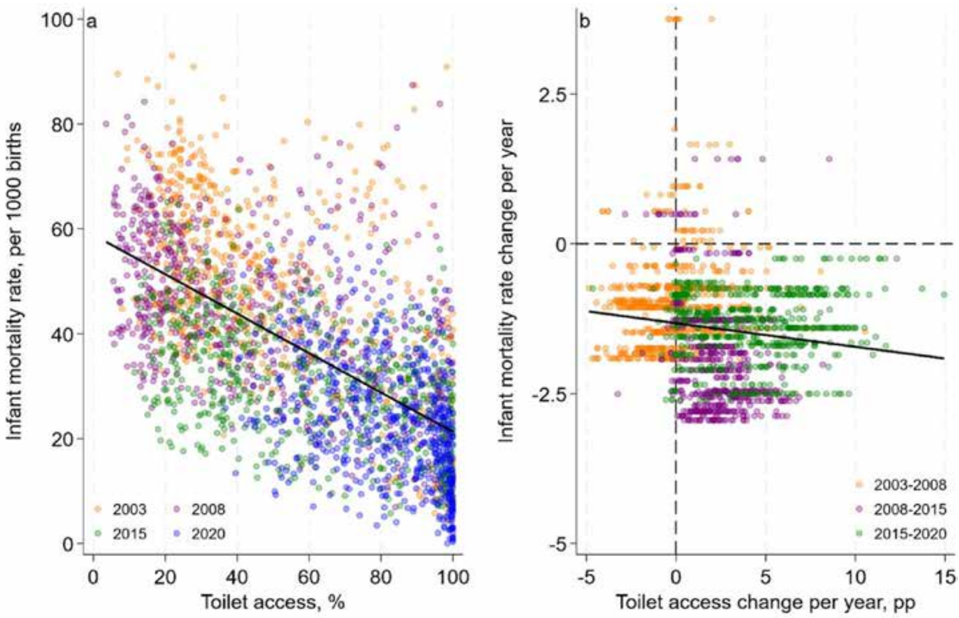


**Fig. 2.** Cross-sectional and first difference district-level association between infant mortality and any toilet access in India, 2003–2020. *Pp* percentage point. *Notes* Panel (**a**)—Cross-sectional scatter plot where each dot is a district. Panel (**b**)—first difference scatter plot where each dot is a district.

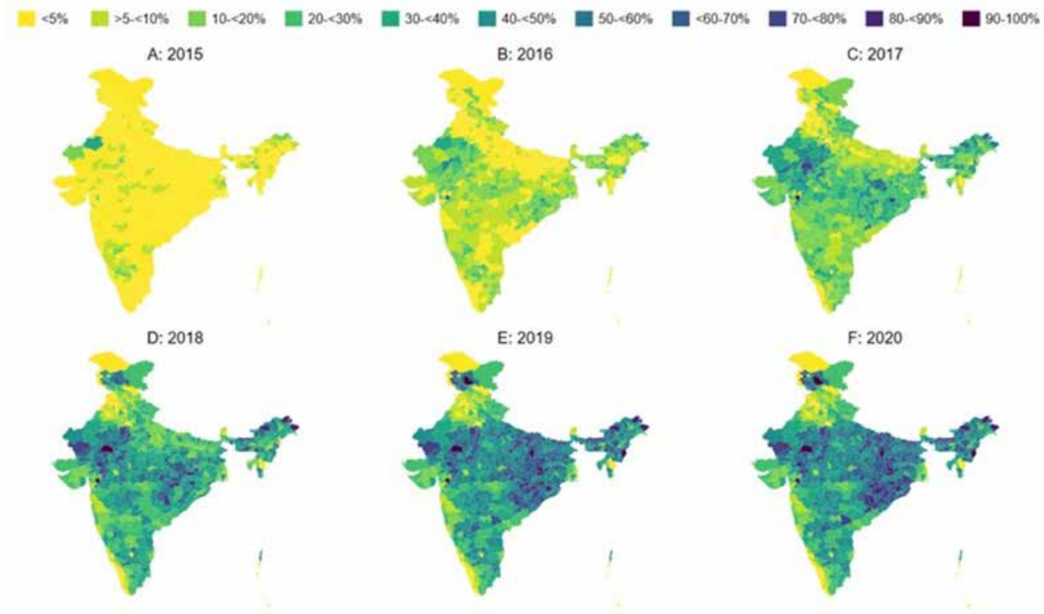


**Fig. 3.** District-level cumulative Swachh Bharat Mission (SBM) coverage, 2015–2020. *Note*: Cumulative SBM coverage was estimated as the proportion of households that were covered by SBM in a given year. The cumulative SBM coverage was calculated using yearly district-level SBM coverage data. SBM coverage in a year was defined as proportion of households which received a toilet under SBM.

| | Before SBM (pre-2015) | | SBM (2015 onwards) | |
|---|---|---|---|---|
| | Mean/% | [95% CI] | Mean/% | [95% CI] |
| Infant mortality rate (per 1000) | 38.3 | [37.1, 39.4] | 32.1 | [31.1, 33.2] |
| Under 5 mortality rate (per 1000) | 41.1 | [39.9, 42.4] | 33.2 | [32.1, 34.3] |
| Cumulative households covered under SBM, % | 0.0 | [0.0, 0.0] | 23.0 | [22.3, 23.8] |
| Mean child birth-order, # | 2.2 | [2.1, 2.2] | 2.0 | [2.0, 2.1] |
| Women who completed 10 or more years of schooling | 32.7 | [31.9, 33.4] | 42.8 | [42.1, 43.6] |
| Women who are Hindu | 72.9 | [71.8, 74.0] | 73.1 | [72.0, 74.1] |
| Women who are Muslim | 14.4 | [13.7, 15.2] | 14.0 | [13.3, 14.7] |
| Women who are Scheduled caste | 19.3 | [18.8, 19.8] | 20.6 | [20.1, 21.1] |
| Women who are Scheduled tribes | 19.4 | [18.3, 20.5] | 19.5 | [18.5, 20.5] |
| Women who are other disadvantaged groups | 37.7 | [36.8, 38.6] | 37.2 | [36.4, 38.0] |
| Women who received 4 or more antenatal care visits from a skilled provider | 49.6 | [48.6, 50.7] | 56.0 | [55.2, 56.8] |
| Women who delivered in a hospital | 78.4 | [77.7, 79.1] | 88.3 | [87.8, 88.8] |
| Children who received BCG vaccination | 89.3 | [88.9, 89.8] | 90.9 | [90.5, 91.3] |
| Urban households | 25.7 | [24.8, 26.5] | 25.0 | [24.2, 25.8] |
| Households with health insurance | 24.9 | [24.1, 25.8] | 37.5 | [36.6, 38.3] |
| Mean number of individuals residing in households | 6.0 | [6.0, 6.0] | 5.9 | [5.9, 5.9] |
| Mean household wealth score | 2.6 | [2.6, 2.6] | 3.0 | [3.0, 3.1] |
| Households with clean cooking fuel | 34.5 | [33.6, 35.4] | 47.9 | [47.0, 48.8] |
| Households with piped water | 43.8 | [42.6, 44.9] | 45.7 | [44.8, 46.7] |
| Observations (district-years) | 2560 | | 3247 | |

**Table 1.** Characteristics of districts before and after the Swachh Bharat Mission (SBM). Data are from the National Family Health Survey waves 4 and 5.

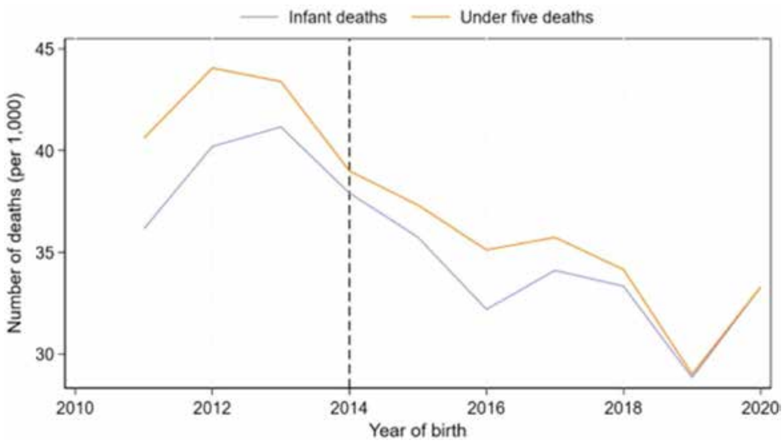


**Fig. 4.** Trends in infant and under-five deaths (per 1000) by birth cohort. *Note*: The mean mortality rate was estimated for each birth cohort by dividing the number of child deaths among infants and children below 5 years in each cohort by the total number of children born in each cohort. The rate was then multiplied by 10,000 to obtain the mean number of infant and under five deaths per 1000 in each cohort. Line placed at 2014 as this was the year SBM was launched.

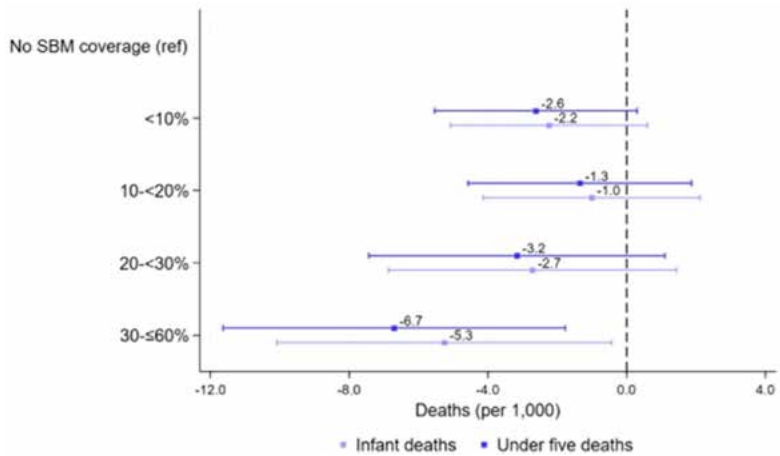


**Fig. 5.** Panel data analysis examining the relationship between intensity of exposure to SBM and infant and child mortality. *Note*: A categorical variable was created using mean SBM coverage among households at the district-level with the following categories: 0%, > 0 and < 10%, 10 to < 20%, 20 to < 30%, and ≤ 60% coverage between 2015 and 2020. The reference group was districts with no toilets constructed under SBM in a particular year between 2015 and 2020. The model includes district-level controls for child birth order, maternal education, religion, caste, access to health services and insurance, and household wealth, cooking fuel, and piped water access. The model includes district-level fixed effects and standard errors are clustered at the district-level.

7 placebo outcomes shows that SBM coverage was not significantly associated with these outcomes except for ANC (0.1 percentage points (pp)), and any ICDS service during pregnancy and lactation (− 0.1 pp).

### Exploring the effects on child health outcomes and interaction effects with contextual factors

Table S6 presents results from the examination of the relation between intensity of exposure to SBM and child growth. We observe evidence of a threshold effect at coverage levels exceeding 30%, where the coefficients on height-for-age z-scores are both substantial and statistically significant (coefficient = 0.18, $p < 0.05$). In Table S7,

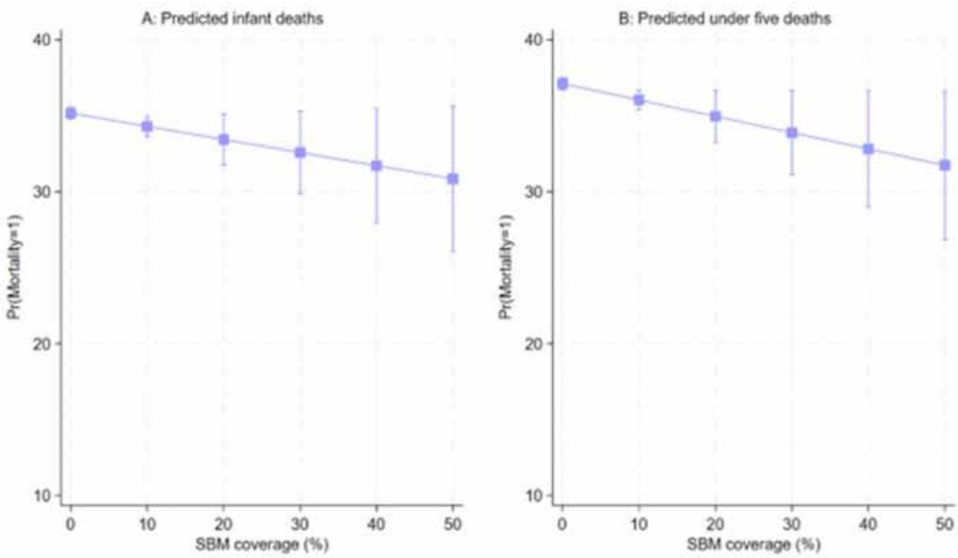


**Fig. 6.** Predicted mortality among infants and children below 5 years obtained from panel data analysis using a continuous SBM exposure and mortality. *Note*: The model includes district-level controls for child birth order, maternal education, religion, caste, access to health services and insurance, and household wealth, cooking fuel, and piped water access. The model includes district-level fixed effects and standard errors are clustered at the district-level.

| | Infant mortality (per 1000) | Under five mortality (per 1000) |
|---|---|---|
| | β [95% CI] | β [95% CI} |
| SBM coverage (%) | −0.09 [−0.19, 0.02] | −0.11 [−0.21, −0.00] |
| District fixed effects | Yes | Yes |
| Controls | Yes | Yes |
| Observations (district-years) | 5807 | 5807 |

**Table 2.** Results of panel data analysis examining the relationship between continuous SBM exposure and infant and child mortality. The model includes district-level controls for child birth order, maternal education, religion, caste, access to health services and insurance, and household wealth, cooking fuel, and piped water access. The model includes district-level fixed effects and standard errors are clustered at the district-level.

examination of the relation between SBM and diarrhea, ARI shows an inverse relation between SBM and both outcomes but does not reach conventional levels of statistical significance at high SBM levels. We attribute this pattern of results to the short recall period of incidence measures for diarrhea and ARI, which may not capture the full spectrum of illness experienced by children. A more ideal measure would be the yearly disease burden at the district-level.

In supplement Table S8, results from interaction of BCG vaccine and SBM coverage show that in districts with low BCG coverage, even small increases in toilet access correspond with reductions in IMR and U5MR. However, we observe an attenuation of this association for areas with high BCG coverage and high SBM coverage, indicating that higher vaccination levels (and attendant health services) may play a key role in reducing infant and child mortality.

In Table S9 interaction tests of SBM and piped water coverage show significant effects at lower levels of SBM coverage (< 20%) when piped water access is low. However, as piped water access increases, these effects at lower levels of SBM coverage appear attenuated. Notably, effects at high levels of SBM coverage (> 30%) appear to be independent of piped water access. Under SBM guideline recommendations, toilets constructed under SBM were encouraged to use twin-pit technology which does not require direct connection of the toilet to the sewage system and the fecal sludge from these toilets only requires to be cleared with water every 2–3 years[15]. Therefore, it is possible that the relation between SBM and child mortality may not rely strongly on access to piped water.

### Robustness checks

Figure S1 (panel A) compares the observed trend in IMR from 2015 to 2020 with an estimated counterfactual trend derived from pre-SBM state-level data spanning 2000 to 2015 (ITS model). We find a noticeable deviation in the observed trend, indicating that IMR reductions occurred more rapidly during the post-SBM period. Panel B (Fig. S1) shows the results of the state-level ITS model based on Eq. 1. IMR exhibited an annual decline of three percent between 2000 and 2015. Furthermore, the post-SBM period witnessed a mean IMR that was ten percent lower compared to the pre-SBM period. Remarkably, the rate of IMR reduction in the post-SBM period was eight to nine percent per year higher than the pre-SBM rate of reduction ($p < 0.001$). In Fig. S2 where we conduct individual-level examination of the relation between SBM and the probability of infant, under five deaths shows a consistent decline in these probabilities with increase in SBM coverage, in alignment with our district-level specification results. Table S10 presents the results of the analysis of examining the relationship between intensity of cumulative exposure to SBM and infant and under five mortality rates. Cumulative SBM coverage between 25 and < 50% in a district was associated with 6.2 fewer infant deaths per 1000 ($p < 0.05$) relative to districts that had no SBM coverage. Interestingly, a cumulative SBM coverage of above 0 was associated with 4.4–7.6 fewer under five deaths per 1000 ($p < 0.05$) with the largest association observed for cumulative coverage between 25 and 50% indicating that exposure to the SBM program through increased coverage has potential persisting benefits for child survival.

## Discussion

India's national sanitation campaign, the Swachh Bharat Mission (SBM), aimed to provide toilets to all households by 2019. As one of the largest global public health interventions, its benefits for infant and child health was explored in this study. Analyzing data from multiple large, nationally representative surveys covering 35 states/union territories and over 600 districts over 20 years, we investigated the relation between increased toilet access under SBM and infant and child mortality reduction from 2000 to 2020. Toilet access and child mortality have a historically robust inverse relation in India. Results from our quasi-experimental analyses suggest for every 10-percentage point increase in district-level toilet access following SBM corresponds with a reduction in district-level IMR by 0.9 points and U5MR by 1.1 points, on average. We further find evidence of a threshold effect wherein the district-level toilet coverage of 30% (and above) corresponds with substantial reductions in infant and child mortality. Similar critical thresholds have also been identified in other recent studies on open defecation[36,37]. In abolute numbers, this coefficient would scale to an estimated 60,000–70,000 infant lives annually. Our study provides novel evidence of reductions in infant and child mortality following a comprehensive national sanitation program in India, potentially indicating the transformative role of SBM.

Our study's strengths lie in its strong internal validity in that we utilize a quasi-experimental design with SBM as a plausibly exogenous programmatic exposure. Our longitudinal analyses control for birth year and district fixed effects, and a number of important control variables, thereby minimizing confounding bias. Leveraging annual district-level toilet construction, we also avoid the atomistic fallacy and consider unsanitary behaviors' negative externality at a larger geographic scale[38]. For LMICs struggling with open defecation, our study also may hold external validity—but of course only replication can establish this case.

Our findings on child mortalty and anthropometry align with evidence from global and South Asian contexts, where multiple studies using population representative surveys have indicated that enhanced sanitation can potentially reduce child mortality rates by 5–30%[39–41]. Furthermore, observational data strongly support the notion that improved sanitation practices in India lead to reductions in child mortality, growth faltering, and incidence of diarrheal disease[8,42,43]. However, it is essential to interpret our findings in light of India's existing primary health care infrastructure, which provides a considerable portion of the population with preventive and curative health services that address various diseases stemming from inadequate sanitation and resulting in child mortality[44]. Consequently, the effectiveness of the SBM may have been influenced by the availability of universal health services. We contend that that the benefits of improved sanitation measures may vary based on availability of comprehensive healthcare access and synergistic programming aspects of the SBM campaign, above and beyond toilet construction, in relation to behavior change and oral-fecal exposure to contaminants. Results from our analysis of interactions between vaccine coverage and SBM support these synergistic effects. Districts that had higher vaccine coverage showed smaller SBM benefits, suggesting that the existing disease environment, gauged by coverage of preventive health interventions, plays a significant role in moderating sanitation benefits.

Our study adds to the growing body of evidence linking large-scale national sanitation campaigns to improved child health outcomes[6,9]. Interestingly, recent research also highlights the broader benefits of increased toilet access, including women's safety, financial savings from reduced medical expenses, and overall improvements in quality of life[45–47]. However, despite these positive benefits, disparities in toilet adoption and usage persist due to caste and religion-based discriminatory practices[48]. Concerningly, some studies indicate that coercive measures and discrimination implemented by local authorities to meet campaign targets have violated individuals' rights, particularly affecting marginalized communities like manual scavengers and lower-caste individuals[49]. These practices pose challenges to the effective and equitable implementation of the SBM, and raise legitimate concerns about the long-term sustainability of hygiene-related behavior change. While this examination falls outside the scope of our present study, we encourage future research to utilize following rounds of national survey data to explore long-term changes in toilet use and its relation to child mortality in India.

### Limitations

Like most observational studies, we acknowledge limitations. We caution readers regarding potential endogeneity in the coverage of SBM. Adoption of SBM presents legitimate issues regarding the non-random distribution of program intensity among districts, which may be correlated with unobserved district features like political dynamics or pre-existing infrastructure. If these features also have an impact on the outcomes we are interested in, they may introduce bias into our estimations. While other researchers have adopted an instrumental variables strategy to address endogeneity in placement of sanitation programs, finding a valid instrument for SBM coverage at the district level is challenging because most instruments (such as distance to political capitals or political affiliation) are directly linked to other determinants of health and sanitation outcomes, violating the exclusion restriction. Thus, we instead decided to use a TWFE strategy, making use of SBM's district-by-district phased deployment and conducted falsification and robustness checks to increase confidence in our estimates. With respect to the degree of detail in program coverage statistics, we also acknowledge that using coverage data at the district level rather than at the village or household level might obscure variations in program implementation and results within a district.

Unmeasured factors that could cause residual confounding would meet the following criteria to be a significant threat to our results: (1) correlate positively with SBM but not be caused by it, (2) vary inversely with IMR and U5MR, (3) exhibit the same regional variation as our SBM exposure across districts over time, and (4) not be accounted for by the set of control variables included in our analyses. Despite our results being supported by several placebo tests and robustness checks, we acknowledge that the parallel trends assumption cannot be directly tested with our data, therefore we cannot interpret our findings as causal. Further, in our falsification tests, we detected a simultaneous scale-up of antenatal care and SBM, however, the analysis showed that potential biases stemming from this variable are likely of a small order. Additionally, we lack cause-specific IMR and U5MR data, preventing differentiation of mortality causes like diarrhea from other reasons. Future studies should explore these disaggregations when detailed and consistent data become available.

## Conclusion
Our study provides evidence of the benefits of India's national sanitation campaign, the Swachh Bharat Mission or Clean India Mission, for infant and child mortality reduction. Our findings add to the growing body of evidence linking national sanitation campaigns to improved child health outcomes and emphasizes the need for similar interventions in other low- and middle-income countries.

## Data availability
All data used in this study are publicly available at https://dhsprogram.com/data/, https://iipsindia.ac.in/content/district-level-household-project and https://www.nitiforstates.gov.in/data-landing. The NFHS and DLHS unit level data cannot be shared by users. The government SBM data were downloaded from https://www.data.gov.in/keywords/SBM. Authors will share state and district-level datasets used in this study via email upon request (s.chakrabarti@cgiar.org).

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## Author contributions

Conceptualization: SC and PS, data curation: SC and PS, formal analysis: SC and SG, funding acquisition: NA, investigation: SC, PS, SG and TB, methodology: SC, SG and PS, project administration: SC, SG, PS and TB, resources: SC, software: SC, supervision: SC, PS and JS, validation: SC, SG, PS and TB, visualization: SC, SG, writing—original draft: SC, PS, TB and JS, and writing—review and editing: SC, SG, PS, TB JS.

## Competing interests

The authors declare no competing interests.

## Additional information

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RESEARCH ARTICLE

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# Sustainable Urban Sanitation and Septage Management: A Study of Small Towns in Uttar Pradesh

*A. K. Gupta* and Mahendra Joshi*

**Abstract: When sanitation is first conceived, its scope is restricted to the removal of human waste using methods such as cesspools, open ditches, pit latrines, bucket systems, and the like. Today, it refers to a more comprehensive concept that encompasses the elimination of solid and liquid waste, the hygiene of food, as well as personal, domestic, and environmental cleanliness. Sanitation is one of the fundamental factors that determines both quality of life and the indicator of human growth. Infections can be avoided altogether by adhering to proper sanitation practices, which stop the contamination of water and soil. As a result, the concept of sanitation is broadened to encompass not only personal hygiene but also the cleanliness of the home, the provision of clean water, the removal of waste products (including feces and urine), and the disposal of waste water. The government of India has implemented the Swachchatam Sarvekshan programme and begun developing protocols like as ODF, ODF+, and ODF++ in order to guarantee the long-term viability of inclusive sanitation infrastructure and the efficient application of these facilities. In light of this, the purpose of the current article is to investigate the state of urban sanitation and the management of septage in a few select small towns in the Indian state of Uttar Pradesh. The information used in the paper has been collected through filed survey.**

## 1. Introduction

Sanitation is vital to a healthy and civilized existence. Sanitation is linked to the environment because it raises the risk of water-borne illnesses. Only larger cities have sewer lines, therefore they only serve a small percentage of the urban population. As a result, most urban Indians use private septic tanks. As a result, increasing basic urban services including water, sanitation, drainage, and solid waste disposal in slums requires building infrastructure and enhancing basic urban services. Affordable and adequate sanitation for the urban poor is also required. The lack of a sewage network, inadequate wastewater treatment plant performance, and poor sanitation service delivery in metropolitan areas all contribute to poor sanitation conditions. Due to a lack of facilities, many slum dwellers defecate in public. Sanitation of water supplies is a challenging endeavor in the country with the second most people on the planet. The industry's troubles stem mostly from municipal governments' disinterest. An environment like India's makes this task even more challenging. Sanitation of the environment is an effort to better people's lives and advance civilization. It includes the sanitary disposal of human waste, both liquid and solid, as well as the management of disease vectors. Sanitation of the environment encompasses both human behavior and physical infrastructure. Most waterborne infections, such as diarrhea, are spread by microorganisms found in human excrement. In India's main cities, massive underground pipelines, pumping stations, and treatment facilities exist. It costs a lot to create and manage these systems since they require constant electricity, lots of water, and expert operators. There is a severe shortage of infrastructure in India's smaller towns, and it is highly doubtful that they will be connected to centralized sewerage systems any time soon. According to the 2011 Census of India, only 32.7% of urban homes use piped sewers, 38.2% use septic tanks, and 7% use pit latrines, indicating the prevalence of onsite systems. Septic tanks, pit latrines, and open defecation pollute groundwater and surface water in many cities around the country. Sludge collection, treatment, disposal, and reuse are tough parts of urban sanitation. Fecal sludge collection, processing, and disposal is lacking in most Indian cities and towns. Sediment and non-fecal detritus collected from on-site sanitation systems such latrines, public toilets, septic tanks, and aqua privies. Septage is septic tank feces sludge. On-site sanitation systems (OSS) are responsible for the majority of facilities. Urban septic tanks and pits are commonly overlooked due to a lack of resources and abilities to monitor cleanliness and maintenance. Despite the use of high-tech cleaning equipment and commercial contractors, certain ULBs lack desludging services. Disposal of sewage waste, especially sludge, poses major health and environmental problems.

Septage refers broadly to feces removed from pit latrines and other similar on-site facilities as well as septic tanks. Fecal sludge is the slurry that builds up in onsite sanitation systems (OSS), such as septic tanks, and contains both solid and liquid waste.

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The collection, storage, or treatment of mixtures of excreta and black water, with or without grey water, results in raw or partially digested slurry. Water that has been tainted by human activity is called wastewater. Sewage is another name for it. It is typically divided into three categories based on how it is produced: storm sewage, industrial sewage, and domestic sewage. Wastewater that can be recycled and treated for re-use is referred to as used waste water.[1]

Swachh Bharat Mission was introduced in October 2014 by the Ministry of Urban Development, Government of India, with the goal of eradicating open defecation and enhancing sanitary conditions in urban areas. The Mission was implemented in all statutory towns for the years 2014–2019. Both the Swachh Bharat Mission (urban) and the Atal Mission for Rejuvenation and Urban Transformation have increased their focus on the importance of sanitation over the last 5 years. While Atal Mission for Rejuvenation and Urban Transformation (AMRUT) 1.0 concentrated on septage and fecal sludge management in addition to water supply in urban centers, Swachh Bharat Mission 1.0 focused on the development of sanitation infrastructure and improving sanitation in order to ensure communities free from open defecation. AMRUT 2.0 aims to provide all urban residents with access to clean water as well as expand the coverage of sewerage and septage, while Swachh Bharat Mission 2.0, which was launched on October 1, 2022, has as its overall goal the creation of Garbage Free Cities.[2]

In 2011, the total population of Uttar Pradesh was 19.96 crore, with 15.51 crore living in rural regions and 4.45 crore living in urban areas, representing 22.28% of the total population. About 16% of India's statutory towns are in Uttar Pradesh. On the other hand, there are 653 urban local bodies in Uttar Pradesh. The management of water supply, drainage, and sewage systems, together with solid waste, are all areas of emphasis. According to the 2011 census, 34.04% of state toilets are piped, while 56.39% use septic tanks. Many toilets discharge into open drains, damaging the environment. We focused on these four towns and cities. These are the regions of Bahraich (located in Eastern Uttar Pradesh), Loni (located in Western Uttar Pradesh), Banda (located in Bundelkhand), and Mirzapur (Eastern Uttar Pradesh). River towns include Ghaghra, which is located in Bahraich, as well as Mirzapur (on the Ganga) and Banda (Ken). AMRUT encompasses all Nagar Palika Parishads. Bahraich is in eastern Uttar Pradesh. In 2011, the town had 186 241 residents and 30 061 homes. The town has nine zones. Despite 87% toilet coverage, there is no sewerage infrastructure or sewage treatment facility. The waste created was calculated as 27 MLD. As a result, wastewater and fecal sludge management infrastructure is lacking. Loni is a city in Ghaziabad district with 512 296 inhabitants distributed into 14 zones. This area has 91 138 households. Coverage of latrines (individual or communal) was 99.94%, and sewerage network coverage was 5.10%. There is a 22.5 km sewer network and a 30 MLD sewer treatment facility with a 50% treatment efficiency. Banda is a rocky town in Bundelkhand. The city has 160 473 residents, distributed into 31 wards and 28 748 dwellings. SLIP reported 57.55% coverage of latrines under AMRUT. The sewerage network is 14.3 km long and covers barely 4% of the town. 11 563 households will need septage management in 2021. Mirzapur is on the Ganga in eastern Uttar Pradesh. It has a population of 233 691 and 35 wards. It is estimated that 34 029 houses have latrines. Although sewage systems service roughly 40% of homes, the effectiveness of wastewater collection is said to be less than 40%. The length of the sewage network was 240.4 km, and it had a capacity of 18 million liters per day. 16 875 households will need septage management in 2021. The majority of the state's ULBs do not have adequate sewage and fecal sludge management. Although there is a mechanism in place for emptying sewer lines and de-clogging septic tanks, septic tanks are not cleaned on a regular basis, and private operators only empty them when they are alerted of an overflow. They are self-contained and dump feces in open drains, water bodies, and open areas because most septic tanks are not designed to scientific or industry standards, environmental degradation is more likely. Fecal sludge is not properly treated or disposed of in the selected municipalities. This increases ground water contamination. As a result, proper septage and fecal sludge control is required. It would also be essential to set up and operate a sewage treatment plant in each of the nominated communities.

### 1.1. Review of Literature

Sanitary facilities, such as toilets and systems for the disposal of septage, are often lacking in the majority of Indian towns. To adequately address the issue of sewage sludge and septage, a comprehensive plan is required, one that is both acceptable and cost-effective for a wide range of communities and individuals.[3] Sludge management and ecological sanitation in Indian cities need urgent improvement.[4,5] WSP says the lack of infrastructure to safely carry waste from septic tanks and pits is a big issue in many municipalities and states.[6] Municipalities normally provide manual septic tank and pit removal, or privately operated honey suckers. Finding an alternative to traditional STPs for sewage sludge is difficult. AECOM & Sandec and WSP-TARU say that collected rubbish is normally dumped in the open.[7,8] The six technological and physical elements that determine the choosing of a user interface are 1) location and 2) ground type. In certain old cultures like China and India, night soil manure is still utilized, but artificial fertilizers have mostly supplanted it. Night-soil manure is still used in Japan, Vietnam, the Netherlands, and Scandinavia.[9] Pumping septage from a cesspool or other treatment facility is called septage. Scum rises to the top of the septic tank, sludge sinks. Septage has a nasty odor and appearance. With so much oil, grit, hair, and other debris, it attracts a wide range of illnesses. Septic tanks generate a lot of septage. In horizontal, continuous flow sedimentation tanks, with this device, you can settle and digest waste. Anaerobic degradation of wastewater solids and organic matter accumulates near the tank bottom. Oil and grease, for example, will float to the surface of the liquid. It is called "scum" by some. Sludge and scum together fill half to two-thirds of the tank's capacity (prior to de-sludging). A soak-away pit should be built after a septic tank to transport sewage into the earth. Most of the rain runs into a nearby storm drain. Anaerobic digestion produces sludge and scum that settle to the tank's bottom for months. From a "traditional centralized sewerage system" to a "holistic framework," The National Urban Sanitation Policy (NUSP) of India has undergone some changes. The National Urban Sanitation policy (NUSP) was the impetus behind the creation of the city sanitation plan (CSP) framework as well as the urban sanitation awards (USA). The lack of specific guidance on septage management in NUSP standards allowed for greater policy formation and state responsibility. Scavenging is prohibited by municipal building codes and institutional laws controlling the creation, powers, and obligations of local authorities and organizations. The Environmental Protection Act of 1986, the Municipal Act of Ontario, and the Water Pollution Act of 1974 are the pieces of legislation that control the regulation of effluent and sewage discharges. Solid waste management (SWM) rules of 2016, mandates that this be done. The solid waste management rules of 2016 authorize the recycling or composting of septage in sanitary landfills. The National Building Code of India (also known as BIS) requires that drainage fields and leach pits be installed (BIS). The Prohibition of Manual Scavengers and Dry Latrines Act of 1993 places restrictions on the use of manual scavengers and dry latrines, which are restrooms that do not contain a water seal or flushing mechanism. The Prohibition of Employment as a Manual Scavenger and their Rehabilitation Act of 2013 made "hazardous" sewage and septic tank cleaning illegal. For more information, see the CPHEEO Sewerage and Wastewater Treatment Manual, 2013. Most Indian cities lack data on onsite sanitation infrastructure, toilets, and septage disposal practices. The issue of sewage sludge and septage/sewerage needs to be addressed comprehensively, with a strategy that is acceptable and cost-effective for all communities and individuals.[10] Poor sludge management and ecological sanitation are widespread problems in Indian cities.[4,5] According to WSP, there are significant differences between municipalities and states in terms of the removal of septic tank sludge and the safe evacuation of cesspools. While some cities provide these services, most homeowners use manual or mechanical sweepers to clear pits and septic tanks.[6] Few sewage sludge treatment plants exist, and those that do typically use co-treatment. The trash is routinely thrown out in the open.[7,8] The selection of a user interface is based on a combination of technological and physical factors, including the following: 1) a suitable location; 2) groundwater levels; 3) contaminants; 4) water availability; and 5) climate.[9] Depending on the circumstances of the specific location, a number of different methods can be used to prepare night-soil manure.[11,12]Mexico, dubbed "the world's dry sanitation capital," is a forerunner in this industry.[13] The rising demand for organic fertilizers has given this old practice fresh life in recent years. Chemical fertilizer's severe ecological repercussions, as well as the natural environment, have rekindled interest.[14] The fact that it is located in the Himalayan desert, which is known for its harsh climate, makes it a challenging endeavor.[15–18] The need to enhance yields has led to an overuse of artificial fertilizers and pesticides in recent years.[19] As a result, the ecosystem's long-term consequences are clear.[20] The study area lacks suitable soils, nitrogen, and water for plant growth.[21] Winter snowfall not only ruins terraced fields but also causes soil nutrient leakage.[22] Using this method year after year depletes the soil's fertility. Organic manure is always in high demand in Lahaul valley to replenish lost soil fertility and increase harvests. Due to animal population shortages, grown manure cannot meet high demand. Night-soil manure was used by farmers seeking a different manure.[16,23] Until recently, farmers in the Lahaul valley used night-soil for manure.

Source segregation, collection, transportation, and processing are the main focuses of Swachch Bharat Mission 2.0, along with efficient management of construction and demolition waste, plastic waste management, including a reduction in single-use plastic, and remediation of all legacy dumpsites. Additionally, it emphasizes maintaining the ODF status and avoiding slippage. Along with making sure that all waste (used) water and fecal sludge are safely contained, transported, processed, and disposed of, so that neither of them pollutes the ground or water sources. Water supply for urban residents, water resource preservation, and the development of infrastructure for the control of feces and septage are all highlighted in AMRUT 2.0. The financial outlay for SBM-U 2.0 is Rs. 141 600 crores, which is more than 2.5 times the outlay for the previous phase of Rs. 62 009 crores and includes the central share of Rs. 36 465 for 2021–2022 to 2025–2026. The Hon. Prime Minister introduced SBM-U 2.0 on October 1, 2021. It concentrated on maintaining sanitation and solid waste management which is likely to result and accelerating momentum to realize the Mission's goal of Garbage Free urban India. The Mission will be entirely digital and paperless, relying on digital technology for complete transparency and accountability through GIS—mapped waste management infrastructure, a strong user interface, an online grievance redressal system, and end-to-end online monitoring of projects from project creation to fund release.[24]

In order to safeguard people and the environment, sanitation systems are a collection of several functional units that together enable managing, reusing, or discarding the various waste flows from households, institutions, agriculture, or industry. The systems are made to address the entire water cycle as well as the nutrient cycle, starting with the person using the toilet and the production of wastewater and continuing through collection, treatment, and reuse or disposal. Off-site conventional sanitation systems typically relate to massive sewer networks with centralized, cutting-edge treatment facilities. These systems may be effective and have made a significant contribution over the years to both lowering the environmental impact of wastewater discharge and enhancing public health. However, they consume a significant amount of water, which is combined with wastes and excrement to produce wastewater that is extremely polluted. The centralized treatment stations for these slurries not only have high construction and operating costs, use a lot of energy and chemicals, and require a lot of management, but the nutrients are also lost to the air or are ultimately disposed of in landfills. By using less water (e.g., dry systems) and enhancing the recovery and reuse of nutrients and energy, conventional wastewater treatment systems have a significant amount of potential to be improved and made more sustainable. Excreta and wastewater are collected, stored, or treated on the property where they are produced in an on-site sanitation system. The degree of treatment could be anything from minimal to advance. Septic tanks and pit latrines (without treatment) are two examples (primary treatment of wastewater). Fecal sludge management (FSM) systems, in which on-site waste is handled at a distance, are typically connected to on-site sanitation systems. Only when a piped water supply is present inside or close to the structures can wastewater (sewage) be created. The wastewater component of on-site sanitation is referred to as a decentralized wastewater system in a similar phrase. Similar to that, an onsite sewage facility can handle the treatment of locally generated wastewater.

 

In the last 5 years, sanitation has received more attention from the Swachh Bharat Mission (urban) and the Atal Mission for rejuvenation and urban transformation. The SBM (U) database estimates that 6.16 million individual household toilets, 0.59 million public restrooms, and 4324 cities are free of open defecation. A database maintained by the Ministry of Housing and Urban Affairs shows that, as of July 2019, 109 fecal sludge treatment plants constructed under the AMRUT programme were complete. The sanitation industry has made exceptional progress, and this accomplishment is admirable. Despite notable physical advancement, there is concern over the neglect of inclusive and equitable strategies to help marginalized urban communities. Cities are becoming more aware of the importance of equity and inclusivity.

Sustainable sanitation entails the development and upkeep of sanitation infrastructure, the regular provision of sanitation services, and the maintenance of open defecation-free communities. Equity and inclusiveness must be incorporated into planning, designing, implementing, regulating, monitoring, and management in order to comprehend urban sanitation challenges, particularly for the sustainable sanitation entails the development and upkeep of sanitation infrastructure, the regular provision of sanitation services, and the maintenance of open defecation-free communities. Equity and inclusiveness must be incorporated into planning, designing, implementing, regulating, monitoring, and management in order to comprehend urban sanitation challenges, particularly for the urban poor. This emphasizes the requirement for cutting-edge technology to improve accessibility, safety, and security for women, the elderly, people with disabilities, transgender people, and other vulnerable groups in public locations like workplaces, schools, health facilities, markets, parks, and transportation hubs. To achieve citywide inclusive sanitation, it will be necessary to monitor the use and access of equitable sanitation infrastructure as well as to comprehend unequal access and variability throughout the sanitation chain. Some issues with toilet cleanliness included inadequate toilets, filthy toilets, clogged toilets, and toilets used frequently, foul odors, toilets filled to the brim, toilets blocked, and subpar building materials. Some of the biggest issues with open defecation and the sustainability of sanitation include a lack of water facilities in home toilets, early certification of ODF, poor quality toilets, a lack of room for toilet construction, and discomfort when using communal toilets.[25]

### 1.2. Objectives and Methodology

The purpose of this study is to investigate the current state of urban sanitation, as well as the management of septage and fecal sludge in a small town in Uttar Pradesh, and to make policy recommendations for achieving sustainable sanitation. The present paper has following main objectives:

- To examine the status of sanitation in selected urban centers;
- To examine the outreach and accessibility of sanitation infrastructure and uses of toilets by the urban dwellers;
- To assess the utilization of urban sanitation services by urban dwellers;
- To suggest policy measures for sustainability of sanitation and effective management of septage and fecal sludge.

The paper is based on primary data, collected through field survey in Loni (Ghaziabad, Mirzapur, Banda, and Bahraich towns of Uttar Pradesh). The quantitative technique has been adopted for collecting field data; however, it has also applied analytical and descriptive research approach. The survey has been conducted with the help of structured interview schedule for urban dwellers. Overall, 609 urban households were surveyed in all the selected cities. The field's data have been processed through the use of SPSS while data have been interpreted, discussed, and analyzed along with critical review of pertinent literature.

The paper has its own limitations. The paper is based on a major research study that was conducted in state of Uttar Pradesh. Only four small towns/cities were selected in the sample of study. The paper focuses mainly on septage and waste water management in small cities/towns of the state. These towns were covered under Swachch Bharat Mission as well as Atal Mission for Rejuvenation and Urban Transformation during 2014–2019.

The bar charts have used to show the comparison of research findings and ensuring more data visibility. The city wise variation in outreach and accessibility of sanitation infrastructure and sanitation services emerge due to existence of partial centralized sewerage system in Mirzapur and Loni cities while other two cities are depend on on-site sanitation system.

### 1.3. Analysis of Research Findings

Sanitation is an essential part of human development and a healthy, civilized life. Sanitation is linked to the environment because it reduces the incidence of water-borne infections, which leads to poor health. Larger cities have sewer systems, thus they only service a tiny percentage of the urban population. As a result, many Indian cities still use individual septic tanks. As a result, improving essential urban services like water, sanitation, drainage, and garbage disposal in slums is critical. It is also necessary to provide adequate sanitary facilities for the urban poor. Most of the country's towns and cities suffer from a lack of cleanliness due to the absence of a sewage network, inadequate operation of sewage treatment facilities, and inadequate provision of sanitation services in metropolitan areas. It is a challenging endeavor to provide sanitation that is ecologically sound to the country that has the second highest population in the world. The difficulties facing the urban sanitation sector stem from municipal governments' poor priority. This endeavor is made more challenging in India, where new paradigms of plans, programmes, and initiatives might challenge people's customs and beliefs. Environmental sanitation seeks to improve people's lives while simultaneously advancing society. This includes disposing of human waste, controlling disease vectors, and providing personal and home hygiene washing facilities. Environmental sanitation includes both behavior and facilities. The vast majority of diseases that are transmitted by water, such as diarrhea, are caused by germs that are found in human feces. By a significant margin, the feces-to-mouth route is the most important mode of transmission. This mechanism operates in a variety of different ways. The management of feces at home is typically the fundamental intervention that has the greatest positive impact on health. This is due to the facts that a) the majority of activities pertaining to hygiene take place in or close to the home, and b) the improve-

**Table 1.** Accessible to toilet/latrine facility (source: field survey).

| City | Individual/Separate | Individual /Combined | Public | Community | Total |
|---|---|---|---|---|---|
| Mirzapur | 154 | 3 | 0 | 0 | 157 |
| | 98.1% | 1.9% | 0.0% | 0.0% | 100.0% |
| Loni | 146 | 0 | 5 | 0 | 151 |
| | 96.7% | 0.0% | 3.3% | 0.0% | 100.0% |
| Banda | 123 | 22 | 2 | 2 | 149 |
| | 82.6% | 14.8% | 1.3% | 1.3% | 100.0% |
| Bahraich | 94 | 58 | 0 | 0 | 152 |
| | 61.8% | 38.2% | 0.0% | 0.0% | 100.0% |
| Total | **517** | **83** | **7** | **2** | **609** |
| | **84.9%** | **13.6%** | **1.1%** | **0.3%** | **100.0%** |

ment of hygiene practices typically begins with the household. Secondary barriers stop feces-borne germs from reproducing and spreading to new hosts once they have been introduced into the environment by feces or hands. The practice of washing one's hands before handling food, preparing, cooking, storing, and reheating food are examples of secondary barriers that help lower the likelihood of pathogens surviving and growing. Water and proper sanitation create a barrier that separates humans from the toxins that are found in nature. The number and percentage of individuals who do not have access to sanitation services continues to climb, despite a decade of attention being focused on the plight of the urban poor and the lack of access to clean water. Even though the percentage of urban residents with access to sanitation systems is relatively high (63%), the rate of access for the urban poor is significantly lower.

Thus, developing country governments and local governments face an increasing sanitation challenge. Unsanitary circumstances often have ramifications beyond their origins. Untreated human and residential waste can affect not only the local ecosystem, but also groundwater, lakes, and rivers. Many Indian cities get their raw water from reservoirs 30–50 km distant. Environmental pollution not only endangers public health but also poses a huge financial burden on cities. Urban pollution is a key impediment to sustained economic progress in emerging countries.

Accessible to toilet/latrine facility is shown in Table 1. Most of the respondents reported that they have access to toilet facilities. However, about 38% respondents in Bahraich had combined household toilet facility. A negligible proportion of respondents in Loni and Banda were found using public/community toilets.

The majority of respondents stated that they do have access to sanitary facilities of some kind. Nevertheless, over 38% of those polled in Bahraich had a combined household toilet facility. A negligible proportion of respondents in Loni and Banda were found using public/community toilets. About 29% respondents revealed that there is sever line facility in their areas. However, piped sever network facility in Bahraich was found to be defunct. The availability of sever line facility was recorded high in Mirzapur (50.3%) followed by Banda (32.2%).

Main problem in their areas is shown in Table 2. Lack of toilets, inadequacy of toilets, flies and termites, disposal of local sludge in area, blocking of toilets, dirty toilets, dilapidated toilets, long distance of toilets, filling of tank of toilets are some of the main problems being faced by the residence.

Most of the respondents reported that they have flush toilet facility in their house. However, a negligible proportion of respondents in Banda and Loni were found depending on community toilet. Lack of toilets, inadequacy of toilets, flies and termites, disposal of local sludge in area, blocking of toilets, dirty toilets, dilapidated toilets, long distance of toilets, filling of tank of toilets are some of the main problems being faced by the residence. About 1/4th respondents in Mirzapur reported that their toilets are connected with sever line. Thus, most of the respondents reported that they are depending on septic tank. It is to be noted that partial coverage of sever line has been reported in Loni and Banda and thus, a significant proportion of household have got connection of their toilet with sever line besides connecting with septic tank.

Sixty-two percent of people who took the survey said that their septic tank is positioned on the inside of their home. It was found to be more prevalent in Loni, where it made up 80.1% of the population, followed by Mirzapur (79.8%). More than half of the respondents in Bahraich reported that septic tank is located in front or backside of their house. Similarly about 2/5th respondents in Banda admitted that septic tank is located inside or backside of their house (**Figure 1**).

**Figure 2** depicts the overall layout of the septic tank. More over half of those who participated in the survey said that they have a septic system with two pits. After Banda, Bahraich was the language in which it was discovered to be pronounced the most. On the other hand, more than half of the people who responded said that they have a single pit septic tank in their homes in Loni and Mirzapur. The majority of people who responded to the survey in Bahraich and Banda said that their homes have three outhouses or pit toilets.

The question that who constructed the septic tank was posed to those who took part in the survey. The majority of respondents disclosed that Mason was responsible for the construction of their septic tank without receiving any expert guidance. Even a sizeable percentage of people who participated in the survey in Mirzapur and Loni indicated that the septic tanks were built by laborers. Therefore, around 12% of respondents in Mirzapur confirmed that septic tanks were built under the direction of technical professionals (**Figure 3**). The time period of the construction of sep-

**Table 2.** Main problem in your area (source: field survey).

| Problems | Mirzapur | Loni | Banda | Bahraich | Total |
|---|---|---|---|---|---|
| Lack of toilets | 0 | 1 | 125 | 124 | 250 |
| | 0.0% | 0.7% | 83.9% | 81.6% | 41.1% |
| Inadequate of toilets | 0 | 1 | 73 | 21 | 95 |
| | 0.0% | 0.7% | 49.0% | 13.8% | 15.6% |
| Dirty toilets | 0 | 0 | 4 | 2 | 6 |
| | 0.0% | 0.0% | 2.7% | 1.3% | 1.0% |
| Dilapidated toilet | 1 | 4 | 6 | 5 | 16 |
| | 0.6% | 2.6% | 4.0% | 3.3% | 2.6% |
| Blocking of toilet | 1 | 0 | 1 | 6 | 8 |
| | 0.6% | 0.0% | 0.7% | 3.9% | 1.3% |
| Poor maintenance of toilet | 0 | 0 | 0 | 4 | 4 |
| | 0.0% | 0.0% | 0.0% | 2.6% | 0.7% |
| Long distance of toilet | 0 | 3 | 1 | 5 | 9 |
| | 0.0% | 2.0% | 0.7% | 3.3% | 1.5% |
| Insecurity use of toilet in night | 1 | 1 | 0 | 0 | 2 |
| | 0.6% | 0.7% | 0.0% | 0.0% | 0.3% |
| Bad odor from toilet | 1 | 1 | 0 | 3 | 5 |
| | 0.6% | 0.7% | 0.0% | 2.0% | 0.8% |
| Lack of electricity in toilet | 0 | 0 | 0 | 2 | 2 |
| | 0.0% | 0.0% | 0.0% | 1.3% | 0.3% |
| Filling of tank of toilet | 0 | 0 | 6 | 4 | 10 |
| | 0.0% | 0.0% | 4.0% | 2.6% | 1.6% |
| Use of toilet is costly | 0 | 3 | 1 | 1 | 5 |
| | 0.0% | 2.0% | 0.7% | 0.7% | 0.8% |
| Disposal of local sludge in area | 0 | 0 | 0 | 17 | 17 |
| | 0.0% | 0.0% | 0.0% | 11.2% | 2.8% |
| Breakage of pets | 0 | 0 | 0 | 5 | 5 |
| | 0.0% | 0.0% | 0.0% | 3.3% | 0.8% |
| Flies and termites | 3 | 0 | 0 | 17 | 20 |
| | 1.9% | 0.0% | 0.0% | 11.2% | 3.3% |
| Lack of privacy in toilet | 1 | 1 | 0 | 2 | 4 |
| | 0.6% | 0.7% | 0.0% | 1.3% | 0.7% |
| Multi users of toilets | 1 | 0 | 0 | 4 | 5 |
| | 0.6% | 0.0% | 0.0% | 2.6% | 0.8% |
| No problem | 0 | 3 | 0 | 0 | 3 |
| | 0.0% | 2.0% | 0.0% | 0.0% | 0.5% |
| Cannot say/do not know | 0 | 1 | 1 | 1 | 3 |
| | 0.0% | 0.7% | 0.7% | 0.7% | 0.5% |
| Others | 0 | 0 | 0 | 4 | 4 |
| | 0.0% | 0.0% | 0.0% | 2.6% | 0.7% |

tic tanks is depicted in **Figure 4**. About one-third of those who participated in the survey stated that they had built a septic tank during the past 5 years or less. On the other hand, approximately half of those who participated in the survey mentioned that they had built their septic tank during the past 5–15 years. In addition, around 20% of respondents claimed that they had built their septic tank more than 15 years ago.

Eighteen percent of those who participated in the survey said that their septic tanks are not yet full. After Mirzapur (where it was detected in 95% of the cases), Banda was the next most common place to find it (85.5%). According to the responses, almost 20% of people's septic tanks were full between the ages of 3 and 15 years. **Figure 5** illustrates how often septic tanks should be pumped out and cleaned. A sizeable number of those who participated in the survey stated that they empty and clean their septic tanks anywhere between once every 3 and 15 years. Cleaning of septic tank is shown in **Figure 6**. Septic tanks are being cleaned by mainly suction machine of ULBs, private machine operators, and contractors. However, about 1/4th respondents admitted that they themselves cleaned septic tank with the help

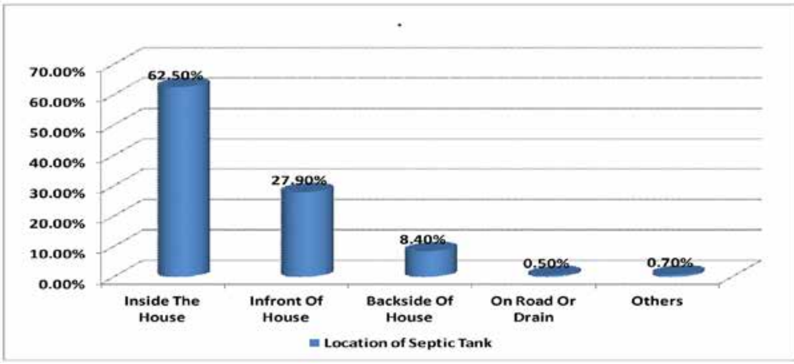


**Figure 1.** Location of septic tank.

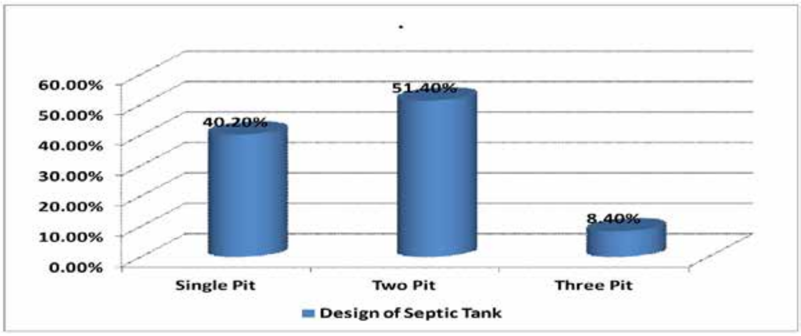


**Figure 2.** Design of septic tank.

of labors. It was found higher in Bahraich followed by Banda. **Figure 7** presents the costs associated with the cleaning of septic tanks. Two out of every five respondents admitted that the amount of money needed to clean a septic tank was less than 1000 rupees. However, more than half of the respondents admitted that the cost of one time cleaning of septic tank was more than Rs. 1000. Place of water was fecal sludge being disposed is shown in

**Figure 8**. Majority of the respondents were not aware about the places of waste wear/fecel sludge disposal. However, waste

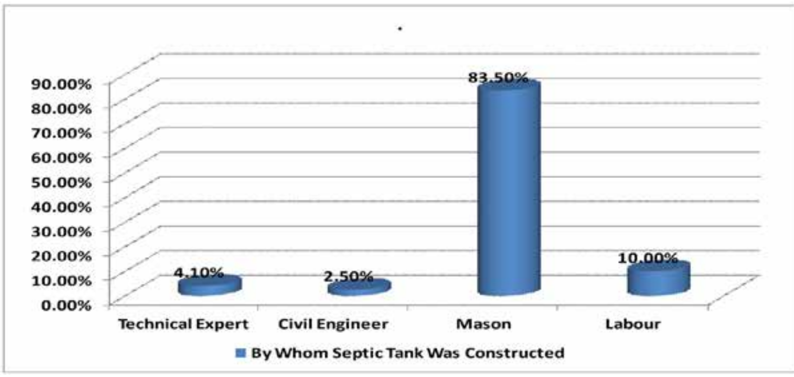


**Figure 3.** By whom septic tank was constructed.

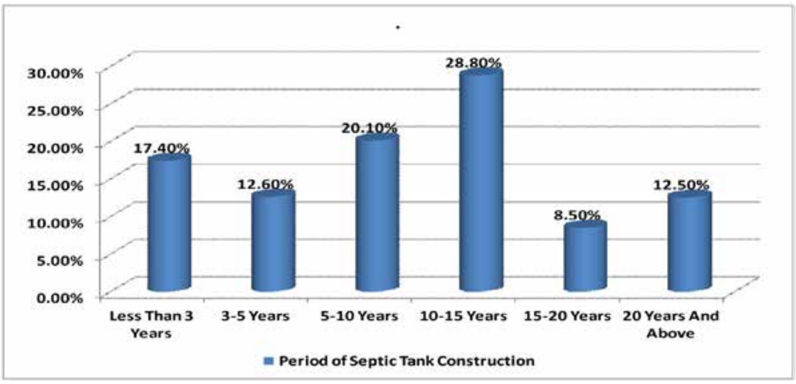


**Figure 4.** Period of septic tank construction.

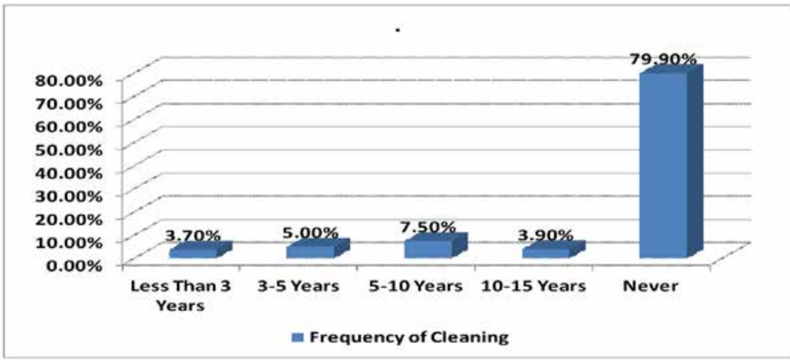


**Figure 5.** Frequency of cleaning of septic tank.

water and septic tank sludge are not being properly collected, treated, and scientifically disposed off in many local bodies.

The respondents were asked that whether they agree that septic tank need to be cleaned at interval of 3 years. About 60% respondents were found agreed on the view point that septic tanks will be regularly cleaned on the interval of 3 years period. However, a large proportion of respondents in Mirzapur and Loniwere against the view point (**Figure 9**).

Lack of access to the septic tank by suction machines or truck loaders, lack of funds, lack of public awareness, lack of adequate cleaning equipments, lack of truck loaders, lack of technically qualified municipal staff, and lack of sludge operators are the primary challenges associated with the cleaning of septic tanks.

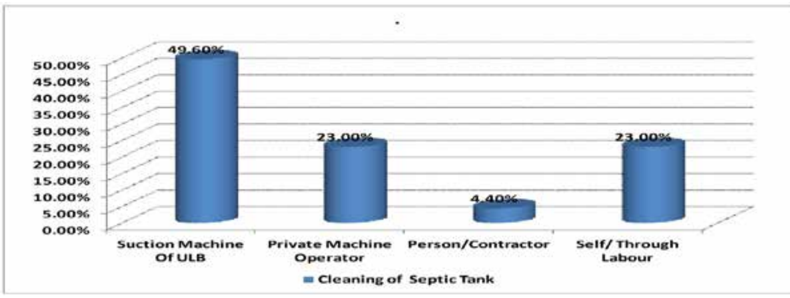


**Figure 6.** Cleaning of septic tank.

 

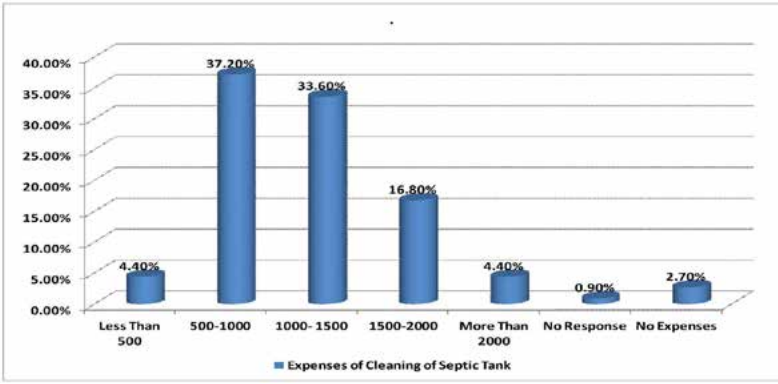


**Figure 7.** Expenses of cleaning of septic tank.

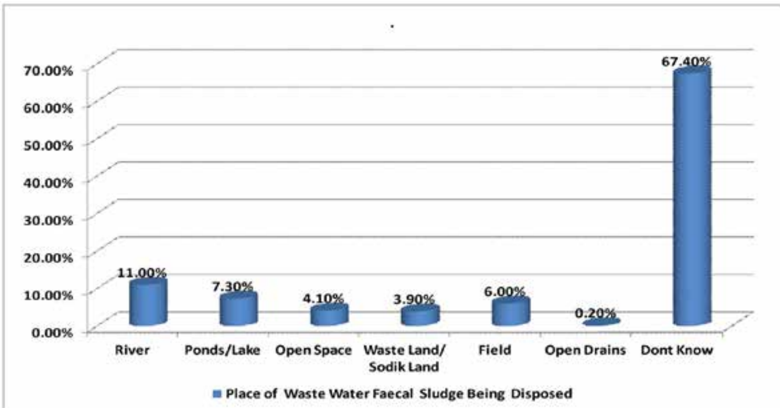


**Figure 8.** Place of waste water fecal sludge being disposed.

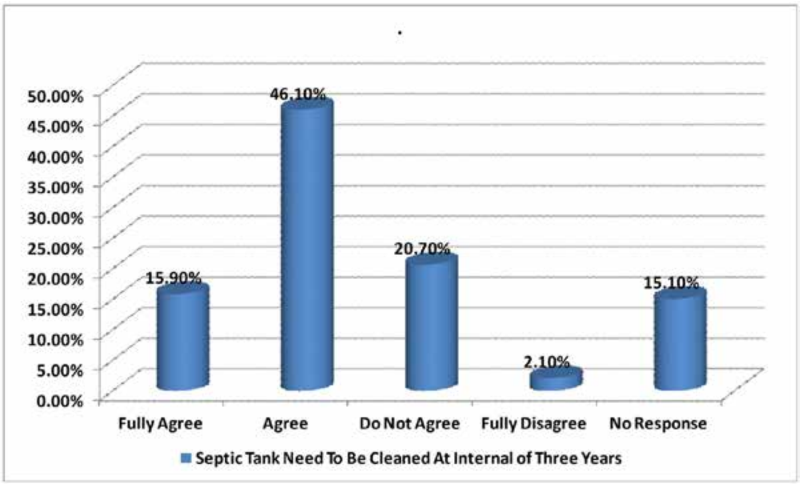


**Figure 9.** Do you agree that septic tank need to be cleaned at interval of 3 years.

**Table 3.** Satisfaction level of sanitation services (source: field survey).

| | Very satisfied | Satisfied | Dissatisfied | Total |
|---|---|---|---|---|
| Water supply | 48 | 336 | 225 | 609 |
| | 7.9% | 55.2% | 36.9% | 100.0% |
| Flow of water | 45 | 324 | 240 | 609 |
| | 7.4% | 53.2% | 39.4% | 100.0% |
| Sweeping of street/road | 47 | 375 | 187 | 609 |
| | 7.7% | 61.6% | 30.7% | 100.0% |
| Cleaning of drainages | 46 | 327 | 236 | 609 |
| | 7.6% | 53.7% | 38.8% | 100.0% |
| Maintenance of sewerage | 41 | 254 | 314 | 609 |
| | 6.7% | 41.7% | 51.6% | 100.0% |
| Collection of waste | 46 | 412 | 151 | 609 |
| | 7.6% | 67.7% | 24.8% | 100.0% |
| Transportation of solid waste | 43 | 356 | 210 | 609 |
| | 7.1% | 58.5% | 34.5% | 100.0% |
| Cleaning of public toilets | 40 | 223 | 346 | 609 |
| | 6.6% | 36.6% | 56.8% | 100.0% |

Other challenges include a lack of sludge operators. Roughly 60% of respondents said that they would be ready to pay user fees in exchange for regular septic tank cleaning. However, a significant number of people who responded to the survey in Mirzapur and Bahraich stated that they were unwilling to pay any user fees for the cleaning of septic tanks. Approximately 57% of those polled indicated that they would be ready to pay if it were guaranteed that ULB would be responsible for the routine cleaning of the septic tank. Banda was found to be the most effective at pronouncing the word, followed by Loni.

The vast majority of respondents expressed happiness with the level of sanitation. On the other hand, around 22% of respondents in Loni and 10% of respondents in Bahraich were unable to react to the view point. The majority of those who responded expressed contentment with the level of road and street cleaning. After Mirzapur, Banda was the next most frequent location where it was pronounced. The level of satisfaction with the sanitation services was found to be high in relation to the following: the collection of garbage, the sweeping of streets and roads, the transportation of solid waste, the water supply, the flow of water, and the cleaning of drainage. On the other hand, a sizeable proportion of respondents reported being dissatisfied with the flow of drinking water, the flow of public toilets, the maintenance of sewerage, and the cleaning of public toilets.

Satisfaction level of sanitation services is shown in Table 3. Satisfaction level of sanitation services was found high for collection of waste, sweeping of streets/roads, transportation of solid waste, water supply, flow of water, cleaning of drainage. However, large promotion of respondents was dissatisfied with cleaning of public toilets, maintenance of sewerage, flow of drinking water, and water supply.

There have been marked variations in outreach, accessibility, and utilization of urban sanitation infrastructure and services across the selected towns/cities.

## 2. Conclusion

Sanitation is an essential part of human development and a healthy, civilized life. Sanitation is linked to the environment because it reduces the incidence of water-borne infections, which leads to poor health. Larger cities have sewer systems, thus they only service a tiny percentage of the urban population. As a result, many Indian cities still use individual septic tanks. Due to a lack of sanitation coverage and reliance on conventional septic tanks, sanitation workers clean and scavenge toilets. Also, sanitation workers lack the tools, equipment, and supplies to regularly clean septic tanks, communal toilets, and roadways. As a result, improving essential urban services like water, sanitation, drainage, and garbage disposal in slums is critical. It is also necessary to provide adequate sanitary facilities for the urban poor. Most of the country's towns and cities suffer from a lack of cleanliness due to the absence of a sewage network, inadequate operation of sewage treatment facilities, and inadequate provision of sanitation services in metropolitan areas. Many people who live in slums are forced to defecate in the open since there are no facilities available. Only the construction and upkeep of public/community toilets in slums can prevent open defecation. Because the government alone cannot provide universal sanitation, all stakeholders, including the community, civil society, NGOs, local governments, and women's groups, must actively participate. This component of the research looks at urban demography and access to water, sanitation, and sewerage. Managing fecal sludge involves collecting, transporting, processing, and using or disposing of it (like a pit latrine or septic tank). It covers the last three aspects of sanitation. The data show that sludge operators are responsible for emptying septic tanks and pit latrines, but citizens do not regularly clean septic tanks. Desludging costs vary by city, and sludge operators struggle. Private operators provide services outside of ULB jurisdictions, whereas ULBs provide services within their domains. Private operators sometimes dump sludge into open drains after desludging septic tanks and pit latrines at designated sites at sewer line/STP if sewer line exists or drains, while government sludge operators do the same. Most sludge operators and workers are unaware of basic health, hygiene, and safety hazards.

The paper is useful in understanding the dynamics of urban sanitation, outreach and accessibility of sanitation infrastructure, and services. It also highlights the imperative need for management of seepage and fecal sludge management in small cities/towns in the state. In view of the improving sanitation conditions in urban centers, Government of India has taken initiative for conducting Swachchata Sarvekshan and ranking of cities based on their performance in sanitation sector. The protocols such as creating inclusive sanitation infrastructure, ODF status, and their sustainability were taken by the Ministry. Though, most of the ULBs have been declared ODF and majority of them have got their status of ODF flush. However, their sustainability is crucial. The survey was mainly conducted in slums and backward areas where construction of individual household toilets and community toilets has been ensured under SBM. Hence, the beneficiaries of the programme are not able to differentiate between the functioning of community toilets and public toilets besides, their awareness of schemes under which toilets have been constructed so far. Even, many poor selected households were not aware about the functioning of public and community toilets, their maintenance, and available facilities therein as they had no experience of using these toilets.

### 2.1. Policy Measures

- Local governments must educate communities about the benefit and importance of frequent desludging after building fecal sludge treatment plants. Surveying family perceptions and concerns regarding sanitation and septic tanks can help cities identify target audiences and tailor essential messaging. Cities can then implement the campaign, measure public sentiment, and adjust future advertising efforts.
- ULBs will need to explore the efficacy of alternative treatment methods, improvements, reuse, and recycling options, as well as new treatment technologies such as combining solid and human waste composting. This strategy may also assist integrate onsite sanitation management and treatment into the curriculum, which would result in future professionals who are both capable of and dedicated to solving this significant national issue.
- Suction machines/vacuum tanks must be upgraded, mechanized vehicles purchased, and safety procedures and equipment implemented. The number of sanitary workers necessary should be increased due to increased community awareness and sensitization. In order to remind communities to desludge septic tanks on time, ULBs should create a system to manage community applications, funds received, and desludge dates. A study of the community is going to be necessary in order to determine the number of septic tanks, the number of people who are prepared to pay user fees, and the number of times that septic tanks need to be cleaned out.
- Urban local governments are required to construct fecal sludge treatment facilities, increase public awareness about the need for regular septic tank desludging, ensure the safe disposal of fecal sludge at fecal sludge treatment facilities, and ensure the composting of human excreta, animal dung, and solid wastes.
- Public–private partnerships should be promoted more in sanitation. Women's groups, thrift and credit clubs, civic societies, NGOs, and other non-profit organizations should be involved in waste collecting and street and road cleaning. Stakeholders should be active participants. Residents, businesses, and regulators are all stakeholders. Government and non-governmental sanitation measures can only reach a tiny population.
- User charges for sanitary services such as garbage collection, cleaning and upkeep of public restrooms, street sweeping, and drainage should be enforced properly. Due to escalating costs of water production and sewerage services, citizens must pay user fees to keep water utilities and sewage treatment plants operational.
- In order to guarantee their incorporation into the formal system and to make strides toward better sanitation, it is imperative that the infrastructure and service gap be bridged as quickly as possible. The accessibility of affordable sanitation services is a significant obstacle, as is the maintenance of financial and environmental sustainability.
- NGOs, RWSs, volunteer groups, and other academic institutions can help raise community awareness about the need of establishing and maintaining scientific septic tanks. Masons, on the other hand, need to be trained to build better septic tanks. The same goes for NGOs and other non-profits. Efforts should be focused on establishing Master Trainers to quickly sensitize the community.
- There is imperative need to create, construct, develop, and maintain inclusive sanitation infrastructure such as public toilets, community toilets, and urinals. Such inclusive sanitation infrastructure needs to be constructed and maintained in slums and backward areas mainly in outskirt areas or urban fringes.
- Strategically placed community toilets are needed to reduce open defecation and improve urban living conditions. ULBs should build more public restrooms in markets, schools, universities, bus terminals, and train stations. Existing public bathrooms require more seats. Community toilets need water, so failing bore wells must be rebored.
- Infrastructure and services must be linked. Improving financial and environmental sustainability, encouraging public–private cooperation, mobilizing resources, institutional construction, and supporting behavioral change are major problems

## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Keywords

fecal sludge management, septage management, sustainable sanitation

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# Performance Assessment of Urban Sanitation Services in India: An Alternate Perspective

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## Abstract

In the new millennia, improving sanitation services has become one of the main agenda of the governments, both in India and the global South. Within India, many initiatives and policies were introduced, e.g., a sub-component within the JnNURM (Jawaharlal Nehru Urban Renewal Mission), National Urban Sanitation Policy and Swachch Bharat Mission (Clean India Mission) at Central government level to ensure improved urban sanitation service delivery. Performance Assessment Frameworks (PAFs) were introduced in India with Service-level Benchmarking, Swachch Survekshan (Cleanliness Surveys), etc. for monitoring the performance of sanitation services.

This research aims to study different PAFs, adopted within India and other countries, in order to re-identify indicators, whether already included or not in Indian PAFs on the basis of their applicability in Indian context. It has been observed that the existing PAFs in Indian context have been developed with the perspective of 'Efficiency of Services' only, whereas this research article is an attempt to revise the existing PAFs with the perspective of 'Societal Outcomes' to prepare a more holistic and result- oriented PAFs.

## Keywords

Assessment, Efficiency, Performance, Sanitation Services, Societal Outcomes.

## Introduction

Sanitation services and their management in India and in countries of global South remained poorly addressed until the late 20th century. In the new millennia, improving sanitation practices and stopping open defecation became one of the main agenda of the governments, both within India and in the global South. There are multiple benefits to households having access to sanitation facilities, for example, toilets and safe containment of liquid waste add value to the dwellings, which can serve as a collateral for a loan or be sold if required, increasing a household's ability to borrow or acquire

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other assets. Secondly, toilets play a crucial role in improvement of family health, which has a great value in maintaining productivity of a household. Thirdly, toilets increase intangible benefits as a utility, such as status, comfort and even marriage prospects for grooms-to-be (Augsburg et al, 2020). Access to safe sanitation for the poor is a key factor in improving public health and economic productivity and is therefore, an essential component of any effort to alleviate poverty.

During the United Nations Summit in 2000, the member nations pledged to ’provide access to safe & basic sanitation to whole humanity by year 2015‘ under the umbrella of ‘Millennium Development Goals – 2015’ (UN Water, 2005). However, even after a number of attempts, the situation did not improve much, as 2.4 billion people still did not have basic sanitation facilities world-wide (WHO, 2016). This led UN to revisit its vision, and accordingly “Sustainable Development Goals” were launched at UN Summit in New York on September 25, 2015 and Goal-6 was adopted ’to ensure availability and sustainable management of sanitation for all‘ (UNEP 2020). Citizens of developing and under-developed countries do require improved sanitation but these nations lack the resources to obtain or maintain access to toilets and sanitation system as a whole. Such deprivation is responsible for their ‘behavior change’, which also triggers a deficiency in mindset that fails to capture contextual factors affecting sanitation access (Van Riper et al, 2021). Therefore, countries around the world, especially Global South are making mammoth efforts to achieve SDG Goal-6 by focusing on mitigating the deficit between sanitation infrastructure and service delivery. At the same time, to ensure the results of efforts made for improvement of sanitation scenario, International agencies like, World Health Organization, UNICEF, World Bank, etc.(WSP, 2006; SEAWUN et al, 2007; GWOPA et al, 2009; IB-NET, 2014; IWA et al, 2014, etc.) under the umbrella of UN and government agencies of different countries introduced number of monitoring and performance assessment frameworks (SLB, 2010; Swachch Survekshan 2017-2021, etc.) to review the condition of sanitation service delivery from time- to- time.

India is also making similar efforts to ensure access to improved sanitation for its citizens taking cues from the paradigms in vogue in the world. Ministry of Urban Development (MoUD), Government of India launched the Jawaharlal Nehru National Urban Renewal Mission (JnNURM) in 2005 to address the need of urban infrastructure development, including the sanitation infrastructure. To ensure the prioritization of sanitation, the Ministry of Urban Development, Government of India further launched the National Urban Sanitation Policy (NUSP) in 2008. This policy highlighted numerous issues including a general lack of awareness with regards to sanitation, fragmented roles and responsibilities of stakeholders in the sanitation sector, including lack of focus on the un-served poor and limited sanitation technology choices. Government of India introduced first Performance Assessment Framework (PAF) to review and monitor the performance of sanitation services i.e., Service Level Benchmarking (SLB) in 2010, whereby cities were ranked on the basis of performance indicators listed in the SLB toolkit (Vaidya et al, 2019).

Government of India launched ‘Swachch Bharat Mission’ (SBM) (Clean India Mission) in 2014 to accelerate the efforts to achieve universal sanitation coverage and to put the focus on sanitation to solve the problems of waste management in India. One of the main objectives of the project was to create sanitation facilities for all and provide access to toilet to every urban as well as rural family. The SBM led to improvement in overall ‘Water, Sanitation and Hygiene’ (WASH) practices. It was for the first time that 12 per cent allocation of any scheme budget was granted to focus on public awareness and public participation purpose only, which led to behavioral change in the people under the SBM (Sarkara et al, 2021). Further, a process to monitor and review these efforts and rank the urban settlements was introduced as ‘Swachch Survekshan’ (cleanliness survey) in 2016. In 2017, ‘Swachch Survekshan Guidelines’ were released which were further revised in the successive years (2018, 2019, 2020 and 2021). Apart from the ‘Swachch Survekshan’, few other PAFs were also introduced in India by independent research institutions (Centre for Water & Sanitation C-WAS of CEPT University, Ahmedabad: SAN-Benchmarking & City-wide sanitation approach, etc.) and Ministry of Urban Affairs, Government of India: Open Defecation Free (ODF) protocols, ODF+, ODF++ & Water Plus Protocols (Vaidya et al, 2019).

## Need for Research

As per the report of UNICEF, around 597 million population of India were openly defecating till 2013-14 (UNICEF, 2015), whereas 2.4 billion world population didn’t have access to sanitation in the same period of time (WHO, 2016). This indicated that out of total population of world under sanitation vulnerability, 25 per cent of the population was from India itself. Out of total 1.21 billion population of India, 42.6 per cent were residents of urban India (Census 2011). Out of total urban India, around 32 per cent residents didn’t have access to improved sanitation till 2013-14 (UNICEF, 2015). Of these, 17.4 per cent population resided in slums in urban India (Census 2011). Even after a lot of efforts made by the governments, local authorities, institutions and NGOs till date, the current status of sanitation services in the country has not been able to attain the goals set in **National Urban Sanitation Policy** (NUSP) and Sustainable development Goals(SDGs). As compared to other sectors of infrastructure, there is a dearth of reliable, internationally comparable data for urban sanitation, including the cost and service efficiency aspects. In the absence of reliable data, the full cost of urban sanitation services is being underestimated and partially addressed (Sainati et al, 2020).

A sanitation service chain comprises the capture, storage, transfer, treatment, disposal as well as recycle and reuse of wastewater under the network based ‘Sewerage System’ and non-network based ‘Onsite System’. But what if, the approach of performance review focuses mainly on the provisioning and processes of services rather than the desired outcome. The whole service chain of sanitation services from planning to development and management to sustenance is indispensable to offer good sanitation services. The governments or service providing agencies are always interested to achieve: 1) value for money against their investments and efforts and, 2) the high level of efficiency of services to offer quality of life to their citizens. But current practices of service-level assessment in urban sanitation are based on the perspective of ‘Efficiency of Services', which primarily focus on the efficiency in bridging the infrastructure gaps and setting the targets to achieve the output for incurred investments, but does not focus on the actual gains to people and affirmative changes in their quality of life.

At this juncture, questions arise that why the existing PAFs are not able to help in achieving the expected results? How the perspectives of different stakeholders differ with respect to the existing performance assessment mechanisms of urban sanitation services? The existing PAFs are formulated to assess the achievements of infrastructure targets and thereby it may be said these have a perspective of efficiency. At the same time, large scale investments in sanitation infrastructure and its continued management is supposed to yield societal outcomes and societal capabilities. The perspective of societal outcomes is largely not included in the existing PAFs.

Hence, it is required to identify unaddressed aspects as well as inadequacy of parameters in Indian context under different perspectives to ascertain the standard levels of sanitation, cleanliness and hygiene, expected to be achieved by Indian Cities. This research attempts to re-structure the existing PAF's indices by exploring the need of including the perspective of societal outcomes in the overall performance assessment process.

## Research Approach

This research mainly focuses on sewage management aspect only, out of overall sanitation system. As elaborated in the earlier section, the approach adopted explores the possibility of including an alternative perspective to ensure societal gains and improvement in the quality of life of the people, i.e. with perspective of 'Society Outcomes'.

Thus, this study revisits the existing PAFs with both perspectives in order to create a revised PAF that is more holistic. This will help to investigate how the existing PAFs may be better evaluated with the perspective of 'Societal Outcome', apart from conventional perspective of 'Efficiency of Services'.

## Capability Approach for Sanitation Service Delivery Assessment

The perspective of 'Societal Outcomes' is identified with improvement in capabilities of the citizens after providing improved public services. The 'Capability Approach' as elaborated by Sen & Nussbuaum' explains how the change in quality of public services can impact the capability of individual and society, and ultimately respond to the main aim of a thriving and reasonable service delivery. If one reviews the performance of indicators of PAFs while keeping in mind the intention of positive change in capabilities of individuals and society, the results may reveal different outcomes from the perspective of 'Societal Outcomes'. This may be different from the conventional approach of target achievement for infrastructure provisions with the perspective of 'Efficiency of service' (Allwine et al, 2014).

## Process of Research

At first, 'Nominal Group Technique' was explored to conduct highly controlled expert opinion survey with the chosen domain experts from academics and research to select PAFs for review. 22 PAFs were selected for the review, out of which 9 PAFs were from India and the remaining 13 PAFs were from abroad. In this context, this study, has reviewed the documents in use in India and literature available on performance assessment for urban sanitation in selected other countries.

As outlined in the previous section , actual gain to the society as well as target achievement, two separate assessments were made for the existing PAFs. Accordingly two sets of experts' opinion surveys were conducted under two different perspectives to find out the level of importance for the indicators of various selected PAFs within India and from abroad for urban sanitation services. One expert opinion survey was conducted with academicians and researchers with the perspective of 'Societal Outcomes' and another opinion survey was conducted with industry practitioners with the perspective of 'Efficiency of Services'. Both had the aim to identify the set of indicators that require inclusion as part of a revision of existing PAFs in India. In both cases, opinion on importance and applicability in Indian context were sought.

Indicators were extracted from these various existing PAFs within India and from abroad and then these were sorted and checked for similarities. The similar ones were given a single code or identity and made as one. Identified indicators were then categorised into three overall conceptualised categories with sub- categories for each. Importance or relevance was sought from experts for these indicators in a Likert scale and the respondents were free to give suggestions as well.

## Performance Assessment Frameworks (PAFs) from India and Abroad

The list of identified 22 PAFs, Indian (Table-1) and International (Table-2) are mentioned below:

**Table 1:** List of 9 identified Indian PAFs from Government and Research Organisations

| S. No. | Documents |
|---|---|
| 1 | Improving Urban Services through Service level Benchmarking (2010), Ministry of Urban Development, Government of India. (Ref. 23) |
| 2 | Performance Measurement Framework for Urban Water and Sanitation, Vol I & Vol II (2010). CEPT University, India. (Ref. 36) |
| 3 | SAN –Benchmarks Citywide Sanitation Service Delivery, Including Onsite Sanitation (Framework and Indicators) – 2015 by PAS Project, CEPT University, India. (Ref. 26) |

| S. No. | Documents |
|---|---|
| 4 | Swachch Survekshan: A Guidebook for Urban Local Bodies (2017), Ministry of Housing and Urban Affairs (MoHUA), Government of India. (Ref. 42) |
| 5 | Swachch Survekshan Toolkit: A Guideline for Urban Local Bodies (2018), MoHUA, Government of India. (Ref. 23) |
| 6 | Swachch Survekshan Survey Toolkit (2019) and Swachch Bharat Mission (SBM) ODF, ODF+ & ODF++ Protocol and Toolkit (2019), MoHUA, Govt. of India. (Ref. 15, 44) |
| 7 | A Framework for Assessing Citywide Inclusive Sanitation (2019), Centre for Water and Sanitation (C-WAS), CEPT University, India. (Ref. 2, 52) |
| 8 | Swachch Survekshan Survey Toolkit (2020) and SBM Water Plus Protocol and Toolkit (2020), MoHUA, Govt. of India. (Ref. 43, 44) |
| 9 | Swachch Survekshan Survey Toolkit (2021), MoHUA, Government of India. (Ref. 44) |

**Source:** As Reference Number mentioned with above PAF

**Table 2:** List of 13 identified International PAFs from Developed, Developing and Undeveloped Countries, UN & Other Organizations

| S. No. | Documents |
|---|---|
| 1 | Urban Water Sector in South Asia: Benchmarking Performance (2006). Water and Sanitation Programme (WSP). (Ref. 48) |
| 2 | Data Book of Southeast Asian Water Utilities 2005 The Southeast Asian Water Utilities Network (SEAWUN) and Asian Development Bank (ADB). (2007) (Ref. 13). |
| 3 | Asian Sanitation Data Book – Achieving Sanitation For All (2008), Asian Development Bank (ADB). (Ref. 14) |
| 4 | The State of African Utilities: Performance Assessment and Benchmarking Report (2009). Global Water Operator's Partnerships Alliance–United Nations Human Settlements Programme (GWOPA/UN-Habitat), African Water Association (AfWA) and Water & Sanitation Program (WSP-Africa). (Ref. 45) |
| 5 | The Challenge of Extending And Sustaining Services (2012). UN-Water Global Analysis and Assessment of Sanitation and Drinking Water (GLAAS), WHO. (Ref. 19) |
| 6 | German International Cooperation with Ukraine- Improvement of Municipal Services Performance; Water & Sanitation Module 3 – Performance Monitoring and Benchmarking (2012). GIZ and GFA Consulting Group, Ukraine. (Ref. 20) |

| S. No. | Documents |
|---|---|
| 7 | Canadian National Water & Wastewater Benchmarking Initiative (2013). AECOM, Canada. |
| 8 | The International Benchmarking Network (IB-Net) for Water and Sanitation Utilities Data book (2014). World Bank Group, Water and Sanitation Program (WSP). (Ref. 35) |
| 9 | Sanitation 21: A Planning Framework for Improving City-wide Sanitation Services (2014). IWA, Eawag-Sandec, GIZ. (Ref. 40) |
| 10 | Metadata on Suggested Indicators for Global Monitoring of the Sustainable Development Goal 6 on Water and Sanitation (2015). Inter-agency and Expert Group on Sustainable Development Goal Indicators (IAEG-SDGs), UN-Water. (Ref. 29) |
| 11 | WASH Post-2015: Proposed indicators for drinking water, sanitation and hygiene (2015). WHO / UNICEF Joint Monitoring Program (JMP). (Ref. 51) |
| 12 | Monitoring Water and Sanitation in the 2030 Agenda for Sustainable Development (2016). The Integrated Monitoring initiative (GEMI), UN-Water. (Ref. 30) |
| 13 | Performance Management for Water and Wastewater (2018). American Water Works Association (AWWA) Utility Benchmarking, USA. (Ref. 1) |

**Source:** As Reference Number mentioned with above PAF

## Identification of Indicators from PAFs from India and Abroad

The initiation of this research started with re-identifying indicators whether already included or not included in Indian PAFs considering applicability in Indian context for efficient delivery of urban sanitation services. Accordingly, process of elimination of repetition and similarity of extracted indicators were undertaken through coding. Total of 117 indicators were shortlisted out of 348 indicators from 22 PAFs from India and abroad at this stage after elimination of similarities in indicators. For the systematic assessment of both perspectives, all urban sanitation indicators from the national and international level PAFs were classified into three adopted conceptual categories of Service Delivery Assessment (SDA) framework based on their thematic groups, which is a concept of the life cycle mechanism of service delivery with categories of Enabling Services, Developing Services and Sustaining Services by covering the whole sanitation service chain, given by the Water Sanitation Programme and World Bank Organization (WSP – WBO) in 2015. Then, these identified indicators were distributed in nine thematic groups within three SDA categories Table 3. At the same time, based on the suggestions of the experts, 17 new indicators were also added in the list of tentative selected indicators, which resulted finally into total count of 134 identified indicators for the study.

**Table 3:** Service Delivery Assessment Framework of WSP-WB with SDA categories

| SDA Category | S. No. | Sub-Heads of SDA Categories |
|---|---|---|
| Enabling Services | 1 | Policy |
| | 2 | Planning |
| | 3 | Budget |
| Developing Services | 4 | Expenditure/ Input |
| | 5 | Equity |
| | 6 | Service Output |
| Sustaining Services | 7 | Operation and Maintenance |
| | 8 | Expansion/ Capacity Building |
| | 9 | Outcomes |

**Sources:** AMCOW Regional Synthesis Report 2011, 2. Regional Synthesis on SDA for East-Asia and the Pacific by World Bank 2015

Further, in order to ascertain usefulness, importance and applicability of Indicators in Indian context, expert opinion surveys were conducted using domain experts from academics, research and people from industry involved in policy, planning, design, execution and management of urban sanitation system.

## Finalization of Tentative List of Indicators from selected PAFs

In the first expert opinion survey, the domain experts (i.e. academicians and researchers from India and abroad) were asked to rate the level of importance to the identified indicators with perspective of 'societal outcomes' in a 7-point Likert Scale, with ranges from 'not important' to 'extremely important'. This means, experts rated the indicators by keeping in mind the associated capacity of indicators to offer the societal gains in the form of positive changes in quality of life of the people and society as a whole. Whereas, second expert opinion survey was conducted with industry practitioners from India only with perspective of 'efficiency of services' by focusing on provisioning of infrastructure and improvement of service in a 7-point Likert Scale again.

## Listing of Tentative Selected Indicators based on the Evolution of PAFs

These indicators were further divided in four representative groups based on their evolution from India and abroad. First group 'A' portrays common indicators from 'Indian and international PAFs', a second group 'B' depicts indicators from India only, whereas third group 'C' represents only international indicators and fourth group is 'D' is the new indicator proposed to overcome gaps in all indentified PAFs in India and abroad, as mentioned below:

**A** Common Indicators from Indian and International PAFs

**B** Indicators from Indian PAFs only

**C** Indicators from International PAFs only

**D** Newly proposed Indicators

## Findings of Research

(a) Out of total 134 identified indicators, 117 were from 22 selected PAFs and rest 17 were newly proposed indicators.

(b) While the initial list contained 117 identified indicators from all 22 PAFs of India and abroad, 65 indicators were selected from International PAFs and 37 indicators were selected from Indian PAFs, whereas 15 indicators were having common representation from PAFs of India and abroad.

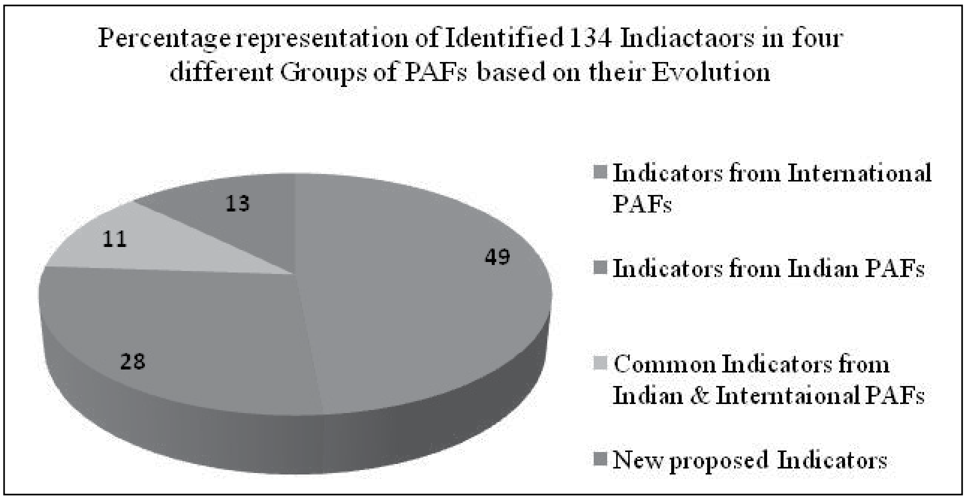


**Figure 1:** Group-wise representation of Identified Indicators based on their evolution

**Source:** Based on authors' study

Figure 1 clearly shows that majority of identified indicators which were from international PAFs have not been included in Indian context. Experts suggested few new indicators for addition in the list.

(c) Based on the results of expert opinion surveys, 91 indicators were chosen. The basis of such selection was indicators securing a higher level of importance (above scale-5 in 7-point Likert Scale), in both the rounds of opinion surveys with different perspectives as focus. This led to the development of a **'Revised Performance Assessment Framework (RPAF)'** Table-4.

**Table 4:** 'Revised PAF' with final list of identified Indicators in Indian Context distributed in Sub-heads of SDA Categories along with the groups of PAFs based on their evolution

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| Policy | 1 | Provision of Laws/ rules for improvement in condition of sanitation (national/ state/ local level) | C |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 2 | Do measures in-place for user fees and penal action to curb open defecation and urination | B |
| | 3 | Establishment of policy and strategy making system for improved sanitation (provision to prepare City Sanitation Plan/ master plan for sewage management Faecal Sludge and Septage Management (FSSM) Action Plan, etc.) | C |
| | 4 | Customer satisfaction review and performance review made public | C |
| | 5 | Provision of users charges and connection charges, defined as per Residential (Households), Commercial, Institutions, Establishments and Public areas at Urban Local Body level for sanitation services | D |
| | 6 | City/ Town level Policy on Waste Water reuse for city landscape, road washing, industrial use, agriculture, non-potable domestic use | D |
| Planning | 1 | Average water provided for sanitation needs per capita (estimation of water consumption per capita) | C |
| | 2 | City- level Planning to connect all (old and new) Households, Commercial Institutions, Establishments and Public area CTs/ PTs with a closed system (sewerage/ onsite system, etc.) | B |
| | 3 | Planning and procedures for community participation for sanitation management and building of Community Toilets (CTs) and Public Toilets (PTs) | A |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 4 | Independent testing proposed against national sanitation service standards | C |
| | 5 | Consideration of load on sanitation facilities due to floating population in the city during planning and execution | C |
| | 6 | Vision period to achieve goals of existing sanitation plan | C |
| | 7 | Clarity on the role of various responsible agencies (Whether more than one agency is involved for collection & transfer of WW) | B |
| | 8 | Clarity on the role of various responsible agencies (Whether more than one agency is involved in treatment & disposal of WW) | B |
| | 9 | Provision of demand based desludging of septic tanks by ULBs from public and private agencies | C |
| Budget | 1 | Financial Viability of sanitation services | C |
| | 2 | Resource allocation – (staff, finance, machines etc.) | C |
| | 3 | Amount of sanitation related official development assistance (ODA) that is part of a government coordinated spending plan | C |
| | 4 | Assessment of alternative financial sources and strategies to address needs of capital investment | C |
| | 5 | Provision of Budget for new connection charges and defining per connection users charges (HHs/ Commercial units etc.) | C |
| | 6 | Provision of any incentive and subsidy strategy to connect people with improved sanitation system | D |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 7 | Short- term and long- term investment strategy for sanitation infrastructure and service improvement | D |
| | 8 | Provision of sector specific financial mechanism in ULBs (separate budget and planning for sanitation) | D |
| | 9 | Earmarking of budget for sanitation services to urban poor (EWS group) | D |
| Input/ Expenditure | 1 | Overall Coverage of Toilets ( through individual, shared and community toilets) | A |
| | 2 | Coverage of individual toilets facilities at HH Level | A |
| | 3 | Coverage of Community Toilets & Public Toilets (sanitation facilities in educational Institutes, health centres and commercial centres, etc.) | C |
| | 4 | Coverage of Individual HHs with sewerage network services (for sewage with and without sullage) | A |
| | 5 | Coverage of Individual HHs with FSSM (Onsite) system for sanitation services | B |
| | 6 | Percentage of HHs connected to individual Septic tank | B |
| | 7 | Scientific disposal of untreated and residue sewage/ septage | D |
| | 8 | Volume of septage/ sludge transported to and disposed in designated locations with scientific measures | C |
| | 9 | Percentage availability of onsite toilet facility ensured in construction sites with safe disposal of faecal sludge | B |
| | 10 | Action taken by city (issued and notified fine) against persons/ desludging operators dumping untreated faecal sludge in drains/ | B |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 11 | Percentage of HHs not releasing sewage directly in natural drains and open spaces (with or without sullage) | D |
| | 12 | Overall Coverage for sanitation services (with sewerage and FSSM Onsite system) | B |
| | 13 | ICT/ Mobile App/ Social Media based monitoring mechanism to monitor open defecation/ urination/ littering in the City | C |
| | 14 | Do Public toilets uploaded as SBM toilet on Google map in the city? | B |
| | 15 | Number of septage sucking machines per 1000 septic tanks | C |
| | 16 | Percentage Estimated HHs Population dependent on shared sanitation facilities (shared toilets, community toilets) | C |
| Equity | 1 | Access to affordable sewerage services to Economically Weaker Section (within the dwelling/ walkable distance) | A |
| | 2 | Availability and service conditions of Community Toilets/ Public Toilets in slums / disadvantaged areas | C |
| | 3 | Safety, security and welfare provisions for all sanitary workers | C |
| | 4 | Provision of Llw income assistance program OR low income billing assistance | C |
| | 5 | Percentage HHs with partial access to toilet facility (only for females or elderly) | D |
| Service Output | 1 | Collection efficiency of sewerage network | A |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 2 | Extent of cost recovery in WW management (Operating cost coverage ratio – OCCR/ Percentage recovery of Operations and Maintenance (O&M) cost to service provider agency) | A |
| | 3 | Extent of recycling and reuse of treated WW of sewerage system | A |
| | 4 | Extent of recycling and reuse of treated septage (from septic tanks) | B |
| | 5 | Overall Waste Water collection efficiency | A |
| | 6 | Efficiency in collection of sewage related user charges | A |
| | 7 | Efficiency in redressal of customer complaints (Customer/ technical service) | A |
| | 8 | Collection efficiency of septage from septic tanks | B |
| | 9 | Operational efficiency of STP (Out of total capacity, and actual operation in practice) | C |
| | 10 | Extent of recycling and reuse of overall treated WW (from sewerage system, Faecal Sludge and Septage Management (FSSM) onsite system, industry effluents, storm water system, etc.) | C |
| | 11 | Extent of users/ public contribution in the O&M of CTs/PTs | C |
| | 12 | Percentage of CT/PTs completed Vs Target | B |
| Operation & Maintenance | 1 | Adequacy of capacity of STP in case of sewerage system (Capacity Ratio of STP) | C |
| | 2 | Adequacy of capacity of FSTP (STP for Faecal sludge & septage) in | B |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 3 | Do ULBs have private sector participation in O&M of STP (with PPP or any other model) | B |
| | 4 | ICT- based monitoring of community toilets and public toilets | B |
| | 5 | Operation efficiency for O&M (staff & equipment availability) | C |
| | 6 | Staff productivity for O&M (by skills, availability of equipments, work place environment, etc.) | C |
| | 7 | Rate of BOD discharged to the environment per capita | C |
| | 8 | Managing O&M implications through decentralised sanitation management and wastewater treatment | C |
| | 9 | Percentage compliance with specific secondary and tertiary treatment standards | C |
| | 10 | Desludging operators registered and being monitored | B |
| | 11 | Adequacy of capacity of WW treatment Plants in combined sewerage system (sewage with storm water, etc.) | A |
| | 12 | Unplanned/ emergency maintenance readiness for sanitation Infrastructure | C |
| | 13 | Total personnel per 1000 population for Operation & Maintenance of sanitation services | C |
| | 14 | Does ULB addresses environmental-friendly disposal practices as controlling measures | D |
| Expansion & Capacity Building | 1 | Training and skill development efforts (management/ technical/ O&M) | C |
| | 2 | Provision of emergency response readiness training | C |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 3 | Desludging operators (staff) trained on safety issues, registered with ULB and being monitored by ULB | B |
| | 4 | Institution involved in sanitation services (Public/ Private) | C |
| | 5 | Coordination training to the agencies involved in the management of sanitation services (if more than one agency for the clarity on role and responsibility, easy communication etc.) | D |
| Outcomes | 1 | Percentage of HHs (expected to) not practicing open defecation | A |
| | 2 | Quality of WW treatment in separate sewerage system (Sewage + Sullage) | A |
| | 3 | Quality of sepatge treatment in absence of sewerage system | B |
| | 4 | Percentage of households ,not openly defecating in slums | B |
| | 5 | Quality of water source if used for WW disposal (impact of pollution due to WW on good ambient water quality) | C |
| | 6 | Percentage population using improved sanitation facilities over last 3 years (tap, flush and electric bulb in operational toilets) | B |
| | 7 | Quality of WW treatment in combined sewerage system (including sewage, septage and storm water) | B |
| | 8 | Sanitation related disease reported | C |
| | 9 | System Reliability with sufficient capacity | C |
| | 10 | Vector-borne/ water-borne (WASH listed) diseases outbreak due to poor sanitation scenario | C |

| Sub-heads of SDA Categories | Sl. No. | List of identified Indicators | Group based on evolution |
|---|---|---|---|
| | 11 | Percentage of effluents (industrial sewage) from cottage industries and workshops releasing into open drains | D |
| | 12 | Use of existing sanitation facility at HH level (remaining not using due to water scarcity, unhygienic condition of community toilets, or other socio-cultural reasons, etc.) | D |
| | 13 | NGT Order compliances for safe disposal of sewage by state governments and ULBs | D |
| | 14 | Acceptance of treated WW for reuse | D |
| | 15 | Review of complaints of poor workmanships during maintenance and repairs | D |

**Source:** Based on various indicator adopted from various PAFs and other associated references.

d) Out of 91 indicators of the revised PAF, developed on the basis of the responses from both expert opinion surveys, 14 indicators were from both PAFs of India and abroad (i.e. from group-A), 39 indicators were from International PAFs only (group-C), 22 indicators were from Indian PAFs only (group-B), and rest 16 indicators are newly proposed (group-D).

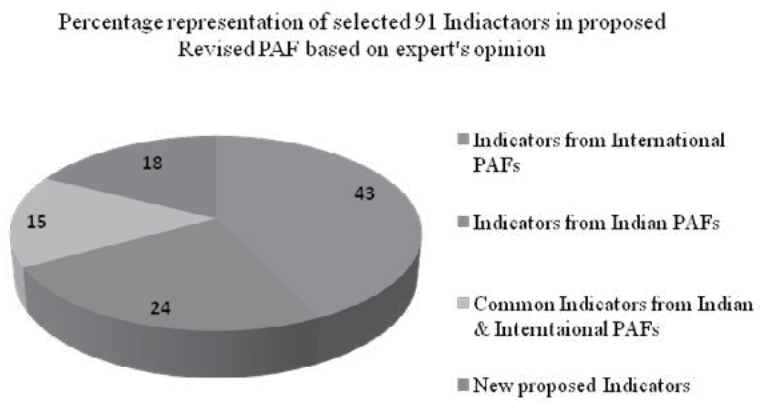


**Figure 2:** Group-wise representation of selected Indicators in Revised PAF

**Source:** Based on authors' study

Figure 2 clearly shows that opinion survey favours a altogether different list of indicators as a majority of selected indicators in revised PAF were from international PAFs. Second largest share of indicators were from Indian PAFs indicating a convergence of choice between the decision- makers for the existing PAFs and the pool of expert respondents. It is also important to note that the share of common indicators between International PAFs and Indian existing PAF is relatively small (15% or 14 out of 91) reflecting a very small share of commonality or convergence of choice. This convergence choice is even less than the respondents' newly proposed indicators reflecting a large divergence of choice of indicators between the existing preference and the need for newer ones.

e) Out of 91 indicators of the revised PAF above scale-5, 46 indicators received comparatively higher preference over other indicators with perspective of 'Societal outcomes' and 45 indicators received comparatively higher preference over other indicators with perspective of 'Efficiency of Services'

f) Out of 22 indicators selected from Indian PAFs above scale-5, 15 indicators received comparatively higher preference with perspective of 'Societal outcomes' and 7 indicators received comparatively higher preference with perspective of 'Efficiency of Services'

g) Out of 39 indicators selected from International PAFs above scale-5, 18 indicators received higher preference with perspective of 'Societal outcomes' and 21 indicators received higher preference with perspective of 'Efficiency of Services'

h) Out of 14 common indicators selected from PAFs of India & Abroad above scale-5, 9 indicators received comparatively higher preference with perspective of 'Societal outcome' and 5 indicators received comparatively higher preference with perspective of 'Efficiency of Services'

i) Out of 16 newly proposed indicators above scale-5, 4 indicators received comparatively higher preference with perspective of 'Societal outcome' and 12 indicators received comparatively higher preference with perspective of 'Efficiency of Services'

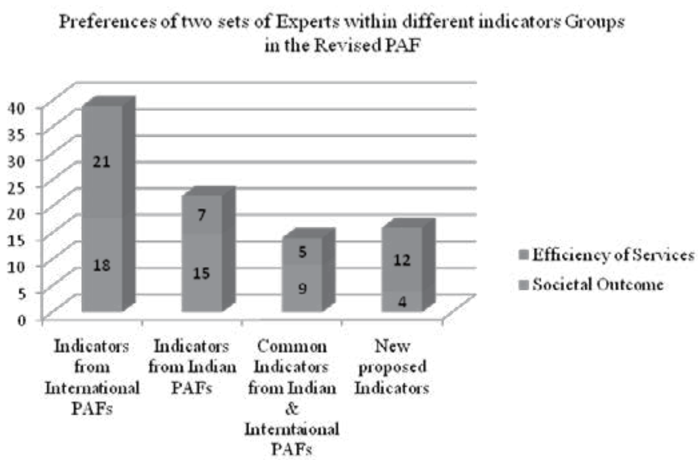


**Figure 3:** Preferences of both sets of experts within different indicator Groups in Revised PAF

**Source:** Based on authors' study

It is clearly revealed from Figure 3 that experts chose more indicators from International PAFs and new proposed indicators for ‘Efficiency of Services’ approach. Whereas experts chose more indicators from Indian PAFs and list of common indicators from both PAFs for ‘Societal Outcome’ approach. The opinion survey resulted in list of indicators that has an almost equal share of indicators important from both the perspectives.

j) Assessment of responses with respect to SDA categories reveals that the perspective of ‘societal outcome’ has 13 indicators whereas perspective of ‘efficiency of services’ has 11 indicators out of total 24 indicators of ‘Enabling Services’ category. In ‘Developing Services’ category, out of total 33 indicators, the respective numbers are 17 and 16; whereas in ‘Sustaining Services’ category, out of total 34 indicators, the respective numbers are 16 and 18.

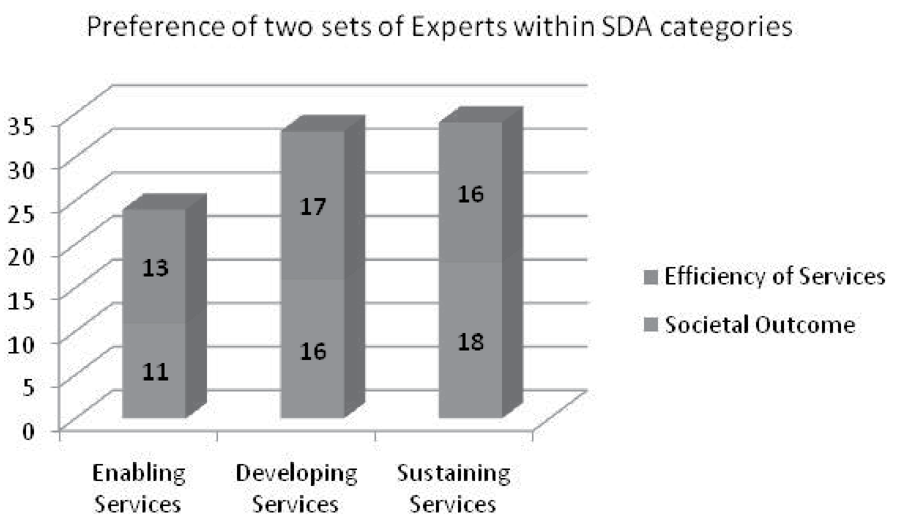


**Figure 4:** Preferences of both sets of experts within three SDA Categories in Revised PAF

**Source:** Based on authors’ study

## Conclusion and Way Forward

The current Swachch Survekshan (2021) conducted a survey on the basis of 10 indicators. Expert opinion surveys revealed a need for 91 indicators to holistically assess the sanitation scenario in urban settlements. Of these, 74 indicators were borrowed from the PAFs from India and abroad, and a total of 17 new indicators were proposed based on the suggestions of experts. It was evident from the literature review that the currently adopted performance assessment frameworks for urban sanitation were developed with a perspective of ‘Efficiency of Services’, focusing on meeting the infrastructural gaps, meeting and utilising financial and other resources, governance, and setting targets against the investment made on various sanitation systems and services. The framework of assessment did not consider the result or impact of unmet targets necessitating a revisit of the existing PAFs with an alternate perspective i.e., 'Societal Outcomes' to ensure a holistic and better approach to evaluate the performance of the sanitation services.

Overall, these opinion surveys revealed the need to modify and expand the existing performance assessment framework with larger number of parameters / indicators. Within this expanded indicator list, it was observed that there was an almost equal distribution of efficiency and outcome related indicators (proxy indicators for outcome) which were 45 and 46 respectively in a total of 91 indicators. In the context of this study, the perspective of 'societal outcomes' was considered to be related with individual capability as well as long-term goals and social sustainability, whereas the perspective of 'efficiency of services' was considered to be relatively more associated with institutional capabilities followed by environmental capabilities. The two perspectives together address all the three paradigms of 'societal capability', i.e., individual, institutional and environmental capabilities.

This research contributes towards national, state and local policies in India regarding urban sanitation as the revisiting of performance assessment framework of the same (Swachch Survekshan) helped to identify coverage of issues as well as non-coverage of issues in the three categories of mechanisms of enabling, developing and sustaining the services (SDA categories). This research has also identified the scope of expansion in the number of indicators which are required to be included in performance evaluation of sanitation services in India combining two different perspectives. With this research, it is being realised that the modified PAF can help to make appropriate policy shifts and prioritization of financial outlays for improvement of urban sanitation services in different classes of towns with both perspectives; 'societal outcomes' and 'efficiency of services'.

This work has resulted into revised framework of assessment but does not detail out how the same may be used for ranking of performance. This will require determination of relative importance of different indicators within a sub-group, relative importance of each sub-group of indicators (within category of indicators) and relative importance of the three categories of indicators (or in other words, relative importance of each indicator). Also this research has not attempted to actually determine societal outcomes; rather it has attempted to check which indicators reflect such outcomes as proxy indicators. Determination of societal outcomes arising out of the public expenditure is another scope of future research. Societal outcomes in this context may refer to individual and institutional capabilities and freedom.

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# Impact of Swachh Bharat Abhiyan

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**ABSTRACT**

To accelerate the efforts to achieve universal sanitation coverage and to put focus on sanitation, the Prime Minister of India launched the Swachh Bharat Mission on 2nd October, 2014.The Mission Coordinator was given to the Secretary, Ministry of Drinking Water and Sanitation (MDWS) with two Sub-Missions, the Swachh Bharat Mission (Gramin) and the Swachh Bharat Mission (Urban),which aims to achieve Swachh Bharat by 2019, as a fitting tribute to the 150th Birth Anniversary of Mahatma Gandhi, which in rural areas shall mean improving the levels of cleanliness in rural areas through Solid and Liquid Waste Management activities and making Gram Panchayats Open Defecation Free (ODF), clean and sanitized. It is India's biggest ever cleanliness drive and 3 million government employees and school and college students of India participated in this event. The core objectives of the Swachh Bharat Mission (SBM) are to bring about an improvement in the general quality of life in the rural areas, by promoting cleanliness, hygiene and eliminating open defecation and to accelerate sanitation coverage in rural areas to achieve the vision of Swachh Bharat by 2ndOctober 2019. A massive community mobilization for Plastic Waste Shramdan and banning of Single Use Plastics was organized under Swachhata Hi Sewa program in 2019 through large scale for cleaning of public and tourist places, markets, statues, hospitals and bus stands.

## INTRODUCTION

Government of India initiated the Central Rural Sanitation Programme (CRSP) in 1986 primarily with the objective of improving the quality of life of the rural people and also to provide privacy and dignity to women. From 1999, a "demand driven" approach under the "Total Sanitation Campaign" (TSC) emphasized more on Information, Education and Communication (IEC), Human Resource Development (HRD), Capacity Development activities to increase awareness among the rural masses and generation of demand for sanitary facilities. This enhanced people's capacity to choose appropriate options through alternate delivery mechanisms as per their economic condition. Financial incentives were provided to Below Poverty Line (BPL) households for construction and usage of individual household latrines (IHHL). The "Nirmal Bharat Abhiyan" (NBA) the successor program of the TSC, was launched w.e.f. 1.4.2012 (Table 1). The objective was to accelerate the sanitation coverage in the rural areas so as to comprehensively cover the rural community through renewed strategies and saturation approach. Nirmal Bharat Abhiyan (NBA) envisaged covering the entire community for saturated outcomes with a view to create Nirmal Gram Panchayats. Under NBA, the incentives for IHHLs were increased and further focused support was obtained from MNREGA. However, there were implementation difficulties in convergence of NBA with MNREGA as funding from different sources created delays at the implementation mechanism.

**Table 1: Genesis of Swachh Bharat Mission**

| Time line | Efforts of sanitation |
|---|---|
| 1954 | First Five-Year Plan of the Government of India Included The National Water Supply and Sanitation Program introduced in the health sector |
| 1972 | Accelerated Rural Water Supply Program (ARWSP), Designed to provide funds for —problem villages‖ (tribal peoples, Scheduled Caste and ,backward classes) |
| 1981 | Beginning of the International Drinking Water and Sanitation Decade, Creation of the International Drinking Water Supply & Sanitation Program, Government of India made its first sanitation target |
| 1986 | Central Rural Sanitation Program (CRSP) launched. The focus of the CRSP was on supply (providing toilets) and subsidy driven |
| 1991 | National Technology Mission renamed the Rajiv Gandhi National Drinking Water Mission (RGNDWM) |
| 1999 | CRSP restructured, and TSC launched |
| 2003 | Nirmal Gram Puraskar (NGP) launched, Incentive scheme to encourage Panchayati Raj Institutions to become open defecation free |
| 2005 | Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) |
| 2012 | TSC is renamed Nirmal Bharat Abhiyan (NBA) Target set for 100% coverage of sanitation in rural areas by 2020 |
| 2014 | Swachh Bharat Abhiyan (SBA) replaced NBA, New target to make India 100% clean by 2019 |

To accelerate the efforts to achieve universal sanitation coverage and to put focus on sanitation, the Prime Minister of India launched the Swachh Bharat Mission on 2nd October, 2014.The Mission Coordinator was given to the Secretary, Ministry of Drinking Water and Sanitation (MDWS) with two Sub-Missions, the Swachh Bharat Mission (Gramin) and the Swachh Bharat Mission (Urban),which aims to achieve Swachh Bharat by 2019, as a fitting tribute to the 150th Birth Anniversary of Mahatma Gandhi, which in rural areas shall mean improving the levels of cleanliness in rural areas through Solid and Liquid Waste Management activities and making Gram Panchayats Open Defecation Free (ODF), clean and sanitized. The Mission shall strive for this by removing the difficulties that were hindering the progress, including partial funding for Individual Household Latrines from MNREGS, and focusing on critical issues affecting outcomes.

The main objectives of the Swachh Bharat Mission (SBM) are

a) To bring about an improvement in the general quality of life in the rural areas, by promoting cleanliness, hygiene and eliminating open defecation.

b) To accelerate sanitation coverage in rural areas to achieve the vision of Swachh Bharat by 2$^{nd}$October 2019.

c) To motivate Communities and Panchayati Raj Institutions to adopt sustainable sanitation practices and facilities through awareness creation and health education.

d) To encourage cost effective and appropriate technologies for ecologically safe and sustainable sanitation.

e) To develop where required, Community managed sanitation systems focusing on scientific Solid & Liquid Waste Management systems for overall cleanliness in the rural areas.

**Reasons for Swachh Bharat Abhiyan**

Diarrhoea kills over one lakh children every year, lack of sanitation leads to physical and cognitive stunt in children which made less productive for future work force in India and open defecation is a serious threat to safety and dignity of women which could be improved through proper sanitation program.

**The Pledge for All**

Hon'ble PM Narendra Modi has urged each and every one to pledge the following as a part of the Swachh Bharat Abhiyan: (Clean India Journal, I Pledge).

"I take this pledge that I will remain committed towards cleanliness and devote time for this. I will devote100 hours per year—that is two hours per week—to voluntary work for cleanliness. I will neither litter nor let others litter. I will initiate the quest for cleanliness with myself, my family, my locality, my village and my work place. I believe that the countries of the world that appear clean are so because their citizens don't indulge in littering nor do they allow it to happen. With this firm belief, I will propagate the message of Swachh Bharat Mission in villages and towns. I will encourage 100 other persons to take this pledge which I am taking today. I will endeavor to make them devote their 100 hours for cleanliness. I am confident that every step I take towards cleanliness will help in making my country clean."—*Narendra Modi, Hon'ble Prime Minister, India.*

**Swachh Bharat Mission: Urban Areas**

The mission aims to cover 1.04 crore households, provide 2.5 lakh community toilets, 2.6 lakh public toilets, and a solid waste management facility in each town. Under the programme, community toilets will be built in residential areas where it is difficult to construct individual household toilets. Public toilets will also be constructed in designated locations such as tourist places, markets, bus stations, railway stations, etc. The programme will be implemented over a five-year period in 4,401 towns. Of the Rs 62,009 crores likely to be spent on the programme, the Centre will pitch in Rs 14,623 crores. Of the Centre's share of Rs 14,623 crore, Rs 7,366 crores will be spent on solid waste management, Rs 4,165 crores on individual household toilets, Rs 1,828 crores on public awareness and Rs 655 crores on community toilets.

- No of Individual Household toilets constructed (2020-2021): 62.64 lacs
- Number of Community and Public toilets constructed (2020-2021): 6.20 lacs
- Wards and cities with 100% Door to Door Waste Collection (2020-2021) are 83434 and 4372, respectively
- ODF declared (99%): 4371
- ODF Certified: 4316
- Garbage free cities (2020-2021): 167*, 166***, 9*****

**Swachh Bharat Mission: Gramin Areas**

The Nirmal Bharat Abhiyan has been restructured into the Swachh Bharat Mission (Gramin). The mission aims to make India an open defecation free country in Five Years. Under the mission, One lakh thirty four thousand crore rupees will be spent for construction of about 11 crore 11 lakh toilets in the country. Technology will be used on a large scale to convert waste into wealth in rural India in the forms of bio-fertilizer and different forms of energy. The mission is to be executed on war footing with the involvement of every gram panchayat, panchayat samiti and Zila Parishad in the country, besides roping in large sections of rural population and school teachers and students in this endeavour.

- From October 2014 to 26.12.2020 (2020-2021) 10.84 crores toilets have been constructed under SBM (G). Also, 16.41 lakhs toilets have been constructed under MNREGA as on 31st March, 2017.
- Sanitation Coverage as on 2.10.2014 was **38.7%**. This has increased to 61.25**%** as on 26.12.2020 (2020-2021).
- 711 Districts, 2,62,772 GPs and 602988 Villages have been declared Open Defecation Free (ODF) as on 26.12.2020 (2020-2021). As on 04.07.2019, 30 States/UTs have been declared ODF.

- Central allocations under Swachh Bharat Mission Gramin were Rs. 2850 crores, Rs. 6525 crores, Rs. 10,500 crores, Rs. 14,000 crores and Rs.34303 crores, Rs. 140881 crores in 2014-15, 2015-16, 2016-17, 2017-18, 2018-19 and 2019-2020, respectively.

**Present Status of Swachh Bharat (Gramin)**

Only about 22% of the rural families had access to toilets in 2001. With the efforts put into the Total Sanitation Campaign/Nirmal Bharat Abhiyan (NBA) this has gone up to 32.70% as per Census 2011. Further as per NSSO 2012, 40.60% rural households have toilets. All rural households are planned to be covered with sanitary facilities by 2019 through Swachh Bharat Abhiyan. The government decides to achieve an Open Defecation Free (ODF) India by 2 October 2019, the 150th birth anniversary of Mahatma Gandhi, by constructing 12 crores toilets in rural India, at a projected cost of Rs1.96 lakh crore (US$29 billion). Prime Minister Narendra Modi spoke of the need for toilets in his 2014 Independence Day speech. As of May 2015, 14 companies including Tata Consulting Services, Mahindra Group and Rotary International have pledged to construct 3,195 new toilets. As of the same month, 71 Public Sector Undertakings in India supported the construction of 86,781 new toilets. Most of these toilets are a type of pit latrine, mostly the twin pit pour flush type.

Between April 2014 and January 2015, 31.83 lakh toilets were built. Karnataka led all States in construction of toilets under the programme. As of August 2015, 80 lakh toilets have been constructed under the program. As of 18 March 2016, 10 districts in India were ODF.

**Achievements made under SBM (Gramin) upto 2020-21 as under:**

| Component | 2013-14 | 2014-15 | 2015-16 | 2016-17 | 2017-18 | 2018-19 | 2020-21 |
|---|---|---|---|---|---|---|---|
| Household toilets | 49,76,294 | 4810142 | 12398184 | 21510893 | 29257956 | 21850583 | 3936590 |

Source: ***Ministry of Drinking Water and Sanitation, Government of India***

**Bal Swachhta Mission**

The Union Minister of Women and Child Development Smt. Maneka Sanjay Gandhi launched the National Bal Swachhta Mission in New Delhi on 14.11.2014. The Bal Swachhta Mission is a part of the nationwide sanitation initiative of 'Swachh Bharat Mission' launched by the Prime Minister on 2nd October, 2014. Speaking at the launch of Bal Swachhta Mission, Smt. Maneka Sanjay Gandhi said that children can play a very important role in achieving a Swachh Bharat. She said that they can become ambassadors of cleanliness and motivate others to keep their homes, schools, and surroundings clean. Cleanliness habits should be imbibed in the children in informal ways like small games, poems, storytelling, conversation with children among others, she added. The Minister praised the message of cleanliness given by the children on the occasion through their innocent performances. The Minister said that the cleanliness drive has to be a nationwide effort and should include sustained measures taken up on a continuous basis.

The nationwide Bal Swachhta Mission will have the following six themes:

- Clean Anganwadis
- Clean Surroundings e.g., Playgrounds
- Clean Self (Personal Hygiene/Child Health)
- Clean Food
- Clean Drinking Water
- Clean Toilets

During the Bal Swachhta Week from 14th to 19th November, one of the above themes would be covered at each Anganwadi Centre in the states. The Women and Child Development Departments of various states have been asked to implement the Bal Swachhta Mission with the help of Departments of School Education, Urban Development, Drinking Water and Sanitation, and Information and Publicity. The events will be organized at State, District, Block, and Gram Panchayat level.

**Financial assistance**

The programme has also obtained funding and technical support from the World Bank, corporations as part of corporate social responsibility initiatives, and by state governments under the Sarva Shiksha Abhiyan and Rashtriya Madhyamik Shiksha Abhiyan schemes. Swachh Bharat Abhiyan is expected to cost over ₹620 billion (US$9.2 billion). The government provides an incentive of ₹12,000 (US$180) for each toilet constructed by a BPL family. Total fund mobilized under *Swachh Bharat Kosh* (SBK) as on 31 January 2016 stood at ₹3.69 billion (US$55 million). An amount of ₹90 billion (US$1.3 billion) was allocated for the mission in 2016 Union budget of India. Government and the World Bank signed a US$1.5 billion loan agreement on 30 March 2016 for the *Swachh Bharat* Mission to support India's universal sanitation initiative. The World Bank will also provide a parallel $25 million technical assistance to build the capacity of select states in implementing community led behavioral change programmes targeting social norms to help ensure widespread usage of toilets by rural households.

**Ambassadors**

Hon'ble Prime Minister Narendra Modi selected 9 public figures to propagate this campaign. They are Sachin Tendulkar, Priyanka Chopra, Anil Ambani, Baba Ramdev, Salman Khan, Shashi Tharoor,Team of Tarak Mehta Ka Oolta Chasma, Nridula Sinha, Kamal Hassan, Virat Kohli, M.S. Dhoni. Urban Development Minister M. Venkaiah Naidu picked up a broom to help clean the cyclone hit port city of Visakhapatnam in the southern state of Andhra Pradesh, as part of the cleanliness campaign.

**Brand ambassadors**

Venkaiah Naidu listed brand ambassadors in various fields. They are Rajyogini Brahmakumari, Dadi Jankiji, Pawan Kalyan, S. P. Balasubrahmanyam, Amala (actress), K. Kavitha, GunupatiV enkata Krishna Reddy, Suddala Ashok Teja, Pullela Gopich and, Humpy Koneru., Galla Jayadev, Nithin, V. V. S. Laxman, J. Rameshwar Rao, Shivlal Yadav, B. V. R. Mohan Reddy, Lakshmi Manchu.

On 2 October 2014, Prime Minister Modi nominated nine people, including Comedian Kapil Sharma, Former captain of Indian cricket team Sourav Ganguly, Sonal Man Singh, classical dancer, Ramoji Rao of Eenadu group, Former IPS officer Kiran Bedi for taking forward his 'Swachh Bharat Abhiyaan', AroonPurie of the India Today Group, Padmanabha Acharya, Nagaland Governor. He also nominated some organisations, including the Institute of Chartered Accountants of India, Eenadu and *India Today* besides *dabbawala* of Mumbai, who deliver home-made food to lakhs of people in the city.

On 8 November 2014, Modijee carried the message to Uttar Pradesh and nominated another set of nine people for the state which includes Akhilesh Yadav, Deviprasad Dwivedi Raju Srivastava, Suresh Raina, Kailash Kher, Swami Rambhadracharya, Manoj Tiwari, Mohammad Kaif, Deviprasad Dwivedi.

**Swachhta Iconic places**

Under the inspiration of Hon'ble Prime Minister, the Ministry has taken up a multi-stakeholder initiative focusing on cleaning up 100 places across India that are "iconic" due to their heritage, religious and/or cultural significance.

*The 10 iconic sites which were taken up in the first phase as follows:*

- Ajmer Sharif Dargah, Ajmer, Rajasthan
- CST, Mumbai, Maharashtra
- Golden Temple, Amritsar, Punjab
- Kamakhya Temple, Guwahati, Assam
- Maikarnika Ghat, Varanasi, Uttar Pradesh
- Meenakshi Temple, Madurai, Tamil Nadu
- Shri Mata Vaishno Devi, Katra, J&K
- Shree Jagannath Temple, Puri, Odisha
- The Taj Mahal, Agra, Uttar Pradesh

- Tirumala Tirupati Devasthanams, Tirupati, Andhra Pradesh

*The Phase II launched in November, 2017 included*

- Gangotri (Uttarakhand),
- Yamunotri (Uttarakhand),
- Mahakaleshwar Temple (Ujjain),
- Charminar (Hyderabad),
- Convent and Church of St Francis of Assissi (Goa),
- Kalady (Kerala),
- Gommateswara (Karnataka),
- Baidyanath Dham (Jharkhand),
- Gaya Tirth (Bihar) and
- Somnath temple (Gujarat)

*During June, 2018, the government today added ten Swachh Iconic Places (SIP) under phase III of its flagship programme, Swachh Bharat Mission.*

- Raghavendra Swamy Temple (Kurnool, Andhra Pradesh),
- Hazardwari Palace (Murshidabad, West Bengal),
- Brahma Sarovar Temple (Kurukshetra, Haryana),
- Vidur Kuti (Bijnor, Uttar Pradesh),
- Mana village (Chamoli, Uttarakhand),
- Pangong Lake (Leh-Ladakh, Jammu & Kashmir),
- Nagvasuki Temple (Allahabad, Uttar Pradesh),
- Ima Keithal/market (Imphal, Manipur),
- Sabarimala Temple (Kerala) and
- Kanvashram (Uttarakhand)

**Swachh Survekshan**

Government of India released a "Cleanliness Ranking" for 73 cities on 15 February 2016. 1. Mysore, 2. Chandigarh, 3. Tiruchirapalli, 4. New Delhi Municipal Council, 5. Visakhapatnam, 6. Surat, 7. Rajkot, 8. Gangtok, 9. Pimprichinchwad, 10. Greater Mumbai.

**Mysuru tops the list, Dhanbad at the bottom**

**15 Leaders, 20 Aspiring Leaders, 18 cities needing acceleration, 20 Slow Movers identified**

15 cities who scored more than 70% of the total marks of 2000 were categorized as Leaders, 20 cities with scores in the range of 60%-70% are Aspiring Leaders, those with scores in the range of 50%-60% are the cities who need to accelerate their efforts and cities who scored below 50% are named Slow Movers who need to work harder to improve sanitation.

**Leaders:** 1.Mysuru, 2.Chadigarh, 3.Tiruchirapalli, 4.New Delhi Municipal council, 5.Visakhapatnam, 6.Surat, 7.Rajkot, 8.Gangtok, 9.Pimprichindwad, 10.Greater Mumbai, 11.Pune

12.Navi Mumabi, 13. Vadodara, 14. Ahmedabad, 15. Imphal

**Aspiring Leaders:** 16.Panaji, 17.Thane, 18.Coimattore, 19.Hyderabad, 20.Nagpur, 21.Bhopal, 22.Allahabad, 23.Vijayawada, 24.Bhubaneswar, 25.Indore, 26.Madurai, 27.Shimla, 28.Lucknow

29.Jaipur, 30. Gwalior, 31. Nashik, 32. Warangal, 33. Agartala, 34. Ludhiana, 35. Vasai-Virar

**Acceleration required:** 36. Chennai, 37. Gurgaon, 38. Bengaluru, 39. South Muncipal Corporation of Delhi, 40. Thiruvananthapuram, 41. Aizawl, 42. Gandhinagar, 43. North MCD, 44. Kozhikode, 45. Kanpur, 46. Durg, 47. Agra, 48. Srinagar, 49. Amritsar, 50. Guwahati, 51. Faridabad, 52. East MCD, 53. Shillong

**Slow Movers:** 54.Hubbali-Dharwad (Karnataka), 55.Kochi, 56.Aurangabad, 57.Jodhpur, 58.Kota, 59.Cuttack, 60.Kohima, 61.Dehradun, 62.Ranchi, 63.Jabalpur, 64.Kalyan Dombivili (Maharashtra), 65.Varanasi, 66.Jamshedpur, 67.Ghaziabad, 68.Raipur, 69.Meerut, 70.Patna, 71.Itanagar, 72.Asansol, 73.Dhanbad.

***Swachh Sarvekshan 2017 was conducted across 500 cities between 4 January 2017 and 7 February 2017.***

The top 10 cities are 1. Indore, 2. Bhopal, 3. Visakhapatnam, 4. Surat, 5. Mysore, 6. Tiruchirapalli, 7. New Delhi Municipal Council, 8. Navi Mumbai, 9. Tirupati, 10. Vadodara

*Under Swachh Sarvekshan 2019*

- Among large states Tamil Nadu bagged the top spot, Haryana came 2nd and Gujarat was 3rd in the pecking order.
- Among small states Mizoram came up top, followed by Daman & Diu and Sikkim emerged 3rd. The top districts of India were Peddapalli, Faridabad and Rewari.
- Among zones and UT, Haryana ranked topmost in North, Gujarat in West, TN in South, Jharkhand in East, Mizoram in North-East and Daman & Diu as UT.

***Under Swachh Sarvekshan 2021***

- Indore as India's cleanest city for the 5th time again whereas Surat and Vijayawada were given the second and third prizes for the best clean city. Chhattisgarh has got the honor of cleanest state.
- After this Jharkhand stood second and Varanasi was given the award for the cleanest Ganga city. Maharashtra and Madhya Pradesh with more than 100 urban local bodies have been declared the second and third cleanest states in the country after Chhattisgarh in the state category.

Ranking of top 20 cities: 1. Indore, 2. Surat, 3. Vijayawada, 4. Navi Mumbai, 5. Pune, 6. Raipur, 7. Bhopal, 8. Vadodara, 9. GVMC Vishakhapatnam, 10. Ahmedabad, 11. Rajkot, 12. Lucknow, 13. Greater Hyderabad, 14. Thane, 15. Gwalior, 16. Chandigarh, 17. Nashik, 18. Ghaziabad, 19. Pimpri Chinchwad and 20. Jabalpur.

**Source**: **Press Information Bureau, Government of India, Ministry of Urban Development.**

**Swachh Bharat Run**

A Swachh Bharat Run was organized at the Rashtrapati Bhavan on 2 October 2014. According to a statement from the Rashtrapati Bhavan around 1500 people participated and the event was flagged off by President Pranab Mukherjee. Participants in the run included officers and their families. The Times of India published an article on how "Desi companies beat Facebook in 'Swachh' apps race".

**Realtime monitoring**

The government will be launching a nationwide real time monitoring system for toilets constructed under the Swachh Bharat Abhiyan. For this the government of India is bringing awareness among the people through advertisements. With this system, the government aims to attain a fully open defecation free India by 2019. The Indo Nepal Doctors Association has launched Swachh Bharat Nepal on 3 January 2015 after getting inspired from the Prime Minister of India. Swasth Bharat Nepal Abhiyan was launched at the Indo-Nepali border region of Sunauli-Belihiya, which is the entry to the birthplace of the Buddha, Lumbini, Nepal.

**Appropriate Sewage and Garbage disposal system**

It is important to note that unsafe disposal of the human excreta imposes significant threat to public health and environmental cost particularly to urban areas. A study has shown that it costs around 60 per cent of the country's GDP. As indicated in the National Urban Sanitation Policy, impacts of poor sanitation are especially significant for the urban poor (22 percent of the total urban population), women, children and the elderly. It is also observed that inadequate discharge of untreated domestic/municipal wastewater has resulted in contamination of75 per cent of all surface water across India.

**Construction of Individual Household Latrines**

A duly completed household sanitary latrine shall comprise of a Toilet Unit including a substructure which is sanitary (that safely confines human faeces and eliminates the need of human handling before it is fully decomposed), a super structure, with water facility and hand wash unit for cleaning and hand washing. The Mission aims to ensure that all rural families have access to toilets. There are various models of toilets available based on safe sanitation technologies like the Twin Pit, Septic tank, Bio toilets amongst others.

Incentive as provided under the Mission for the construction of Individual House Hold Latrines (IHHL) shall be available for all Below Poverty Line (BPL) Households and Above Poverty Line (APL)Households restricted to SCs/STs, small and marginal farmers, landless labourers with homestead, physically handicapped and women headed households.

The Incentive amount provided under SBM(G) to Below Poverty Line (BPL) /identified APLs households shall be up to Rs.12,000 for construction of one unit of IHHL and provide for water availability, including for storing for hand-washing and cleaning of the toilet.

Central Share of this Incentive for IHHLs shall be Rs.9,000/- (75%) from Swachh Bharat Mission (Gramin). The State share will be Rs.3,000/-(25%). For North Eastern State, and Special category States, the Central share will be 10,800/- and the State hare Rs.1,200/- (90%: 10%).

**Community Sanitary Complex**

Community Sanitary Complexes comprising an appropriate number of toilet seats, bathing cubicles, washing platforms, Wash basins etc, can be set up in a place in the village acceptable and accessible to all. Ordinarily such Complexes shall be constructed only when there is lack of space in the village for construction of household toilets and the Community/GP owns up the responsibility of their operation and maintenance and gives a specific demand for the same. Such Complexes can be made at public places, markets, bus stands etc., where large scale congregation of people takes place. The maximum support per unit prescribed for a Community Sanitary Complex is Rs.2 lakh. Sharing pattern amongst Central Government, State Government and the Community shall be in the ratio of 60:30:10.

**Solid and Liquid Waste Management**

The objective of SBM(G) is to bring about improvement in the cleanliness, hygiene and the general quality of life in rural areas. Solid and Liquid Waste Management (SLWM) is one of the key components of the program. To create clean villages, it is essential that the IEC interventions focus on Solid and Liquid Waste Management so as to create a felt need for these activities amongst the population. This must lead to the setting up of systems for the scientific disposal of waste in sucha way that has a tangible impact on the population. The Community /Gram panchayat has to be motivated to come forward and demand for such a system, which they have to subsequently operate and maintain.

Once the demand is created, to ensure that the resources are used efficiently, SLWM is to be taken up in project mode for each Gram Panchayat (GP) with financial assistance capped for a GP on number of household basis to enable all GPs to implement sustainable SLWM projects. The total assistance under SBM(G) for SLWM projects shall be worked out on the basis of total number of households in each GP, subject to a maximum of Rs.7 lakh for a GP having up to 150 households, Rs.12 lakh up to 300 households, Rs.15 lakh up to 500 households and Rs.20 lakh for GPs having more than 500 households. Funding for SLWM project under SBM(G) is provided by the Central and State Government in the ratio of 75:25. Any additional cost requirement is to be met with funds from the State/GP, and from other sources like Finance Commission funding, CSR, Swachh Bharat Khosh and through the PPP model.

**For Solid Waste Management**: States are to decide the technologies suitable to their areas. Technologies identified by the Committee on Technologies may also be considered for implementation. Collection, segregation and safe disposal of household garbage, decentralized systems like household composting and biogas plants shall be permitted. Activities related to maximum reuse of organic solid wastes as manure should be adopted. Such technologies may include vermi-composting, NADEP composting, or any other composting method, individual and community biogas plants. Funds allocated for Solid and Liquid Waste Management may be used to implement safe disposal solutions for menstrual waste (used sanitary cloths and pads) and setting up incinerators in Schools, Women's Community Sanitary Complexes, Primary Health Centre, or in any other suitable place in village and collection mechanisms etc can be taken up. Technologies may include appropriate options that are socially acceptable and environmentally safe.

**For Liquid Waste Management**: States are to identify suitable technologies. Methods adopted for management of liquid wastes may focus on maximum reuse of such waste for agriculture purposes with least operation and maintenance costs. For collection of waste water, low-cost drainage/ small bore system, soakage pit may be adopted.

For treatment of waste water, the following technologies may inter-alia be considered:

a. Waste Stabilization Pond (WSP) technology- Waste stabilization ponds (WSPs)

b. Duckweed based waste water treatment.

c. Phytoroid Technology (developed by NEERI)

d. Anaerobic decentralized waste water treatment.

**Swachh Vidyalaya**

Swachh Vidyalaya is the national campaign driving 'Clean India: Clean Schools'. A key feature of the campaign is to ensure that every school in India has a set of functioning and well-maintained water, sanitation and hygiene facilities. Water, sanitation and hygiene in schools refers to a combination of technical and human development components that are necessary to produce a healthy school environment and to develop or support appropriate health and hygiene behaviours. The technical components include drinking water, hand washing, toilet and soap facilities in the school compound for use by children and teachers. The human development components are the activities that promote conditions within the school and the practices of children that help to prevent water, hygiene and sanitation related diseases. School sanitation and hygiene depend on a process of capacity enhancement of teachers, community members, SMCs, Non-Governmental Organisations (NGOs) and Community Based Organisations (CBOs) and education administrators. Water, sanitation and hygiene in school aims to make a visible impact on the health and hygiene of children through improvement in their health and hygiene practices, and those of their families and the communities. It also aims to improve the curriculum and teaching methods while promoting hygiene practices and community ownership of water and sanitation facilities within schools. it improves children's health, school enrolment, attendance and retention and paves the way for new generation of healthy children. It is the role of policymakers, government representatives, citizens and parents to make sure that every child attends a school that has access to safe drinking water, proper sanitation and hygiene facilities. This is every child's right.

**National Rural Drinking Water Program (NRDWP)-JJM**

Restructured and subsumed into Jal Jeevan Mission (JJM) to provide Functional Household Tap Connection (FHTC) to every rural household i.e., Har Ghar Jal, by 2024. National Rural Drinking Water Program (NRDWP) aims to provide adequate and safe drinking water to the rural people of India. About 77% of rural habitations have achieved fully covered status i.e, getting at least 40 litres per capita per day under the NRDWP and 54% of the rural population have access to tap water. During 2014-15 to 2016-17 the schemes completed are Piped Water Supply Multi-village schemes (8761 Nos.), Piped Water Supply Single Village Schemes (1,56,942 Nos.), Tube wells, HPS, Wells etc. (3,66,622 Nos.), Recharge structures (59716 Nos.) and Point Treatment Systems (7711

Nos.) and total 14.58 crores rural people benefitted by these schemes. In FY 2019-20, GoI allocated Rs.10,001 crore for NRDWM

**Elimination of Single Use Plastic (SUP)**

The Indian plastics industry made a promising beginning during 1957 with the production of polystyrene. Nineteen sixties and seventies saw significant progress and the industry has grown and diversified rapidly. The industry spans the country and hosts around 50,000 processing units, over 2,000 exporters and employs about 4 million people across value chain. About 85-90 of these units are small and medium-sized enterprises employing bulk of human resources.

India generates 95 lakh tonnes plastic waste per year of which 38 lakh tonnes is uncollected i.e. Single Use Plastics (SUP), ended in dumps, rivers and even our animals. About 6 lakh tonnes of plastic waste enters sea annually.

- Most of the states around 18 have banned plastic carry bags and selected states like Maharashtra, Tamil Nadu, Odisha, Madhya Pradesh have also banned 'one-time use and throw away plastic items' like cutlery, plates, cups, straws, etc.
- A massive community mobilization for Plastic Waste Shramdan and banning of Single Use Plastics was organized under Swachhata Hi Sewa program in 2019 through large scale for cleaning of public and tourist places, markets, statues, hospitals and bus stands.
- **11th September to 1st October 2019**: Awareness generation across towns and villages, preparations for collection, disposal of plastic waste Shramdaan for general Swachhata
- **2nd October, 2019**: Nationwide shramdan for plastic waste collection and segregation
- **3rd October-27th October, 2019**: Recycling and effective disposal of the collected plastic waste.

**Alternatives to Single Use Plastics (SUP)**

- Use of plastic alternatives such as glass, paper and cardboard
- Converting plastic waste into poly-fuel which is a high calorie fuel which is an alternative to Kerosene
- Converting plastic waste into fertilizer which increases the yielding capability of crops
- Converting plastics into electricity which is a good option for our country with scarcity of electricity
- Plastic waste added to bitumen in road construction has proved to extend life of road and improve quality
- Using plastic waste as additive to furnaces in cement kiln and power plants should be mandated
- Converting plastic waste materials into value added items

**Optimum use of technology**

Various cost-effective tools and techniques for water supply and sanitation have been evolved by many agencies and organization at national and international level. In this regard, it may be suggested that various cost-effective measures and techniques demonstrated by institutions like Sulabh International should be applied widely.

**Technological interventions**

- MIS
- The App: (SwachhApp)
- Ganga Shravan Abhiyaan (GSA)
- Indigenous water purification technologies
- Environment friendly Plasma technologies
- Unique Multi Stage Biological Treatment Solution

- The BARC UF Membrane Technology for Domestic Water Purifiers
- Environmental isotope techniques in the water resources development and management
- Earthen Pot Composting/ Pit composting/Vermi-composting/Rotary Drum composting

**Electronic tools**

- Arduino
- Ultrasonic Sensor
- GSM Module
- Radiation Hygienization of Municipal Sewage Sludge
- Refuse Derived Fuel: An Emerging Processing Technology in MSWM

**Need for mass awareness**

Every segment of population, from primary school children to elderly persons need to be properly sensitized about inherent linkages of sanitation for public health. Besides roping in the educational institutions, particularly the schools in awareness campaigns, optimum use needs to be made of social media as well as electronic and print media to spread the message to grassroot level. For ensuring an effective sanitation policy, the following also need to be considered:

i) Need for mass awareness; ii) Social and occupational aspects of sanitation; iii) Coordination among administrative bodies/ institutions; iv) Comprehensive approach; v) Optimum use of technology; vi) Reaching the unreached; viii) Bridging the demand-supply gap.

**Convergence**

Convergence is useful to make such a nation-wide programme successful. Through convergence with MNREGS, MPLADS and other schemes, the following steps should be taken up: i) Construction of toilets in households, schools, anganwadis, SLWM and community sanitary complexes. ii) Construction of individual household toilets based on a community approach, under the MPLAD scheme and one time grant for operation and maintenance of the community toilets.iii) Adopting convergence of TSC with other Centrally Sponsored Schemes like PURA, IAY, NRHM, Adarsh Gram Yojana and other schemes and Departments/ Ministries.

**Comprehensive approach**

There should be no piecemeal approach for improving sanitation in our country. Investment in sanitation, as suggested under National Urban Sanitation Policy, should taken into account, the full cycle of safe confinement, treatment and safe disposal. Sanitation programmes would

also have to use a menu of different approaches, such as financing at the household level and a range of affordable sanitation options for potential consumers. This may need working with a range of new partners, including public health officials, grass-root organizations and private sectors.

**Sensitization**

It is also necessary to sensitize the political leadership at national, state and district levels on the principles of demand driven approaches to total sanitation and to enable high level political support for sanitation with following programs

- The concept of Bal Panchayat
- The sports meet and cultural programmes
- Cleanliness Drive
- Swachh Bharat Pakhawada
- Swachhta Hi Sewa

**Capacity Building**

Capacity building is essential for effective implementation of the programme. There should be a tie up with international institutions of repute for mandatory training of Centre/State officials engaged in the sanitation sector. It is desirable that a national level institute on water and sanitation on the lines of National Institute of Rural Development is to be set up by the Ministry for capacity building at various levels. This suggestion has also been made by the Working Group on Rural Domestic Water and Sanitation for the 12th Plan 2012-17. Government of India along-with the State Governments has been endeavoring for achievement of sanitation goals and also for promoting partnership with public, private and non-governmental agencies for improved provisions, maintenance and management of sanitation facilities. About **3%** of the total Central Government allocation under the mission will be earmarked for capacity building, administrative and office expenses of States and ULBs. About **2%** of the total Central Government allocation under the mission will be utilized at MoUD level for capacity building, convening national and regional workshops, various awards and best practice recognition, programme research, studies, international cooperation for capacity building and technology development, A&OE and various eligible purposes in consultation with the Integrated Finance Division (IFD) of the M/o UD.

States shall propose extensive capacity building activities to be implemented in a mission-mode manner, which will enable the progressive achievement of objectives of SBM (Urban) in a time-bound manner. These will be specified in the comprehensive annual action plan prepared by each state. This will be approved by State Level High Power Committee after sharing and considering suggestions from MoUD. At least 50% of this fund, in each annual plan, as approved by State HPC, must go to the ULB's for activities at the ULB level.

**Slogans on Swachh Bharat Abhiyan given by Eminent Personalities**

'Every road, path, office, home, hut, stream and particle of air around us can and must be kept clean'--- **President Pranab Mukherjee**

**'**No positive factor can help you, until you are single minded for success. Take up one idea as your life –think of it, dream of it and live on that idea. And success is yours for sure'--- **Swami Vivekananda.**

'If we make a public movement, we can make our country being counted as one among the cleanest nations'--- **Prime Minister Narendra Modi.**

**Other Slogans**

"Ek kadam swachhata ki ore."

"Cleanliness is next to godliness."

"India can do it. People of India can do it."

"let's make the right choice and use dustbin."

"Clean India beautiful India."

"Dharti mata kare pukar, aas paas ka karo sudhaar."

"Clean city, clean city, My dream city."

"It's our Planet don't throw it away."

"Devote the 100 hours every year towards the cause of cleanliness."

"Cleanliness is the Only solution to stay away from diseases**.**"

## CONCLUSION

Moreover, Prime Minister of India's target of complete sanitation in the next five years is aiming to change situation and behavioural pattern of India. A significant investment in cleanliness, hygiene training, maintenance and human resource linked to Swach Bharat Abhiyan will certainly aid in the Incredible India Campaign. Besides, it can be a direct influence on the medical tourism, increasing its scope even further. The days are not too far when we will send off tourists with fond memories of a cleaner and welcoming India, adorned with cultural heritage, aesthetic artefacts, rich flora & fauna and natural scenic beauties. The PM has rightly asserted that Swachh Bharat Abhiyan should be a combined approach of both the Government as well as the people. Everybody is in the hope that the Swachh Bharat Mission does not repeat another Nirmal Bharat Abhiyan started by the previous Government in 1999 with the same mission but was far from a success.

There is no doubt about the fact that change begins at home. Every citizen of the country at various levels. This suggestion has also been made by the Working Group on Rural Domestic Water and Sanitation for the 12th Plan 2012-17. Government of India along-with the State Governments has been endeavoring for achievement of sanitation goals and also for promoting partnership with public, private and non-governmental agencies for improved provisions, maintenance and management of sanitation facilities. About **3%** of the total Central Government allocation under the mission will be earmarked for capacity building, administrative and office expenses of States and ULBs. About **2%** of the total Central Government allocation under the mission will be utilized at MoUD level for capacity building, convening national and regional workshops, various awards and best practice recognition, programme research, studies, international cooperation for capacity building and technology development, A&OE and various eligible purposes in consultation with the Integrated Finance Division (IFD) of the M/o UD.

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# Assessment of the effectiveness of open defecation free system on the incidence of faecal contamination on environment through microbial source tracking

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**Research Article**

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## Abstract

The aim of this study was to assess the effectiveness of open defecation free (ODF) system on the incidence of faecal contamination on environment (water, soil and food mediums). The magnitude of contamination of environmental medium of ODF and non-open defecation free (n-ODF) villages by faecal indicator bacteria (FIB) in three states of India, was investigated. The FIB positive samples were further processed to determine the source of faecal contamination using *Bacteroidale* molecular markers for human (HuBac). The matrix of relative risk (RR) due to FIB and HuBaC contamination was developed to assess the effectiveness of ODF interventions. When compared to ODF villages, the RR of faecal contamination in n-ODF villages was estimated 11.25 times more likely in groundwater, 2.68 times more likely in household storage drinking water, 2.71 times more likely in piped water supplies, 1.13 times more likely in soil and 1.48 times more likely in food. The RR of faecal contamination traceable to humans was estimated 12.66, 2.48, 2.40, 1.10 and 2.16 times more likely in n-ODF villages as compared to ODF villages in cases of groundwater, household storage drinking water, piped water supplies, soil and food respectively. The risk assessment matrix designed in present study can be useful towards evaluation of the performance of ODF missions being implemented in many developing countries to achieve sanitation and hygiene objectives in accordance to the target 6.2 of Sustainable Development Goals 2030.

## Introduction

The United Nation's Sustainable Development Goal 6 (Target 6.2) seeks by 2030, the end of open defecation in addition to the achievement of universal, adequate and equitable access to safely managed sanitation by all with special attention in this context towards the need of women and vulnerable section of society (United Nations 2018; UNICEF and WHO 2020). The worldwide rate of open defecation has been reduced from 21–9% (0.7 percentage points per year) since the year 2000, but 673 million people were still practicing open defecation in the year 2017, that too were increasingly concentrated in small number of countries (WHO and UNICEF 2019). During the year 2020, 580 million people had limited sanitation services; 616 million used unimproved sanitation facilities, and 494 million practiced open defecation (WHO and UNICEF 2021).

The *Swachh Bharat Mission* (SBM) in India was launched in the year 2014 to make the country open defecation free (ODF) by ensuring use of household toilets, especially in rural areas (DDWS 2016). The rural (*Gramin*) component of the mission SBM-G has demonstrated spectacular achievement in this context, with over 660,000 villages declared themselves as being ODF after achieving full sanitation coverage in their communities. Through the SBM-G, India has significantly accelerated its progress towards SDG 6.2, with a decade to spare (DDWS-SBM-G 2015). However, there emerged the inquisitiveness whether the awareness mission to eliminate open defecation and creation of ODF communities has resulted in the reduction in faecal contamination in the environment, which was the expected impact for such programme with particular focus on sustaining clean water resources for communities. In order to ascertain the impacts of faecal contamination due to human sources on environmental medium, a study was designed to compare such parameters in water, soil and food samples drawn from ODF and n-ODF villages in three states of India namely Odisha, Bihar and West Bengal from December 2018 to January 2019, when the Mission was still active and these state were still having n-ODF villages (MoJS 2019).

The faecal contamination in environment occurs when excreta containing bacterial coliforms, from humans or animals enter the source (Banda et al. 2007). Most of the groundwater coliforms come from leaching and percolation of liquids through soils and other materials, originating from sources with solid (human and animal excreta) and liquid wastes. Identifying sources of human exposure to faecal coliforms that increases potential transmission of disease through multiple faecal-oral transmission pathways, can help to mitigate future risks to human health and improve how water, sanitation and hygiene interventions are designed (Ashbolt et al. 2001). The faecal coliform group includes all rod-shaped anaerobic and aerobic bacteria that are non-spore forming, gram-negative, lactose-fermenting in 24 hours at 44.5°C. *Escherichia coli* are one of the dominant members of faecal group. (Ashbolt et al. 2001; Cabral 2010; Kinzelman et al. 2012; Zseni 2015).

As standard detection of faecal indicator bacteria (FIB) (*Escherichia* coli, faecal coliforms and enterococci) unable to identify and differentiate between the host sources of faecal contamination, more state-of-the-art detection methods are, therefore, needed where open defecation occurs without any demarcation from domestic animal faecal loading. Accordingly, methods which combine microbial and molecular biological techniques are the only modalities to distinguish whether the contamination is a result of human or animal excreta, through microbial source tracking (Domingo and Edge 2010; Schriewer et al. 2015; Staley et al. 2016). In this context, the first step to be performed is microbiological examination by enumerating FIB, which is commonly found in the faeces of warm-blooded animals including humans, followed by subsequent study based on genetic markers in the positive samples. (Ahmed et al. 2009; Carson et al. 2001; Bachoon et al. 2012; Xue and Feng 2018). Detection of host associated genetic markers in water samples has been reported to compare sensitivities and specificities of the host-associated genetic markers (Xue and Feng 2018). Faecal indicators together with occurrence of host-specific molecular markers were enumerated in sewage spiked freshwater, seawater and distilled water samples (Ahmed et al. 2009). The groundwater samples analysis for total and faecal coliform count were reported in ODF villages and Multiple Antibiotic Resistance (MAR) index values estimated to unravel the source of contamination human or non-human (Malan et al. 2020).

## Materials And Methods

# Selection of Study Population

The selection of the ODF and n-ODF districts (one each per state) was decided, the data of which was made available by the respective State Government and UNICEF, by considering the conditions such as (i) the existing status of the districts in the state (ODF versus n-ODF) and (ii) the approachability of the district to the nearest airport to permit rapid transportation of samples to the laboratory. Further, ten number of villages were identified in each category of ODF and n-ODF, from pre-selected districts in the state of Odisha, Bihar, and West Bengal (total number of 60 villages), using selection criteria such as villages that (i) have a population of 500 or more persons and (ii) have been declared ODF for at least 6 months; subsequently 4 villages of each classification (ODF and n-ODF) were randomly selected from the shortlist, from each state thereby in totality 24 villages were finalized for study (Census of India, 2011; MoJS 2019).

## Details of Study Area

The study areas in Odisha, Bihar and West Bengal, are represented in the Fig. 1. The landuse in the study areas of Odisha consist of 62 to 75 percent area in ODF villages and 50 to 99 percent area in n-ODF villages under net sown area (agricultural use), whereas 2.2 to 5.7 percent area in ODF villages and upto 10 percent area in n-ODF villages is culturable waste land; the study areas of Bihar consist of 67 to 95 percent area in ODF villages and 80 to 90 percent area in n-ODF villages, is under net sown area (agriculture use), whereas 5.5 to 33 percent area in ODF villages and 9.9 to 20 percent area in n-ODF villages is under non-agricultural Use; in case of West Bengal, ODF villages comes under census town and hence these have no agricultural land, whereas in n-ODF villages, 53 to 87 percent area comes under agricultural use and 13.5 to 38 percent area is under non-agricultural use (Census of India, 2011).

## Sampling Design for Water, Soil, and Food Medium

Sampling design comprised of collection of water, soil and food samples from strategic locations in 24 numbers of villages as decided. Water samples were collected from sources available at the village level such as (i) Groundwater sources (preferably public handpumps), (ii) Piped water supply (wherever available) and (iii) Household storage drinking water. The soil sampling locations were selected in the vicinity of community toilet. In the event of non-existence of community toilet in any village, the soil was sampled from open field near to the current or earlier open defecation areas, depending on whether it is an ODF or n-ODF village. The sampling of food was done by following the scheme such as collection of cooked food from village *dhabas* (local eatery) or from mid-day meal (MDM) of school or from *Anganwadi* (rural child care centre in India), whatever is available at the location (MoJS 2019).

In totality, 129 number of water sources (64 in ODF and 65 in n-ODF villages) from Odisha; 145 number of water sources (76 in ODF and 69 in n-ODF villages) from Bihar and 122 number of water sources (65 in ODF and 57 in n-ODF villages) from West Bengal were sampled (Table 1); 64 numbers of soil samples (32 each from ODF and n-ODF villages) were collected each from Odisha, Bihar and West Bengal (Table 2); and 24 number of food samples (10 in ODF and 14 in n-ODF villages) from Odisha, 11 number of food samples (5 in ODF and 6 in n-ODF villages) from Bihar and 26 number of food samples (9 from ODF and 17 from n-ODF villages) from West Bengal were collected (Table 3).

Sampling was carried out as per the guidelines of standard protocols and methods (APHA, AWWA, WEF 2017; BIS IS: 1622: 2003; BIS, IS: 3025, Part-1 2008). The samples duly preserved under controlled temperature conditions, were transported to laboratory within the permissible time limits. The sampling was done in bottles sterilized through gamma irradiation (George et al. 2010). Sampling chain-of-custody consisted of information pertaining to identification of site such as habitation/ village/ *gram panchyat* along with nearest caretaker/ household/ landmark along with GPS geocodes and general site conditions (Kumar et al. 2000; Kumar et al. 2009; Verma et al. 2009).

# Laboratory Investigations

The samples (water, soil and food) were homogenized thoroughly then the samples were analyzed for faecal coliforms by the multiple tube dilution method incorporated by presumptive and confirmatory steps. Accordingly results were reported as Most Probable Number (MPN) for faecal coliform/ 100 ml in case of water and MPN faecal coliform / g in cases of soil and food (BIS, IS:1622: 2003). The *Escherichia coli* in water samples was determined by Membrane Filter Technique. A 100 ml of water sample was filtered through 0.45 µm filter paper then placed on selective agar plate and further identification was carried out (BIS, IS 15185: 2016 / ISO 9308-1: 2014). The enumeration of *Escherichia coli* per gm in soil and food samples were performed by using serial dilution technique with spread plate method followed by further confirmation (BIS, IS 5887 Part-1: 2018). The Enterococci in water samples was determined by Membrane Filter Technique. A 100 ml water sample was passed through 0.45 micron filter paper and placed on selective agar plate. Further confirmation was done as per the method given in IS: 15186: 2002/ ISO 7899-2:2000. The enumeration of Enterococci per gm in soil and food sample was performed by using serial dilution technique with spread plate method. Further confirmation was carried out by recommended Indian Standard (BIS, IS: 15186: 2002/ ISO 7899 Part 2: 2000). The minimum detection limit (MDL) for faecal coliform is 2 MPN/ 100 ml in case of water samples and 0.18 MPN/g in cases of soil and food samples (BIS, IS: 1622: 2003); for *Escherichia coli*, the MDL is 1 cfu/ 100 ml in case of water samples and 1 cfu/g in cases of soil and food samples (BIS, IS 15185:2016 / ISO 9308-1:2014) and for Enterococci, the MDL is 1 cfu/ 100 ml in case of water samples and 1 cfu/g in cases of soil and food samples (BIS, IS: 15186: 2002/ ISO 7899 Part 2: 2000). Below the detectable limit, it is assumed that environmental medium (water, soil and food) is free from FIB and values in such cases are taken as ‘zero’ for statistical calculations.

Microbial Source Tracking was done through processing faecal positive samples for DNA extraction. Specific bacterial group primers *Bacteroidales* molecular markers for ruminant (RuBac) and human (HuBac) were used to determine the source of faecal pollution environment samples. Ruminant and human *Bacteroides* specific primers amplify the target DNA by PCR technique. DNA was extracted from soil, food and water samples using DNeasy powersoil kit and QIAamp Fast DNA stool kit, respectively. Water samples were vacuum filtered through 0.45 µm pore size, 47 mm diameter nitrocellulose membrane filters prior to DNA extraction. 250–300 mg of soil and food samples were processed as per the protocol. DNA from water samples was extracted from the membrane filters by cutting them into small pieces in an eppendorf tube. The extracted DNA was then quantified using UV-spectrophotometer by taking absorbance at 260 nm and further calculating the concentration of DNA. Extracted DNA was amplified by SYBR Green Real-time PCR with specific primers. Distinctive $T_m$ curve profile for RuBac and HuBac assays signifies the source of contamination in samples. Quantitative detection of host-associated faecal *Bacteroidales* genetic markers via quantitative real-time polymerase chain reaction (qPCR) to identify contamination sources, referred to as microbial source tracking, is increasingly applied as addition to FIB enumeration to identify microbial risks emanating from specific fecal sources (Ahmed et al. 2009; Bachoon et al. 2012; Sargeant et al. 2011; Xue and Feng 2018).

Physico-chemical properties of water were studied to understand hydrogeology and stoichiometry of water resources (APHA, AWWA, WEF 2017). The pH value measured by electrometric method (BIS, IS: 3025, Part-11 2017), indicates acidic/ alkaline/ normal character of water and its acceptable limit in drinking water is 6.5 to 8.5 (BIS, IS 10500: 2012). Turbidity measured by Nephelometric method (BIS, IS: 3025, Part-10 2017), indicates clearness and transparency of water and its permissible limit in drinking water is 5 NTU (BIS, IS 10500: 2012). Total Dissolved Solids (TDS) measured by gravimetric method (BIS, IS: 3025, Part-16 2017), indicates dissolved salt concentration and its maximum permissible limit in drinking water is 2000 mg/l (BIS, IS 10500: 2012).

## Data Analysis

Risk assessment matrix has been designed to estimate Relative Risk (RR) due faecal contamination in ODF and n-ODF environment. An RR of 1.00 indicates the risk is comparable in the two groups. A value greater than 1.00 indicates increased risk and accordingly the interpretation matrix was developed. The water, soil and food, the sources of environmental medium in n-ODF villages were marked 'A' in event of contamination and 'B' in event of non-contamination, hence total sources in n-ODF become (A + B). Accordingly, the contaminated sources in ODF villages were marked 'C' and non-contaminated as 'D', hence making the total sources in ODF as (C + D). The probability of contamination in n-ODF villages, therefore, be "A / (A + B)" = "E" (say) and probability of contamination in ODF villages be "C / (C + D)" = "F" (say). The Relative Risk, therefore, would be = E/F. Accordingly, RR is calculated with respect to FIB Contamination and with respect to HuBac contamination. To address the 'zeros' in effect outcome, the Haldane-Anscombe Correction method was used, which recommends substituting zeros with 0.5 (Andrade 2015; Shrier and Steele 2006). In addition, the one-way analysis of variance (ANOVA) ($p < 0.05$) test conducted to compare the mean ± SD of ODF with corresponding value of n-ODF for statistical significance. The percentile values 90th (P90), 70th (P70) and 50th (P50) were also estimated for the purpose of interpretation.

### Results

## Physico-chemical profile of water medium

The pH value of water samples from all the sources in ODF and n-ODF villages of all the three states was found within normal range (acceptable limits); in case of TDS (in mg/l), P90 value in samples from Odisha (ODF and n-ODF villages), maximum values in samples both from Bihar (ODF and n-ODF villages) and West Bengal (ODF and n-ODF), were found within permissible limits; in case of Turbidity (in NTU), P50 value in samples from Odisha (ODF and n-ODF), P70 value in samples from Bihar (ODF and n-ODF), P50 value in samples from West Bengal (ODF) and P70 value in samples from West Bengal (n-ODF) were found within the acceptable limit (Table 4) (BIS, IS 10500: 2012). The results of physic-chemical investigation of water quality were found free from significant contamination.

## Contamination by Faecal Indicator Bacteria (FIB)

Contamination of water medium by FIB: in case of Odisha, the groundwater in ODF villages indicate contamination of 8.6 percent sources, whereas in n-ODF villages, 30.3 percent sources were found contaminated; the HH storage water in ODF villages indicated contamination of 39.1 percent sampling locations, whereas in n-ODF villages, 67.9 percent samples were found contaminated; the PWS water in ODF villages was found contaminated at 33.3 percent locations, whereas in n-ODF villages, 25.0 percent locations were found contaminated (Fig. 2a). In case of Bihar, the groundwater in ODF villages indicate contamination in none of the sources, whereas in n-ODF villages, 52.5 percent sources were found contaminated; the HH storage water in ODF villages indicated contaminated water at 23.8 percent sampling locations, whereas in n-ODF villages, 82.6 percent samples were found contaminated; the PWS water in ODF villages was found contaminated at none of the locations, whereas in n-ODF villages, 66.7 percent locations were found contaminated (Fig. 2b). In case of West Bengal, the groundwater in ODF villages showed contamination in 2.6 percent sources, whereas in n-ODF villages, 16.7 percent sources were found contaminated; the HH storage water in ODF villages indicated contamination at 15.0 percent sampling locations, whereas in n-ODF villages, 65.5 percent samples were found contaminated; the PWS water in ODF villages was found contaminated at 16.7 percent sampling locations, whereas in n-ODF villages, 63.6 percent of PWS locations were found contaminated (Fig. 2c). The mean ± SD values of contamination of water samples (groundwater, HH storage and PWS) with respect to faecal coliform (MPN/100 ml), *Escherichia coli* (cfu/100 ml) and Enterococci (cfu/100 ml), were observed higher in n-ODF villages as compared to the samples studied from ODF villages in the states of Odisha, Bihar and west Bengal, though the magnitude of contamination in both in n-ODF and ODF villages varies widely (Table 1).

Contamination of soil medium by FIB: the soil samples in ODF villages in Odisha were found contaminated at 87.5 percent sampling location, whereas in n-ODF villages, 81.3 percent samples were found contaminated (Fig. 2a). The samples of soil collected from ODF villages in Bihar were found contaminated at 59.4 percent sampling location, whereas in n-ODF villages, 71.9 percent samples were found contaminated (Fig. 2b). In West Bengal, the soil samples showed contamination at 46.9 percent sampling locations in ODF villages, whereas in n-ODF villages, 65.6 percent samples were found contaminated (Fig. 2c). The mean ± SD values of contamination of soil samples with respect to faecal coliform (MPN/g), *Escherichia coli* (cfu/g) and Enterococci (cfu/g), were observed higher in n-ODF villages as compared to the samples studied from ODF villages in the states of Bihar and West Bengal, but in the state of Odisha these values were observed higher in ODF villages (Table 2).

Contamination of food medium by FIB: 100% food samples were found contaminated in ODF villages in Odisha, whereas in n-ODF contamination was seen in 85.4% samples (Fig. 2a). Contamination status of food in ODF and n-ODF villages in Bihar showed, none of the sample was found contaminated in ODF villages, whereas in case of n-ODF, contamination was seen in 66.7 percent of samples (Fig. 2b). In case of food samples drawn from West Bengal, none of the sample was found contaminated in ODF villages, whereas in n-ODF contamination was seen in 47.1 percent of samples (Fig. 2c). The mean ± SD values of contamination of food samples with respect to faecal coliform (MPN/g), *Escherichia coli* (cfu/g) and Enterococci (cfu/g), were observed higher in n-ODF villages as compared to the samples studied from ODF villages in the states of Bihar and West Bengal, but in the state of Odisha these values were observed higher in ODF villages (Table 2).

# Faecal Contamination of Human Origin (HuBaC)

HuBaC Contamination status of ODF and n-ODF villages in Odisha: the groundwater in ODF villages showed contamination of 2.9 percent sources, whereas in n-ODF villages, 15.2 percent sources were found contaminated; the HH storage water studied in ODF villages indicated contamination at 17.4 percent sampling locations, whereas in n-ODF villages, 25.0 percent samples were found contaminated; the PWS water in ODF villages was found contaminated at 16.7 percent locations, whereas in n-ODF villages, 25.0 percent locations were found contaminated; the soil samples in ODF villages were found contaminated at 81.3 percent sampling location, whereas in n-ODF villages, 71.9 percent samples were found contaminated; in case of food, 50.0 percent samples were found contaminated in ODF villages, whereas in n-ODF villages, contamination was seen in 57.1 percent samples (Fig. 3a).

HuBaC Contamination status of ODF and n-ODF villages in Bihar: the groundwater in ODF villages indicated contamination in none of the sources, whereas in n-ODF villages, 35.0 percent sources were found contaminated; the HH storage water studied in ODF villages indicated contamination at 19.0 percent sampling locations, whereas in n-ODF villages, 52.2 percent samples were found contaminated; in case of PWS water in ODF villages, none of the sample was found contaminated, whereas in n-ODF villages, 16.7 percent locations were found contaminated; the soil samples in ODF villages were found contaminated at 59.4 percent sampling location, whereas in n-ODF villages, 71.9 percent samples were found contaminated; In case of food samples (from MDM and *Dabha*), none of the sample was found contaminated in ODF villages, whereas in n-ODF villages, contamination was seen in 66.7 percent samples (Fig. 3b).

HuBaC Contamination status of ODF and n-ODF villages in West Bengal: in case of groundwater in ODF villages, 2.6 percent sources were found contaminated, whereas in n-ODF villages, 16.7 percent sources were found contaminated; the HH storage water in ODF villages indicated contamination at 10.0 percent sampling locations, whereas in n-ODF villages, 41.4 percent samples were found contaminated; in case of PWS water in ODF villages, 16.7 percent samples were found contaminated, whereas in n-ODF villages, 45.5 percent locations were found contaminated; the soil samples in ODF villages were found contaminated at 40.6 percent sampling location, whereas in n-ODF villages, 56.3 percent samples were found contaminated; in case of food, none of the sample was found contaminated in ODF villages, whereas in n-ODF villages, contamination was seen in 47.1 percent samples (Fig. 3c).

# Relative Risk (RR) Matrix

The relative risk evaluation matrix developed in present work facilitated to assess the effectiveness of ODF interventions in different environmental medium. The faecal contamination of groundwater showed RR 11.25 times more likely in n-ODF villages as compared to ODF villages (53.6 times more likely in Bihar;

6.50 times more likely in West Bengal and 3.54 times more likely in Odisha); the faecal contamination of groundwater traceable to humans indicated RR 12.66 times more likely in n-ODF villages as compared to ODF villages (35.7 times more likely in Bihar; 6.50 times more likely in West Bengal and 5.30 times more likely in Odisha); the RR of faecal contamination of HH storage water was estimated 2.68 times more likely in n-ODF villages as compared to ODF villages (3.47 times more likely in Bihar; 4.37 times more likely in West Bengal and 1.73 times more likely in Odisha); the RR of faecal contamination of HH storage water traceable to humans was calculated 2.48 times more likely in n-ODF villages as compared to ODF villages (2.74 times more likely in Bihar; 4.14 times more likely in West Bengal and 1.44 times more likely in Odisha); the faecal contamination of PWS water showed 2.71 times more likely RR in n-ODF villages as compared to ODF villages (5.33 times more likely in Bihar; 3.82 times more likely in West Bengal and 0.75 times more likely in Odisha); the RR of faecal contamination of PWS water traceable to humans was found 2.40 times more likely in n-ODF villages as compared to ODF villages (1.33 times more likely in Bihar; 2.73 times more likely in West Bengal and 1.50 times more likely in Odisha) (Table 5).

The faecal contamination of soil indicated 1.13 times more likely RR in n-ODF villages as compared to ODF villages (1.40 times more likely in West Bengal; 1.21 times more likely in Bihar and 0.93 times more likely in Odisha), whereas the faecal contamination of soil traceable to humans shows 1.10 times more likely RR in n-ODF villages as compared to ODF villages (1.38 times more likely in West Bengal; 1.21 times more likely in Bihar; and 0.88 times more likely in Odisha) (Table 5).

The faecal contamination of food indicated 1.48 times more likely RR in n-ODF villages as compared to ODF villages (8.47 times more likely in West Bengal; 6.67 times more likely in Bihar; and 0.90 times more likely in Odisha); the RR of faecal contamination of food traceable to humans was estimated 2.16 times more likely in n-ODF villages as compared to ODF villages (8.47 times more likely in West Bengal; 6.67 times more likely in Bihar and 1.14 times more likely in Odisha) (Table 5).

## Discussion

The present study demonstrates Relative Risk estimation due to contamination of water, soil and food with respect to FIB and HuBac, to understand the magnitude of contamination in n-ODF villages in comparison to ODF villages. The study results show mitigation of risk due to faecal contamination of human origin in ODF villages in comparison to n-ODF villages albeit spectrum and intensity of reduction varies in different mediums of environment.

The findings with respect to water exhibits variable intensity of reduction, specifically groundwater indicates significant risk reduction. In case of piped water supply, considerable improvement is noticed. The potentiality of positive impacts of behavior change component of the *Swachh Bharat* Mission (SBM) to improve handling and storage of water by adopting safe and hygienic practices resulted in interesting findings in case of HH storage water (DDWS White Paper May 2019).

The findings with respect to soil manifest a relatively low risk reduction of faecal contamination of human origin in case of ODF villages as compared to n-ODF villages. This emphasizes the importance of faecal sludge and septage management together with solid and liquid waste management in more efficient ways to further prevent risks of soil contamination (DDWS 2019–2029).

The investigations in context to food shows significant risk reduction due to faecal contamination of human origin in ODF villages, which may be due to notable improvement in terms of hygiene practices and probably the monitoring systems to ensure safe practices in terms of preparation and storage of food (DDWS 2016; DDWS-SBM-G). However, the major limitation of study was the non-availability of adequate size of food samples and hence investigations were carried out on available sample size.

This study provides the baseline status for the period December-2018 to January-2019, when ODF mission of the Government of India was still alive and active in rural areas and only few districts of three states namely Odisha, Bihar and West Bengal were still having villages with n-ODF status. Due to this reason and limitation, the study was conducted in only three states of India. However, by October-2019, entire Rural India (more than 660,000 villages) was declared ODF. Hence, investigation results for both ODF and n-ODF villages reported in this work will set bottom-line for the future investigations.

In order to ensure sustainability in ODF behaviors, the *Swachh Bharat* Mission is moving towards next phase that is ODF plus to focus on providing interventions for the safe and adequate management of solid and liquid waste in villages as well as to reinforce the ODF behavior (DDWS 2020-21). The implementation of ODF plus is further expected to reduce the risk of faecal contamination of environmental medium. The Relative Risk investigation framework will, therefore, be useful to assess the performance of ODF plus system.

## Conclusions

The findings of present study in overall manifests the amelioration in sanitation and hygiene practices in ODF villages. The FIB and microbial source tracking based relative risk assessment matrix designed and used in present study, can be helpful towards evaluation of the performance ODF missions being implemented elsewhere in developing countries so that necessary corrective and preventive actions can be envisaged well in time to effectively achieve the targets of sanitation and hygiene as delineated by the Sustainable Development Goal 2030 of the United Nations. The study would also facilitate towards development of guidelines and protocols to assess the effectiveness of such interventions, which are the pressing needs to ensure sustainability. The evaluation of the effectiveness of the implementation of ODF system to achieve the targets of sanitation and hygiene is specifically important during the recovery phase of COVID-19 pandemic.

## Abbreviations

American Public Health Association (APHA); American Water Works Association (AWWA); Bureau of Indian Standard (BIS); Colony Forming Unit (cfu); Department of Drinking Water and Sanitation (DDWS); Deoxyribonucleic acid (DNA); Faecal Indicator Bacteria (FIB); Global Positioning System (GPS);

Household (HH); Human *Bacteriodales* (HuBac); Ministry of Jal Shakti (MoJS); Most Probable Number (MPN); Nephelometric Turbidity Unit (NTU); Open Defecation Free (ODF); Polymerase chain reaction (PCR); Piped Water Supply (PWS); Relative Risk (RR); Ruminant *Bacteriodales* (RuBac); *Swachh Bharat* Mission-Gramin/ Rural (SBM-G); Sustainable Development Goal (SDG); Total Dissolved Solids (TDS); Ultra-violet (UV); Water Environment Federation (WEF).

## Declarations


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**Author Contribution** Jagdish Kumar developed the study design, methodology, sampling design and performed work execution, interpretation, data analysis and drafting of manuscript. Deep Shankar Chatterjee participated in sampling execution, site analysis, landuse pattern and data interpretation. Dushyant Singh was involved in sampling and laboratory investigation. Shifa Chaudhary participated in laboratory investigation. Gaurav participated in sampling and laboratory investigation. Mukul Das performed overall review, in-depth analysis of facts and findings and overall value additions. Swathi Manchikanti performed data analysis and interpretation. Sujoy Mojumdar developed survey concept and sampling design. Nicolas Osbert developed study concept and performed project management and data analysis. All authors read and approved the final version of the manuscript.

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## Tables

Tables 1 to 5 are available in the Supplementary Files section.

## Figures

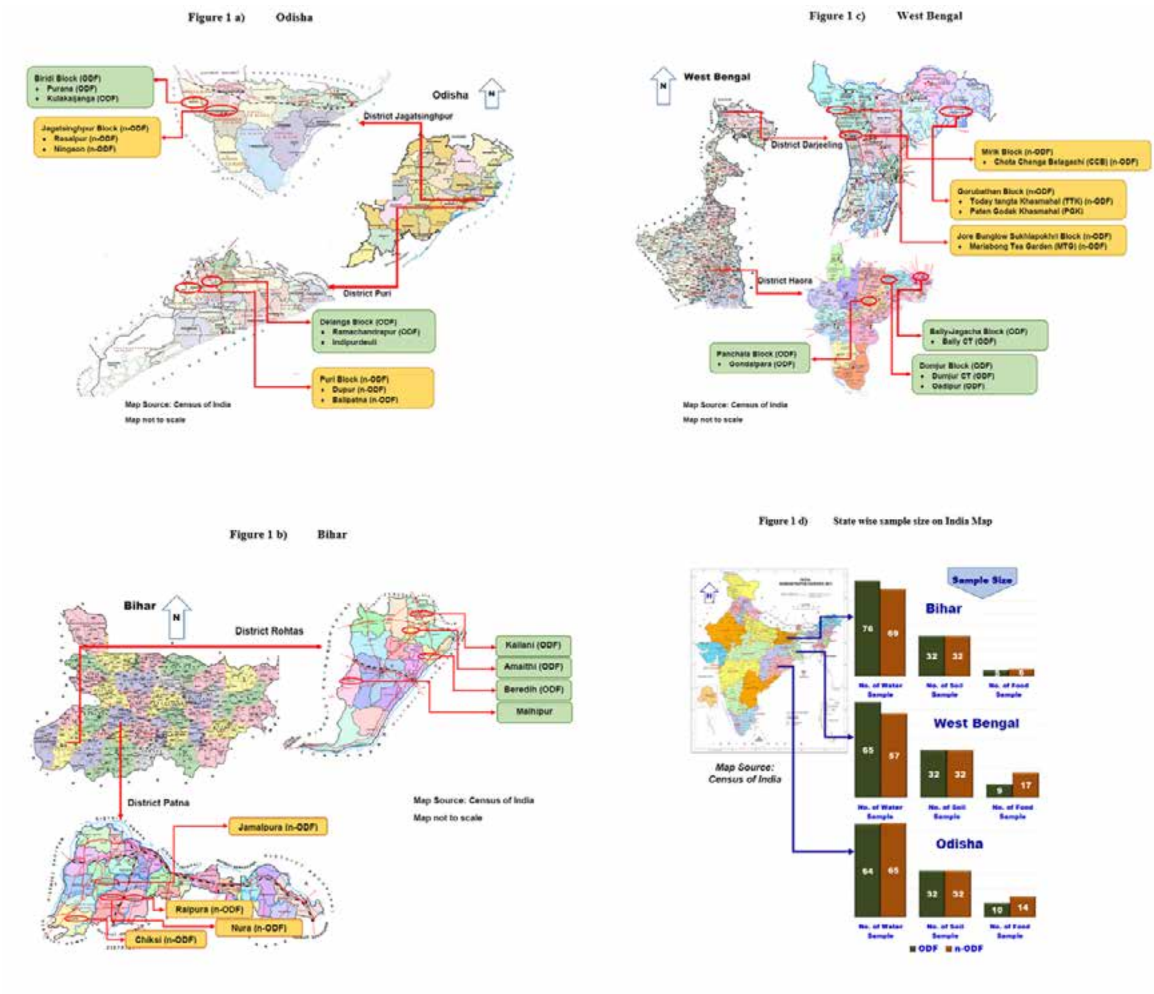


Figure 1

Study areas depicted on map: a) Odisha, b) Bihar,

c) West Bengal and d) State wise sample size on India Map

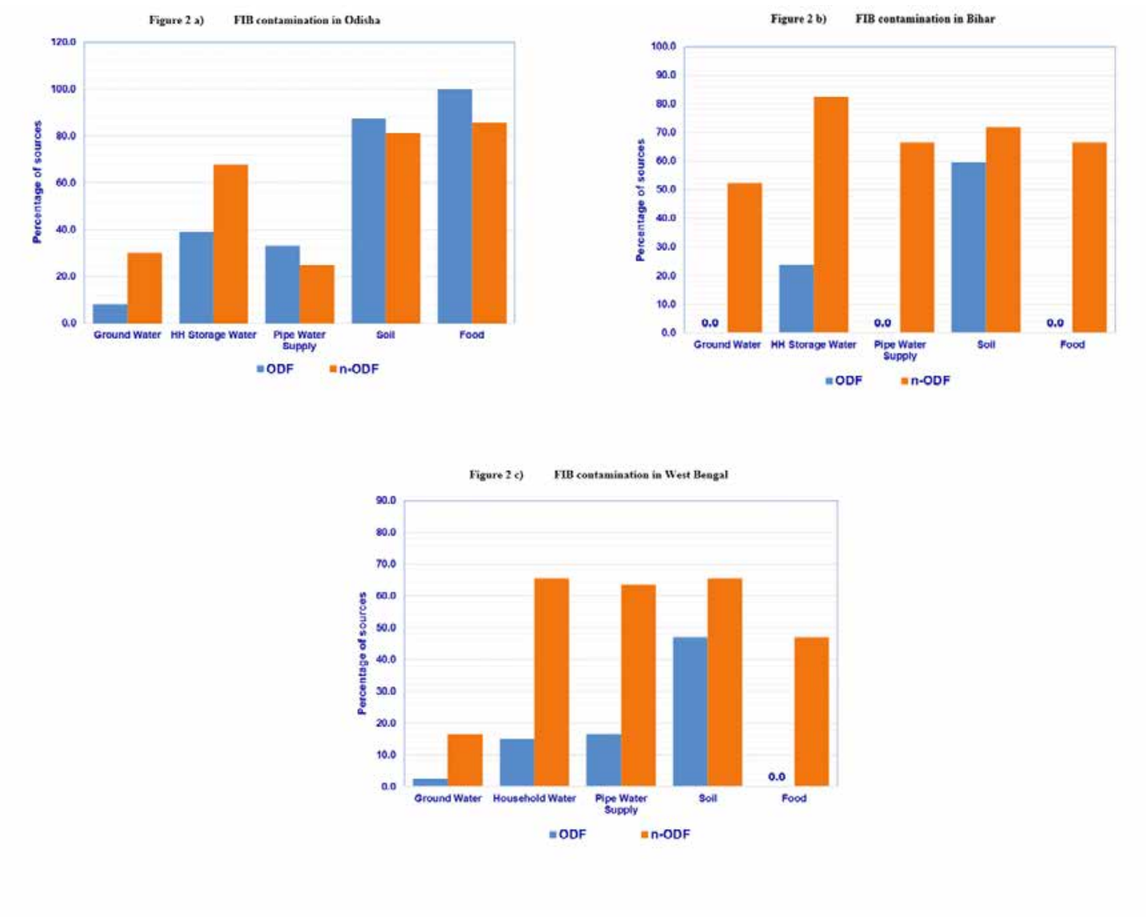


Figure 2

Percentage of sources contaminated with FIB in a) Odisha,

b) Bihar and c) West Bengal

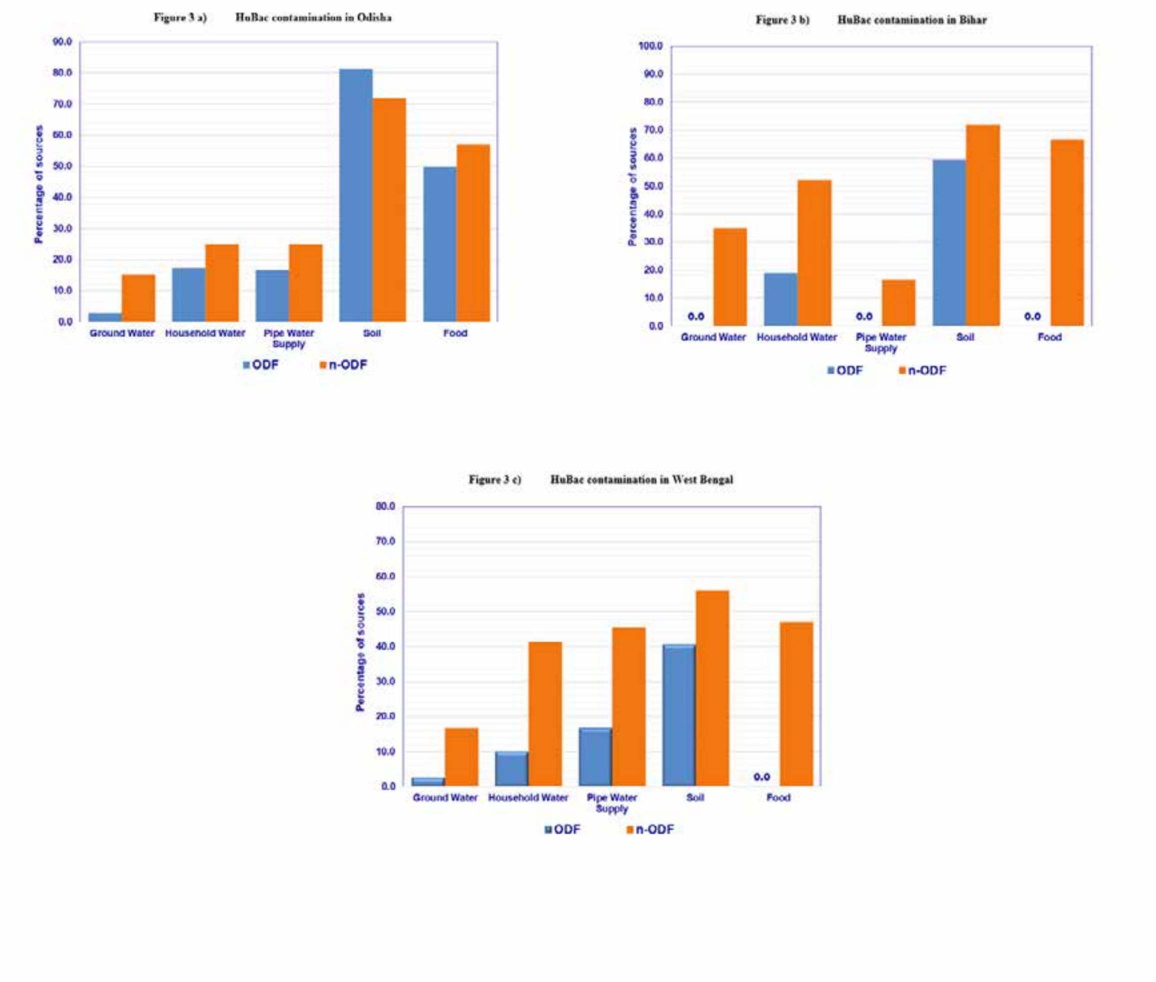


Figure 3

Percentage of sources contaminated due to HuBac in

a) Odisha, b) Bihar and c) West Bengal

## Supplementary Files

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# Experimenting with Urban–Rural Partnerships for Sustainable Sanitation in India: Learning from Practice

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**Abstract:** Local government partnerships for producing services are ubiquitous in many countries. However, the approach has rarely been applied in India—likely owing to a history of centralized planning and independent urban and rural governance systems. Nonetheless, the country's transforming sanitation landscape could benefit from intergovernmental partnerships for scaling services with speed and efficiency. The ongoing national sanitation program has espoused the approach in theory but the body of practice to support its wide deployment is sparse. This paper critically reviews one of the first experiments with the approach for producing sanitation services in the Dhenkanal district, Odisha, India. We ask the question: what can Dhenkanal's case tell us about the challenges and opportunities for delivering sanitation services through local-level intergovernmental urban–rural partnerships in India? As part of our practice research, we supported the district government pilot the approach. The data, consultations, and observations underpinning the experiment form the basis of our insights. We find that the urban–rural partnership increased access to sanitation services among rural households within a short period, lowered service charges, and clarified institutional responsibilities. The experiment highlighted issues relating to planning, responsibility, accountability, and financing that need tackling in order to strengthen the model going forward. We recommend that evolving a definitive model(s) of intergovernmental partnerships would require experimenting with the approach in diverse institutional contexts and granting governments the flexibility to recreate and renegotiate the form of the partnership.

**Keywords:** intermunicipal cooperation; India; urban–rural partnership; sanitation; faecal sludge management; wastewater management; local governance; local government partnership



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## 1. Introduction

India's sanitation landscape is undergoing a rapid transformation. In 2012, India was home to a population of 2.5 billion that lacked access to improved sanitation [1]. The incumbent national government launched a large-scale program, the *Swachh Bharat Mission* (SBM), to eliminate open defecation in 2014. The program aimed to provide subsidized toilets to households lacking a toilet—a whopping 67% of all rural households and 13% of all urban households, as revealed by the Census of India in 2011. The program has reportedly enabled the construction of 110 million and 6 million new rural and urban toilets, respectively, to date [2,3]. The low and slow availability of centralized sewerage systems in urban India and their infeasibility in rural India result in a high national dependence on on-site sanitation systems (Figure 1). The increase in the number of toilets without a commensurate expansion of sewerage systems has increased the dependence significantly [4].

On-site sanitation systems prevalent in India produce the need for faecal sludge management (FSM) systems, i.e., systems to ensure the evacuation and conveyance of faecal waste from on-site sanitation systems and its treatment and disposal (or recycle) off-site. Faecal waste accumulating in septic tanks and single pits must be emptied periodically and conveyed via emptying vehicles (typically vacuum trucks). The evacuated waste must be treated at facilities, such as a Faecal Sludge Treatment Plant (FSTP) before disposal. Over time, the proliferation of centralized sewerage systems may diminish the need for FSM in the bigger cities. However, low-density small towns and peri-urban and rural settlements require FSM to be able to achieve 'safely managed sanitation' in accordance with the Sustainable Development Goal 6 [5]. The challenge of ensuring proper FSM is not unique to India; developing countries across Asia and Africa confront it [6]. What may distinguish India is the sheer scale of the challenge: developing FSM systems to serve more than 255,000 *gram panchayats*, or rural local bodies, and upwards of 4000 cities and towns. It begs the question: how to scale-up sanitation services across India with speed and efficiency?

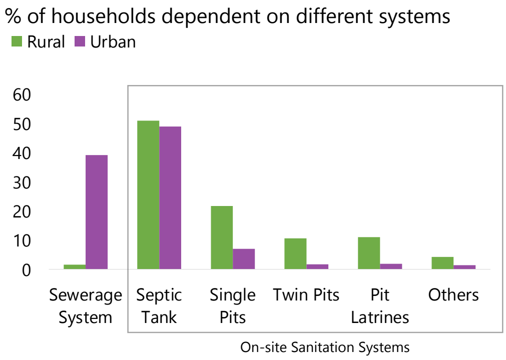


**Figure 1.** Dependence on different systems for managing wastewater.

Local government partnerships for the efficient production of services are common in several countries, including the United States of America (USA) and many more in Europe [7–11]. Commonly framed as 'intermunicipal cooperation', local government partnerships present an opportunity to achieve economies of scale for small local governments, especially when the alternatives of region-scale privatisation and political consolidation (e.g., in the form of metropolitan government) are infeasible or undesirable. Higher standards for services and raised citizen expectations are also proposed as imperatives for intermunicipal cooperation [12]. Cooperation can also help surmount the limitations of individual capacity and action in solving problems, such as environmental pollution, that transcend administrative boundaries. It can be formal or informal, hierarchy-based or network-based, or somewhere in the middle. For example, in the USA, cooperation can occur informally through councils of government that lack legal standing or, at its most formal, take the form of special districts for single functions (e.g., education, transport, etc.). Formal inter-municipal cooperation is also effectuated through 'empowered' counties that deliver services to all or a majority of the municipalities within their borders [7].

In contrast to its ubiquity in many countries, India has rarely applied the approach of intergovernmental partnership to produce services so far. A possible reason is that the production of many services, including sanitation, is effectuated through national programs (such as SBM). It may be that the phenomenon provides a weak incentive for local governments to partner and cooperate since national programs: (1) are bifurcated along the urban–rural divide, (2) predetermine local-level solutions, and (3) allocate financing to local governments individually. Nonetheless, in a new precedent, the national government espoused the approach of intergovernmental urban–rural partnerships (at the local level) for sanitation service delivery in 2021. The ongoing phase (2020–2025 in rural and 2021–2026 in urban) of SBM targets increasing the levels of wastewater management in both urban and rural India. The national government noted that many cities and towns already possess wastewater management systems (in the form of both FSTPs and the conventional sewage treatment plants) and that many more have such systems upcoming. It accordingly recommended that urban local governments in these cases extend their services to the neighbouring *gram panchayats* (vide its letter S-18011/6/2021-SBM-DDWS dated 14 September 2021).

The national-level mainstreaming of the intergovernmental partnership approach could be a step in the right direction. An early understanding of the challenges associated with its implementation could help evaluate its suitability and trajectory, specific to the Indian context. Towards this goal, in this paper, we discuss one of the first Indian experiments with an intergovernmental urban–rural partnership at the local level. The experiment of concern—predating the national mainstreaming—is situated in Dhenkanal district in the Indian state of Odisha. Under the experiment, the district utilized the urban–rural partnership approach to produce sanitation services for rural households.

In the following sections, we discuss our experience of supporting the government(s) conceptualize and implement a pilot model of urban–rural partnership in the Dhenkanal district. We ask the question: what can Dhenkanal's case tell us about the challenges and opportunities for producing sanitation services via local-level intergovernmental urban–rural partnerships in India? Since the case we discuss is the first-of-its-kind in India, the present paper may serve as a pioneering contribution to the body of work on urban–rural partnerships in India. We hope that it would also provide a jumping-off point for further research on, and experimentation with, the approach in India and regions with a similar institutional context and sanitation-related issues.

## 2. Background

### *2.1. Methods and Materials*

The present paper is based on the authors' practice research on urban–rural partnerships in the Dhenkanal district of Odisha. The authors supported the district-level and local-level governments develop an experimental urban–rural partnership that would allow rural households to access sanitation services via urban infrastructural systems. The authors' direct participation in the entire process from the ideation and development of the partnership model to its implementation (during the period 2019–2021) has informed the paper. Over the course of the process, we interacted with and consulted officials of:

- The district government, or 'District Administration' (as it is called in India);
- The urban local government;
- The rural local governments, or '*gram panchayats*', shortlisted for forming the partnership with the urban local government(s).

The process commenced with an assessment of the sanitation landscape in the Dhenkanal district (Figure 2). To inform the assessment, we conducted a sample survey of 1000 rural households and structured interviews with political leaders, or *sarpanch(s),* of eight rural local governments in 2020. The findings of the survey are discussed in the authors' previous work [13,14]. A variety of secondary data also informed the assessment and later steps of the process. It included:

- Geospatial data relating to administrative boundaries and the road networks;
- Demographic data from the Census of India 2011;
- Transactional data relating to emptying services and records of FSTP utilization from the urban local government (2019–2020).

The assessment was followed by analysis to identify the gram panchayats that were good fits for the urban–rural partnership. We presented the preliminary results of the analysis to the district administration and the relevant local governments for review. The local governments held further consultations to develop the terms of the partnership, including inter alia mechanisms for coordination, tariff design, and roles and responsibilities. On finalization of the terms, the urban local government and 17 *gram panchayats* signed a Memorandum of Agreement (MoA) to codify their partnership for service delivery on 28 December 2020. The signing was soon followed by multiple Information, Education, and Communication (IEC) campaigns aimed at raising awareness about services among rural households.

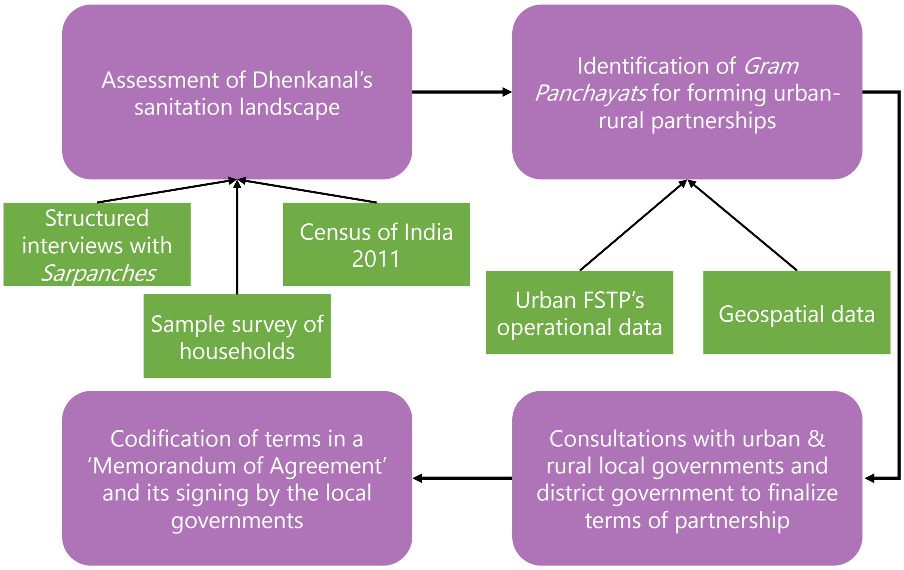


**Figure 2.** Process of developing the urban–rural partnership.

In addition to the communication with different government representatives, our direct and indirect observations of how the entire process unfolded forms an important basis of the paper. Complementing our practice research, we reviewed literature on more mature implementations of intergovernmental partnership to develop an understanding of what forms the partnerships can take (Figure 3). Our intent in doing so was to relate the findings from the Dhenkanal district to other cases. Given the paucity of its implementation in India, we relied primarily on literature discussing the European experience. The findings from our analysis discussed in Section 4 cluster around three main pillars: planning, responsibility and accountability, and financing.

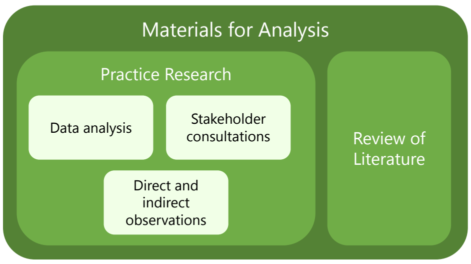


**Figure 3.** Materials forming the basis of analysis.

### 2.2. Site of Enquiry

Dhenkanal is one of the 30 districts in the coastal state of Odisha in India (Figure 4). A district in India is an administrative division at the state level and comprises multiple urban and rural local bodies. The Dhenkanal district has 216 local bodies-four urban local bodies, viz., the eponymous Dhenkanal, Bhuban, Hindol, and Kamkhyanagar, and 212 *gram panchayats*. These 212 *gram panchayats* cumulatively house 1237 villages. Only 9% of the district's total population of approximately 1.2 million resides in towns and the vast majority of 91% in *gram panchayats*. The four towns are small and do not exhibit urban primacy; the largest among the four, the Dhenkanal municipality, houses a population of about 67,000. Overall, the district is spread out over an area of 4452 square kilometres and has a population density of 268 persons per square kilometres.

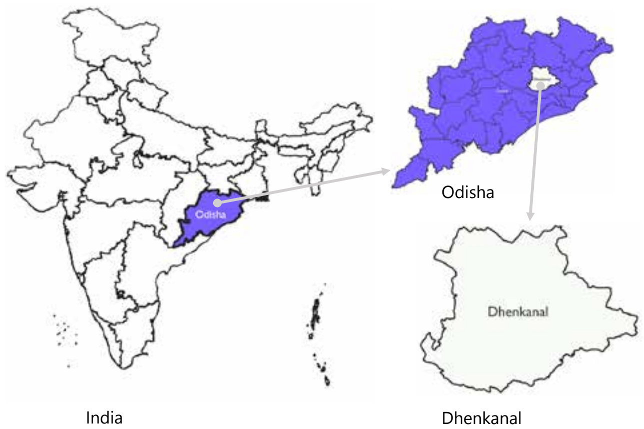


**Figure 4.** Site of enquiry.

The Dhenkanal municipality in the district is one of the first small towns in the country to develop an urban FSM system. The municipality's FSM system became operational in October 2018 under a pilot project focused on urban FSM called Project Nirmal. The authors' organisation had served as a knowledge partner for Project Nirmal. Under Project Nirmal, the municipality undertook town-level sanitation planning, procured emptying vehicles, and constructed a nature-based FSTP. It also systematized recordkeeping of the continuous operational data generated by the FSM system.

Following the implementation of SBM during 2014–2019, the share of rural households in the district with an individual toilet climbed from 18% to a purported 100%. Addressing the lack of proper systems for managing faecal waste beyond the toilets emerged as an important issue at the end of the program. The high share of rural population in the district lent the issue especially high importance. The second and ongoing phase of SBM also created an external imperative to solve for rural sanitation, and the Odisha Rural Sanitation Policy, issued in 2020, provided further impetus.

The availability of a functional and determinable FSM system, as well as the scope of the rural sanitation challenge made the Dhenkanal district a suitable site for piloting the approach. We discussed the pilot with the Dhenkanal's district administration and later worked with the Dhenkanal municipality and its neighbouring rural local governments to implement it.

## 3. Overview of Key Concepts

### *3.1. Local Governance in India*

Most of India's population resides in rural areas, although the share has been declining steadily over time (~89% in 1901 to ~69% in 2011). As per the Local Government Directory 2021, rural and urban areas in the country comprise a little over 255,000 and 4700 local governments, respectively [15]. Local governments in India are tasked with the central role in "the provision of public services, the creation and maintenance of local public goods, and the planning and implemental of developmental activities and programs" [16]. They are part of a multi-tiered governance structure that is vertically bifurcated along the urban–rural divide. The main tiers are: national or central, state, district, and local, where the district provides a singular point of convergence between urban and rural governance.

At the national level, the Ministry of Housing and Urban Affairs steers all aspects of urban development, including sanitation and wastewater management. On the other hand, the responsibility for rural development is split between the Ministry of Rural Development and the Ministry of Jal Shakti; here, the latter administers programmes for improving rural sanitation. State-level administrations similarly house separate urban and rural departments. In Odisha's case, these are the Housing and Urban Development Department and the (rural) Panchayati Raj and Drinking Water Department.

Until the passage of the 73rd and 74th amendments in 1992, the Indian Constitution recognized states as the only official subnational units. The two amendments together accorded urban and rural local governments constitutional status [16]. The objective of the amendments was "decentralization and enduring popular participation in planning, management, and delivery of civic services" [17]. Schedule XI and XII of the Indian Constitution defined the scope of responsibilities of rural and urban local governments, respectively. The two schedules placed sanitation squarely within the purview of the local government (Figure 5). Further, the amendments directed the states to devolve powers and resources to local governments to allow the latter to fulfil their new responsibilities [16]. Article 243ZD of the 74th amendment also mandated the creation of District Planning Committees (DPCs) that would create district-level integrated development plans by consolidating plans developed by all the urban and rural local governments in a district. DPCs, at least in theory, have been tasked with identifying and facilitating joint development of projects that are of common interest to urban and rural local governments [18].

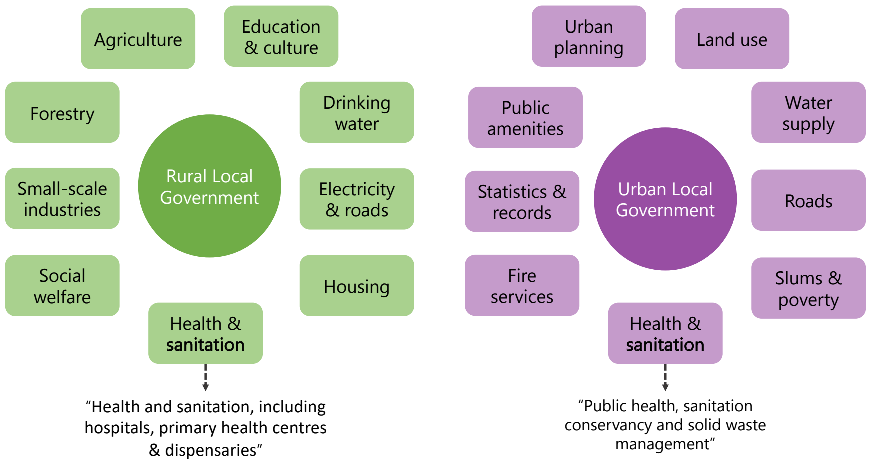


**Figure 5.** Indicative list of responsibilities of rural and urban local governments as per Schedule XI and XII of the Indian Constitution.

Despite its strong legal underpinnings, decentralization has been erratic in India. Studies conducted in the aftermath of the amendments observed a resistance to administrative and fiscal decentralization within rural governance. The functions for rural local governments may have been broadly specified as per the schedules, but an unclear definition of responsibilities and lack of resources for their fulfilment have inhibited local action and ownership over outcomes [16,19]. Rural local governments have played a limited role in planning, instead serving as local-level implementing agencies for programs and schemes determined and designed at the national and state levels [16]. Urban local governments purportedly confront similar challenges; state-level departments and parastatal agencies can diminish the urban local government's role in planning and, sometimes, even in the management of infrastructure and services [20]. Similarly, DPCs are absent or non-functional in most states; where they do function, they have failed at enabling urban–rural linkages and developing integrated plans [16,18]. Arguably, with local governments playing only a limited role in planning (if at all), the role of DPCs as an aggregator of local-level plans naturally diminishes too.

*3.2. Sanitation in India*

In the decades following independence, governance and developmental planning in India had been highly centralized [21]. Planning occurred via five-year plans that the national government's 'Planning Commission' developed and that the states were responsible for implementing. Sanitation has been articulated as an issue of national importance since the issue of the first five-year plan (1951–1956). The first plan recommended either one of individual or shared toilets, both preferably water-borne, for different types of urban housing and sanitary latrines for rural housing. Without being specific, it also emphasized the importance of "arrangements for the disposal of sewage" in relation to the latter. However, the national focus on sanitation culminated into a program only with the Central Rural Sanitation Programme (CRSP) in 1986. Subsequent efforts to improve sanitation have been channelled through large-scale national programmes underwritten by a mix of national and state-level financing.

Over several decades, successive programmes have targeted furthering access to toilets among rural households. The underlying principle of the programmes has oscillated from supply-driven and subsidized toilet construction to that which is community-led and demand-driven. Nonetheless, the spate of programs had reported low success in the past. Factors cited for toilet disuse include poor quality construction, fear of pit overflowing, and lack of knowledge about maintenance [22]. The latest programme, SBM, brought an explicit focus on Information, Education, and Communication (IEC) like its recent predecessors, but many old issues appear to persist; rural households in Odisha have cited the small size and subsequent filling up of pits as a reason to not use toilets regularly [13,23].

Regardless, in its ongoing second phase (2020–2025), SBM has shifted the focus from the construction of toilets to the safe and complete management of faecal waste beyond toilets. FSM has emerged as an important option in this regard given the high prevalence of septic tanks and single pits in rural areas, as previously noted. The recent global mainstreaming of FSM as a lower-cost alternative to sewerage systems in specific urban settings has also led to its greater acceptance in urban India [24,25]. The concomitant emergence of the two phenomenon–an increased need for FSM in rural areas and its increased adoption in urban-has produced a kind of convergence between urban and rural sanitation.

### *3.3. Intermunicipal Cooperation*

The varied models of intermunicipal cooperation arise under differing contexts of national institutional histories, socio-techno-economic landscapes, local bodies' sizes and competencies, and goals. Four different models of intermunicipal cooperation have been proposed: (1) quasi-regional governments, (2) planning forums, (3) service delivery organisations, and (4) service delivery agreements [12]. Each model presents unique opportunities and challenges, and although it is debatable whether cooperation can sustain efficiency gains in the long run, it has been shown to at least able to improve service coverage and quality by overcoming scale-related obstacles [7,26,27]. In addition, an intensifying focus on urban sustainability and transition in recent times has provided a new impetus for shared urban governance [28].

## 4. Results

### *4.1. Planning*

The main question for planning was how to size the extended service area for the urban FSM system. In the present case, it translated to: how many and which *gram panchayats* are apt for forming a partnership with the Dhenkanal municipality. We first considered supply-side constraints. Given that service delivery to the additional rural households had to utilize the existing urban FSM systems, the ability of the system to cater to additional households was one obvious factor. Although an FSM system, in general, is more modular than a centralised sewerage system, the costs of augmenting capacity may not always be insignificant. The municipality was amenable to expanding the vehicle fleet but increasing the capacity of an FSTP, requiring capital financing and land, was deemed infeasible. As a result, the available spare capacity of the FSTP provided a hard constraint for determining the service area.

A second important factor we considered on the supply side was the average distance of the gram panchayat from the urban local body. The delivery of services entails a roundtrip of the emptying vehicle and fuel has shown to be the largest cost driver of emptying services [29,30]. Even if the FSTP had infinite capacity, the exorbitant costs of longer trips would constrain the service area that is economically feasible to serve. Therefore, the identification of the suitable *gram panchayats* had to strike the right balance between the two factors.

The FSTP in the Dhenkanal municipality has a capacity of 27 kilolitres per day. Approximately 50% of the capacity (daily average) was being utilized in the first two years of its operation, with no clear year-to-year rise in utilization. Equally importantly, the records showed that the urban local body had been serving requests from rural households outside its periphery since before the commencement of the pilot. The arrangement was informal, market-led, and imposed a service charge on rural households that was 1.5–2 times of that paid by urban household per roundtrip of the vehicle. Over the period of January 2019 to February 2020, rural households constituted 13% of all households served. The relative share of the types of on-site sanitation systems emptied differed between urban and rural households (Figure 6). Overall, the analysis did establish that the FSTP in the Dhenkanal municipality was well-suited to serving rural households in addition to the urban jurisdiction.

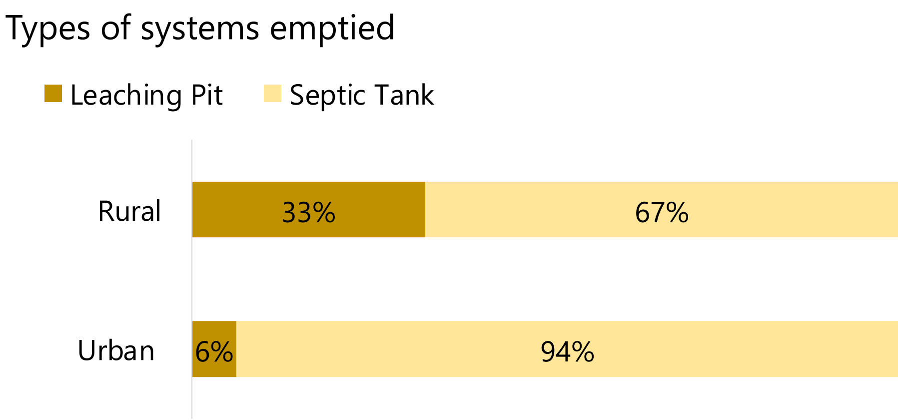


**Figure 6.** Relative share of different types of on-site sanitation systems emptied.

Once the magnitude of supply was established, we aimed to match it with the demand for services based on the household survey. The household survey presented three important considerations:

- The majority of households owned on-site sanitation systems (viz., septic tanks and single pits) that would require FSM over their lifetime of operation;
- A significant share of households that had emptied their on-site sanitation systems in the past reported utilizing the cheaper (almost by 50% on average) but unsafe alternative of manual emptying of the system.

The characteristics of on-site sanitation systems revealed by the survey helped estimate the number of rural households that would fit within the available spare capacity. We started with an initial arbitrary radius of 10 km and listed all *gram panchayats* falling within the perimeter. Based on the number of circumscribed rural households, the type of and characteristics of on-site sanitation systems, and the reported trends in toilet usage, we estimated that the FSTP had just enough spare capacity to serve the *gram panchayats* falling within 10 km for the next five years [31]. However, determining which *gram panchayats* 'fell within 10 km' was not straightforward.

Unlike most urban local bodies, *gram panchayats* lack a single unified landmass bound by an unbroken perimeter. One or more villages constitute a *gram panchayat*, and one or more hamlets constitute a village. The different villages and hamlets can abut each other or be separated by large tracts of land (Figure 7). Of these villages, one of the villages—

generally the largest—houses the rural local government's office and serves as the seat of the administration. The distance of a single village or hamlet from the urban local body can be greater or lesser than the average distance between the rural local body as a whole and the urban local body.

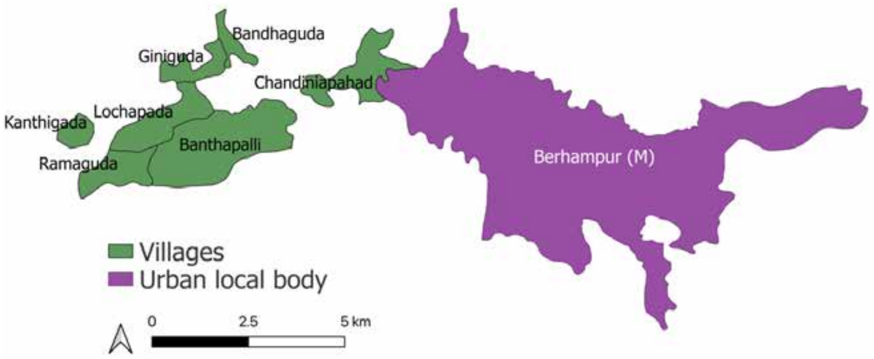


**Figure 7.** An example of a gram panchayat, Banthapalli (Ganjam district) with non-contiguous villages.

Therefore, we had to establish an unambiguous criterion to when a *gram panchayat* can be said to meet the distance threshold. What happens when some villages of the *gram panchayat* qualify for an urban–rural partnership by falling within the threshold and some do not? Does a *gram panchayat* only qualify if all of its constituent villages qualify? Or does it quality if a certain proportion of its villages, e.g., 50%, 75%, etc., qualify? Should the urban local body serve the entire *gram panchayat* even if one of the villages qualifies for an urban–rural partnership? These questions may appear of minor consequence but were important to consider for ensuring the long-term viability of the urban–rural partnership for three main reasons.

First, the *gram panchayat* is accountable for all the villages in its jurisdiction regardless of the distance. Although an urban–rural partnership is not the only approach to serving rural households, it is faster than the alternative of building greenfield rural FSM systems from the ground up. If only the villages individually qualifying are served under the urban–rural partnership, the remaining would be left relying on the status quo of no services or unreliable services in the short term. The *gram panchayats* could find explaining the resulting institutionally sanctioned unequal access to services difficult to justify to their jurisdictions.

Second, as previously noted, fuel is shown to be the largest cost driver of emptying services. Therefore, failing to predict how much distance the emptying vehicles would need to travel to serve a particular rural local body with reasonable accuracy could lead to a misestimation of operating costs and a failure in setting tariffs that help achieve cost recovery.

Third, the novelty of FSM as a concept in rural India has meant that *gram panchayats* have limited initial capacities for its management. The discourse on increasing access to toilets is not new to rural India owing to the long history of national sanitation programs focused on increasing access to toilets in rural areas. However, the issue of how to manage faecal waste safely beyond the toilet in the absence of centralized sewerage systems gained mainstream traction only over the last decade in India and globally [13,24,32]. Expectedly, *gram panchayats* are still learning about FSM. Therefore, holding them responsible for managing multiple FSM models within a single jurisdiction could make strenuous and unsustainable demands on their still-developing capacities.

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# Planning fecal sludge management systems: Challenges observed in a small town in southern India☆

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ABSTRACT

Fecal Sludge Treatment or Septage Management is increasingly being recognised as an effective and appropriate method to scale urban sanitation systems to achieve safe sanitation, particularly in small towns and cities. As implementation progresses, data-based evidence is emerging, highlighting the challenges faced on the ground, and the requisite planning necessary to address them. This paper presents the findings, challenges and possible ways ahead from a study conducted to provide data for Fecal Sludge Management (FSM) planning for a small town in a state in southern India. With the objective of understanding the nature of containment structures and on-ground desludging practices, 8,001 households and 1,667 establishments were studied in Periyanaicken-Palayam (PNP), a non-sewered Town Panchayat in Coimbatore District, Tamil Nadu, to provide evidence for effective decision-making. The study showed wide variations in the sizing and design of the containment systems, which, when combined with the irregular frequency of desludging, has implications for FSM planning by municipal bodies. This study also highlights the methodological difficulties in studying containment systems, exposes a significant response bias given the limited understanding of containment systems within households, and spotlights the difficulty in physically verifying the reported data given the underground nature of these systems.

## 1. Introduction

The Millennium Development Goals aimed to provide access to improved sanitation. Keeping with that, the Sustainable Development Goals (SDG), particularly SDG 6, retains the focus for access to safe and improved sanitation, but also refers to reducing the amount of untreated wastewater.[1] This effectively means that sanitation targets for SDG 6 can only be met if the focus expands from just access to the full cycle of sanitation – access, conveyance, treatment and re-use. Fecal Sludge Treatment or Septage Management is increasingly being recognised as an effective and appropriate method to scale urban sanitation systems to achieve safe sanitation, particularly in small towns and cities. As implementation progresses, data-based evidence is emerging, highlighting the challenges faced on the ground, and the requisite planning necessary to address them. This paper presents the findings, challenges and possible ways ahead from a study conducted to provide data for Fecal Sludge Management (FSM) planning for a small town in a state in southern India. (see Tables 1 and 2)

Around 31 per cent of India's population is urban according (Census 2011), and Tamil Nadu, with an urban population of 34.9 million (48 per cent of the total state population), is one its most urbanised states. There are 8.9 million households in urban Tamil Nadu, out of which 4.2 million (48 per cent) depend on on-site systems. In Tamil Nadu, Urban Local Bodies (ULBs) are classified into Municipal Corporations, Municipalities and Town Panchayats, depending on the population and income of the ULBs.[2] There are 12 Corporations, 124 Municipalities and 528 Town Panchayats, accounting for 43 per cent, 32 per cent and 25 per cent of urban population respectively.

☆ Note: This paper is based on a report, 'GIS Mapping including Household and Establishment Study in PNP and NNP Town Panchayats, Coimbatore District, Tamil Nadu, 2019', TNUSSP.

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[1] https://sdgs.un.org/goals/goal6.

[2] Commissionerate of Municipal Administration (Accessed at https://www.tnurbantree.tn.gov.in/about-us/on 28 June 2020) and Directorate of Town Panchayat (Accessed at http://www.tn.gov.in/dtp/introduction.htm on 28 June 2020).

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Urban Tamil Nadu largely depends on on-site sanitation systems (OSS), as only 27 per cent of household toilets are connected to networked sewer systems. Around 42 per cent depend on OSS like septic tanks and improved pit latrines (Census 2011).[3] This percentage goes up to 50 per cent in Town Panchayats which have lesser population (average population size of around 15,000), and considerably lesser staff strength in the urban local body.

The Government of Tamil Nadu (GoTN) has committed to the rapid scaling up of FSM as a complementary solution to networked sewer systems in corporations and larger municipalities, and as a standalone solution in smaller municipalities and Town Panchayats. As a step towards recognising the significance of FSM, the GoTN issued the Operative Guideline for Septage Management in 2014, and subsequently launched a programme for scaling FSM.

Given the limited examples globally of scaling FSM, the GoTN chose two non-sewered town panchayats – Periyanaicken-palayam (PNP) and Narasimhanaicken-palayam (NNP) – in Coimbatore, Tamil Nadu, to demonstrate FSM as an economical and effective means to scale sanitation across its 500+ town panchayats. Extensive studies were conducted across the full cycle of sanitation to understand field realities and provide inputs for effective FSM planning. This paper outlines the findings from one of the baseline studies.

Sanitation mapping was carried out in PNP (2018) to aid the preparation of an FSM plan and to serve as a management and monitoring support system. This involved a census of properties (residential, commercial and others) with data collected on the household sanitation arrangements including details of OSS, and desludging practices followed. The process of data collection and analysis raised issues of data robustness, analytical tolerance/sensitivity and the practicality of the methods used in FSM design and planning.

This paper revisits the survey data on containment and de-sludging practices to discuss the ramifications for planning towards FSM and meeting the goal of SDG 6. It presents findings from the ground and then discusses the wider implications of the same for sanitation design and planning. It focusses on two specific components of the sanitation chain – containment systems, and de-sludging practices.

### 1.1. Study area

PNP town panchayat located 17 km north of Coimbatore city, has an area of 9.38 sq. km,[4] (GoTN,) with a population of 25,930 comprising 7,377 households (Census 2011). Almost 83 per cent of households in PNP have individual household toilets, and 14 per cent depend on public sanitary conveniences (PSCs). Open defecation is reported at 3 per cent. Septic tanks constitute 55 per cent of containments, and improved pits 9 per cent (Census, 2011). Around 19 per cent of households reported to be connected to the sewered network, but there is no sewered network in PNP. Therefore, the reported numbers for sewers are incorrect. Anecdotal evidence suggests that covered drains were mistakenly identified as sewers by surveyors across multiple cities during Census (2011).

There are 13 PSCs including public toilets and community toilets located across the town (TNUSSP, 2016). Households largely depend on private de-sludging operators who use trucks called ‘cesspool vehicles’ to empty the containments and to carry the septage. There are four private operators located in and around PNP with eight cesspool vehicles (TNUSSP, 2018A).

PNP has a Fecal Sludge Treatment Plant (FSTP) with a capacity to treat 25,000 L of fecal sludge per day or a volume equivalent to the capacity of four to six cess pool vehicles. The FSTP, which uses mechanised technology to treat fecal sludge, is meant to serve a cluster of town panchayats including PNP.

**Table 2**
Distribution of reported septic tanks with or without outlets.

| | No outlet | Outlet (soak-pits/open drains, reed bed etc/) | Total |
|---|---|---|---|
| HOUSEHOLDS | | | |
| Reported septic tanks that were waterproof | 491 | 34 | 525 |
| Reported septic tanks that were not waterproof | 4463 | 490 | 4953 |
| No response/don't know | | | 282 |
| Total septic tanks | | | 5760 |
| **ESTABLISHMENTS** | | | |
| Reported septic tanks that were waterproof | 69 | 9 | 78 |
| Reported septic tanks that were not waterproof | 264 | 23 | 287 |
| No response/ Don't Know | | | 12 |
| Total septic tanks | | | 377 |

## 2. Objectives and methods

This study was undertaken to help the urban local body to design, plan and execute an effective fecal sludge management plan for the town. It targeted 100 per cent coverage of all households and establishments, complemented by a mapping exercise. Given this, the objectives of the study were:

- To understand access, containment and on-ground desludging practices to enable more effective planning.
- To prepare a GIS-linked database of properties (households and establishments) and help build a spatially explicit database of

**Table 1**
Distribution of arrangements for household sanitation – Periyanaicken-palayam Town Panchayat.

| Type of Residential property | No. of HHs | Proportion of households with access to sanitation through | | | | | |
|---|---|---|---|---|---|---|---|
| | | Individual Household Toilets | No Latrine in own house, but | | | | |
| | | | Shared Toilet | PT/CT | Combination of PT/CT + Shared Toilet | OD | Combination of OD + PT/CT + toilet |
| Plotted Housing | 6,980 | 79.6 | 10.5 | 7.3 | 0.7 | 1.0 | 0.9 |
| Mixed use | 644 | 83.4 | 13.0 | 2.1 | 0.8 | 0.2 | 0.5 |
| Group Housing | 336 | 83.3 | 11.6 | 2.4 | 2.7 | 0.0 | 0.0 |
| Slum Housing | 41 | 58.5 | 2.4 | 14.7 | 0.0 | 24.4 | 0.0 |
| **All Properties** | **8,001** | **79.9** | **10.7** | **6.7** | **0.8** | **1.0** | **0.9** |

*Source:* TNUSSP survey 2018, Households contacted N = 8,896, No consent = 895.

[3] On-site sanitation system is a system in which excreta and wastewater are collected and stored or treated on the plot where they are generated. Containment systems are containers like a septic tank or a single pit in which the fecal waste from the toilet is stored. (Tilley et al., 2014).

[4] Government of Tamil Nadu, P N Palayam Town Profile (Accessed at http://www.townpanchayat.in/Periyanaickenpalayam/town_profile on 28 Jun 2020).

containments and networks for conveyance and access that could be updated/tracked over time.

- To provide spatial and non-spatial inputs for effective decision-making.
- To validate the appropriateness of the selected locations and sizing of the treatment systems.

### 2.1. Methods

The study conducted from February to May 2018, attempted to cover all households and establishments in PNP through door-to-door data collection using surveys. There were three parts to the survey: a detailed questionnaire administered to the households, an observation form filled by the field team, and a recording of geo-coordinates of households and establishments. In addition, a total station study using surveying equipment was conducted to map access roads and streets and collect details on their width.

Since this paper presents only a sub-set of findings – on containment and de-sludging – it primarily utilises the information gathered from the questionnaires such as demographic details, types of sanitation arrangements, containment details including reported data on dimensions of the underground structure, materials used, and desludging practices. Information was also collected on the location of the drinking water source with respect to the containment structure, to understand the potential health risks that can arise from contamination. For a few findings, the paper draws upon mapping done for properties and roads.

The questionnaire was pre-tested and based on inputs from the field. A few questions were added and modified before the questionnaire was finalised and transferred to an Android app. Enumerators were then trained on the Computer Assisted Personal Interview (CAPI) methodology and data capture process. In order to ensure data accuracy, quality controls and checks were in-built within the data collection application. Further, throughout the data collection process, the research agency followed field quality procedures and protocols including back checks and accompanied calls.[5] In addition to real-time data monitoring, IIHS had a clear field monitoring plan in which a sample of households and establishments were visited by the team to validate the collected data.

All buildings including residential, commercial, industrial, institutional and mixed use were visited. A total of 11,924 buildings were listed in PNP. During listing, these buildings were further classified into three categories based on their current functioning status – occupied, unoccupied or locked.[6] This classification was used to select only those buildings that were eligible for further data collection. Only occupied buildings with an owner or occupant were considered eligible. Of the occupied buildings that is, 11,013 buildings, consent to capture building level details was obtained for 10,937 buildings which included 8896 household units and 2,041 establishments. In order to capture unit level details, consent was further obtained from households and establishments. A total number of 8,001 households and 1,667 establishments consented to the survey.

More than half of the respondents were not owners, and the establishments were mostly of the mixed-use and commercial type. Public and semi-public structures and industrial goods establishments were the most common type.

Depending on the type of land use, the surveyed residential buildings were classified as either mixed use or standalone residential use. In PNP, the majority of buildings (92 per cent; N = 7,357) were standalone residential and 8 per cent belonged to the mixed-use category.[7] Residential buildings were further sub-categorized as group housing, plotted housing and slum housing. Most of the residential buildings were plotted houses, followed by group houses and slum houses. Of the 644 mixed-use buildings, the majority were used for both residential and commercial purposes. Of the 1,667 establishments surveyed, mixed-use and commercial type constituted the majority, accounting for 51 per cent and 36 per cent respectively. The majority of establishments (92 per cent) employed between one and ten employees.

A major challenge during data collection was that several households were reluctant to give consent, due to rampant theft in the area. The nature of information that the survey intended to capture, especially on containments, also proved to be a challenge since the structures were located underground, and hence could increase response bias.

## 3. Findings

Findings from the study are presented across the sanitation chain including access, containment and collection.

### 3.1. Sanitation arrangements in households and establishments

**Households Arrangements for Sanitation:** Around 80 per cent of the surveyed households had access to individual household toilets, which approximately tallied with Census (2011) data that reported a total number of 7,377 households and reported 83 per cent of households with individual household toilets. A significant proportion (87 per cent) of reporting households were residents in plotted houses[8] exclusively for residential use. Of this, 80 per cent reported access to sanitation facilities within their houses. About 11 per cent of households reported access to shared sanitation facilities.

Properties of mixed-use character, which accounted for 8 per cent, were the next significant category in the town. Access to sanitation facilities within the premises was comparatively higher at 83 per cent. Shared facilities were reported by about 13 per cent of these households. Group housing (multiple households residing in the same building)[9] accounted for only 4 percent of households. In this category, 83 per cent reported access to sanitation facilities within their house, while about 11 per cent reported using shared facilities.

About 1 per cent of the households were residents in slums,[10] of which only 59 per cent had access to sanitation facilities within their

[5] Back checks – In-person visits conducted after the completion of an interview among randomly selected samples and by re-administering a few questions from the survey questionnaire to verify and validate the responses. Accompanied calls – The field supervisor is present during the entire duration of the interview as an observer to check on the quality of the interview.

[6] Occupied building was any building that is under continuous or periodic habitation, occupancy or use. Unoccupied building was any vacant or under construction building that is not under continuous or periodic habitation, occupancy or use. Locked building was any building that is locked during the time of interviewer visit. The building maybe occupied or unoccupied. To distinguish between unoccupied and occupied, during listing, if they find a building locked, they will enquire nearby about the building and its status. If the building is in use but the owner is away or has been locked for a few weeks/months, the surveyor will visit the place two more times (not immediately but sometime during the study period). If the building is still locked even after two visits, the building is categorized as 'locked'.

[7] A mixed use building incorporates more than one uses into one structure such as residential, retail, hotel, entertainment, etc.

[8] Plotted Development/Housing is a type of development layout wherein a stretch of developed land is divided into regular sized plots for uniform controlled building volumes (MoUD, 2016). This type of housing is common across different socio-economic classifications.

[9] Group Housing refers to a building unit with one or more floors having more than two dwelling units, and having common service facilities where land is owned jointly (as in the case of co-operative societies or the public agencies, such as local authorities or housing boards, etc) (MoUD, 2016).

[10] Slum Housing refers to houses located within slums. Slums are buildings that are in poor condition of maintenance or have compromised habitability due to poor ventilation, sanitation or otherwise are termed slums. These are generally declared or notified as slums under relevant legislation by competent authority. (MoUD, 2016).

premises. A significant proportion of households in this category (17.1 per cent) reported access to shared and community facilities, and nearly a quarter (24.4 per cent) reported resorting to open defecation. It is to be noted that the number of properties where households were locked, or consent was not given was higher in slum areas, hence the percentage of property types may not be representative.

For households that did not have individual household toilets, this study examined the availability of space to build toilets. Of the households with no access to toilets within their premises (1,607), 1,004 or 62.6 per cent reported that they did not have sufficient space to build a toilet. Hence, availability of space is a key constraint to building individual toilets within own premises.

**Arrangement for Sanitation in Establishments:** Sixty-four per cent of the establishments (n = 1,064) in PNP had access to sanitation facilities within their premises. Most remaining establishments (around 34 per cent) depended on shared toilets outside their premises as well as public/community toilets. Establishments reporting this arrangement had an average staff strength of 1.8. A small proportion of establishments (about 2 per cent) had a staff strength of just one, who reported resorting to defecating in the open. While the establishments were bucketed into various categories such as manufacturing, socio-cultural, and commercial, there were no significant variations across categories. The only notable finding was that all manufacturing establishments had toilets in their premises. Out of 603 establishments without toilets in their premises, 93 or 15.4 per cent reported adequate space for construction of sanitation facilities within the premises. It was also attempted to collect disaggregated data for women employees, but the responses were inadequate to come to a conclusion.

In PNP, 36 per cent of the establishments did not provide access to sanitation facilities within the premises which caused inconveniences for employees and visitors. However, it is not easy to establish whether these establishments were in compliance of the bye-laws or not. For shops and commercial offices, the byelaws indicate one water closet for every 25 persons or part thereof exceeding 15 (including employees and customers). Further, it for female personnel, 1 water closet should be available for every 15 persons or part thereof exceeding 10. (GoTN, 2019). Adequacy of sanitation facilities is mandated based on employee strength in the establishment and an estimate of customers. Since the study of customer footfall was beyond the scope of this study, it is not possible to comment on the adequacy of sanitation facilities for establishments. Out of the 12 public sanitation facilities in PNP, only one was a public toilet (TNUSSP, 2018B).[11] Absence of adequate public toilet facilities, and lack of toilets in establishment (even if in compliance with the law) indicates a need for examine regulatory provisioning and access if there is a need to plan and design sanitation supplementary facilities in a sustainable manner.

### 3.2. *Containment structures: construction practices and impacts*

**Design of the containment structure:** In order to understand the type of containment systems, households (n = 6,394) and establishments (1,064) were asked about the containment system their toilets were connected to. A small percentage of households (4.5 per cent) and a significant percentage of establishments (63 per cent) were unable to respond to this question due to a lack of knowledge. A significant proportion of households (90.1 per cent, n = 5,760) with individual household toilets (n = 6,394) reported septic tanks as their containment system, as did 377 (or 35.4 per cent) of 1,064 establishments with toilets within their premises. The next most significant containment structure noted was the single pit, reported by 5.3 per cent households and 1.4 per cent establishments.

Other studies and discussions with masons and building contractors in different parts of the state had indicated that containment systems reported as 'septic tanks' deviate significantly from key design standards, which could affect their performance.[12] In most cases, it is surmised that these so-called 'septic tanks' actually behave like leach pits.

Thus, for the study in PNP, a series of discrete questions regarding wall material, roof material, plastering of wall and base, presence of partition, and number of chambers, were asked. This helped validate the responses on the type of containment system present in the premises and confirm if they were built according to standards.

Of the 5,760 households that reported their containment structures as septic tanks, only 525 (9.1 per cent) households reported the walls and base as being plastered with the possibility of achieving water-tightness as is required for a well-functioning septic tank. Some structures reported as 'pit latrines' noted the wall and/or base as being plastered.

Fig. 2 details the coating practice for both wall and base materials in septic tanks reported by establishments (see Fig. 1). Only 78 (20.7 per cent) of the 377 septic tanks reported by establishments could possibly achieve water tightness, as they had both walls and base plastered (see Fig. 3).

Thus, amongst both households and establishments in PNP, the majority of the containments reported as septic tanks did not function in a water-tight manner, but worked in a manner similar to leach pits with either the wall or/and the base left without plastering.

**Partition:** In households, out of the 525 structures with walls and base plastered, 87 containments (16.5 per cent) were partitioned. Among establishments, out of reported 78 septic tanks with plastered walls and base, 17 (21.7 per cent) were partitioned. Most of the septic tanks in households and establishments with both walls and base plastered were single chamber tanks, and thus did not induce greater sedimentation or solid-liquid separation.

Out of 6,394 households and 1,064 establishments, only 1.5 per cent of households, and 4.5 per cent of establishments had partitions and were waterproof, thereby being able to function as a septic tank, as opposed to the reported percentages of 90 and 35 respectively.

**Disposal of septic tank effluents:** Households that reported having septic tanks were queried on practices followed for the disposal of effluents from the tank. In PNP, 90.7 per cent or 5,229 households reported that the containment structure did not have any outlet. Further, 7 per cent reported that the containment was connected to surface or open drains, and only 1.8 per cent of the households' reported connecting containments to soak pits or leach pits. Amongst the establishments reporting septic tanks (n = 377), 90.5 per cent reported having no outlet and 10 per cent were connected to a soak-pit.

As reported earlier, many of these reported septic tanks had either walls or base left un-plastered. Therefore, in the absence of any outlet, it can be assumed that they function as leach pits. Out of 525 waterproof septic tanks in households, and 78 waterproof tanks in establishments, 93.5 per cent and 88.4 per cent respectively reported having no outlets.

[11] The Advisory on Public and Community Toilets developed by Ministry of Housing and Urban Affairs, Government of India (2018) defines public toilets as facilities provided for floating population/general public in places such as markets, train stations or public areas and mostly used by undefined users (MoHUA, 2018).

[12] Septic tanks are watertight single-storied tanks. The floor of the septic tank should be watertight and should be able to support the weight of the walls and contents. The walls maybe built of brick and should be plastered with cement mortar. For septic tanks that exceed 2,00 L, the tank may be divided into two chambers. The outlet should be connected to a seepage pit or dispersion trench from where it overflows into or is absorbed by the surrounding soil. The septic tank should be provided with a rectangle or circular opening for access (BIS, 1993). Leach pits/Twin pits should be lined to avoid collapsing. Bricks, stones or laterite bricks cement concrete rings could also be used depending upon their availability and cost. Except where precautions are to be taken to prevent pollution of water sources, the pit bottom should be left in a natural condition. RCC slabs should be used to cover the pit (CPHEEO, 2013). No standard exists in India for Ecosan, VIP and other OSS containment systems.

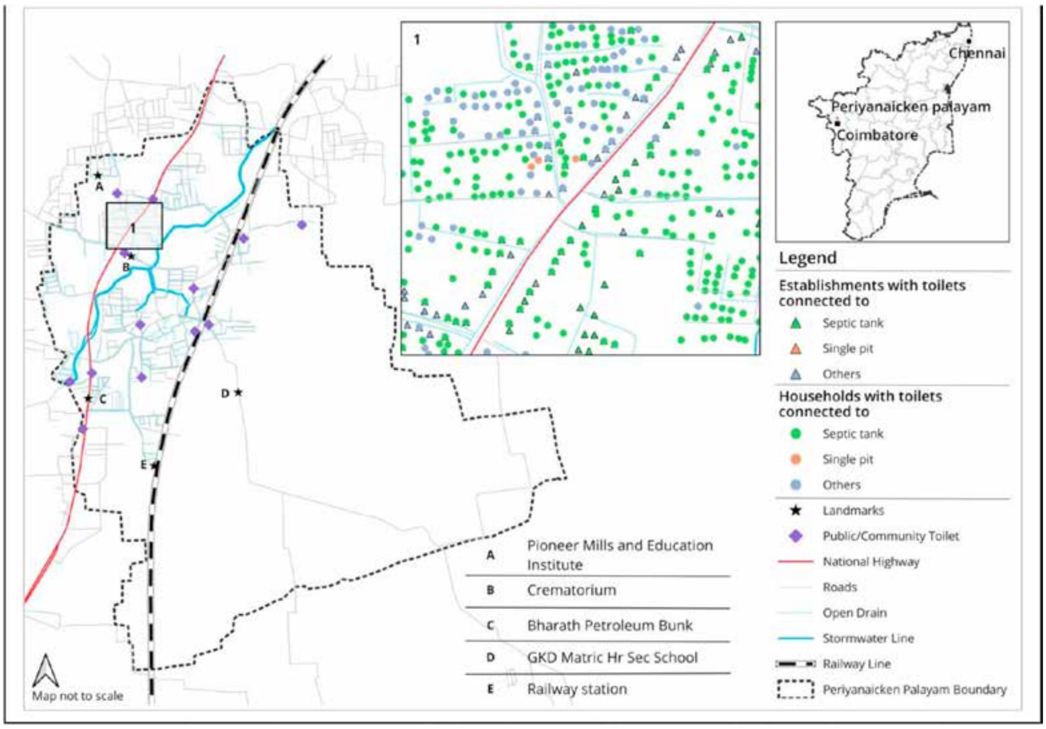


**Fig. 1.** Map of Periyanaicken-palayam town panchayat.

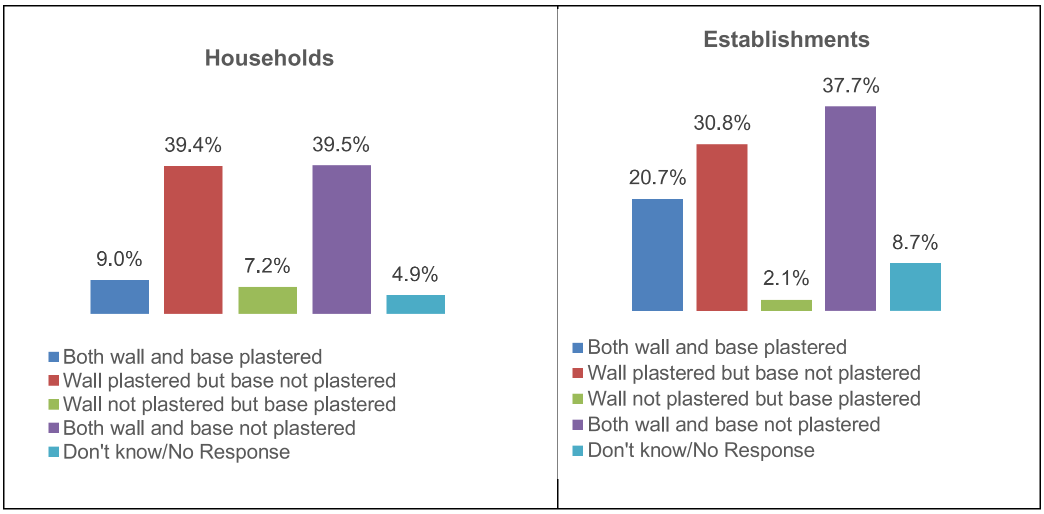


**Fig. 2.** Coating for wall and base for reported 'septic tanks'- Households and Establishments.

In these cases, the septic tanks functioned as holding tanks.

Overall, only 3 septic tanks in establishments were waterproof, had partitions and were connected to soak pits.

**Size of Containment structures:** Of 6,394 households with toilets within premises, 5,760 reported septic tanks, and 341 reported single pits. Out of these, 4023 households with reported septic tanks knew the size of their septic tanks, and 85 households with reported leach pits knew their dimensions. According to Indian standards, the recommended size of septic tanks for up to 5 users is 1,500 L, and the recommended size of single pits is 827 (CPHEEO, 2013). The mean household size of the reporting households was 3.22.

Most of the reported septic tanks in the households were over-sized, with nearly a third (34 per cent) reporting over-sizing by a factor of 10. About a quarter of the households (21 per cent) reported single pits with volumes that followed Central Public Health and Environmental Engineering Organisation (CPHEEO) recommendations, while the remaining were oversized. However, nearly 60 percent of the single pits were oversized by a factor of 2. It was observed that septic tanks had greater

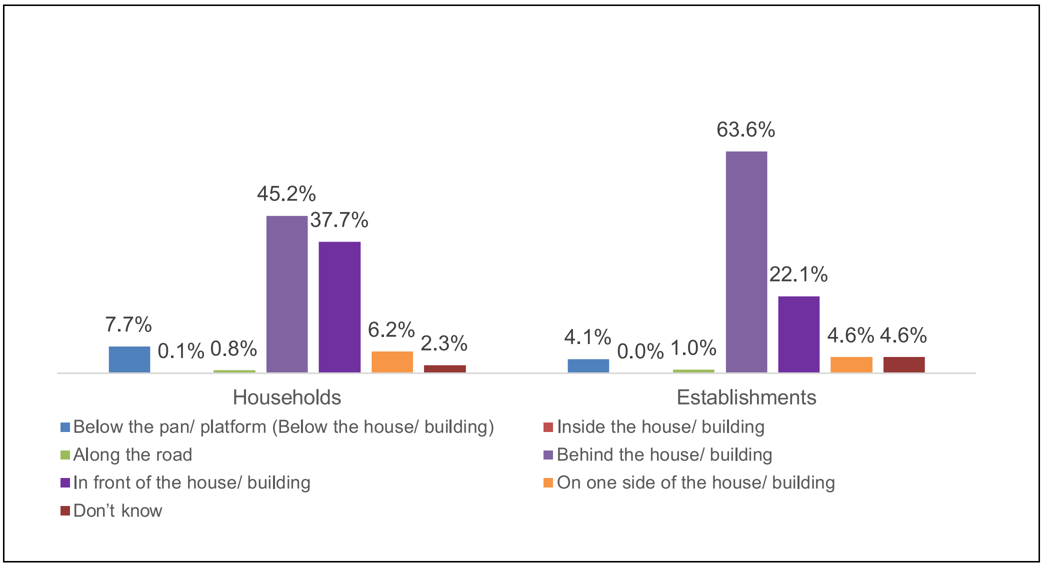


**Fig. 3.** Location of OSS.

propensity to be oversized than pits, and significantly so. It is noted that many reported septic tanks functioned as pits, but since the size of pits requirements is even lesser, the over-estimation will only increase.

**Physical Verification:** Given that data on containment systems was heavily dependent on information provided by respondents, and that the subterranean nature meant minimal chances for observation, the study team carried out a physical verification of a sample of containment systems at households in PNP to cross check the responses given by households. The team physically measured containment dimensions and the measurements were then compared with the reported data. The team also checked for the presence of manholes and vent pipes.

Forty-three samples were checked. Given the lack of manholes as well as the reluctance of households to open the tank, only 4 were opened and observed. In the other 39 containments, the length and breadth were measures for only the visible portion of the septic tank on the top. The significant observations were as follows:

- Sample checks concluded that location and respondent names tallied.
- None of the containment structures had a separate soakaway.
- Manholes were not present for 75 per cent of checked samples.
- Length X breadth dimensions were verified and found to be within ± 20 per cent of reported data values.

**Vertical distance between containment systems and water source:** The maximum reported depth of single pits in PNP was 20 feet in households and 8 feet in establishments. Given that groundwater depth for PNP was over 90 feet (Water Resources Organisation, Tamil Nadu Public Works Department), the vertical safe distance between containments and water source had been maintained (Standards, n.d.).

**Accessibility of containment systems:** Direct and easy access to the containment system for desludging depends on three parameters: location of the containment system, ease of opening the lid, and width of the road to accommodate the desludging vehicles. This study covered the first two parameters and analysed these criteria for 6,101 households and 392 establishments who reported having either septic tanks or pit latrines.

Most households had containment systems that were located in accessible locations, and in a majority of cases, the structures were located either in front or behind the building. In a few households and establishments, the containment systems (reported septic tank/single pit) were located in a manner where access was challenging. In 469 (7.6 per cent) households and 16 establishments, (4.1 per cent) containments were located below the toilet pan/platform, or below the house or building, and hence were inaccessible.

Of 5,490 household containment structures that were located in an accessible area (either along the road, behind or in front of the house/ building, or on one side of the house/building), 1,711 containments (31.12 per cent) had a manhole or pipe with cover. Likewise, in establishments, 29.8 per cent containments located in accessible areas had a manhole or pipe with cap, which are essential for inspection and desludging. The absence of a manhole would mean that the containment lid has to be broken in order to remove the fecal sludge. Accounting for inaccessible location and absence of cover, only 28 per cent of households and 27 per cent of establishments had accessible containment systems.

### 3.3. Emptying practices

Of the 6,101 households with reported septic tanks and single pits, only 8.2 per cent or 498 households reported having ever de-sludged their containment systems. Of the 5,760 reported septic tanks, only 8.2 per cent reported ever desludging. Further, of the 525 households that reported construction of septic tanks with walls and base plastered, only 22.8 per cent reported having ever de-sludged. Out of 87 households with reported wall and bases plastered and having partitions, 36.8 per cent or 32 households reported having ever de-sludged. Out of 491 households that had wall and bases plastered, and no outlet, 18 per cent reported ever having de-sludged. Only 29 establishments of the 393 reported having ever emptied the containment systems.

When the households and establishments who reported de-sludging at least once were asked about the interval of de-sludging, nearly one-third households and half the establishments reported de-sludging only when it fills up. Nearly a quarter of households and establishments reported that they had emptied the containment structure only once. Hence, only a few households and establishments emptied the tanks on a regular basis. This finding is not surprising since the earlier section showed that most containment systems actually performed as pit latrines.

### 3.4. Proximity of properties to treatment facility

Initial studies revealed that the lack of adequate treatment facilities within a certain distance was the primary reason for de-sludging operators to dump septage in the open. Hence, the government decided to increase number of treatment facilities across the state. There was a proposal to build an FSTP at PNP to service a cluster of FSTPs.

At the time of the study, the closest disposal facility for de-sludging operators was located in Coimbatore Municipal Corporation, at a distance of around 25 kms.[13] A study had revealed that operators faced accessibility issues and restrictions from travelling on certain city roads during specific hours which made a huge impact on the business (TNUSSP, 2018A). Discussions with operators had highlighted that they would be willing to bring vehicles to the FSTP, provided that the distance from the households was not more than 10–12 km.

The purpose of this study was to also ascertain the suitability of the location of the proposed FSTP. Mapping showed that the closest distance from settlements in PNP to the FSTP was 2 kms and the farthest distance was 5 kms, implying that the FSTP site was at a suitable distance from the town panchayats.

## 4. Discussion

The findings show that considerable progress has been made in the provisioning of access to toilets. Only a small percentage of households practice open defecation, and need to be provided with individual, shared or community toilets. The key challenge in PNP (and illustrative of urban India) is to move households up the sanitation ladder. This is likely to be the case across much of urban India, where investments have been made in community toilets to provide access. There are three primary barriers in access to individual household toilets: lack of space, affordability and land tenure (WSP, 2016). This study has only explored the issue of land availability, and it appears to be a significant challenge given that two-thirds of households (1,004 or 63 per cent) did not have adequate space to build toilets. Out of 603 establishments without toilets in premises, 93 or 15.4 per cent reported adequate space for construction of sanitation facilities within the premises.

While there are certain methodological challenges that are discussed later, the findings clearly illustrate that there is widespread deviance from the standards in the construction of OSS. These include the absence of soakaways, oversized structures, and absence of openable lids. Amongst both households and establishments in PNP, the majority of the containments reported as septic tanks did not function in a water-tight manner, but instead were similar to leach pits with either the wall or/and the base, not plastered. Of the remaining septic tanks that could achieve watertightness, a large percentage did not have partitions. Thus, most of the reported septic tanks failed to function as septic tanks and instead behaved like leach pits, and in few cases, like holding tanks. Only a small percentage conformed to design specifications and could function as a septic tank. Other studies indicate that this could be because of lack of knowledge in the masons who constructed them, or because the households did not want to de-sludge frequently.

While the corrections for some deviances such as ensuring access to containment systems by putting a removable lid are easier to carry out, other design deviances are more complicated. For example, many structures reported as septic tanks did not have a soakaway, but most of these structures behaved like leach pits, and hence would not require a soakaway. Single pits could be an adequate solution in the interim if adequate distances are maintained from drinking water sources Containment systems require improvement, but rather than recommending the construction of new septic tanks, a more nuanced plan for retrofitting and improvement is required.

[13] FSTP at PNP is operational currently, however was not operational at the time of the study.

The findings highlight the need to pay attention to the containment systems, and this necessitates a two-pronged strategy: to ensure that new containment systems are built according to standards (BIS, 1985a, BIS, 1985b), and that existing ones are retrofitted or upgraded. One way to ensure that new containment systems are built to standards is by making necessary amendments to the building approval process, and ensuring that containment systems are verified before a building is approved. Towards this end, the Government of Tamil Nadu has passed amendments in the Building Rules to ensure that containment systems conform to standards and are verified in the building-plan approval stage (GoTN, 2019). This, however, is only the first step; processes for verification need to evolve and be developed as this moves forward.

This still leaves open the question of retrofitting existing OSS. A requisite containment improvement plan at the household level with technology options and low-cost improvements could be devised. While households might be reluctant to reconstruct their OSS, ULBs can opt for certain effective improvements such as ensuring manholes are built, which can be done without incurring a high cost. A rolling plan which allows the reconstruction of the containments as and when they fill up could also be devised.

It must be recognised that any containment improvement plan would require substantial time and effort for scaling. The immediate priority should be to safely secure the fecal sludge that is being emptied by ensuring proper conveyance and treatment. In addition, FSM planning for other parts of the chain – de-sludging and treatment – needs to account for the variance in containment systems, until they are retrofitted/upgraded.

Most guidelines that stipulate ideal de-sludging frequencies are based on the assumptions that containment systems are built to specifications, including meeting the size requirements. However, if the containment systems are larger, frequent de-sludging is likely to face resistance from households because it imposes an additional financial burden – something that ought to be taken into consideration, and to plan for affordable de-sludging. More importantly, it is not immediately clear that sticking to the stipulated 2-to-3-year cycle of de-sludging renders either the containment system or overall FSM planning safer. It is beyond the scope of this paper to comment on ideal de-sludging periods, but a case is being made by this paper to take local conditions into consideration before deciding de-sludging periods. It also calls upon a change in household behaviour because if even lengthier cycles are stipulated, the de-sludging should happen before the tanks overflow.

Further, variance in containment systems affects both the volume and nature of the fecal sludge. Treatment plants are usually designed on the basis of population served, and assuming a specific de-sludging interval could lead to over-estimation of sizes. Local data collection is imperative to address this. One of the practical ways to deal with uncertainties of volumes is to adopt a modular approach for treatment facilities like what is being done in Tamil Nadu, with land and capital kept in reserve for future expansion. While one can start small, it is imperative to build some redundancy, and secure financial flows in the medium term for expansion if needed.

The findings also highlight methodological challenges for gathering data. The paper demonstrates how there can be a 'response bias' (Lavrakas, 2008)[14] in household surveys about containments – where containment structures that are reported as 'septic tanks' may not function like septic tanks. About 90 per cent of households reported that they had septic tanks, but when further probed about the porosity of the structures as well as partitions, only 1.6 per cent of the structures met

[14] Response bias is a general term that refers to conditions or factors that take place during the process of responding to surveys, affecting the way responses are provided. Such circumstances lead to a non-random deviation of the answers from their true value. (Encyclopedia of Survey Research Methods, Sage Research Methods, 2008) https://methods.sagepub.com/reference/encyclopedia-of-survey-research-methods.

the criterion to be termed a septic tank. In addition, several households as well as a significant proportion of establishments did not know what type of containment system they had access to. Tenants are also unlikely to give accurate answers about de-sludging.

The respondent bias is due to multiple reasons: inadequate understanding amongst residents about technical terms used to describe containment systems; respondents not being in a position to observe the construction or repair of the containment; and a high proportion of tenants in the study area who may not know details about the construction. All these biases affect survey results, as well as estimations such as dimensions of containment systems and their functioning.

Data collection regarding containment systems is further complicated by thr fact that they are located underground. Data regarding the structures e.g., size and porosity of the structure, and presence of partitions is household reported data which the team tried to cross-verify through observation. However, only some features could be 'observed'; for the other, the septic tanks need to be opened, and there was resistance to do so from households.

One of the ways to overcome/compensate this is to triangulate data collected at the property level (households and establishments) by gathering information from other stakeholders. Discussions with masons is likely to reveal local practices of construction, as well as a sense of dimensions. Further, to understand de-sludging frequency, information can be triangulated by speaking with de-sludging operators.

ULBs, who require such data for planning, may not be able to conduct a Census or detailed study. A simpler database could possibly be built through a sample study based on transects (Center for Applied Transect Studies, 1988)[15].Information can be aggregated transect-wise and supplemented by primary data from interactions with local masons, builders or contractors. One could also start with a basic database of containment structures such as a simplified version of the current study and refine the database with data collected as and when each unit is de-sludged.

## 5. Conclusion

The learnings from the study point to a series of checks and steps that need to be taken to achieve and sustain SDG 6. Providing access to toilets, which government programmes such as Swacch Bharat Mission have kickstarted, and inculcating/ensuring their use which has been emphasised earlier as well, are only the beginning. The wider mandate of the SDGs, which includes the treatment of wastewater, requires practitioners, planners and administrators to broaden the scope of urban sanitation.

The above findings confirm what is generally accepted by practitioners based on anecdotal evidence – that there is significant deviance from prescribed standards in construction practices of OSS. Responses recorded as 'septic tanks' could actually be structures that behave as 'holding tanks' or 'leach pits'. As the first link in the FSM chain, containments are a vital point of fecal disposal. Any variation in containment systems will have cascading implications for design and planning for subsequent parts of the chain. These findings are thus critical to design an appropriate scaling strategy for FSM.

This paper highlights the need to pay more attention to containment systems, a part of the chain often ignored. More work needs to be done to devise methods and practices to ensure that new containments are built to standard, and that old ones are retrofitted. Further, it is necessary to understand the implications of containment systems for FSM planning to avoid over-estimation of capacities.

This paper also points to a larger point that planning for relatively new areas like FSM must be grounded in the local context and realities.

While thumb rules and standards are useful and can provide a baseline, it is essential to validate these with practices on the ground given local contexts. Also, any containment improvement plan will require engagement with households and establishments. Therefore, there is an increasing need to pay attention to the communication around FSM. The Kakkaman campaign in Tamil Nadu aims to address this by making sanitation communication fun (Nagarajan and Sudhakar, 2020).

Finally, this paper calls for increased attention to data collection methods to ensure effective planning. Large scale data sets like the Census in India are based on resident reported data, and hence are likely to be affected by respondent bias, in particular in the reporting of 'septic tanks'. For instance, Census (2011) reports that 67 per cent of households in PNP are connected to septic tanks; but this study undertaken in PNP shows that in reality, most of these are not likely to function as septic tanks. A case could be made that large, generic data sets like those of the Census need to be supplemented by local data collection efforts for planning. There is a strong need to develop and implement methods for measurement which are simple and scalable, incorporating aspects of socio-economic nature of households/neighbourhoods and sub-surface character. While possibilities have been suggested in the Discussion section, this is an area that requires much research and innovation.

## Credit author statement

Reeba Devaraj: Writing – original draft, Formal analysis, Project administration, Data curation, Rajiv K Raman.: Conceptualization, Writing – review & editing, Supervision. Kavita Wankhade: Conceptualization, Writing – original draft, Writing – review & editing. Dhanik Narayan: Validation, Formal analysis.: Navamani Ramasamy: Project administration, Data curation, Validation.: Teja Malladi: Visualization, Validation.

## Competing interest

None.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Research Paper**

# The clean plan: analysing sanitation planning in India using the CWIS planning framework

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## ABSTRACT

Sanitation in India has received national attention for over a decade, especially with the Swachh Bharat Mission (SBM) making it a political priority. However, due to the lack of appropriate sanitation planning practices, there have been little long-term gains made in urban sanitation beyond the ending of open defaecation. In this paper, we analyse the key barriers to sanitation planning, in India, in the context of the emerging paradigm of Citywide Inclusive Sanitation (CWIS). A mixed method approach of shit flow diagrams, social network analysis, policy analysis, interviews and workshops at the national, state (2) and city (4) levels was conducted. Eight factors were identified as important barriers for planning including inadequate planning capacities, lack of ownership of city sanitation plans among city governments, poor community involvement, absence of a uniform planning framework, unreliable political and financial support, overlapping jurisdictions, and scheme-based funding. The paper also proposes the CWIS Planning Framework which offers a perspective at overcoming these barriers with the recommendation of bridging top-down and bottom-up planning approaches. While there is increasingly more clarity on what CWIS means, there is little understanding on how to plan for it. Therefore, this framework provides the theoretical basis for planning with the CWIS approach.

**Key words:** Citywide Inclusive Sanitation, CWIS planning framework, India, sanitation planning, Swachh Bharat Mission

## HIGHLIGHTS

- This is the first comprehensive study of sanitation planning practices in India with a CWIS lens.
- In-depth methodology drawing from 60 interviews, 4 workshops, 4 Shit Flow Diagrams (SFDs) and Social Network Analyses (SNA) for the 4 cities, document and policy analyses.
- Identifies the barriers for planning CWIS in Indian cities and makes overarching recommendations on ways to overcome these barriers based on the '4S' pillars.
- CWIS Planning Framework based on the Manila Principles on CWIS includes operational outcomes, functional linkages and '4S' pillars of comprehensive sanitation planning.

## 1. INTRODUCTION

Over the last decade, the sanitation landscape of India has been rapidly changing, with progressive laws, programmes and policies (Wankhade 2015; TERI University 2017). The most notable among them is the Swachh Bharat Abhiyan (SBM) or Clean India Mission, which helped the country declare itself open defaecation free in 2019. The success of this mission, as the world's largest sanitation campaign, has prompted it to be replicated in other countries; for example the Clean Nigeria Campaign (GoN 2019). However, the plans of SBM did not go beyond the latrine, leaving the rest of sanitation service chain unattended and the sustainability of the outcomes in significant uncertainty (Kumar 2017; Gupta *et al.* 2019).

In India, 32% of the urban households are connected to sewers, of which only 30% of the sewage generated is treated, leaving over 43,000 million litres of untreated sewage into the environment every day and 30 million households (not including the newly added latrines of the SBM) relying on septic tanks with no proper disposal strategy (WaterAid 2016). The aspirational centralised sewer-based sanitation systems are resource and time-intensive (GoI 2008; Gambrill *et al.* 2020). This prompted the National Government to embrace non-conventional solutions such as Faecal Sludge Management (FSM) by introducing specific funding schemes and policies to meet the rising sustainable sanitation demands (GoI 2017). Similarly, small-scale sanitation (SSS) systems are steadily gaining prominence in complementing centralised treatment plants in large Indian cities (Klinger *et al.* 2020; Narayan *et al.* 2020). However, the systematic uptake of both these alternative non-sewered sanitation systems (FSM and SSS) in India has been challenging their implementation, an operational and governance struggle (Reymond *et al.* 2020; Devaraj *et al.* 2021).

This struggle to provide safe sanitation can also be observed in other cities globally due to the complexity of population density, migration, urbanisation, slum expansion, settlement heterogeneity, tenure security and sheer urban poverty (Chaplin 1999; Scott *et al.* 2015). Despite the overall sanitation service levels being higher in cities than in rural areas, its implementation progress has been slower; between 2000 and 2017, the access to improved sanitation in rural areas has increased by 23%, while in urban contexts the increase has been a meagre 6% (UNICEF and WHO 2019).

One of the key reasons for failure in provision of sustainable sanitation, especially in complex settings such as cities in low- and middle-income countries (LMICs), is the lack of adequate sanitation planning (Kennedy-Walker *et al.* 2015). While the technologies and policies for sanitation, especially in India, have advanced to accommodate contextual needs, planning practices have largely remained conventional and dominated by expert driven rational-comprehensive approaches, in places where they are not most appropriate (McConville *et al.* 2011). Although top-down technocratic planning has been successful in the Global North, these planning approaches struggle to handle the complexity of sanitation provision in the Global South where urban demographics, socio-cultural factors and equity criteria vary significantly (Hawkins *et al.* 2013). This complexity of urban sanitation in LMICs demands borrowing solutions from all different technical and non-technical sources (Schertenleib *et al.* 2021).

Good sanitation planning practices allow for a systematic evaluation of solutions based on a holistic understanding of contextual demands that lead to community acceptance, long-term sustenance and leveraging synergies with other urban development goals (McGranahan & Mitlin 2016; Narayan *et al.* 2021). Benjamin Franklin's words 'failing to plan is planning to fail' are relevant in the case of India, where sanitation is often an *ad hoc* activity and city governments do not adequately spend time and effort in planning sanitation. This results in poorly managed urban sanitation and even visible pollution of urban water bodies (TERI University 2017; Sharada Prasad & Ray 2019). The existing capacities and attitudes of local planners, consultants and decision-makers in most city governments across LMICs including India still follow a one-size-fits-all top-down approach and are therefore yet to meet the standards of the emerging concept of Citywide Inclusive Sanitation (CWIS).

CWIS is a paradigm shift from the conventional approach to urban sanitation that can be characterised as technocratic, infrastructure focused, sewer aspirational and context-insensitive (Schrecongost *et al.* 2020). Instead, CWIS places equity and service-based safe management of entire sanitation value chain at the forefront while encouraging a mix of technological solutions and business models (Narayan & Luthi 2020). It brings multi-sectoral and multi-level stakeholders involved in sanitation provision together, an action often neglected in past planning practices. CWIS is gaining traction across international development agencies, governments, academia and NGOs (Gambrill *et al.* 2020), and even in India, it is being piloted across eight cities.

Therefore, the dual aims of this paper are to (i) analyse sanitation planning practices in India at the national, state and city levels and (ii) introduce the theoretical basis for a new CWIS Planning Framework, through which we can indicate possible ways forward to operationalise the CWIS approach in cities across India, thereby accelerating progress towards sustainable and equitable urban sanitation in the country.

## 2. RESEARCH DESIGN AND METHODS

This research followed a case study approach and used a mix of qualitative and quantitative research methods. The fieldwork and data collection spanned a total of 6 months between 2018 and 2020. The methods used include key informant interviews, participant observations, expert workshops, social network analysis, shit flow diagrams (SFDs), and policy and document analyses (Bryman 2012).

The initial sampling for experts was purposeful through stakeholder mapping and then complemented with snowball sampling and networking at major sector conferences. The use of the innovative social network analysis (Narayan *et al.* 2020) allowed for the identification of key actors within the sanitation landscape.[1] Eighty-four repeated in-depth interviews

[1] See Narayan *et al.* (2020) for the social network analysis components. This paper builds on the previously published work exploring aspects of sanitation governance in the same case studies.

were conducted with 60 experts for an average of 45 min, while some extended up to 3 h. The interviews were mostly in English; however, around 20% of the interviews were in the local languages of Tamil and Hindi.

Furthermore, four workshops were organised with national and international sanitation experts from international development agencies, NGOs, academia and public sector to analyse sanitation planning practices and past implementation experiences in India (Table 1). These workshops often happened in conference and training settings, such as the World Toilet Summit, Mumbai in 2018 and Eawag-ConCaD Training Bangalore in 2019, which provided easy access to expert participants.

Participant observations of sanitation service provision, policy interpretation, infrastructure decision-making and stakeholder engagement were carried out wherever possible at the national and city levels. Document analysis through the procurement of publicly listed and unlisted or undisclosed documents helped triangulate data through additional independent sources.

Qualitative data were mostly analysed through thematic content analysis coded in nVivo software following standard case study research protocols (Bryman 2012). Further in-depth information including interview and workshop guides, anonymised interviewee list and thematic analyses codes are provided in the Supplementary Material to make this research as reproducible as possible. There may be inherent research biases in data interpretation during the analysis, but preventive steps were undertaken such as a multi-perspective approach, corroboration and triangulation. According to Eawag Ethical Review of Projects involving human subjects (PD-16-09), this was deemed minimal risk. All participatory data were obtained after verbal consent and fully anonymised.[2]

## 3. STUDY LOCATION

The spotlight on India's sanitation sector in the last decade, right from adopting one of the most comprehensive sanitation planning policies (GoI 2008) to solving the world's largest open defaecation challenge (even having dedicated Bollywood movies on it), makes it a worthwhile case to explore how urban sanitation is being planned. This has to be done at the levels of national, state and city, to unpack the intricacies of policies, mandates, planning and implementation.

The primary study sites for the study were located in two comparable Southern states of Tamil Nadu and Karnataka, which have two of the most progressive sanitation policies. The four cities within these states were Chennai, Coimbatore, Bangalore and Mysore. While the site selection was partly based on the purposive sampling technique due to the availability and accessibility of data, it was also due to their comparable size, demography and sanitation statuses. Chennai and Bangalore are capital and mega cities in the respective states, while Coimbatore and Mysore are secondary cities with populations of approximately 1.5 million. They are also the cleanest cities in their respective states according to the Swachh Survekshan national sanitation survey (MoHUA 2019). Table 2 summarises key information about the cities based on the individual SFDs and their accompanying reports prepared as part of this research (see Supplementary Material for SFD graphics).[3]

**Table 1** | Type of key informants participated in interviews and workshops

| Type of stakeholder | Number of stakeholders interviewed | Total number of workshop participants in four workshops |
|---|---|---|
| National Government (NGV) | 5 | 3 |
| State/City Government (SGV) | 13 | 7 |
| Academia (ACD) | 15 | 9 |
| Private Sector (PVT) | 8 | 4 |
| NGOs and Resident Welfare Organizations (NRW) | 11 | 10 |
| International Development Agencies (IDA) | 8 | 9 |
| Total | 60 | 42 |

There is a 50% overlap between the experts interviewed and experts who participated in the workshops. Disaggregated information on this provided in the Supplementary Material.

[2] The stakeholders are referred using codes given in Table 1 and the anonymised interview list in the Supplementary Material.

[3] The expert-reviewed SFD reports for the cities are available for free in the SFD portal at www.sfd.susana.org.

It is useful to note that these cities are representative of 'Class IA with population over one million', which account for a third of the urban population in India. However, there are several cities and small towns in India that are smaller than these four cities, in terms of area and population, where certain aspects of the CWIS approach would still be applicable depending on their specific contexts. The four cities chosen here provide a wider scope to explore various aspects of CWIS, such as the co-existence of a mix of technologies and service models, due to their size and history.

## 4. RESULTS AND DISCUSSION

### 4.1. Analysis of current sanitation planning practices[4]

Urban sanitation planning in India has largely gained prominence only since the introduction of the National Urban Sanitation Policy (NUSP) in 2008, which specifically highlighted the use of the City Sanitation Plan (CSP) process (GoI 2008). This CSP process is a comprehensive planning approach that is cross-sectoral and aims to be a key document for city managers in all aspects covering environmental sanitation (including water supply, solid waste and storm water drainage) (GIZ 2016). In many ways, the NUSP and the CSP have been forward-looking and are well aligned with most of the CWIS principles (Workshop 4). Despite this, over 80% of the interviewees agree that the policy has fallen short in delivering the impact it promised.

Based on the responses mentioned by the interviewees and workshop participants, the major themes were grouped, and the top eight are highlighted in Figure 1. See Supplementary Material for all the 27 identified themes with their detailed meaning. These themes are highly interrelated and have direct influences between each other. 1. For example, lack of political and financial support are critical reasons for poor planning capacities and dependency on sanitation-related schemes. Similarly, the lack of coordination and community involvement could have a significant effect on ownership.

#### 4.1.1. Lack of planning capacity (35 respondents)

'*Most cities in India have limited capacities to plan for safe sanitation*' is a statement that was often heard throughout most interviews (ACD14, NGV06, SGV17, NRW05, IDA05). Since city governments do not have the adequate human capacity themselves to systematically plan sanitation, this work is outsourced to external consultants. Often, these consultants themselves lack technical capacities for comprehensive CWIS planning, which not only includes engineering skills including estimating quantities and qualities of faecal sludge to design collection systems and treatment plants, but also social science skills such as community engagement and gender-sensitive planning (NRW11, PVT04). The consultants to whom the entire mandate is shifted onto are given little time and resources to understand the context, which leads them reproduce 'template solutions' from other cities (IDA05, Workshop 4). New capacity building initiatives geared towards CWIS have started with national and international support (Dash & Kapur 2021).

**Table 2** | Key facts regarding the case study locations and their sanitation status

| City | State | Population (in millions) | Swachh Survekshan Rank 2019 | % of population using Safely Managed Sanitation | % of population using Sewered Sanitation | No. of interviewees |
|---|---|---|---|---|---|---|
| Chennai | Tamil Nadu | 10.5 | 61 | 62 | 42 | 14 |
| Coimbatore | Tamil Nadu | 1.6 | 40 | 76 | 34 | 12 |
| Bangalore | Karnataka | 12 | 194 | 52 | 84 | 10 |
| Mysore | Karnataka | 1.5 | 3 | 72 | 82 | 8 |

[4] All results obtained from interviews, workshops, document analysis and scholarly literature are clearly cited as such. The results from interviews are corroborated in at least three instances before being picked or come from highly reliable sources. Those results that are not cited are to be seen as inferences from the aforementioned sources.

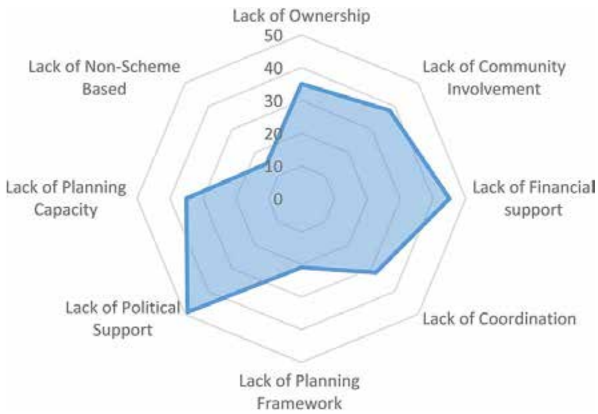


**Figure 1** | Key barriers to sanitation planning in India as stated in interviews are depicted in no particular order. The radial axis indicates the number of experts who mentioned the respective factors in the interviews.

#### 4.1.2. Lack of non-scheme-based approach (15 respondents)

'*CSPs were scheme based; with the introduction of new national urban schemes (called "AMRUT" and "Smart Cities Mission"), we moved to a different template*' (SGV13). Sanitation is tied closely to the interests of the national schemes which are pegged onto changing political priorities, rather than the actual needs of the cities (ACD12, Chaplin 1999; Jain *et al.* 2020). With the advent of the SBM and AMRUT schemes, the planning format was changed from CSPs to detailed project reports of sanitation infrastructure (GoTN 2017). This meant that key aspects of CWIS and the NUSP were diluted with the omission of equity, sustainability and accountability factors. The funding tied to other urban development schemes, including the Smart Cities Mission, did not request submission of the old format CSPs (Workshop 4).

#### 4.1.3. Lack of planning framework (21 respondents)

'*There is no uniform framework to plan sanitation in India*' (NGV02). Although there was international support for the creation of the CSP process which led to the development of toolkits and guidance material (GIZ 2016), its uptake at the local level has been poor (Workshop 4). Different cities follow different sanitation planning methodologies or the lack thereof, which results in ineffective implementation and misinterpretation of sanitation targets set by the NUSP (ACD13, PVT06). Two-thirds of all national-level interviewees and 80% of all international development representatives agreed that this was of high importance. The lack of a targeted planning framework potentially has spill-over effects on other aspects such as ownership, coordination and community involvement (Workshop 4).

#### 4.1.4. Lack of ownership (35 respondents)

'*How do you expect municipalities to have ownership of a checklist document that they did not prepare by themselves?*' (NRW05). Respondents mentioned that CSPs were widely regarded merely as the checklist document and that city governments are required to submit in order to apply for national funding schemes. Furthermore, CSPs were mandated as part of the NUSP by the national government and did not have the complete buy-in from cities and states (ACD13, IDA02). Constitutionally sanitation is a state subject (Cullet & Bhullar 2015), but the national government provides the majority of funding, announces sanitation schemes, drafts policies, sets standards and regulations, and controls the narrative, thereby preventing states to freely execute their own governance mechanisms (Workshop 1).[5] This disconnect between national agenda, state's mandate and the implementation at the city level, in addition to planning carried out by external consultants instead of local authorities, causes a lack of ownership at the local level.

[5] The national benchmarking schemes and the Swachh Survekshan ranking systems are, however, reported to boost healthy competition, thereby creating a positive effect on the annual performance of cities in terms of provision of safely managed sanitation.

#### 4.1.5. Lack of coordination (32 respondents)

'*To build a sewer, we need to coordinate between 11 different governmental departments*' (SGV11). Apart from the aforementioned disconnect in levels of the government, there is also the challenge of institutional coordination to plan and implement sanitation solutions. Previous research shows that there is inadequate flow of information between 10 relevant agencies for the governance of small-scale sanitation in the four selected Indian cities (Narayan *et al.* 2020). The overlapping jurisdictions of multiple agencies that are responsible for different aspects of the sanitation service chain create bureaucratic silos that present a barrier to implement solutions quickly and easily (Workshop 3). The regular transferring of bureaucrats between various governmental departments (outside of the water sector) leads to a lack of continuity and poor institutional memory (Raman 2020).

#### 4.1.6. Lack of financial support (45 respondents)

'*NUSP was not directly tied to any financial schemes*' (PVT06). Although CSPs were required for the application of funding from national schemes, there were no exclusive financial resources for the sanitation planning process itself, leaving the cash-tight city governments to solely invest in the planning process (SGV15). Given that little time and money are available for the planning process even in mega cities, sanitation often fares low among competing urban priorities (Workshop 2). Adequate ring-fenced financial and human resources must be budgeted for the planning process, and this must be provided regardless of the schemes, in order for it to be comprehensive.

#### 4.1.7. Lack of political support (49 respondents)

'*Sanitation planning requires political support*' (NRW01). Political will at all levels is required for effective sanitation planning, since the process is costly, time consuming and is asynchronous with the election cycles (Chaplin 1999; Hueso & Bell 2013). Competing priorities include solid waste management and water supply (SGV11). Even at the local level, the ward councillors rely on these competing priorities to sway the vote bank (NRW05).

#### 4.1.8. Lack of community involvement (38 respondents)

'*Swachh Bharat Mission is a jan andolan (people's movement)*' (NGV06). Community involvement allows for the incorporation of local knowledge and increases the acceptance of the solutions from the beneficiaries, which is critical for long-term success, especially in low-income communities (McGranahan & Mitlin 2016). However, community consultation at the ward level is given little importance and often follows technocratic decisions which are based on limited criteria that are not validated by the local residents (ACD01, PVT06).

### 4.2. Analysing differences in responses

While there was large agreement in the results, a number of differences in the elicited response were identified between the key informants grouped by the type of stakeholder, where they were from and their affiliation level (national, state and city) (see Supplementary Material for details).

The mega cities – Chennai and Bangalore – have separate utilities that are mandated with sanitation provision and have at least 10 times more skilled labour in their force than their secondary city counterparts. They also follow a much more top-down approach with little community involvement (Workshop 2); this leads to increased reported ownership from the utility managers (SGV01, SGV02, SGV06 and SGV10). Furthermore, non-sewered solutions are seen as interim, and all state and city governmental stakeholders clearly indicated sewer-aspirations. '*Chennai will have 100% sewerage. FSM is only a stopgap measure for us*' (SGV06). The state government's vision document and action plan for central funding corroborates this (GoTN 2017). In the case of the secondary cities, Coimbatore and Mysore, there is a more long-term vision of multiple solutions co-existing in these urbanising cities. The governmental stakeholders in these cities are cognizant of their limited planning capacities and rely on parastatal organisations for this purpose. Interestingly, community participation through direct consultations and the involvement of NGOs are reported to be better in these smaller cities (Narayan *et al.* 2020).

There is a clear difference in perception and vision for urban sanitation between the national-, state- and city-level stakeholders. National stakeholders strongly emphasise the importance of community participation and underscore the state's own financial contribution to the success of sanitation interventions (NGV05, NGV04). The state-level stakeholders on the other hand make little reference to community involvement and refer to national schemes as the main source of urban infrastructure funding (SGV17, NRW05). The city-level stakeholders report that community involvement is a tedious process for which they have little time, and most of their capacities are utilised in urgently fixing the broken pipes (SGV10, SGV14, ACD05).

The stakeholder types also reflect in the priority reasons highlighted for causing failure in sanitation planning. Academic stakeholders predominantly stated the lack of a uniform planning framework and community participation. NGOs and resident associations also agreed on the latter and added the need for financial support for sanitation planning. Stakeholders from private companies reported a lack of inter-agency coordination and a scheme-based approach as the main barriers. Inadequate community participation and a lack of planning frameworks were the main issues highlighted by international development agencies. Finally, all levels of government interviewees concurred that poor capacities and complexity in coordination within the governmental departments were their main hurdles for effective sanitation planning. Almost all interviews and workshops without prompting arrived at the conclusion that political and financial support is essential for comprehensive planning for CWIS.

## 5. FURTHER DISCUSSION USING THE CWIS PLANNING FRAMEWORK

The results clearly show systematic barriers to sanitation planning in India, among which the lack of a planning framework is highlighted. This section justifies the need for a new approach and introduces the CWIS planning framework. Furthermore, a discussion of CWIS planning in India is made in light of the framework, where it offers a perspective to overcome the aforementioned barriers.

### 5.1. Introduction to the CWIS planning framework

With the advent of the CWIS approach, which views sanitation as a holistic service and puts equity, safety and sustainability in focus, planning sanitation interventions according to its principles need to be more comprehensive (Schrecongost *et al.* 2020). Currently, there are no planning frameworks that have been exclusively developed, or existing frameworks adapted to meet this promising yet, complex mandate. Several sanitation planning theories and frameworks have been developed in the past, right from the 'Strategic Sanitation Approach' (Kalbermatten *et al.* 1980) that led to top-down planning approaches such as 'Sanitation 21' (Parkinson *et al.* 2014) to bottom-up approaches such as 'CLUES' and 'U-CLTS' (Lüthi *et al.* 2011; Myers *et al.* 2018). While it would be useful to adapt existing planning frameworks for CWIS, a theoretical basis for CWIS planning is necessary to test their performance in terms of the outcome of the plans and the planning process itself.

Debates on the appropriate approach for planning urban sanitation in LMICs continue to exist between top-down technocratic planning (Schmitt *et al.* 2017; Mara 2018) and bottom-up communicative planning (McGranahan & Mitlin 2016; Narayanan *et al.* 2017). Since CWIS planning needs to be comprehensive, for example, it needs both community involvement (characteristic of bottom-up approaches) and inter-agency coordination (characteristic of top-down approach), it would benefit from the bridging of top-down and bottom-up planning approaches. But such a bridged approach is not available in the current sanitation planning landscape.

The proposed CWIS planning framework aims to set the theoretical basis for contextualised and procedural CWIS planning. It places the bridging of top-down and bottom-up approaches as a centre-piece. The framework is based on the largely agreed Manila principles (Narayan & Luthi 2020). Since the justification and explanation of the CWIS approach is already covered in detail in previous research (Lüthi & Narayan 2018; Gambrill *et al.* 2020; Schrecongost *et al.* 2020), this paper will directly use the elements of the principles in explaining the planning framework.

It is important to note that this planning framework does not prescribe any procedural steps at this stage, since such a generic methodology requires empirical evidence from various contexts. Therefore, this paper introduces the framework, which will then help further research on developing contextualised methodologies for CWIS planning, which has been identified as one of the key reasons for the failure of sanitation planning in India.

The CWIS Planning Framework (Figure 2) places comprehensive planning at the centre, surrounded by four operational outcomes that are directly borrowed from the Manila principles on CWIS: (i) Public Health, (ii) Environmental Health, (iii) Mix of Technologies and (iv) Mix of Business Models. The following functional linkages are seen to connect these outcomes appropriately:

1. Safety links (i) and (iii), since it is achieved only when the entire value chain is managed while ensuring public and environmental health.
2. Sustainability links (ii) and (iii), since sanitation systems must sustain from both the environmental and financial perspectives. Mix of technologies allows for contextual and incremental improvements offering financial viability. Environmental health outcomes directly impact environmental sustainability.

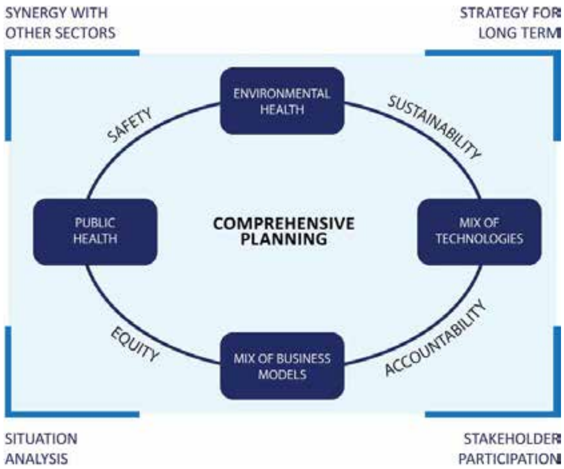


**Figure 2** | CWIS planning framework.

3. Accountability links (iii) and (iv), since a mix of technologies and business models inherently increase operational and governance complexity. Therefore, clear accountability mechanisms enhance the long-term functionality of a mix of sanitation services.
4. Equity links (iv) and (i), since equitable sanitation means everyone in the city receives equal public health outcomes while enjoying equal quality and affordability of sanitation services from any operating business model.

These operational outcomes and functional linkages are supplemented with the conceptualised four 'S' pillars (4S) of comprehensive planning: (1) Situation analysis, (2) Stakeholder participation, (3) Synergies with other sectors and (4) Strategy for the long term. These 4S pillars emerged from the aim of bridging top-down and bottom-up approaches. While top-down approaches provide the advantages of exploring synergies with other public services and strategies for the long term, bottom-up approaches encourage detailed situational analysis through co-production of knowledge and meaningful stakeholder participation.

The CWIS planning framework is useful when designing CWIS projects, in order to highlight key aspects of the CWIS concept; the operational outcomes serve as the targets to operationalise, and the functional linkages serve as the essentials of the approach. The operationalisation of targets must be context-specific and incremental. The outcomes of environmental health and public health must follow the respective jurisdiction's standards, and the mix of technologies and business models must be set according to the needs of the particular city/neighbourhood. The functional linkages on the other hand allow the design of the enabling environment of sanitation systems; for example, the tariff structure for the services are set equitably with subsidies for the poor, or that the institutional mandates are clarified so that there is clear accountability for service provision.

The 4S pillars serve as the cross-cutting steps to consider during the CWIS planning process. The process must begin bottom-up with (1) situational analysis, which helps set operational targets for CWIS and then (2) closely engage community and stakeholders throughout the planning process. The top-down approach ensures that there is strong will from the public sector which helps foster coordination between various institutions to (3) plan for the long term and (4) synergise with other related urban services such as water supply, solid waste management, stormwater drains and slum redevelopment.

In the CWIS Planning Framework, the operational outcomes and functional linkages are aspects that are to be used in prospective planning to set targets and outcomes. Whereas the 4S pillars of comprehensive planning could be used to (1) formulate planning methodologies and (2) analyse sanitation planning practices retrospectively and propose ways forward, such as in this paper for the Indian context.

The proposed planning framework clearly sets out the objectives of sanitation planning that is in line with the latest development in the urban sanitation sector, i.e., the CWIS principles. CSPs, on the other hand, lacked the full scope of CWIS and missed operationalising the principles of equity and mix of business models. CSPs were completely procedural and lacked a theoretical framework that could be customised to the contextual needs. The CWIS Planning Framework on the contrary begins with a theoretical backing based on which the procedural methodology could be developed.

### 5.2. Discussion of Indian case using the CWIS planning framework

Prime Minister Narendra Modi stated '*To reach India's sanitation goals, we need 4Ps – Political Leadership, Public Funding, Partnerships and People's Participation*'. There is a need for a fifth 'P' – Planning. In order to achieve the operational outcomes and functional linkages of CWIS in India, comprehensive planning is necessary. Based on the 4S pillars provided in the CWIS Planning Framework (Figure 2) and the qualitative analysis of this study (Results and Discussion), overarching ways forward to overcome these barriers are identified and provided below as recommendations.

#### 5.2.1. Situational analysis

There is a lack of planning capacity in terms of human or financial resources allocated for analysing the local situation and its unique context. This requires a systematic methodology that places situational analysis as an initial step. Such detailed information helps create advocacy for political will and community acceptance. Tools that aid in analysing the local context greatly reduce the time and money otherwise spent at this stage, and support the existing capacities for planning (Schertenleib *et al.* 2021). Bottom-up sanitation planning practices, in particular, have been proven to generate detailed knowledge on the local context through co-production in India (Narayanan *et al.* 2017). Situational analysis also provides the data which forms the basis for setting targets for the operational outcomes for CWIS. However, in order to conduct detailed analysis, targeted capacity development programmes for public sector workers and private consultants are key (Dash & Kapur 2021). Overall, these steps help overcome the barriers of community participation, political will and planning capacities.

#### 5.2.2. Stakeholder participation

Community and stakeholder participation were mentioned by more than half of the respondents as a crucial aspect of successful planning since it allows the incorporation of local knowledge and acceptance. However, most interviewed community-based organisations did not report meaningful participation as common practice. The few cases that reported close involvement in sanitation planning were NGOs in the secondary cities of Coimbatore and Mysore, where the sanitation situation is also seen to be faring better (Table 2). Sanitary workers, who are a primary stakeholder, are almost always excluded from planning, which leads to inequitable decisions having detrimental effects for social, public and environmental health (Sharada Prasad & Ray 2019).

Community-based organisations have already been recognised as a catalyst in bringing various stakeholders together and nationally recommended in India through policy documents (UMC 2019). However, a planning approach that clearly emphasises this, such as the CSP's city sanitation task force, needs to be implemented in spirit and not merely remain a checklist item. Furthermore, social specialists and institutional special purpose vehicles[6] are required to coordinate and build consensus during such a stakeholder intensive planning process. This step helps enhance ownership, community involvement, and political will since it directly engages the public, thereby making sanitation a high visibility issue.

#### 5.2.3. Synergy with other sectors

One of the reasons for poor coordination is the jurisdictional overlap between various agencies, which happens because of the cross-cutting nature of sanitation. Coordination is required horizontally; within the sanitation service chain, for example, training masons to use the standardised septic tank designs or planning monitoring mechanisms to ensure that the private vacuum truck operators dispose faecal waste only at the treatment sites (Sharada Prasad & Ray 2019; Dash & Kapur 2021). Coordination vertically with other basic services such as water supply, storm water and solid waste management would also be pertinent for achieving safe sanitation (Scott *et al.* 2019; Narayan *et al.* 2021). For example, planning flush toilets in areas with intermittent water supply or designing small-bore sewers in areas with poor solid waste management will hinder the functionality of the sanitation systems. The NUSP already highlights collaborative planning with the aforementioned sectors and should be brought to practice (GoI 2008). Stakeholders from the National Government reported that such an approach could benefit from lesser financial needs due to the gains of synergistic planning, opportunity to tap funds from varying sources and receive higher priority in fund allocation. However, further research is needed to provide evidence for the gains from such synergistic planning. While the planning process is encouraged to be integrated, the implementation could still function as per the existing institutional set-up as long as the coordination is strengthened. Integrated planning reduces the number of interfaces for the stakeholders, but increases the planning complexity and need for

[6] A governmental multi-institution coordination agency working towards a specific, clearly defined purpose. This is popularly used in the Indian government.

policy changes geared towards planning CWIS. Through this step, the barriers of coordination and financial support could be overcome.

#### 5.2.4. Strategy for the long term

Although political support was mentioned as a crucial factor, sanitation planning has to take a longer term view compared to the 5-year election cycles in India. Respondents who mentioned a scheme-based approach as a barrier pointed out to short-term political vision as a reason for a lack of planning incremental sanitation and a lack of institutional strengthening in the sector. Scheme-based setting of targets and financing could be beneficial for a mission mode of operation, such as the SBM which set the goal of eliminating open defaecation. However, schemes have tunnel vision, and in the past, total sanitation schemes in India have fizzled out at the onset of competing priorities (Hueso & Bell 2013). Even SBM fell short in managing the other parts of the sanitation service chain, since it focussed only on the construction of toilets (Kumar 2017). CWIS requires planning clear accountability mechanisms, a service model that considers an optimal mix of technologies, and private sector partnerships which, in turn, enhance financial sustainability. CWIS plans based on the above framework must be flexible to address emerging social and natural issues such as equity and climate change, in order to remain relevant despite changes in political priorities. By strategizing for the long term and being flexible, the barriers of a scheme-based approach could be overcome and potentially gain political support since planning traverses political timelines.

## 6. CONCLUSION

In the last decade, the Indian sanitation sector has witnessed an evolution with progressive policies, national-level funding, political support and the world's largest sanitation campaign. In spite of these and a national urban sanitation policy mandating local authorities to prepare city sanitation plan, urban sanitation systems are generally poorly planned. With the advent of CWIS, multiple targets are explicitly placed for operational outcomes and functional linkages, which require comprehensive planning that bridges top-down and bottom-up approaches. Although CWIS is widely accepted as the way forward towards achieving the urban sanitation SDGs, the complexity of planning CWIS in India remains to be a challenge.

This paper has identified several key barriers to sanitation planning in India that stem from a fundamental lack of priority given to it at the national, state and city levels. Through the case study approach, it is found that a lack of a framework among others impedes sanitation planning. Furthermore, the secondary cities where community involvement is higher have better sanitation outcomes than mega cities where this is absent. Political support for comprehensive planning and adequate ring-fenced financial and human resources for the planning process are major recommendations. Other reforms are the development of planning capacities in local governments through large-scale training programmes and improving inter-agency coordination through stronger institutional mechanisms.

The new CWIS Planning Framework brings together the Manila principles and provides a theoretical basis for planning CWIS. But, this needs to be followed with the development of a clear step-wise methodology that has scope to be contextualised to local needs, and yet serves as a generic CWIS planning approach. Further empirical research on diverse contexts is required for the conceptualisation of such a planning methodology. The 4S pillars of comprehensive planning propose the fundamental elements for the aforementioned approach towards planning CWIS.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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# Wastewater Discharge Standards in the Evolving Context of Urban Sustainability–The Case of India

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Across the world, recent decades have witnessed large scale and rapid urbanization. Centralized wastewater treatment is typically considered the most desirable solution to meet domestic wastewater treatment needs in growing urban centers. These rely on extensive—and often expensive—infrastructure and treatment solutions that require expert engineering management to ensure effective operation. It is argued that the urban sustainability challenge of inadequate sanitation, deteriorating water quality, and rising water stress are best met through poly-centric and integrated approaches that include nature-based solutions, community-scale and community-managed systems. Today's objectives are to create climate-resilient, enduring, self-governing systems—as well as systems that close the loop, encouraging resource re-use and recycling. This policy review informs on wastewater discharge (and related) standards for sewage treatment plants within the context of present-day India. With its booming urban population, highly visible and impactful pollution, water quality and insecurity challenges, India provides huge opportunities for creative approaches to urban sanitation—but to fully exploit these opportunities will require new policy and regulatory thinking. The current regulatory developments are undergoing frequent changes with observed inconsistencies over the last years leading to a growing confusion in the sector. Examined questions include: How clear are policy objectives and regulations? What are reasons for observed inconsistencies in current pollution control regulations and what are their implications? How well-aligned are standards and regulation with these objectives? How forward-looking? Are solutions sufficiently responsive to the urban sustainability challenge? In particular, this review considers whether regulatory approaches disadvantage decentralized and innovative approaches that could offer resilient, community-based systems—even within the megacities of the twenty-first century. This study further draws on examples from other emerging economies—and contextualizes these examples with the situation in Western Europe, where a single set of targets has let to diverse solutions. Standards and regulations need to be reimagined for this evolving urban context which might require it to become more nuanced, more holistic, more dynamic, more transparent, more participative, and more contextual. Enforcement mechanisms will need to incorporate phased/graded approaches to compliance—to suit various contexts that could include water reuse for different application areas.

**Keywords: wastewater standards, reuse, sustainable sanitation, regulation, policy, decentralized integrated management, nature-based, India**

## INTRODUCTION

Globally water management systems are facing enormous challenges of accelerating water insecurity, flooding, and contamination of water resources. According to the UN 80% of sewage is currently discharged without treatment [UN WWAP (United Nations World Water Assessment Programme), 2017].

The lack of adequate sanitation infrastructure contaminates the environment and permeates through all societal functions increasing the burden on human health, which in turn leads to loss of economic activity and thus the overall development potential. The UN indicates that for every USD spent on sanitation, the estimated returning benefit to society accounts in 5.5 USD [UN WWAP (United Nations World Water Assessment Programme), 2017].

Feasible and financially viable wastewater treatment still represents a significant challenge in the Global South, particularly within a rapidly changing urban environment. It is increasingly recognized that the ideal of the "networked city" fails to address current SDG goals of the wastewater sector and is inadequate for the difficulties and reality of the Global South (MoUD, 2008; Massoud et al., 2009; Libralato et al., 2011; Larsen and Gujer, 2013). Innovative approaches and technologies are required, which enable the overall concept of sustainability in terms of economic feasibility, social equity and acceptance, technical and institutional applicability, environmental protection, and resource recovery—in addition to the central objective of protecting human health and environment (Balkema et al., 2002; MoUD, 2008; Molinos-Senante et al., 2010, 2015; Ganoulis, 2012; Wichelns et al., 2015; Ricart et al., 2019).

With the shifting paradigm from "waste"water treatment to resource recovery systems, the sanitation sector, among a few others, holds the most prospering potential in change toward a sustainability transition (Binz et al., 2012; UN WWAP (United Nations World Water Assessment Programme), 2017; Van Welie and Romijn, 2018; Van Welie et al., 2018). However, the transition faces considerable hurdles and requires changes along all levels, including regimes, landscapes and niches (Markard et al., 2012; Swilling and Annecke, 2012; Lachmann, 2013). While industrialized nations are dealing with the challenge of lock-in mechanisms due to historic investments in established centralized infrastructure and routines formed a passive involvement of society and consumer roles, the main challenge in the Global South remains the establishment of overall access to sanitary systems. This situation provides significant opportunities for emerging economies to leapfrog and establish new alternatives and more sustainable approaches to sanitation that address all dimensions of sustainability.

Decentralized and ecological systems can play a crucial role in delivering this new reality, since they represent comparatively more economically affordable and ecologically sustainable options, which are socially accepted and require low maintenance (Parkinson and Tayler, 2003; Massoud et al., 2009; Libralato et al., 2011; Larsen and Gujer, 2013). However, full and appropriate exploitation of these systems requires regulatory institutions to overcome historical barriers and create an enabling environment to open windows of opportunity.

In India wastewater treatment, especially in booming urban centers, continues to be a big challenge. While the Central Pollution Control Board (CPCB) reported in 2013 that 19,827 MLD out of 53,998 MLD generated were treated in metropolitan, class one and class two cities, it further indicates in 2017 that out of 18.6% of total treatment capacity, only 13.5% of sewage is effectively treated (CPCB, 2013 and CPCB, 2017c). Although the impact of diarrhea has decreased over last years, it still belongs to the five major health burden in India. The disease burden or Disability Adjusted Life Year (DALY) rate for diarrheal diseases, iron-deficiency anemia and tuberculosis was 2.5 to 3.5 times higher compared to global rates and countries with similar geographies (Indian Council for Medical Research, 2017). Alongside the given challenges, more than half the country faces high to extremely high water-stress, and future projections paint an even grimmer water availability scenario (MoWR, 2017; WBSCD, 2019). An integrated view of the wastewater and water supply sectors is not optional but an urgent imperative.

Recognizing these urgent pressures, several jurisdictions within India have established reuse policies and Zero Liquid Discharge regulations. However, implementing these initiatives is currently challenging due to national standards for treated wastewater—which undergo frequent change and have ceased to distinguish between wastewater re-use for irrigation and wastewater discharge to surface or ground waters. Furthermore, inconsistencies in approach and objectives between different governmental institutions, variations in policy at a state level and aggravated access to information are resulting in confusion and hesitation within the sector. The intention behind stringent standards in protecting the environment and public health represents a common shared aim between all stakeholders. However, without a long-range planning and reasonable budget allocation, stringent standards can result in pockets of excellence, leaving the majority of the Indian population and environment at high risk. In addition, one fixed set of standards for different application areas can tend to neglect, both the dangers and also the benefits of this resource.

In this paper, the outputs of a broader evidence review based on Indian policies and regulations and complementary interviews with governmental institutions, sectoral experts, and technology providers in India are combined to analyze and understand pollution control measures and approaches that focus on municipal domestic sewage treatment and wastewater reuse. While the first section of the assessment summarizes wastewater risk management approaches, section two reports the findings on the current scenario of wastewater discharge standards for sewage treatment plants in India and discusses the feasibility and possible implications. Although focused on the current situation in India, a comparative analysis in section three presents examples of institutional approaches and structures on discharge and wastewater reuse in other countries. Based on the review, the possible way forward for India and lessons for other nations of the Global South are suggested.

## ASSESSMENT OF WASTEWATER RISK MANAGEMENT

Within the following the results of the assessment of wastewater risk management in India is presented and discussed. This assessment is built upon three sections to analyze and inform on (a) wastewater risk management approaches with special focus on wastewater reuse, (b) wastewater risk management and related wastewater discharge standards for sewage treatment plants (STPs) in India over time, and (c) wastewater discharge and reuse standards from other countries.

### Methodology

Wastewater risk management approaches, central governmental policies and acts in the scope of wastewater risk management, sanitation, and water management in India have been identified through literature review based on government databases and website research. The Karnataka State policy on urban wastewater reuse was identified through website research and considered as reference for a comparative to central regulations.

Central governmental regulations for pollution control measures in the wastewater sector in India were identified through literature review based on governmental databases and website research. All historically applicable wastewater discharge standards for STPs in India were considered for the assessment.

International regulations on wastewater discharge and reuse standards were informed by representatives of the multinational (EU-funded) INNOQUA-Project with a further extended literature review based on website research. The range of selected countries for assessment was based on the development status, climatic conditions and water insecurity status in order to allow a broad overview and comparative relative to local conditions or limiting factors.

Qualitative interviews with former and present governmental officials at central and state level in India were carried out in order to access printed materials and missing information on (a) the standards setting process, (b) the applicability of wastewater discharge and reuse standards and related norms due to observed inconsistencies during the assessment process, (c) the reasons for observed changes of standards over the years and related inconsistencies in applied and recommended measures among governmental institutions at central level and central-state level, and (d) investment and development plans in the wastewater sector.

Literature review based on website research and complementary qualitative interviews with governmental officials, sectoral experts, and technology providers have been carried out in order to allow a broader perspective for the discussion on the feasibility of discharge and reuse standards and possible implications of recent observed developments in pollution control management in India.

### Wastewater Risk Management Approaches

In the modern era, Britain was among the first nations to address environmental conditions of water bodies in its cities and plays a vital role due to historical regulations in India. The need for coordinated action in Britain was formed as response to growing industrialization, which lead to untreated effluents being discharged into water bodies and breaching their intrinsic carrying capacity. This created human health and environmental crises that are still a common occurrence in rapidly-urbanizing centers of the Global South (Lens et al., 2001). Whilst the initial response to these crises was to assume that "the solution to pollution is dilution," it was soon recognized that sewage treatment would be required. The Royal Commission on Sewage Disposal (which convened between 1898 and 1915) led to the formulation of the first standards for Biochemical Oxygen Demand (BOD) and suspended solids (TSS) in treated wastewater—at 20 and 30 mg/l, respectively. These standards remained in place for several decades, eventually being superseded by the Water Act of 1973 and the Urban Waste Water Treatment Directive at a European level (Johnstone and Horan, 1996). Britain has never set regulatory standards for water re-use, unlike a number of other nations of the Global North. However, regional demographic pressures coupled with changing patterns of precipitation mean that this is set to change. This section summarizes the conceptual underpinnings of wastewater risk management.

#### Wastewater Discharge Standards

Wastewater discharge standards are set (at least) at a national level for centralized treatment systems for salient receiving environments. The key feature of a water body from a discharge perspective is its assimilative capacity i.e., maximum amount of pollution that can be diluted or degraded without affecting preliminary defined designated best uses. Effluent discharge standards can be concentration-based or load-based. Concentration-based standards are the most common and specify a permissible mass of pollutant per liter. A limitation of concentration-based standards can be that it does not promote wastewater treatment, since dilution can be used to meet the discharge standard. The original standards developed in Britain were concentration-based—although those standards assumed a minimum 8-fold dilution in the receiving water body. Most countries in the Global South have adopted discharge standards from the Global North and they have not been developed for their local context.

Load-based standards, as applied in the US, harmonize concepts of ambient water quality and effluent discharge through risk modeling of the water body. The Total Maximum Daily Load (TMDL) allocates the threshold value for a pollutant that will ensure compliance with a desired water quality standard based on stakeholder preference for the use of that water body. Criteria for the prevention of (eco)toxicity are based on both short term and long-term effects. States calculate TMDL for their water bodies based on monitoring evidence and water quality modeling. TMDL is used to issue permits to discharge in the catchment, and risk modeling encompasses variations in flow—from the lowest daily flow occurring once every 10 years (for acute effects) and once every 10 years averaged over a 7-consecutive-day period (for chronic effects) (National Research Council, 2001; US EPA, 2020).

Different countries base their standards on various characteristics of treated wastewater—although BOD is almost universally used. A snapshot of regulated parameters across countries is illustrated in **Figure 1**, which also shows that discharge limits are most commonly set on the basis of organic pollutants and nutrients.

Once the desired discharge standard is fixed, the choice of technology is determined by the desired quality of treated wastewater, and two principle approaches to technology selection have been delineated in the literature: Best Available Technology (BAT) and Best Practicable Technology (BPT). Either approach works in tandem with a discharge standard. BAT is the dominant paradigm in the Global North where treatment technology costs are more affordable. BPT is followed in the Global South where the contextual factors must be considered. The economic and behavioral aspects of risk are considered using the "As Low as Reasonably Achievable" (ALARA) principle, which delimits the risk management envelope ("BPT plus") (CPCB, 2009).

## Wastewater Reuse Approaches

Water is a finite resource with significant variations in spatial and temporal availability. This, and changing climate, are making a strong case for reuse of wastewater for specific applications. Wastewater contains valuable nutrients such as Nitrogen and Phosphorus, essential for plant growth, and further represents a resource for energy recovery. The increasing scarcity of phosphorus in conjunction with land degradation (which is a plant macronutrient and thus plays a major role in food security), paired with the fact that abstraction for agricultural use accounts for 70% of total water withdrawal, makes wastewater a lucrative resource for irrigation (Cordell et al., 2009; FAO - Aquastat, 2016).

However, depending on its source, wastewater carries a broad variety of impurities—which can be toxic, pathogenic, and inhibitory to public health and can harm the environment. In order to achieve maximum beneficial re-use, the extent of wastewater treatment depends on specific reuse applications and their associated characteristics/risks. There are two major categories for wastewater reuse: (a) potable uses and (b) non-potable uses such as: irrigation in agriculture; industrial reuse (e.g., water cooling); aquifer recharge and other urban reuses such as toilet flushing, subway washing, coach cleaning, ground cooling, or building construction. Two major approaches to address risks associated with wastewater re-use were developed

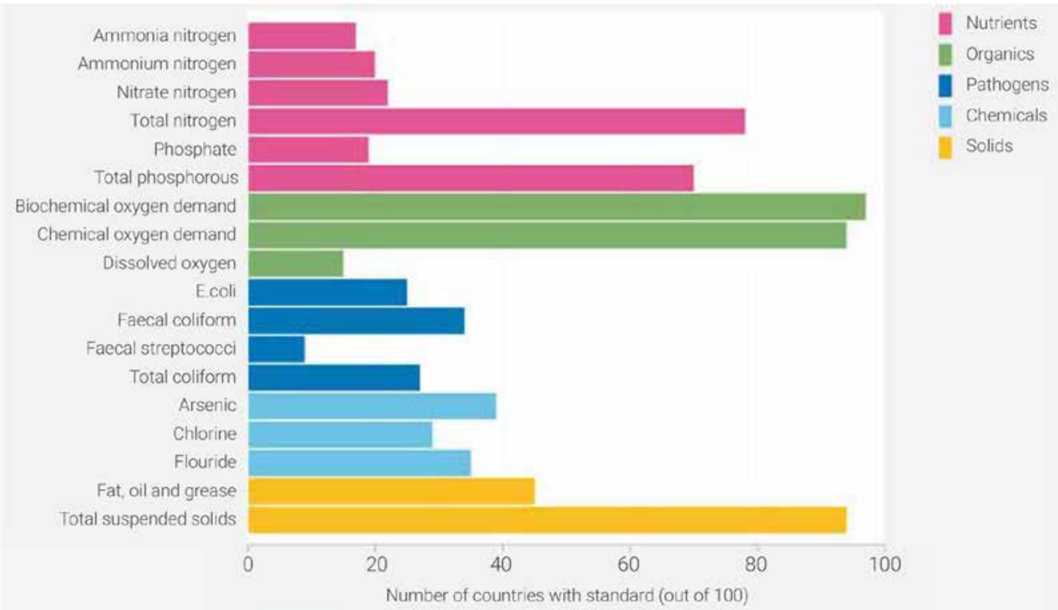


**FIGURE 1 |** National discharge standards of 100 countries (WHO, 2017b).

by the United States Environmental Protection Agency (US EPA) and the World Health Organization.

*USEPA's single barrier approach to reuse risk management*
USEPA follows the no risk approach for setting standards, and consequently adopts comparatively strict limits (US EPA, 2012) with recommendations on technology design to achieve these in the effluent or so-called "single barrier." WHO adherents critique the USEPA standards as impossible to achieve in developing countries, as technological solutions for the specified limits are highly cost intensive. Within the updated guidelines, the USEPA (2012) responded that these standards had evolved over a history of investment and capacity building and were not suitable for the Global South.

*WHO's multiple barrier approach to reuse risk management*
The WHO approach is characterized by: (a) the definition of a maximum tolerable additional burden of disease; and (b) a multi barrier perspective in impact and risk reduction along the whole chain (including treatment, crop restrictions, access to the public, vulnerable groups, irrigation techniques, and produce handling) (WHO, 2006 and WHO, 2016a). The WHO approach focuses on the need for alternative measures and targets locations where conventional and cost-intensive treatment technologies are economically not feasible. The Multi-Barrier Approach is illustrated in **Figure 2**.

Pathogen elimination along several different measures considered, can play in the range of 1–7 log reduction units, which are displayed according to barriers in the following **Table 1**.

## Risk and Benefits of Wastewater Reuse

An integrated risk-benefit approach to wastewater risk management can address inadequate sanitation, waterbody pollution, and water scarcity. The risks and benefits of wastewater are summarized in **Figure 3** from following subsequently presented characteristics of specific parameters.

*Organic matter*
Total Organic Carbon (TOC), BOD, and Chemical Oxygen Demand (COD) represent indicators to identify the concentration of organic matter (OM) in water. The decomposition of OM can lead to a depletion of oxygen which is crucial for other aquatic organisms. In soil iron or manganese along with organic acids can disrupt the absorption of nutrients (Asano et al., 2007). As a nutritious ground for microbes, OM can cause difficulties in disinfection processes and further affects the color and odor of the water (US EPA, 2012). Excessive amounts of BOD can cause problems for irrigation infrastructure. Low to moderate concentration of OM, however, can be beneficial. The Central Public Health and Environmental Engineering Organization (CPHEEO) recommends in their report in 2013 that 11.0 to 28.0 kg/ha/day of organic loading ($BOD_5$) is required to maintain a static organic matter content in the soil to condition the soil with microorganisms and prevent clogging. However, higher rates are manageable depending upon the system type and resting period. The usage of primary effluent can result in loading rates exceeding 22.0 kg/ha and day but without causing problems.

*Nutrients*
Nutrients which are discharged to an aquatic environment can cause eutrophication, which in turn can lead to high accumulation of dead biomass and by this to depletion of oxygen in water bodies. While nutrients are beneficial for plant growth, they can cause water contamination if applied in excessive amounts and in areas with low groundwater table. Ammonia is harmful to freshwater aquatic life and can interfere with

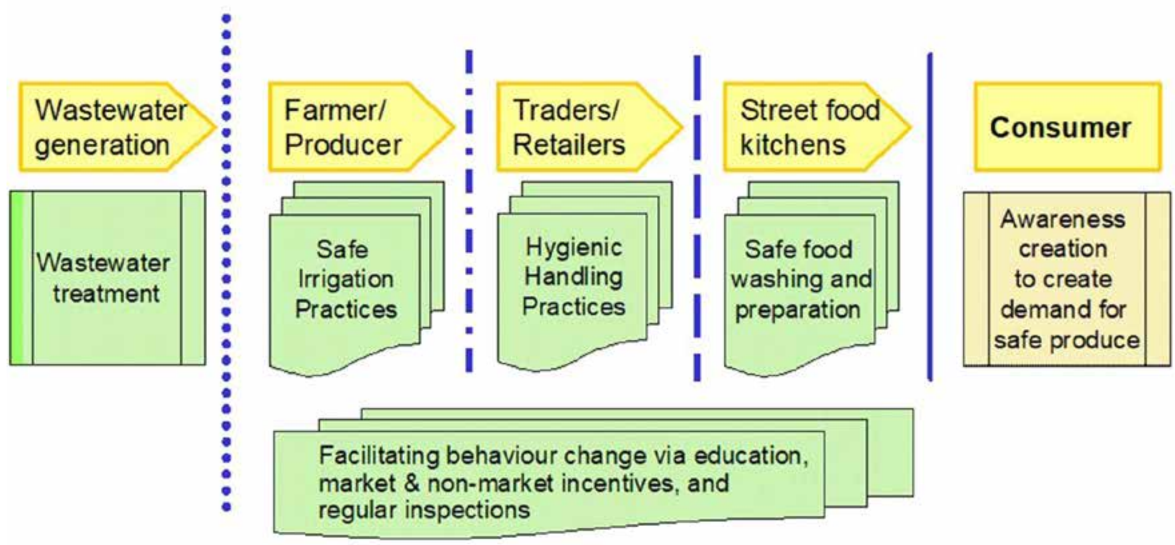


**FIGURE 2 |** Multi-Barrier Approach (Amoah et al., 2011).

**TABLE 1 |** Pathogen reduction along Multi Barrier Approach, modified from Mara et al. (2010).

| Control measures | Pathogen reduction (log units) | Dependence of reduction and options |
|---|---|---|
| **A. Wastewater treatment** | 1–7 | Type and degree of treatment technology |
| **B. On-farm options** | | |
| Crop restriction (i.e., no food crops, raw eaten) | 6–7 | (a) Effectiveness of local enforcement of crop restrictions, and (b) comparative profit margins of the alternative crop(s). |
| On-farm treatment | 0.5–3 | Type and degree of treatment, options can be tree tank system, simple sedimentation, filtration |
| **Method of wastewater application** | | |
| Irrigation method | 1–4 | Method and system, such as furrow - drip irrigation, reduction of splashing |
| Irrigation cessation before harvest | 0.5–2/day | Climate, time, crop type etc. |
| **C. Post-harvest options at local markets** | | |
| Storage and handling | 0.5–3 | Overnight storage in basket, washing crops, removing the outer layer |
| **D. In-kitchen produce preparation options** | | |
| Produce disinfection | 2–7 | Disinfection, produce peeling, cooking |

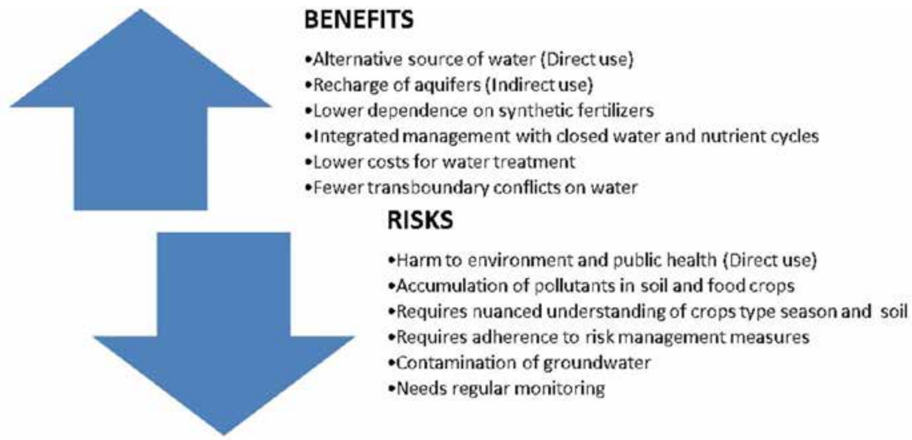


**FIGURE 3 |** Risks and benefits of wastewater reuse.

chlorination processes (US EPA, 2001). Wastewater contains 26–70 mg/l of nitrogen, 9–30 mg/l of phosphorus pentoxide, and 12–40 mg/l of potassium oxide (CPHEEO, 2013). The recommended Nitrogen-Phosphorus-Potassium dose ratio for crops is described as 5:3:2 (CPHEEO, 2013). High levels of total nitrogen concentrations can lead to a decrease in yield production due to lodging, reported especially for application on rice fields (Setter et al., 1997). With a resulting stimulation of algal and bacteria growth, it can further lead to clogging of irrigation infrastructure (Shatanawi and Fayyad, 1996). Application levels as for best practice in agriculture would depend on several factors, such as plant intake ratios, soil type, and groundwater level (WHO, 2006).

### *Solids*

Total Suspended Solids (TSS) and turbidity are measures for particles in a medium, and in excess amounts can lead to clogging of infrastructure and soil, sludge deposition, and by this to anaerobic conditions. Providing a surface area for attachment of microbes, high TSS can be associated with higher microbial contamination. High turbidity levels can further complicate the disinfection processes (US EPA, 2012).

### *pH*

The range of pH affects the solubility and by this also the mobility of metals, which in turn can be absorbed by plants. High levels of alkalinity or acidity have an impact on plant growth and the structure of the soil (WHO, 2006). Wide deviations in the pH can further cause damage to infrastructure.

### *Trace elements and heavy metals*

Heavy metals such as lead or cadmium are usually found in industrial wastewater, which can accumulate in soil and plants and pose high toxicity to livestock or humans (Gupta and Gupta, 1998). While trace elements in specific doses are highly relevant for plant growth, applied in excessive amounts, they can be harmful to crops and may impact the productivity or root growth (Asano et al., 2007).

***Salinity/dissolved inorganics***

Electric conductivity (EC) is used as a parameter to measure the salinity level of a medium. Wastewater contains high levels of salt content. For the application on land via irrigation, this parameter according to the Food and Agriculture Organization (FAO) is considered as one of the most relevant parameters. High salinity can substantially affect plant growth, cause ion toxicity and affect nutrient absorption by plants (Beltran, 1999).

***Pathogens***

Health hazards form one of the main constraints in wastewater reuse and thus, the microbial composition is one of the most important parameters. While pathogens caused vast waves of epidemics in the past, they still constitute a significant health burden in many different countries. Diarrhea as an exemplar, forms the second leading cause of death in children under 5 years and is estimated to cause 485,000 deaths annually (WHO, 2017a, 2019). With restrictions by costs and complexity in analysis, *Escherichia coli* and Fecal Coliforms nowadays still form the major reference indicator for fecal contamination levels in wastewater effluents. However, there are wide debates that the sole quantification of *E. coli* is not sufficient to determine the overall risks in wastewater as some pathogens show higher resistance in disinfection processes (Salgot et al., 2006; WHO, 2016b). The WHO suggests reference indicators covering bacteria, viruses, and protozoa for safe water reuse and drinking water (WHO, 2006, 2011). Further critiques address the difficulty in assessing pathogens in media apart of water and the precision of current risk modeling methods (Salgot et al., 2006; Alcalde-Sanz and Gawlik, 2017). With risk being a function of the microbial agent, the human host and the given environment or application areas, overall risks can differ in a wide range or may not apply according to given local conditions.

## Current Situation of Wastewater Management in India

While wastewater management in India currently faces many challenges, the pollution of rivers and water bodies has come under scrutiny, and their rejuvenation has been subject to much attention. Municipal wastewater has been identified as the chief source of pollution of the Ganga and Yamuna rivers, and the revitalization of these rivers has seen substantial investment over the last several decades (IIT Consortium, 2015; Government of Haryana, 2018). The Central Pollution Control Board has been monitoring water quality in rivers over the last 30 years and uses BOD data to classify river stretches in five priority groups (e.g., stretches where BOD value greater than 30 mg/l is termed "priority 1," while BOD values between 3.1 and 6 mg/l are "priority 5.") (Koshy, 2018). The CPCB observed sharp deterioration in water quality with 71 polluted stretches in 2005 and 375 polluted stretches in 2018 (Koshy, 2018). In September 2018 the Honorable National Green Tribunal (NGT) directed states to constitute a four-member' River Rejuvenation Committee' (RRC) in order to prepare and implement action plans for render polluted river stretches fit for bathing use (National Green Tribunal, 2018). While states have submitted action plans of varying detail, the Hindon River Action Plan, which envisions multi-stakeholder governance management of the Hindon basin till 2030, has been highlighted by CPCB as an example of a comprehensive action plan (State of Uttar Pradesh, 2014; CPCB, 2018a,b; Water Resources Group (WRG), 2018).

With fast depleting fresh and ground water resources, government bodies have also shown interest in centralized reuse of water. In another recent order, the Honorable NGT directed states to submit action plans for utilization of treated wastewater by June 2019 (Press Trust of India (PTI), 2019). In addition to providing a quota for desired applications, reuse action plans are also supposed to include infrastructure augmentation and monitoring plans for reuse (Press Trust of India (PTI), 2019). States including Gujarat and Karnataka have already promulgated reuse policies for some years, but this recent NGT order aims to promote the focused implementation of reuse throughout the whole country.

It is stated that almost half of the wastewater generated in urban India is already being reused [CSE, Bharat lal Seth, (nd)] and most of it is assumed to be reused indirectly and without treatment. Typical reuse applications in India include forestry, horticulture, toilet flushing, industrial use (e.g., non-human contact cooling towers), fish culture, and various indirect uses (CPHEEO, 2013).

### Institutional Structure for Wastewater Management in India

In India pollution control activities are the joint responsibility of three different institutions: The Ministry of Environment Forest and Climate Change (MoEF&CC), the Ministry of Housing and Urban Affairs (MoHUA), and the recently formed Ministry of Jal Shakti. The MoEF&CC is the nodal agency and together with the Central Pollution Control Board these bodies are responsible for laying down policies, acts and related standards. **Table 2** below lists key institutions with related mandates, subunits, and functions.

With water as a precious resource and wastewater as a major pillar of societal infrastructure, wastewater management necessitates inclusion of various disciplines and perspectives. It is observed that other critical sectors such as public health and agriculture do not play an explicit role. While public health is represented indirectly through the MoHUA, the importance of public health and increasing reuse patterns is significant. The recent creation of the Ministry of Jal Shakti is indicative of India's move toward integrated water and wastewater management.

Institutions implement their functions through regulatory statutes. In 1974 the *Water Prevention and Control of Pollution Act* was released as a first regulation for the prevention and control of water pollution and led to the establishment of responsible bodies at central and state level for implementation. While this act was primarily focused on water bodies, in 1986, the *Environment Protection Act* was released—targeting protection and improvement of the wider human environment. With growing urbanization, the National Urban Sanitation Policy was established in 2008 mandating the total coverage of sanitation in all Indian cities and towns. **Table 3** below states important regulations and their functions chronologically.

**TABLE 2 |** Institutional structure for setting wastewater discharge standards.

| Institution | Mandate | Subunit | Subunit function |
|---|---|---|---|
| MoEF&CC | Formulation of policies and programs for the conservation of natural resources and pollution abatement and guidance for sustainable development and enhancement of human well-being (MoEFCC, 2017a) | CPCB | Provision of technical services to MoFE&CC regarding the Environment (Protection) Act, 1986. According to the Water Act, 1974, their function is to promote cleanliness of streams and wells in different areas of the States by prevention, control and abatement of water pollution (CPCB, 2019) |
| | | SPCB | Inspect wastewater treatment facilities; enabled to tighten standards; evolve methods of treatment and utilization of sewage or related disposal (Singh, 2014) |
| MoHUA | a) Formulation of policies, sponsorship and support programs<br>b) Coordination of activities of various Central Ministries, State Governments and other nodal authorities<br>c) Monitoring programs concerning housing and urban affairs (MoHUA, 2017a) | CPHEEO | Technical wing of the ministry with specialists in public health engineering/environmental engineering. The organization does not only support the ministry in policy formulation but also handholds states by way of technical advice, guidelines, scrutiny and appraisal of schemes, and propagation of new technologies. It acts as advisory body at central level for concerned state agencies and Urban Local Bodies (ULBs) in implementation, O&M (operation and maintenance) of urban water supply and sanitation projects (CPHEEO, 2019) |
| Ministry of Jal Shakti | Formed in May 2019 by merging Ministry of Drinking Water and Sanitation, Ministry of Water Resources, River Development and Ganga Rejuvenation for optimal sustainable development, maintenance of quality and efficient use of water resources | 1. Overall planning, policy formulation, coordination and guidance for water resources<br>2. Technical guidance, scrutiny, clearance and monitoring of the irrigation, flood control and multi-purpose projects<br>3. General infrastructural, technical and research support for development<br>4. Providing special central financial assistance for specific projects<br>5.Overall policy formulation, planning and guidance in respect of irrigation management<br>6. Overall planning for the development of ground water resources<br>7. Formulation of national water development perspective<br>8. Coordination, mediation and facilitation of interstate interests<br>9. Operation of the central network for flood forecasting<br>10. Inter-state negotiations<br>11. Ensure effective abatement of pollution and rejuvenation of the river Ganga by river approach (Ministry of Jal Shakti, 2019) | |

## Setting Wastewater Discharge Standards for STPs in India

The fundamental basis for standards-setting is the identification of "designated best uses" (DBU), or the use from any particular water body that demands the highest water quality (CPCB, 2002). A classification system of five common human uses has been adopted that associates each DBU with related water quality criteria that must be fulfilled. **Table 4** below illustrates defined designated-best-uses with the related class of water and relevant criteria.

The DBU concept forms the fundament for risk management in India but is not without limitations. Human use-based water quality criteria may not satisfy ecological health criteria, and this has been found to be the case in practice (CPCB, 2002). Unorganized uses of waterbodies have not been considered, and these may constitute the majority of risks, particularly in rural India. Further, DBU may vary across seasons and stretches of the river and this results in a further challenge in the practical utility of the concept. These problems have been evident in the monitoring of large rivers like Ganga and Yamuna (IIT Consortium, 2015; Government of Haryana, 2018).

Following a review of international standards (USEPA, Europe, and Japan), and consideration of economic feasibility in India, first general discharge standards were proposed in 1986. These are concentration-based, and the first iteration considered four different application areas (MoEFCC, 1986b). Standards are set as minimum requirements for all states, allowing states to set more stringent standards based on the condition of their water bodies.

## Current Scenario of Evolving Discharge and Reuse Standards

The established wastewater discharge standards for STPs have changed considerably over the past 4 years, with changes in terms of limits and overall parameters—as well as a move to just one fixed set of standards irrespective of end uses over land or discharge to inland water. After revision and the formulation of comparatively stringent draft norms in 2015 under one fixed set of standards, these underwent a second change in 2017 with a relaxation of limits and the inclusion of different criteria for metro cities. These norms, in turn, were followed by an order by the NGT (National Green Tribunal) (1995). The frequency of changes, coupled with observed difficulties in direct access to relevant information on central online platforms and the lack of transparency in standards-setting have led to confusion and hesitation within the sector on upcoming projects. An adaptation time of 7 years was proposed by a nominated expert committee for old STPs to comply with updated standards but rejected by the NGT. While water quality criteria form the baseline for setting standards, incoherence is observed. Detailed reports on standards setting procedures, relevant parameters for evaluation or detailed development plans are not accessible or existent and thus could not have been provided. **Table 5** below informs on Indian STP discharge standards over time.

**TABLE 3 |** Overview of policies and acts in India for wastewater management.

| | | |
|---|---|---|
| 1974 | Water (Prevention and Control of Pollution) Act | Prevention and control of water pollution in maintaining or restoring of the wholesomeness of water through the establishment of pollution control boards (central & state level) for implementation[a]. |
| 1986 | Environment Protection Act | Provision of protection and improvement of the environment in a broader sense, including the human environment[b]. |
| 1995 | National Environment Tribunal Act | Provision of strict liability for damages arising out of any accident by hazardous substances; establishment of a National Environment Tribunal for effective and expeditious disposal of cases arising from such accidents[c]. |
| 2008 | National Urban Sanitation Policy | All Indian cities and towns become totally sanitized, healthy and liveable and ensure and sustain good public health and environmental outcomes for all their citizens with a particular focus on hygienic and affordable sanitation facilities for the urban poor and women[d]. |
| 2011 | National Mission for Clean Ganga | Ensure effective abatement of pollution and rejuvenation of the river Ganga by adopting a river basin approach to a) promote intersectoral coordination for comprehensive planning and management and b) maintain minimum ecological flows in the river Ganga[e]. |
| 2012 | National Water Policy (NWP) | NWP proposes the recycling and reuse of water including return flows for demand management and efficient use of water, incentives through efficient water pricing[f]. |

[a] *MoEFCC (1974), accessible via https://cpcb.nic.in/displaypdf.php?id=aG9tZS93YXRlci1wb2xsdXRpb24vRG9jMy5wZGY=.*
[b] *MoEFCC (1986a), accessible via https://cpcb.nic.in/displaypdf.php?id=aG9tZS9lcGEvZXByb3RlY3RfYWN0XzE5ODYucGRm.*
[c] *NGT (National Green Tribunal) (1995), accessible via http://www.greentribunal.gov.in/FileDisplay.aspx?file_id=hp6pqcrv0hY1hc2OYG8Sk8xCFfwF7gv7AbtSt83%2FRxrgXufTbWXFcg%3D%3D.*
[d] *MoUD (2008), accessible via http://www.indiaenvironmentportal.org.in/files/nusb.pdf.*
[e] *NMCG (2019), accessible via https://nmcg.nic.in/about_nmcg.aspx.*
[f] *MoWR (2012), accessible via http://mowr.gov.in/sites/default/files/NWP2012Eng6495132651_1.pdf.*

**TABLE 4 |** Water quality criteria under designated best use classes (CPCB, 2017a).

| Designated-best-use | Class of water | Criteria |
|---|---|---|
| Drinking water source without conventional treatment but after disinfection | A | - Total Coliforms < 50 MPN/100 ml<br>- pH between 6.5 and 8.5<br>- Dissolved Oxygen > 6 mg/l<br>- $BOD_5$ days 20°C 2 mg/l or less |
| Outdoor bathing (organized) | B | - Total Coliforms < 500 MPN/100 ml<br>- pH between 6.5 and 8.5<br>- Dissolved Oxygen > 5 mg/l<br>- $BOD_5$ <3 mg/l or less |
| Drinking water source after conventional treatment and disinfection | C | - Total Coliforms < 5000 MPN/100 ml<br>- pH between 6 to 9<br>- Dissolved Oxygen > 4 mg/l<br>- $BOD_5$ < 3 mg/l |
| Propagation of wildlife and fisheries | D | - pH between 6.5 to 8.5<br>- Dissolved Oxygen > 4mg/l<br>- Free Ammonia (as N) < 1.2 mg/l |
| Irrigation, industrial cooling, controlled waste disposal | E | - pH between 6.0 to 8.5<br>- Electrical conductivity at 25°C micro mhos/cm max. 2250<br>- Sodium absorption ratio max. 26<br>- Boron max. 2 mg/l |
| | Below-E | Not meeting A, B, C, D, & E criteria |

While in 1986 standards, discharge to inland surface water and land irrigation was differentiated, the subsequent draft standards were applied for both categories where human contact with reused effluent was possible (though specific reuse applications were not defined). Apart from the standards set under the CPCB, several different recommended norms for wastewater reuse are provided in guidance documents such as the Manual on Sewerage released in 2013 under the CPHEEO and the MoHUA or the Urban Water Reuse Policy developed under the Urban Development Department in Karnataka state published in 2017 (Government of Karnataka, 2017). While the board for the formulation of the Karnataka policy included a wide range of sectoral bodies under various Ministries (including state pollution control boards) and given parameters and limits refer to CPHEEO norms, the recommended norms are rather different to standards set elsewhere. The recommended norms for wastewater reuse under the CPHEEO are shown in **Table 6**.

In comparison to norms recommended by the CPHEEO, the stated application areas under the Urban Reuse Policy in Karnataka are agriculture, industry, urban non-potable use and environment. For agricultural use, the norms cover pathogens and pH, whilst norms for discharging effluent into water bodies to increase flow (for example) are more stringent and cover similar parameters as to standards proposed.

Furthermore, while under the Open Defecation Free Agenda of the Swachh Bharat Mission decentralized onsite sanitation systems were widely built in urban areas, a specific set of standards for onsite or decentralized systems does not exist, neither standards along the whole sanitation value chain, including fecal sludge management (MoHUA, 2017b).

## Technology Considerations Under the Regulatory Framework

Reported wastewater treatment systems in India comprised a range of 13 different technologies in 2013, with Upflow Anaerobic Sludge Blanket (UASB) as the most commonly used technology. However, current trends and STPs under development include Activated Sludge Process (ASP), Moving Bed Biofilm Reactor (MBBR), and Sequencing Batch Reactor (SBR) plants (CPCB, 2013, 2015). An overview for decentralized technologies is not given. CPCB has previously evaluated several technologies according to performance and cost (CPCB, 2013).

**TABLE 5 |** Overview Indian STP discharge standards over time (MoEFCC, 1986b, 2015, 2017b; National Green Tribunal order, 2019).

| | Parameters | General norms[g] 1986 | | | | Draft norms Nov. 2015** | MoEF & CC notification, Oct. 2017** | NGT order 2019** |
|---|---|---|---|---|---|---|---|---|
| | | Inland surface water | Public sewers | Land irrigation | Marine coastal areas | | | |
| 1 | BOD [mg/l] | 30 | 350 | 100 | 100 | 10 | 30 20 (metro cities)[h] | 10 |
| 2 | COD [mg/l] | 250 | – | – | 250 | 50 | – | 50 |
| 3 | TSS[i] [mg/l] | 100 | 600 | 200 | 100 (process water) | 20 | 100 50 (metro cities) | 20 |
| 4 | pH | 5.5–9 | 5.5–9 | 5.5–9 | 5.5–9 | 6.5–9 | 6.5–9 | 5.5–9 |
| 5 | TN[j] [mg/l] | 100 | – | – | 100 | 10 | – | 10 |
| 6 | Ammonical Nitrogen as N [mg/l] | 50 | | – | 50 | 5[k] | – | – |
| 7 | Free NH3 [mg/l] | 5 | | | 5 | – | – | – |
| 8 | Nitrate [mg/l] | 10 | | | 20 | – | – | – |
| 9 | Diss. PO4 as P [mg/l] | 5 | – | – | – | – | – | 1[l] |
| 10 | Fecal Coliform [MPN/100ml] | – | – | – | – | <100 | <1,000 | <230 |

[g] *Standards set in 1986 cover in total 40 parameters, which are not depicted in this illustration. NOTE: industrial wastewater standards are regulated under CETP (Common Effluent Treatment Plant) set, which is not focus of this this study.*
[h] *Metro Cities, all state capitals except in the state of Arunachal Pradesh, Assam, Manipur, Meghalaya Mizoram, Nagaland, Tripura Sikkim, Himachal Pradesh, Uttarakhand, Jammu and Kashmir and Union Territory of Andaman and Nicobar Islands, Dadar and Nagar Haveli Daman and Diu and Lakshadweep Areas/Regions. **Standards applicable for discharge into water bodies and land disposal/applications, while reuse is encouraged.*
[i] *As SS in [mg/l] in General Norms, 1986.*
[j] *As Total Kjedahl Nitrogen in General Norms, 1986.*
[k] *As $NH_4$-N.*
[l] *Valid for Phosphorus Total (for discharge into ponds and lakes).*

The technologies included ASP, MBBR, SBR, Upflow UASB-EA, Membrane Bioreactor (MBR), and Waste Stabilization Pond (WSP). The following **Table 7** presents the CPCB evaluation alongside DEWATS (Decentralized Wastewater Treatment System), which follows a concept with low cost, O&M and energy intensive nature-based systems, mostly composed of anaerobic treatment and extended planted gravel filtration.

## The Challenges of a Changing Wastewater Management Regime

In light of the changing landscape of pollution control measures and the lack of transparency in standards-setting, literature review, and interviews with several governmental officials, sectoral experts, and technology providers in India have been carried out, to assess applicability of standards and norms set, the reasons for the changes, associated challenges and discuss possible implications. The interviewees provided their comments on an anonymous basis. Their feedback with findings is synthesized and discussed in the following sections.

### *Background for revision of general standards in 2015*

CPCB reported a severe deterioration of river quality, which formed the initial ground for a revision of general standards as indicated in interviews. While polluted river stretches in 2005 only numbered 71, the number rose to 300 in 2012 and further to 351 in 2017 (Bhardwaj, 2005; CPCB, 2018b), although it should be noted that the monitoring network developed over this period from an initial 784 to 3,000 stations in 2018. Considering the increase in both monitoring stations and polluted river stretches, a qualitative analysis of pollution levels at the given stretches would deliver a more holistic picture on the dimension of contamination levels. Reasons for increased pollution in rivers are multiple, ranging from increased water withdrawals coupled with an increase in wastewater volumes and climatic and seasonal variations. Historically, some rivers had base flows only during the monsoon season (for around 3 months annually) while nowadays most streams are perennial as a result of wastewater discharge. Norms for effluent quality were tightened in 2015 since it was argued that dilution effects within water bodies could no longer be considered. Analyzing the compatibility of discharge standards and required water quality criteria for designated best uses, it is observed that set limits under a zero dilution factor cannot fulfill intended thresholds and thus can fail to eliminate risks as to given objectives (compare **Tables 4**, **5**).

### *Background on frequency of constant changes*

In contrast to 1986, standards in 2015 were formulated under the mandate of the MoEF&CC to combat high pollution levels. Since parameters such as economic feasibility were the responsibility of other Ministries, interviewees reported that they were not considered under the first draft. The disparity in the management environment of wastewater discharge and reuse standards is reflected in the contrasting landscape of varying interest and requirements. With water as the central resource and wastewater

**TABLE 6 |** Recommended norms of treated sewage quality for different uses (CPHEEO, 2013).

| Parameter | Toilet flushing | Fire protection | Vehicle exterior washing | Non-contact impound-ments | Landscaping, horticulture & agriculture | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | horticulture, golf courses | Crops | | |
| | | | | | | Non-edible crops | Edible crops | |
| | | | | | | | Raw | Cooked |
| **Turbidity (NTU)** | <2 | <2 | <2 | <2 | <2 | AA | <2 | AA |
| **SS** | nil | nil | nil | nil | nil | 30 | nil | 30 |
| **TDS** | | | | 2100 | | | | |
| **pH** | | | | 6.5 to 8.3 | | | | |
| **Temp. (°C)** | | | | Ambient | | | | |
| **Oil and Grease** | 10 | nil | nil | nil | 10 | 10 | nil | nil |
| **Minimum Residual Chlorine** | 1 | 1 | 1 | 0.5 | 1 | nil | nil | nil |
| **Total Kjeldal Nitrogen** | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **BOD** | 10 | 10 | 10 | 10 | 10 | 20 | 10 | 20 |
| **COD** | AA | AA | AA | AA | AA | 30 | AA | 30 |
| **Dissolved Phosphorus as P** | 1 | 1 | 1 | 1 | 2 | 5 | 2 | 5 |
| **Nitrate** | 10 | 10 | 10 | 5 | 10 | 10 | 10 | 10 |
| **Fecal Coliform/ 100 ml** | nil | nil | nil | nil | nil | 230 | nil | 230 |
| **Helminthic eggs/liter** | AA[m] | AA | AA | AA | AA | <1 | <1 | <1 |
| **Color** | Colorless | Colorless | Colorless | Colorless | Colorless | AA | Colorless | Colorless |
| **Odor** | | | | Aseptic (Not septic and no foul odor) | | | | |

[m] *as arising when other parameters are satisfied.*

**TABLE 7 |** Technology performance (CPCB, 2013; adapted with data based on DEWATS by Singh et al., 2019).

| Assessment parameter/technology | ASP | MBBR | SBR | UASB+EA | MBR | WSP | DEWATS[n] |
|---|---|---|---|---|---|---|---|
| **Performance after Secondary Treatment** | | | | | | | |
| BOD (mg/l) | <20 | <30 | <10 | <20 | <5 | <40 | |
| SS (mg/l) | <30 | <30 | <10 | <30 | <5 | <100 | |
| Fecal Coliform, Log unit | Upto 2<3 | Upto 2<3 | Upto 3<4 | Upto 2<3 | Upto 5<6 | Upto 2<3 | |
| T-N removal efficiency (%) | 10–20 | 10–20 | 70–80 | 10–20 | 70–80 | 10–20 | |
| **Performance after Tertiary Treatment** | | | | | | | |
| BOD (mg/l) | <10 | <10 | <10 | <10 | <10 | <10 | <20 |
| SS (mg/l) | <5 | <5 | <5 | <5 | <5 | <5 | <40 |
| TN | | | | | | | <10 |
| $NH_3N$ (mg/l) | <1 | <1 | <1 | <1 | <1 | <1 | |
| Total Coliforms, MPN/100 ml | 10 | 10 | 10 | 10 | 10 | 10 | |

[n] *DEWATS technology serves as comparative for nature-based solutions due to lack in data availability for other systems.*

treatment as significant pillar of societal infrastructure, a cross-sectional interest is formed. However, it is stated that the process of standards-setting and related decision making does not consider a regulated consensus phase including all stakeholders to devise feasible solutions to complex problems. The lack of consultation or consensus during the development of the 2015 MoEF&CC draft norms meant that they were published and went into application before being reviewed by other institutions and stakeholders. Given the lack of communication and inclusion, the draft norms subsequently underwent two rounds of reversal, while the applicability of current enforced standards is reported to remain under further revision.

Aside from individual stakeholder perspectives, interviewees stated that detailed assessment through health risk or river basin modeling has not been undertaken due to capacity constraints. While the aspiration of the regulatory authorities is toward BAT and zero risk, the absence of detailed human or environmental impact assessments, indicative budgets, and targets for infrastructure implementation mean that the eventual outcome cannot be predicted with any certainty. It was further reported that international limits may not reflect characteristic or the impact of parameters under given environmental conditions found in the Global South. While in the North coliforms may persist for longer timescales, increased UV radiation in the South can have an effect on their elimination. In turn increased temperatures may enhance organic decomposition processes. The given uncertainty due to a lack in profound risk management for local conditions leaves behind room for fundamental recurring questions and discussions. To facilitate a more structured and holistic management process, big data for water bodies, environmental, and public health must be collected and analyzed, and this capacity is yet to be developed within the relevant Indian institutions.

### *Background for the change to fixed set of standards*

Although in interviews it is widely agreed that standards set do not necessarily represent required limits for certain application areas, one fixed set of standards for discharge and reuse has been set because of high mistrust of illegal discharge. It was stated that many STPs cannot meet 1986 standards because of electricity break downs, O&M intensive technologies and the lack of interest in investing in training of operators by the private sector who is often responsible for the O&M of treatment plants. Further dysfunction in the wastewater analysis sector was reported as observation, while illegal disposal of sludge due to lack of appropriate disposal options is a common occurrence. With insufficient resources in monitoring, one fixed set of discharge standards was considered to facilitate pollution control. Illegal discharges are observed along the whole wastewater chain. The causality and net benefit resulting from the implementation of one fixed set of standards remains unclear and fails to address the root cause—which is formed by insufficient capacity in monitoring. Further, without proposing nuanced and feasible pollution control measures for reuse, regulations can fail to address the reality on ground and existing risks to a large proportion of the population, particularly farm laborer and the poor.

While one fixed set of standards can simplify implementation and monitoring, it can also neglect the benefits and risks of wastewater. For example, in an irrigation context, wastewater composition, soil characteristics, type of crop, and protection measures can influence risk. Certain trace elements can affect the integrity of soil structure and accumulate in crops, rendering them unfit for human consumption. Considering the quantities of wastewater used for irrigation in India, and the growth in agriculture in peri-urban areas as a response to perennial flows, the elimination of nutrients essential for crop growth at high cost remains indefensible (CPCB, 2013).

### *Changes in the standards setting approach*

As a primary driving objective indicated in the protection of water bodies, the NGT order envisages stringent standards achieved through the implementation of the BAT approach. Under the focus of one application area and a limited set of technologies considered in the evaluation process, the resulting implementation would require energy and mechanically-intensive technologies that increase electricity consumption and rule out opportunities for direct nutrient recycling. Smith et al. (2019) perform a benefit-cost assessment of China's stringent wastewater standards in 2015, and find an additional annual electricity consumption of 3–6% and a 7-fold benefit to agricultural reuse. There is an ever-increasing landscape of technology options, many of which were not considered during the 2013 CPCB review (CSE 2019; CPCB 2013). While it is claimed that the BAT approach is technology-neutral, it was commonly stated that decentralized and nature-based solutions are disadvantaged under the proposed discharge and reuse standards.

### *Economic and risk implications*

The immense pollution arising from improper or inexistent sanitation requests for allocation of adequate funding schemes in order to achieve set targets. However, most interviewees stated that strict standards were not applicable at the current time in India due to the lack of economic and technical feasibility, with substantial constraints around operation and maintenance. Detailed development plans of the sector including financing schemes and related targets in treatment coverage over time could not have been shared. It is stated that the economic feasibility for implementation of the MoEF&CC norms at all levels has not been fully explored, and the efforts of the wastewater sector to provide sanitation has stalled due to a lack of clarity on goals and a lack of applicable technologies.

It was indicated that the sector would face a mammoth challenge in acquiring finances to retrofit current systems to meet the proposed limits—not just in terms of the infrastructure required, but also the additional land area required to accommodate that infrastructure, especially in highly dense urban areas. According to the Bangalore Water Supply and Sewerage Board, 50 out of 57 STPs would have to be adapted and a budget of 2,000 crore Rs (260 Mio. €) has been already drawn up (Deccan Herald, 2019). It is further reported that 134 STP projects are currently in the bidding stages and that tenders may have to be revised—both for these as well as for proposals that have already been issued (Global Water Intelligence, 2019). The detailed implications for institutional costs and technological retrofitting are not known but are presumably quite large.

When analyzing the capital costs of treatment systems considered in the CPCB report in 2013, prices are indicated in the range from 23 lakhs Rs/MLD (0.029 Mio. €/MLD)[1] for WSP to 300 lakhs Rs/MLD (0.382 Mio. €/MLD) for MBR. While this is a wide range, capital expenditures (CAPEX) for other treatment systems fell within the range of 68–75 lakhs Rs/MLD (around 0.087 to 0.096 Mio. €/MLD). Capital costs for tertiary treatment were indicated as 40 lakhs Rs/MLD (0.051 Mio. €/MLD) representing ~ 60% of total capital investment for ASP, MBBR, SBR or UASB+EA, 13% for MBR and 173% for WSP. Against the intensive investment in tertiary treatment, the overall additional gain in BOD removal rate as for ASP is indicated in 10 mg/l while a comparative for removal efficiencies for nutrients at the different stages is not directly given and cost calculation in relation to removal rates cannot be derived. Considering that half of the wastewater is reused informally for irrigation in India, decentralized plants near agricultural areas could allow to recover

[1]Conversion rate based on 78.87 Rs/EURO annual average for 2019, dated 13th of December, 2019, sourced at https://www.x-rates.com/average/?from=EUR&to=INR&amount=1&year=2019 (X-Rates, 2019).

resources instead of their cost intensive elimination, which in turn could be used for the development of broader coverage of treatment infrastructure.

Unless the total governmental budget for wastewater infrastructure development increases drastically, infrastructural development and coverage are likely to slow down even as the population continues to grow. This trend can result in higher pollution and health burden and enforce higher risk inequalities as only certain areas could be served while others would be exposed to an unsafe and dangerous environment. Overall, it can be stated that there is a wide gap in institutional capacity at all levels—highlighting a pressing need for more holistic management processes.

## International Comparison

In the following chapter an international comparison has been carried out in collaboration with the INNOQUA consortium, informing on institutional approaches and pollution control measures in different countries.

### International Comparison of Approaches and Discharge Standards

The international comparison of approaches and discharge standards provides insights from regulations on the European level, Ireland, France, Tanzania, and different set of standards in a wider perspective in relation to India.

#### *The European Union*

As with India, legislation in Europe has to cover a broad range of geographies with different environmental sensitivities. The initial priority was to ensure that wastewater was captured and treated—with an emphasis on wastewater from "agglomerations" of more than 2,000 Population Equivalent (PE). PE is used as a metric since it allows for the inclusion of combined sewerage systems that are common across Europe—in which mixtures of surface runoff, domestic, commercial, and industrial effluents are conveyed to treatment facilities. This regulatory structure was set out in the 1991 Urban Wastewater Treatment Directive (UWWTD), obligating European member states to:

a. collect and treat wastewater, where PE is higher than 2,000
b. preauthorize industrial discharges into urban treatment plants
c. achieve effluent standards by secondary or equivalent treatment
d. apply nutrient removal objectives, where receiving catchment are sensitive
e. monitor treatment plants and receiving waters
f. control sewage sludge disposal.

The nutrient removal objectives apply to agglomerations of 10,000 PE and above, where the treated wastewater, discharged into water bodies, can cause eutrophication. They cover nitrogen and phosphorus and set limits for these elements.

In principle, the UWWTD prevents the use of decentralized systems within population centers (of >2,000 PE). However, the Directive does include the following caveat: "Where the establishment of a collecting system is not justified either because it would produce no environmental benefit or because it would involve excessive cost, individual systems or other appropriate systems which achieve the same level of environmental protection shall be used" (EEC, 1991). In the following **Figure 4**, the coverage in wastewater treatment and related stages is presented. As it can be seen, there are significant differences in EU countries. It can be assumed that wastewater from the percentage of the population not covered in these statistics is managed in decentralized systems and as illustrated apart of the UK, decentralized systems still represent a significant fraction. Further as illustrated, tertiary treatment is not yet universally applied throughout all EU countries and the implementation of this treatment stage is still a comparatively young development.

More recently, European legislation has moved away from setting specific discharge standards to consider water quality as a whole. Under the 2000 Water Framework Directive (WFD) (European Commission, 2019c), member states are required to understand the current ecological condition of their water bodies (both surface and ground water) and compare this with "good" ecological status. Good ecological status is defined through a number of metrics that are based on the quality of water bodies that might be expected where there was minimal human interference. Programs of measures must then be defined and implemented to improve poor quality water bodies until they achieve at least "good" ecological status. The WFD operates at river basin scale, requiring international cooperation where (for example) rivers pass through more than one country. Since the programs of measures can target point and diffuse sources of pollution, the WFD interacts with a large number of other regulatory instruments—including those relevant to agriculture. Since it is left to individual member states to determine how "good" ecological status should be interpreted for each water body, the WFD does not set prescribed limits for wastewater discharge.

#### *Ireland*

Over 80% of rural households (accounting for one third of Ireland's population) treat and discharge wastewater onsite with a resulting estimated 500,000 domestic wastewater treatment systems (DWWTS) treating wastewater from single houses that are not connected to a public sewer system An Taisce (2015). The Irish Environmental Protection Agency (EPA) has published a *Code of Practice: Wastewater Treatment and Disposal Systems Serving Single Houses* (PE $\leq$ 10) which serves as the key guideline and design practice for DWWTS (EPA, 2010). Technologies considered under the EPA include

a. Septic tanks for primary treatment
b. Constructed wetlands, soil filters and sand filters for secondary treatment
c. Package plants (primary and secondary treatment)
d. Constructed wetlands, soil filters and sand filters for tertiary treatment.

Wastewater treatment plants, processing loads of between 500 and 10,000 PE, must meet the standards listed in the UWWTD, whilst larger plants must meet tighter, site-specific standards—that allow water bodies to comply with the requirements of

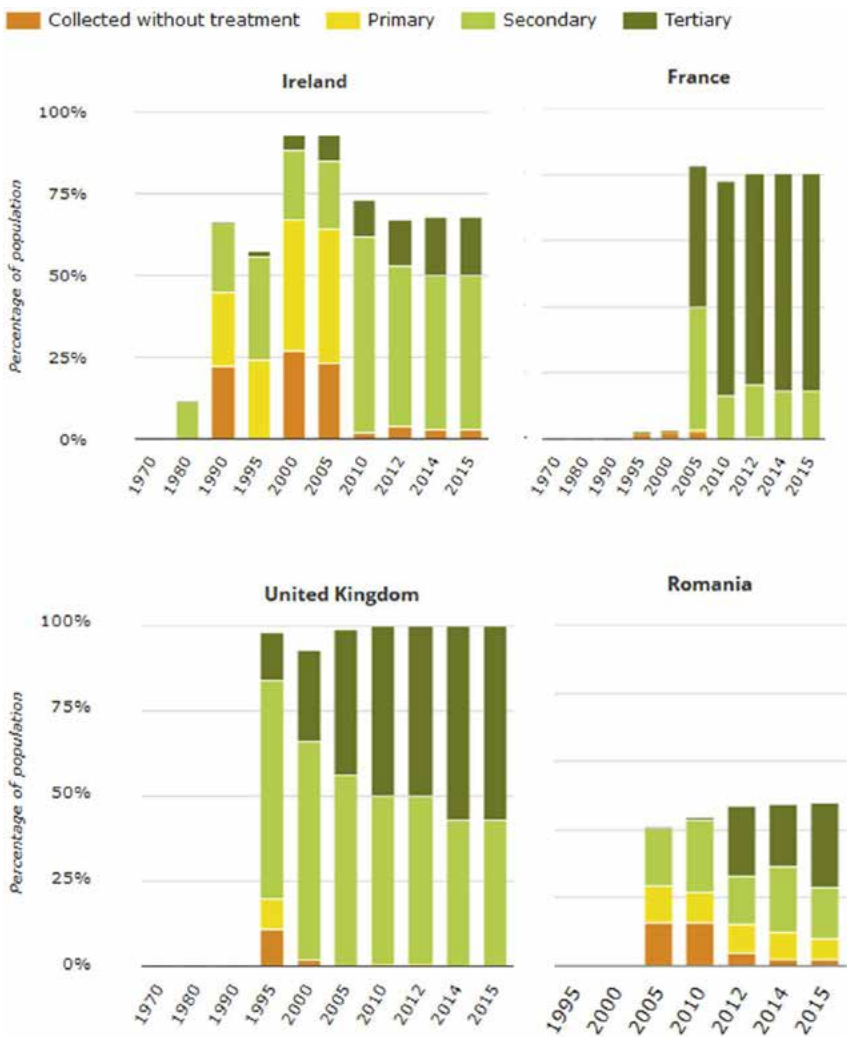


**FIGURE 4 |** Evolution of wastewater treatment in Ireland, France, UK, Romania (European Environment Agency, 2017a,b,c,d).

the Water Framework Directive. Ireland has no specific reuse standards in place.

*France*

As in the case of Ireland, France has set standards for smaller treatment plants. Unlike Ireland, France has standards for reuse, as set out below. Standards are classified amongst systems with a capacity below 1.2 kg of $BOD_5$ per day and above 1.2 kg of $BOD_5$ per day but below 120 kg per day and address BOD, COD and SS as presented in **Table 8** (Legifrance, 2007, 2009).

*Tanzania*

In 1991 the Government of Tanzania prepared the first National Water Policy to address the challenges on water supply and sanitation services (Tanzania Bureau of Standards (TBS), 2005). This policy identified the Government as the sole implementer and provider of water and sanitation services. Under the framework of the National Water Policy, Water Supply and Sanitation Authorities (WSSAs) are mandated with sanitation and sewerage service provision. The policy's objective for urban areas is to implement more appropriate environmentally-friendly technologies for wastewater treatment and recycling. Although discharge standards are comparatively stringent, wastewater treatment only covers a fraction of wastewater production.

Unlike in India, in Tanzania the formulation of discharge standards follows a national standardized participatory process involving stakeholders from several sectors over a phase of up to 5 years. The standards are based on information from other countries (notably Brazil and India, which have similar characteristics in terms of economy and environment). Following the initial expert revision, the draft standards are opened for

**TABLE 8 |** Discharge standards in different countries[o] (MoEFCC, 1986b, 2015, 2017b; EEC, 1991; Tanzania Bureau of Standards (TBS), 2005; Legifrance, 2007, 2009; EPA, 2010; MWI, 2012; Ministerio del Ambiente, 2015; National Green Tribunal order, 2019).

| Country | PE treated | pH | t (°C) | SS (mg SS/l) | DO (mg $O_2$/l) | COD (mg COD/l) | $BOD_5$ (mg $BOD_5$/l) | TN (mg N/L) | Total ammonium (mg $NH_4$-N/l) | Total ammonia (mg $NH_3$-N/l) | TP (mg P/l) | Microbial indicators |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EU Urban Wastewater Treatment Directive (UWWTD)[p] | >2,000 | | | 35/90% reduction | | 125/75% reduction | 25/70-90% reduction | – | | | – | |
| | 10,000 – 100,000 | | | | | | | 15 | | | 2 | |
| | >100,000 | | | | | | | 10 | | | 1 | |
| Ireland | ≤10 | | | 30 | | | 20 | 5 | 20 | | 2 | |
| | >2,000 | UWWTD apply as a minimum, but may be more stringent to comply with Water Framework Directive (WFD) | | | | | | | | | | |
| France | <20 | | | 30 | | | 35 | | | | | |
| | 20 - 2000 | 6–8.5 | <25 | 50% reduction | | 60% reduction | 35, 60% reduction | | | | | |
| | >2000 | UWWTD apply as a minimum, but may be more stringent to comply with Water Framework Directive (WFD) | | | | | | | | | | |
| Romania | >2,000 | UWWTD apply as a minimum, but may be more stringent to comply with Water Framework Directive (WFD) | | | | | | | | | | |
| Ecuador | | 6 - 9 | ±3[q] | 130 | | 200 | 100 | 50 TKN | 30 | | 10 | <2000 FC MPN/100 ml |
| Tanzania | | 6.5–8.5 | 20–35 | 100 TSS | | 60 | 30 | 15 TKN | | | 6 | <10,000 TC counts/ 100 ml |
| Jordan | | | | 60 TSS | >1 | 150 | 60 | 70 | | | 15 as T-$PO_4$ | <1,000 *E. coli* MPN/100 ml Nematodes < 1 |
| India 2015 | | 6.5–9 | | 20 TSS | | 50 | 10 | 10 | <5 | | | <100 FC MPN/100 ml |
| India 2017/18 | Metro | 6.5–9 | | 50 TSS | | | 20 | | | | | <1,000 FC MPN/100 ml |
| | Non-metro | | | 100 TSS | | | 30 | | | | | |
| India NGT 2019 | | 5.5–9 | | 20 TSS | | 50 | 10 | 10 | | | 1 | <230 FC MPN/100 ml |
| India 1986[r] Inland water | | 5.5–9 | <5 | 100 | | 250 | 30 | 100 TKN | | 5 as free $NH_3$ | 5 diss. $PO_4$ as P | |
| Land irrigation | | | | 200 | | | 100 | | | | | |

*Note to the table: Coliforms represented include E. coli, Fecal Coliforms (FC) and Total Coliforms (TC).*

[o] *Detail for ranges of permitted consents omitted from this version for clarity.*

[p] *TP and TN only considered in designated "sensitive" areas.*

[q] *Of the receiving water body.*

[r] *Total set covers a range of 40 parameters and three further application areas for discharge into public sewer, marine coastal areas.*

public comments. The review takes place every 5 years and is thus a constant process. Under the current revision, it is indicated that discharge standards for decentralized systems will be developed. However, a nuanced set of re-use standards is not included, despite reported high volumes of re-use.

When comparing wastewater discharge standards, it can be seen that limits vary considerably—although there is some commonality in determinants, such as TSS, COD, and BOD, TN. It is noticeable that the planned Indian standards have the strictest levels in terms of $BOD_5$, TSS, and TN removal, followed by Peru, Romania and Tanzania. In contrast, Ecuador and Jordan show the most relaxed limits. It can also be observed that—while EU countries must all comply with the same legislation—this still allows individual member states such as Ireland and France to apply discharge standards for small systems that suit their situations. A first iteration toward the principle of load-based standards categorized as metro and non-metro city could be observed in 2017 but contested in 2019.

### International Comparison of Standards for Wastewater Reuse

Globally, a rising number of countries is incorporating regulations for wastewater reuse. In Alcalde-Sanz and Gawlik (2014) reported that criteria were applied in Australia, Canada, China, Israel, Japan, Jordan, Mexico, South Africa, Tunisia, the USA, and several states of the EU. Within the following insights and pollution measures of different countries are presented.

#### *The European Union*

Pressures from climate change, droughts and urban development have put a significant strain on freshwater supplies in Europe (European Environment Agency, 2012). Europe's ability to respond to the increasing risks to water resources could be enhanced by broader reuse of treated wastewater—but to date only six member states have established regulatory or voluntary standards for reuse.

In order to stimulate increased water reuse across Europe, the European Commission has recently proposed a set of standards for implementation across all member states (European Commission, 2019a,b)—but only for water reuse in agricultural irrigation. It classifies four minimum reclaimed water quality classes in relation to crop category, irrigation method, and indication for water treatment (secondary in combination with filtration/disinfection). The quality requirements include: *E. coli*, BOD, TSS, turbidity, and pathogens, as listed in **Table 9**.

#### *France*

Among European nations, France was one of the first countries to issue wastewater reuse standards in 1991. These follow the WHO guidelines, with additional restrictions on irrigation and distances from irrigated areas (Hanseok et al., 2016). They include limits for COD, TSS, Enterococci, phages, and spores (Paranychianakis et al., 2015).

#### *Jordan*

ACWUA reports that Jordan is considered one of the most advanced countries in its approach to the application and safety of wastewater reuse. Due to severe water scarcity, 90% of treated wastewater is reused, mainly for irrigation in agriculture. A pragmatic approach to safety was developed that focusses on water quality at the point of use as outlined by the WHO. Farmers are aware of the nutrient content in wastewater, and this allows to reduce fertilizer application by up to 60%, which in turn provides economic benefits and can reduce the contamination of water (ACWUA, 2010, 2011). In an analysis of the public health indicators in terms of deaths, episodes and DALYs attributable to diarrheal diseases published under Lancet in 2017 (The Lancet, 2017), Jordan indicates one of the lowest ranges globally despite the very high urbanization rate of 83.91% and high reuse (The United Nations Population Division's World Urbanization, 2018).

The comparison of different wastewater reuse standards in different countries shows vast differences in limits, allowable applications and overall approaches. Most commonly, restrictions vary according to the intended use of crops. However, combinative measures are also considered, such as for France or the new standards proposed by Europe, which both vary according to different combinations of crop and irrigation methods. With the proposed regulation on reuse in the EU it can be observed that standards are indicating an evolved combination of safety measures.

The most stringent standards are observed in South Korea, USEPA, and Israel in terms of BOD, however here it can be seen that no limits for TN or TP are applied and there is some variation for TSS. Approaches to pathogen management also vary widely—both from country to country and between uses within a country. For example, *E. coli* limits range from 250 to less than 100,000 CFU per 100 ml in France depending on whether crops are consumed without cooking or whether fruits are harvested from drip-irrigated trees. By comparison, the implementation of just one set of standards for both discharge to inland water and use on land in India is regressive with international practice and discourages nutrient recycling.

## CONCLUSION AND KEY RECOMMENDATIONS FOR THE WAY FORWARD

In the face of continuously growing population and the lack of proportionate sanitation infrastructure, authorities in India face a mammoth task to safeguard the environment and citizens' public health. This paper has explored recent developments in Indian wastewater discharge and reuse standards alongside the approaches adopted elsewhere. Observed constant changes and inconsistencies have led to a widespread confusion and further reported hesitation in sectoral development. Reasons for these developments are rooted in the shortages of adequate institutional capacity, related lack of detailed risk assessment and a missing consensus phase in the standards setting process including all stakeholders. While the contamination of Indian rivers is reported to be tremendously increasing and requires action, the implementation of a single set of stringent standards without a detailed development plan can risk to slow down the

**TABLE 9 |** Wastewater reuse standards in different countries (MoEFCC, 1986b, 2015, 2017b; MWI, 2012; CPHEEO, 2013; Ministerio del Ambiente, 2015; Hanseok et al., 2016; European Commission, 2019a; National Green Tribunal order, 2019).

| | Parameter | BOD | COD | TN | TP | Coliforms | TSS | pH | Helminth eggs (HE)/Intestinal Nematodes (IN) | Turbidity | Conductivity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Unit | mg/l | mg/l | mg/l | mg/l | CFU/100ml | mg/l | – | egg/l or applicable | NTU | |
| WHO | Unrestricted | | | | | <1,000 *E. coli* | | | <1 (IN) | | |
| | Restricted | | | | | <10,000 *E. coli* | | | | | |
| US EPA | Food crops | <10 | | | | ND FC (median) | | 6.0-9.0 | | <2 | |
| | Processed food crops | <30 | | | | <200 FC (median) | <30 | | | – | |
| EU directive[s] | A All irrigation methods | <10 | | | | <10 or ND *E. coli* | <10 | | <1 HE and <1,000 CFU/l Legionella spp. | <5 | |
| | B All irrigation methods | 25 | | | | <100 *E. coli* | 35 | | | | |
| | C Drip irrigation | 25 | | | | <1,000 *E. coli* | 35 | | | | |
| | D All irrigation methods | 25 | | | | <10,000 *E. coli* | 35 | | | | |
| Jordan | Cut flowers | 30 | 100 | 70 | NA | <1.1 *E. coli* | 15 | 6–9 | <1 (HE) | | |
| | Field crops, industrial crops and forest trees (C) | 300 | 500 | 70 | 30 | – | 300 | | | | |
| | Fruit trees, side of road outside city and landscape (B) | 200 | 500 | 45 | 30 | 1,000 *E. coli* | 200 | | | | |
| | Cooked vegetables, parks, playground, side road in city (A) | 30 | 100 | 45 | 30 | 100 *E. coli* | 50 | | | | |
| Israel | | <10 | <100 | <25 | <5 | FC <10 | <10 | 6.5–8.5 | | | <1,400 |
| South Korea | Food crops | <8 | | | | ND TC | | 5.8–8.5 | | <2 | <700 |
| | Processed food crops | | | | | <200 TC (MPN) | | | | <5 | <2,000 |
| Italy | | <20 | <100 | <15 | <2 | <100 (max); <10 (80%) *E. coli* | <10 | 6.0–9.5 | | | <3,000 |
| Spain | Uncooked vegetables | | | | | <100 *E. coli* | <20 | | <1/10l (IN) | | <10 |
| | Crops for human consumption | | | | | <1000 *E. coli* | <35 | | | | |
| | Unit | mg/l | mg/l | mg/l | mg/l | CFU/100ml | mg/l | - | egg/l or applicable | NTU | |
| Portugal | Vegetables consumed raw | | | | | <100 F | <60 | 6.5-8.4 | <1 (IN) | | <1000 |
| | Cooked vegetables | | | | | <1,000 FC | | | | | |
| France[t] | Unrestricted | | <60 | | | ≤250 | <15 | | | | |
| | All crops except those consumed raw | | varies | | | <10,000 | varies | | | | |
| Ecuador[u] | | | | | | 1,000 FC (MPN) | | 6-9 | absent | | |
| India 2015 | | 10 | 50 | 10; 5 for $NH_4$-N | | <100 FC (MPN) | 20 | 6.5-9 | | | |
| India 2017 | Other than metro cities | 30 | | | | <1000 FC (MPN) | 100 | 6.5-9 | | | |
| | Metro cities | 20 | | | | | 50 | | | | |
| NGT 2019 | | <10 | 50 | 10 | 1[v] | <230 FC (MPN) | 20 | 5.5-9 | | | |
| India old norms 1986, | Land for irrigation[w] | 100 | | | | | 200 | 5.5-9 | | | |
| CPHEEO[x] 2013 | Horticulture, golf course | 10 | AA | 10 | 2 | NIL | NIL (SS) | 6.5-8.3 | <1 (HE) | <2 | 2100 |
| | Non-edible crops | 20 | 30 | 10 | 5 | 230 FC (MPN) | 30 | | | AA | |
| | Crops eaten raw | 10 | AA | 10 | 2 | NIL | NIL (SS) | | | <2 | |
| | Crops eaten cooked | 20 | 30 | 10 | 5 | 230 FC (MPN) | 30 (SS) | | | AA | |

*Note to the table: Coliforms represented include E.Coli, Fecal Coliforms (FC) and Total Coliforms (TC).*

[s] *A-Food crops consumed raw, direct contact; B and C-Food crops consumed raw where edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops to feed milk- or meat-producing animals, D-Industrial, energy, and seeded crops; recommendation for all classes is secondary treatment+disinfection.*

[t] *Except during period from blossoming to picking, allowed if drop by drop irrigation; Enterococcus, F-specific bacteriophages, spores of sulfate reducing anaerobic bacteria (all log reduction).*

[u] *additional regulations exist for Al, Fe, Pb, Cd, As, Cr, Zn, Cu, Mn, Ni, sulfate, nitrite, DO; fecal bacteriophages and spores of sulfate-reducing anaerobic bacteria > 4log reduction.*

[v] *Valid for discharge to ponds and lakes.*

[w] *Further include arsenic, oil and grease, cyanide, alpha and beta emitter, a bio-assay test.*

[x] *Values both for TN and N; TP as dissolved P; further includes, oil and grease, color, odor and temperature.*

overall sectoral development through heavy investment and by this result in higher pollution levels and public health concerns for unserved regions. One fixed set of standards for both discharge and reuse is unlikely to be effective in controlling the risks from domestic wastewater pollution and increasing water insecurity in the majority of Indian cities. India's challenges might be better addressed by aiming for treatment throughout the country first, while building-up an evidence base that will allow more nuanced future regulations. Toward this end, the 1986 discharge standards, specifying four receiving environments and location classification, offer a more realistic national level discharge framework with more feasible limits than currently proposed standards. In alignment with the objective to encourage reuse, CPCB could prescribe a range of appropriate norms and best practices for various wastewater reuse applications. Given the risks associated with raw wastewater reuse, "safe reuse" should be operationalized using the best available evidence on the treatment needed for specific environmental and human health exposure scenarios.

CPCB's surface water monitoring guidelines stipulate 25 parameters during the pre-monsoon period and 11 parameters at 2-monthly intervals for the rest of the year (CPCB, 2017b). However, capacity constraints have meant that this frequency has not been achieved in practice. To build a strong evidence base for future water quality modeling, monitoring of four key parameters should be mandated, namely pH, BOD, TSS, and Fecal Coliforms. BOD data is already collected as part of CPCB's National Water Quality Monitoring Program. In addition, information on seasonal flows, surface water and groundwater quantity, and information on existing treatment capacity (quantities collected in sewers and treated at STP, quantities collected on-site and transported and treated off-site, quantities collected and treated *in situ*) will facilitate the development of location-specific discharge standards.

The wholesomeness of rivers must be restored under the River Monitoring Committees, comprising central and state bodies. The State Pollution Control Boards have the authority to set location-specific stringent standards (CPCB, 2009), and this approach could be implemented for specific highly polluted stretches or dry season flows. However, the implementation of these stringent standards must be supported by a targeted investment plan providing comprehensive wastewater treatment coverage and water conservation measures at a catchment scale, following a long-term infrastructure plan. Such a plan (e.g., the 2041 sewerage investment plans for Delhi and Bengaluru) would provide recommendations for sewer networks and appropriate combinations of centralized and decentralized systems for each city based on: population projections, type of buildings, climate and financial aspects—under an urban planning approach (Delhi Jal Board, 2014).

Most exercises to compare technologies in India show a bias toward the state of art or best available technology approaches. This bias has led to a focus on a limited set of mostly conventional systems, thereby omitting innovative, decentralized, nature-based solutions that could provide cost-effective and appropriate treatment. India has a broad landscape in technology innovation. However, many innovative technologies lack real-world and long-term demonstration mainly due to economic factors. Since most funding for research is located in the North, the feasibility of studied systems may not apply in the Global South. Given the lack of appropriate performance trials and data, mistrust of new alternative systems, the comfort provided by widely deployed conventional technologies or capacity constraints in gathering information on novel systems, innovative technologies face many challenges and opportunities are missed. This implies that discharge and reuse standards may be set without due reference to technologies that can be both economically and environmentally suited to the situation at hand. Wider commercial and research portfolios are under constant development and include a broad range of alternative technologies and system configurations that are resilient, sustainable, low O&M, low/zero energy and low/zero chemical consuming, making them economical and technically feasible options (CSE, 2019). Such technologies should be included in future standards-setting to ensure that thresholds for discharge or reuse are both adequate and affordable, while constant research would be required to progress on further technology innovation and prove feasibility through long-term demonstration projects.

While the comparative analysis shows that there is a variety of options for more nuanced setting of standards, the perspective of the paradigm shift in the wastewater sector is still nascent. The European Union directive and experiences of countries under the EU illustrate that legislation for a broad range of countries can be formulated, allowing more flexibility to address given variations of a local context. An integrated river basin approach provides a more holistic ground for assessment, regulation through the facilitation of an overall common target in water body protection; apart of territorial management difficulties and in focus of local requirements. The consideration of all water uses and related stakeholders of a water body is essential to incorporate a consensus on management and avoid incoherence. The EU case shows that both for sensitive areas, more stringent discharge standards can be set, while other areas can have more relaxation. It is observed that proposed wastewater reuse standards consider a set of several measures, including water quality criteria in tandem with irrigation methods and suggested technological options. Although nowadays still most institutional frameworks are lagging in setting regulated measures, despite the reality of reuse on the ground, there is a given trend in adapting regulations and by this also more contextualized solutions will evolve. However, comprehensive risk management and assessment are fundamental and along with long-term studies on water quality and public health to provide further detailed necessary insights for appropriate pollution control measures in the local context and an extended set of application areas.

To address sustainability on a broader level, the whole sanitation chain would have to be considered, starting from rising awareness with active "consumers" rather than a "flush and forget" society, involving the "reduce, reuse, recycle" principle. This would require less water consuming toilets, sewerage systems with smaller loops and separated collection systems.

**TABLE 10 |** Observations and related recommendations for the way forward.

| Observation | | Recommendation |
|---|---|---|
| Frequent changes and inconsistencies | Standards and recommendations throughout involved institutions and policies are not conform | a. Implementation of technical and qualitative consensus finding phase amongst all stakeholders to achieve a better and overall alignment of all interests.<br>b. India has wide variations in environmental conditions and necessities. Formulated standards should be guiding, and target based, providing the possibility for adequate local requirements/interests. |
| | Standards are not aligned to water quality criteria | c. With given high deviations in seasonal patterns, diminishing resources due to increased water use and associated water pollution, the river basin approach and integrated water resources management would offer a holistic solution. Detailed assessment and modeling could help to a) identify uses, pollution and risks, b) understand dimensions of river characteristics better and c) take appropriate practical and justifiable control measures.<br>d. Water quality criteria and wastewater discharge standards have to consider all designated uses and standards have to be aligned. |
| Confusion and hesitation amongst sectoral stakeholders due to frequent, not transparent changes | | Accessible, more transparent and better-structured information systems. |
| Deficits in institutional capacity for regulation and implementation of standards | | Adequate institutional capacity is fundamental for regulation and implementation of pollution control.<br>a. Incremental approach to capacity development<br>b. Partnering with NGOs and address the current trend in rising citizen groups as a window of opportunity to drive further societal awareness, responsibility and community involvement in direct actions and participatory bottom up approaches. |
| Insufficient risk assessment | | a. Better monitoring and assessment of prevalent risks, e.g. detailed data on public health burden.<br>b. Wider interaction and exchange with involved sectors.<br>c. Setting a health-based target, rather than assuming a no risk scenario despite given high risk reality on ground<br>d. Detailed risk modeling, assessment of possible safety measures along multi barriers, including a wider set of urban planning approaches and technological options with detailed plans for coverage targets and related budget allocation over time. |
| "Copied" guidelines targeting at best available technology are adopted as national standards | | a. Each country should follow a holistic risk assessment according to local conditions and by this develop applicable standards. The sectoral development in the Global North took centuries, long-term investment at many stages to arrive at given standards.<br>b. Stringent standards can create pockets of excellence if not aligned with economic feasibility, and by this reinforce inequality and increased risks. A broad coverage and equal access for all should be set as first target. |
| Mistrust on implementing more nuanced standards due to assumed illegal discharge | | a. Increase necessary resources and capacity for monitoring.<br>b. Provision of different discharge options to avoid illegal dumping and establishment of infrastructure along the whole chain. |
| Targeted standards cannot be achieved by treatment plants | | a. Set realistic pollution control measures.<br>b. Treatment technologies have to be aligned to local conditions. Treatment technologies, which are electricity and O&M intensive are reported as not feasible.<br>c. Intensive training campaigns for certified operators. Eliminate conflict of interest by private operators of STPs, through reinforcement of trained operators and increase in monitoring capacity of STPs. |
| Conflicting interest and disfunction of water analysis sector | | More stringent certification process with certified personnel and frequent monitoring |
| The range of parameters in standards set and the limits of given parameters are not adequate | | a. Standards and related limits should address the targeted risk elimination in consideration of economic feasibility and coverage of all relevant parameters<br>b. Water uses and related water quality criteria have to be reassessed and a more nuanced set of standards has to be formulated to address both the dangers and benefits of wastewater for all use and discharge categories. |
| High expenses for overall sectoral development | | a. Sectoral development should consider economic feasible and suitable technologies for application targeted treatment.<br>b. Comparative technology assessment has to cover a broader range of technologies to address best suitable solutions instead of favoring conventional systems, which are capital and O&M cost-intensive<br>c. Identification of polluters and enforced suitable revenue collection<br>d. Associated risk and economic loss due to lack of sanitation is immense. Overall expenses for the development of the sector have to be increased. Regarding reuse the Multi-Barrier-Approach offers a viable and more economic solution. |
| Inadequate monitoring | | a. A nationwide online monitoring was implemented as a first step to address monitoring with related challenges. However, training of operators for proper calibration and maintenance is required to achieve qualitative results.<br>b. Include citizen-based monitoring to achieve a quantitatively wider monitoring. |

*(Continued)*

**TABLE 10 |** Continued

| Observation | Recommendation |
|---|---|
| Low acceptance toward innovative and low-tech sanitation solutions | a. Increase in acceptance through information transfer at all levels, including decision-makers and population.<br>b. Increase in capacity for demonstration projects and innovation research in the Global South to collect more data. |
| Lack in awareness on risks of wastewater | Nation-wide awareness and education campaigns on WASH-related topics. |
| Wastewater composition is not suitable for further reuse | a. Holistic urban planning with designated areas for different sectors.<br>b. Separate collection of varying wastewater streams with appropriate treatment and according to aimed reuse application area.<br>c. Creation of smaller loops through poly- and decentralized solutions. |

Decentralized, onsite, nature and community-based sanitation systems can help to address the urban sustainability challenge, but they would require an enabling environment throughout all levels. Based on the findings and observations of this study, the following related recommendations for the way forward in India are summarized in **Table 10**.

## AUTHOR'S NOTE

Interviewees have requested strict anonymity and that no data from qualitative interviews to be presented that can be traced to individuals and institutions. Hence only insights have been presented.

## AUTHOR CONTRIBUTIONS

GG conceived of the original idea and helped to supervise this study. TS took the lead in assessment and writing of the publication. VS and DT contributed in assessment of data and information and in writing of the publication. RP assisted in assessment through interviews and review of the publication. All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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# Gender Mainstreaming in Urban Sanitation: A Study of Selected Cities in Uttar Pradesh

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## *ABSTRACT*

*Sanitation in India is a State subject. State-level steering committees and urban departments play the role of guidance and support to Urban Local Bodies which are responsible for final implementation of sanitation at the local level. ULBs are mandated to undertake planning, design, implementation, operation and maintenance of water supply and sanitation services in cities and towns. At the central level, the nodal Ministry of Housing and Urban Affairs is tasked with supporting implementation of the National Urban Sanitation Policy on various fronts including designing and implementing national-level strategies on linkages between public health and sanitation, clarifying institutional roles, capacity-building and training support to states and ULBs, providing financial assistance for City Sanitation Plans through existing government schemes, monitoring and evaluating projects, and mainstreaming sanitation into relevant programs on urban infrastructure and housing across various central ministries. Besides the Ministry of Housing and Urban Affairs, institutional responsibility for the full water supply and sanitation chain at the ministerial level falls between a number of ministries, commissions, and boards. This complexity also contributes at times to the failure to implement programs in the sector. There is a direct relationship between water, sanitation and health. Consumption of unsafe drinking water, improper disposal of human excreta, improper environmental sanitation and lack of personal and food hygiene have been major causes of many diseases in developing countries. India is no exception to this. Prevailing high infant mortality rate is also largely attributed to poor sanitation. The concept of sanitation was earlier limited to disposal of human excreta by cesspools, open ditches, pit latrines, bucket system etc. Today, it connotes a comprehensive concept, which includes liquid and solid waste disposal, food hygiene, and personal, domestic as well as environmental hygiene. Present paper highlights the urban sanitation and . imperatives of gender mainstreaming. The paper is based on mainly primary data collected through field survey in AMRUT cities of Banda, Bahraich, Mirzapur and Loni in Uttar Pradesh .*

## Introduction

Proper sanitation is important not only from the general health point of view but it has a vital role to play in our individual and social life too. Sanitation

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is access to, and use of, excreta and waste water facilities and services that ensure privacy and dignity, ensuring a clean and healthy living environment for all. Facilities and services should include the collection, transport, treatment and disposal of human excreta, domestic wastewater and solid waste, and associated hygiene promotion (UN Habitat and Water Aid). Sanitation is one of the basic determinants of quality of life and human development index. Good sanitary practices prevent contamination of water and soil and thereby prevent diseases. The concept of sanitation was, therefore, expanded to include personal hygiene, home sanitation, safe water, garbage disposal, excreta disposal and waste water disposal. Provision of basic services such as water supply, sewerage, sanitation, solid waste disposal and street lighting has traditionally been the responsibility of the local governments. These services are being provided through state government departments, state level boards, corporations etc. Public Health Engineering Department, Public Works Department, Urban Development Department, Housing Boards, Department of Local Self Government, Water Supply and Sewerage Boards etc. are some of the departments of the state government which performs municipal functions. With the passing of 74th Constitutional Amendment Act, Metropolitan Planning Committee and District Planning Committee have been formed to take up developmental activities in the concerned region in place of the parastatals. The ULB's have also been empowered to take up development functions. States have responded in diverse manner with regard to the status of parastatal agencies in the post decentralized period. Many state governments like Kerala and Karnataka have recommended the abolition of the parastatals while some have recommended for a change in their functional role like in Tamil Nadu, Uttar Pradesh, Maharashtra, West Bengal and Andhra Pradesh. The parastatal agencies have also been merged with Urban Development Department. The 74th Constitutional Amendment Act has also transferred administrative and financial process and created an enabling environment for the local bodies to undertake planning and development responsibility.

Universal access of urban sanitation to poor families is major challenge as slums and backward areas have grossly in adequate sanitation infrastructure and sanitation services as compared to the urban areas. This is because of the fact that development work was carried out in only recognized/notified slums areas by the local bodies. However, In 2005 Govt. of India under the JNNURM Mission highlighted that all existing slums are to be integrated in the mainstream of urban planning and development. Thus, with the construction of community and public toilets in the states like Maharashtra, Karnataka, Madhya Pradesh, Gujarat and Orissa accessibility of sanitation services has been increased to the urban poor. Providing environmentally safe sanitation to the people of world's second most populous nation is a challenging task. The challenges that urban sanitation sector faces mainly relate to the low priority accorded to it by the municipal governments. This task becomes more intricate in context to the country like India where introduction of new paradigms of plans, policies or projects can challenge people's tradition and belief. Around 600 million people constituting 55 per cent of country's population do not have access to safe sanitation or any kind of toilet. Open defecation is a large global problem, but it is substantially and importantly an Indian problem. About 60 per cent of the approximately 1 billion people worldwide who defecate openly live in India. Widespread open defecation has major consequences for health and human capital in India. Inadequate sanitation has a great environmental economic and health impacts in India. In order to minimize these impacts, Government of India has under taken several measures including increased investment in urban sanitation, policy initiatives, regulations, and public campaigns to improve sanitary conditions in the country. This has resulted in raising the sanitation status during the last two decades but a marked improvement is yet to be achieved.

Presently fund is available under AMRUT, Swacch Bharat Mission, Namami Gange and 14th Finance Commission for sanitation in urban centres in India. However, septage and faecal sludge management is covered under AMRUT. Sewerage connection is also been ensured under AMRUT and Namami Gange .There has been paradigm shift in urban governance in India in the recent years. The emphasis from schemes and programmes has been shifted to mission mode approach for achieving the targets and project objectives. Massive investment based programmes and schemes in mission mode approach have been implemented recently by the Ministry of Urban Development as Ministry of Housing and Urban Poverty Alleviation, Government of India. The focus of government is on development of urban infrastructure, improvement in delivery of civic services through public private partnership, implementation of reforms and improving service delivery mechanism. The government is also planning to create high quality urban infrastructure and providing smart solutions in civic services through effective use of technology and mobilizing private sectors for investment in selected cities of India. There has been larger focus on improving the sanitary conditions and eradication of open defecation in urban areas through social mobilization and construction of toilets. These schemes and programmes are expected to yield good results in the coming years. As JNNURM and subsidiary schemes has already resulted in construction of urban infrastructure and improvement in urban governance through implementation of urban reforms. The second generation of JNNURM in name of AMRUT is also focusing on urban reforms for service delivery besides creation of infrastructure.

There are many possible definitions of sanitation. Sanitation means the safe management of human excreta and wastewater. It therefore includes both the ‘hardware’ (e.g. latrines and sewers) and the ‘software’ (regulation, hygiene promotion) needed to reduce faecal-oral disease transmission. It encompasses potential reuse, ultimate disposal of human excreta or discharge of wastewater. Environmental sanitation aims at improving the quality of life of the individuals and at contributing to social development. This includes disposal or hygienic management of liquid and solid human waste, control of disease vectors and provision of washing facilities for personal and domestic hygiene. Environmental sanitation comprises both behavior and facilities to form a hygienic environment. Most diseases associated with water supply and sanitation, such as diarrhoea, are spread by pathogens found in human excreta. The faecal-oral mechanism, in which some of the faeces of an infected individual are transmitted to the mouth of a new host through one of a variety of routes, is by far the most significant transmission mechanism. This mechanism works through a variety of routes. Primary interventions with the greatest impact on health often relate to the management of faeces at the household level. This is because (a) a large percentage of hygiene-related activity takes place in or close to the home and (b) first steps to improving hygienic practices is often easiest to implement at the household level. Secondary barriers are hygiene practices preventing faecal pathogens, which have entered the environment via stools or on hands, from multiplying and reaching new hosts. Secondary barriers thus include washing hands before preparing food or eating, and preparing, cooking, storing, and re-heating food in such a way as to avoid pathogen survival and multiplication. The water supply and sanitation provide the necessary barrier between the pollutants, natural - built environment and humans.

The findings of the Census of India 2011 indicate that only 32.7 per cent of urban households are connected to a piped sewer system whereas 38.2 per cent dispose their wastes into septic tanks and about 7 per cent into pit latrines, underlining the predominance of onsite arrangements–and it is not clear how the waste is further disposed by the majority of these installations. Presently, septic tanks and pit latrines along with open defecation are major contributors to groundwater and surface water pollution in many cities in the country. One the major challenges in urban sanitation is the collection, treatment and disposal or reuse of Faecal Sludge. Adequate facilities and services for collection, transportation, treatment and disposal of faecal sludge do not exist in most Indian cities and towns. Faecal Sludge comprises varying concentrations of settleable or settled solids as well as other non-faecal matter that is collected from on-site sanitation systems, such as latrines, non-sewered public toilets, septic tanks and aqua privies. Faecal sludge from septic tanks is specifically termed as septage. FSM should be given priority in urban sanitation programmes and there should be an increased convergence between AMRUT and SBM goals of making India ODF. Achieving ODF should not merely be restricted to the act of going for open defecation but the faecal matter should also be properly disposed to reduce its ill effects. Separate faecal sludge disposal station needs to be constructed such as SWM plants. Need to ensure that there is a reliable fee-based service for FSM at the ULB level by incorporating this requirement as a precondition for funding under SBM. The scheme should strongly incentivize the development of local service providers based on PPP models and encourage resource recovery. Skill development of personnel on plumbing, mechanical desludging of septic tanks/ pits, truck operation with immediate job placement is required ( Singh et. al,2017).

According to the type of toilet facility in India (Census of India, 2011), around 81 per cent of urban households have access to toilet facilities within the household premises, 6 per cent access public toilets, and 12 per cent are forced to resort to open defecation. Thus, nearly 10 million households still defecate in the open. Open defecation, and the lack of access to any kind of toilet facilities, individual or shared, is one of the biggest concerns and challenges for urban sanitation in India. Studies also indicate that the condition and type of toilets in urban areas is highly variable. Toilets, especially among poorer communities, are often dysfunctional: clogged toilets, leaking taps, broken floors or roofs (WSP-TARU, 2008). Access to improved sanitation has increased over the past two decades (from 49 per cent in 1990 to 77 per cent in 2011). While the percentage of households without access to 'basic sanitation' has decreased from 32 per cent to 17 per cent over the corresponding period , the number of households practising open defecation or having unimproved toilets, has reduced from 72 million to 64 million.

Broadly, the sanitation systems in India can be divided into two broad types: network-based systems, which refer to piped sewerage and on-site systems which includes all other categories. It is evident that only a third of the city population is serviced by network-based systems, as apart from piped sewerage, all other categories constitute on-site systems. In a survey carried out in 300 cities, only 100 cities had sewerage systems (NIUA, 2005). The number of cities with sewerage has increased slightly, according to Census 2011. Even now, only 792 or only 10 per cent of cities have more than 50 per cent of households connected to sewerage systems, and it is in all likelihood an overestimate. The various estimates indicate that only one-third of total wastewater generated is collected (CPCB, 2009). In the national sanitation ratings carried out for 423 cities, 274 cities (65 per cent) have unsatisfactory arrangements for safe collection of human excreta. Only about 27 per cent of cities are collecting more than 80 per cent of their waste (MoUD, 2010). The sewerage systems, where they exist, are plagued by multiple problems. The sewers in most Indian cities are badly maintained: frequent blockages, siltation, missing manhole covers, gulley pits. There is hardly any preventive maintenance with repairs being made only in the case of crises (WSP-TARU, 2008). Improper disposal of solid waste also tends to block sewer lines. Sometimes, storm water enters the sewerage network, leading to inflow in excess of the capacity of the system, and hence sewer lines cannot function.( Wankhade et. al, 2014) .

The sanitation systems are often only considered partially. The on-site based sanitation solutions (latrine or septic tank-based) frequently do not include excreta and faecal sludge emptying, transport or treatment services and facilities. Additionally, local business opportunities, as well as demand and potential use of waste resources, such as water, nitrogen or bio- solids, are given little attention. Failures or unsustainable solutions put huge financial burden on municipalities. In cities of developing countries, large amounts of excreta and faecal sludge collect in on-site sanitation facilities, such as private or public latrines, and septic tanks. As opposed to industrialised countries, where excreta is disposed of via cistern-water flush toilets, city-wide sewerage systems and central wastewater treatment plants, all of which are widespread technologies in industrialised countries but unaffordable or inappropriate in developing countries. If faecal sludge is collected at all from on-site sanitation technologies, they are most often disposed of in an uncontrolled manner without prior treatment, thus, posing severe health risks and polluting the environment ( SCBP,2017).

Various technologies which perform the same or similar type of function are called as functional groups. When different technologies from different functional groups are clubbed together, a sanitation system is made. Careful selection of the technologies needs to be done to make the sanitation system functional. A sanitation system should consider all the products generated and all the functional groups these products are subjected to prior to being suitably dispose of. Domestic products mainly run through five different functional groups, which form together a system. All sanitation systems start with User Interface. From this the product either goes to collection and storage/treatment group or to conveyance. This mainly depends on whether there is adequate supply of water available for water based system. After conveyance the products flow in the centralised treatment function group, where the products are treated before moving on to use/disposal group. The product though collection and storage/treatment also end up into use/dsposal functional group. Depending on the system, not every functional group is required. User interface describes the type of toilet, pedestal, pan or urinal the user comes in contact with. User interface also determines the final composition of the product, as it is the place where water is introduced in the system. Thus, the choice of user interface is often dependent on the availability of water. Selection of user interface depends on the following six technical and physical criteria :( 1) availability of space (2) ground condition ( 3) groundwater level and contamination (4) water availability and (5) climate (IWA, 2014) .

The technologies which are used for the collection and storage of the products generated at the user interface. In the case of extended storage, some treatment may be provided, though it is generally minimal and dependent on storage time. All the units have to be either connected to conveyance or use/ disposal function group for liquid effluent and to conveyance to solids. All the units need to be emptied regularly (depending on the design criteria) for solids. These solids in turn need to be treated or processed before use/disposal. The technical and physical criteria for choosing appropriate collection, storage and treatment technology are as follows: (1.) ground condition (2) groundwater level and contamination and (3.) climate. Conveyance describes the way in which products are moved from one process to another. Although products may need to be moved in various ways to reach the required process, the longest and most important gap lies between on-site storage and (semi-) centralised treatment. For the sake of simplicity, conveyance is thus limited to moving products at this point. The technical and physical criteria for choosing appropriate conveyance technology/system are as follows (1) water availability (2.) ground condition (3) ground water level and contamination.

Human-powered emptying and transport refers to the different ways in which people can manually empty and/or transport sludge and solid products generated in on-site sanitation facilities. It can be done by using buckets and shovels, or by manually operated pumps specially designed for faecal sludge. The advantages of manual emptying include the generation of income, low costs and the availability of tools, little or no requirement of electric energy. The large disadvantage that inheres manual emptying is the high health risk. Motorized emptying and transport refers to a vehicle equipped with a motorized pump and a storage tank for emptying and transporting faecal sludge septage and urine. Humans are required to operate the pump and maneuver the hose, but sludge is not manually lifted or transported. Motorised emptying and transport, is fast and generally efficient. Moreover, it can generate local jobs. But large streets are required for the trucks to pass, thick or dried material cannot be pumped and garbage in pits may block the hose. Moreover, capital costs are high and spare parts may be not available locally.

Sludge and septage emptied from on-site sanitation systems need to be transferred to (semi-) centralized infrastructures for further treatment. Transfer stations or underground holding tanks act as intermediate dumping points for faecal sludge and septage when it cannot be easily transported to a (Semi-) Centralized Treatment facility. A vacuum truck is required to empty transfer stations when they are full. Sewer discharge stations are similar to transfer stations, but instead of simply being a holding tank, the stations are directly connected to the sewer transporting the sludge to a (semi-) centralized treatment facility. Transfer stations reduce transport distance, may encourage more community-level emptying solutions and prevent illegal dumping. The moderate capital costs may be offset with access permits and the construction and maintenance can create local income. However, expert design and construction supervision are necessary. The technical and physical criteria for choosing appropriate technology for treatment are as follows: (1) climate (2) availability of space (3.) ground condition (4) ground water level and contamination.

Use or disposal refers to the ways in which products are ultimately returned to the soil, either as harmless substances or useful resources. Furthermore, products can also be re-introduced into the system as new products. A typical example is the use of partially treated grey water used for toilet flushing. The conventional, centralized wastewater management concept, consisting of a water-borne wastewater collection system leading to a central treatment plant, has been successfully applied over many decades in densely populated areas of industrialized countries and has greatly contributed to improving the hygienic conditions in these areas. However, the appropriateness of this model in the context of cities in developing countries must be questioned, given their urgent need for affordable and sustainable infrastructure. A centralized wastewater management system reduces wastewater reuse opportunities and increases the risk to humans and the environment in the event of system failure. Centralized treatment systems are usually much more complex and require professional and skilled operators. Operation and maintenance of centralized systems must be financed by the local government often unable or unwilling to guarantee regular operation.

According to Census 2011, Uttar Pradesh has an urban population of 44.47 million people – which is 11.79 per cent of the total urban population of the country. The state has 653 urban local bodies (ULBs) including 17 Municipal Corporations (Nagar Nigams), 198 Nagar Palika Parishads and 438 Nagar Panchayats. The ULBs, with their limited local resources and state support, are responsible for provision of municipal services. A sanitation snapshot of urban Uttar Pradesh clearly indicates that households with onsite sanitation systems . The three pathways) like septic tanks (47 per cent) far exceed those with sewer connections (28 per cent). In the absence of even a single city that is completely sewered; most households, institutions, commercial areas and public/community toilets in the state depend on onsite sanitation systems like septic tanks and pit latrines. As there is no designated site for disposal, the emptied faecal sludge ends up in open drains nullahs/open fields, which eventually lead to polluting ( CSE, 2018) . Out of the 61 AMRUT cities, 34 have reported zero efficiency regarding collection and treatment of sewage. Aligarh, Agra, Bareilly, Ghaziabad, Gorakhpur, Jhansi, Kanpur, Lucknow, Varanasi, Muradabad, Meerut, Allahbad) are preparing City Sanitation Plan with support from Ministry of Housing and Urban Affairs, World Bank, JICA and GIZ. In addition, 4 small and medium towns' Nagar Pallika Parishads namely Ramnagar, Chunar, Bijnore and Gangaghat are being supported by Centre for Science and Environment (CSE) in preparing City Sanitation Plan and effective Faecal Sludge / Septage Management Plan ( CSE, 2018).

## Objectives and Methods

Present paper is based on major research study conducted in Uttar Pradesh. The study purports to examine the status of urban sanitation in selected cities of state and suggesting roadmap for improving sanitation conditions. The present study is empirical in nature and based on mainly primary data collected through field survey. The sample comprises about 1200 urban households in Loni (Ghaziabad), Banda, Bahraich and Mirzapur Nagar Palika Parishads . All the cities are covered under AMRUT. The survey has been conducted with the help of structured interview schedule. The filled in interview schedules were thoroughly checked and processed through use of SPSS.

### Profile of Selected Cities

Uttar Pradesh is the most populous State of India with a total population of 19.96 crore according to Census, 2011, out of which 15.51 crore live in rural areas and 4.45 crore, constituting 22.28 percent, in urban areas. About 16 percent statutory towns of India exist in Uttar Pradesh. There are 648 statutory towns, 267 census towns and 653 urban local bodies in the state of Uttar Pradesh. There is a tremendous pressure on urban infrastructure systems especially water supply, drainage, sewerage, and solid waste management. As per census 2011, 34.04 percent toilets are linked with piped sewerage system while 56.39 percent toilets are depend on septic tanks in the state. A large number of toilets are having outlet in open drains which cause environmental pollution. We have selected four cities/ towns for the study. These cities/ towns are *Bahraich (Eastern Uttar Pradesh), Loni (Western Uttar Pradesh), Banda (Bundelkhand) , and Mirzapur (Eastern Uttar Pradesh)*. Mirzapur ( Ganga), and Banda (Ken) are situated at the bank of rivers while Ghaghra passes from Bahraich district . All the towns are Nagar Palika Parishads and covered under AMRUT.

Bahraich is located in eastern tarai region of Uttar Pradesh. The town has urban population of 1,86,241 people with 30,061 households as per census, 2011. There are 9 zones in the town. The coverage of latrines was reported to be 87 percent, however, there is no sewerage system and sewage treatment plant. The waste generation was reported 27 MLD. Thus, there is huge gap of infrastructure for management of waste water and faecal sludge. Loni is situated in Ghaziabad district and has urban population of 512296 persons, spread in

14 zones. There are 91,138 households. The coverage of latrines (individual or community) was reported to be 99.94 percent with sewerage network coverage of 5.10 percent. There is sewerage network of 22.5 k.m, with sewerage treatment plant of 30 MLD with treatment efficiency of 50 percent. Banda is situated in Bundelkhand region and is rocky terrain. The urban population as per census, 2011 was reported to be 160473 spread in 31 wards and consists of 28748 households. The coverage of latrines was reported 57.55 percent as per SLIP under AMRUT. The sewerage network of 14.3 K,M. which constitute just 4 percent in the town. It is expected that 11563 households would be require septage management in 2021. Mirzapur is located in eastern Uttar Pradesh on the bank of river Ganga. It has urban population of 233691 and spread in 35 wards. There are 34029 households with coverage of latrines 77.81 percent. About 40 percent households are covered under sewerage system; however, efficiency of collection of waste water was r reported less than 40 percent. The length of sewer network was reported 240.4 k. m. with the capacity of 18 MLD sewerage treatment plant. It is expected that 16875 households would require septage management in 2021. There is no proper system of waste water and faecal sludge management in most the ULBs in the state. The ULBs have system for desludging the septic tanks and cleaning of chock of sewer line , however , there is no regular cleaning of septic tanks and private operators are emptying the tanks when there is any case of owe flowing is reported to them . They charge on their own and dispose of faecal sledge in open drains, water bodies or open spaces without any kind of treatment. Most of the septic tanks are not constructed scientifically and on standard norms and thus, there are higher risks of environmental pollution. There is no proper system of desludging, transportation, treatment and disposal of faecal sludge in the selected towns. This also causes higher level of ground water pollution. Thus, proper septage and faecal sludge management is required in the proposed towns. It would also be required to set up and made functional Faecal Sludge Treatment Plant in each selected town (Table 1).

**Table 1**

**Sanitation Profile of Selected Cities**

| *Particulars* | *Loni* | *Mirzapur* | *Bahraich* | *Banda* |
|---|---|---|---|---|
| Urban Population (Lakh, 2011) | 5.12 | 2.33 | 1.86 | 1.60 |
| No. of Wards | 55 | 35 | 31 | 31 |
| No. of Zones | 14 | 12 | 9 | 6 |
| Toilets Coverage | 99.9% | 77.8% | 87.0% | 57.5% |
| Length of Sewer Network | 22.5 km | 14.87 km | NIL | 14.3 km |
| Coverage of Sewerage Network | 5.1 | 39.5 | NIL | 4.0 |
| Waste water Generation | 36 MLD | 27.2 MLD | 27 MLD | 20 MLD |
| STP Capacity | 30 MLD | 18 MLD | NIL | 4 MLD |

Source: SLIPs of Selected Cities

Government grant constituted a large chunk of municipal revenue in all the selected cities however, it was recorded high in Bahraich as compared to other cities. Tax revenue constituted a larger share in Loni (9.48 per cent) as compared to other cities. Similarly, non-tax revenue constituted a larger share in Banda as compared to other cities. The proportion of expenditure on sanitation services against total municipal expenditure was recorded high in Banda (11.69 per cent) followed by Mirzapur (9.3 per cent), Bahraich (6.07 per cent) and lowest in Loni (3.91 per cent).

## Gender Mainstreaming:

Gender equality is central to the realization of Millennium Development Goals. Gender equality, leading to increased work opportunities, enhanced capacities for livelihood developments, enhanced social protection and overall increasing voice may enable women to participate equally in productive employment, contributing to women's development leading to economic growth of the nation. No nation can afford development without considering women who constitute about half of the stock of human resources. Thus, engendering growth has been internationally recognized instrument of development by incorporating gender perspective and concerns at all levels and stages of development planning, policy, programmes and delivery mechanisms. The issue of engendering development and women empowerment has been in the central stage with the shifting of paradigm of development and governance at the global level and particularly in India  Engendering development and inclusive growth requires an enabling environment in which women's contribution to the economy can be tapped and enhanced in a substantial and holistic way. This environment needs to ensure from conception to death – an environment that provides physical, emotional, economic and political and community security to girls and women. The engendered development also requires addressing the issues of accountability, capacity building and governance that are of utmost importance for gender equity and inclusive growth. Women's role in decision making institutions needs to be enhanced through providing them reservation and enforcement and implementation of all pro-women legislations.

Women being under represented in planning process, JNNURM provided an opportunity to build gender fair and inclusive cities. It seeks to promote planned urban development and equitable cities. Though, urban space, infrastructure and services which contribute to cities economic development, however men and women perceive their utility differently. Infrastructure development is not gender neutral. Lack of basic services affects both men and women; however women in cities especially in low income communities and slums are more severely affected by inadequate and poor services. In absence of access to toilets, women are forced to defecate in open which is unsafe and undignified while it is also a serious health and environmental threat. Women have traditionally been excluded from land ownership and it has contributed more marginalization of women as they are insecure and live in poverty. Women either do not work for wages or earn less than men. Because of their low earnings they cannot afford to buy a house or land for construction of house. Since, women often lack education and technical skills; they tend to be predominantly in informal economy. The informal sector is under regulated and social safety network is lacking. Among the poor, forced evictions from illegal spaces (slums) are a major cause of insecurity. The demolitions of slums not only destruct homes, but also destroy the informal livelihoods. The women being the most vulnerable and disadvantaged group, are mostly affected by such evictions. Women living in slums and low income groups also face problem of domestic violence as the family income is very low to sustain the family. Women and children experience domestic violence through physical abuse sexual assault and threats. Urban violence against women can be attributed due to lack of their power that comes from non ownership of property and shelter. Urban women are also more dependent on public transport to move in the city however, men usually own personal transport. Women use transport differently from men based on the type of work they do. Urban women are bearing more burdens of diseases. Urban poor women are more anemic and modality rate among them is higher.

There is need to set out a clear urban gender policy that will provide the framework for the gender integration. A general policy must have four key components:

- Bring a gender perspective into all aspects of planning, policy and legislation and activities that are within the domain of the Ministries.
- Create an enabling environment for women and thus to realize their full human rights in cities and particularly for women belonging to poor and marginalized groups.
- Outline sustainable mechanism for the equal participation of all including poor women in city development.
- Promote equitable access and control over the urban resources for women and men.

Gender mainstreaming is about promoting inclusive and participatory planning and development of the cities. Women empowerment is essential for inclusive development. Women empowerment through mobilizing and organizing in groups that promote micro-finance and ensure their participation in development planning and livelihoods is imperative. Public private partnership with civil society's involvement for gender equality is an effective instrument for improving basic services to urban poor including women.

Gender-based disadvantages in access to urban water supply are discussed below:

- Time and opportunity cost for work lost due to time spent in water collection.
- Conflicts and fights regarding space to wash clothes and cook.
- Physical and sexual harassment in public transport while collecting water from distant places.
- Exposure to physical and sexual violence while collecting water from tankers.
- Absenteeism and dropout rate of girl children from schools.
- Unsafe drinking water raises the risk of women, men and children being susceptible to waterborne diseases such as cholera and diarrhoea, affecting their health and subsequently livelihood.

Gender-based disadvantages in access to sanitation, sewerage and drainage are given below:

- Incidents of sexual harassment while availing sanitation facilities at Community Toilet Complexes:

- Poor and faulty design of Community Toilets Complexes (CTCs) which put women at the risk of being harassed.
- CTCs are not open for the entire day which causes inconvenience to women to meet their sanitary needs.
- Inadequate and unsafe sanitary public infrastructure causes loss of dignity and privacy to women who are forced to resort to open defecation.
- Inadequate infrastructure raises vital safety concerns for women as they are sexually assaulted or attacked when they resort to open defecation.
- Women have to wait until dark to defecate and urinate in the open, so tend to drink less water during the day, resulting in all kinds of health problems such as urinary tract infections (UTIs).
- Poor maintenance and design of drains leading to conflicts that put women at risk physically.
- Loss of dignity and privacy while disposing menstrual waste.
- Hygienic conditions are often poor in public defecation areas, leading to worm infestation and water-borne diseases.
- Girls, particularly after puberty, miss school due to lack of proper sanitary facilities for dealing with menstrual hygiene.

## Discussions of Results

Majority of the respondents reported that potable drinking water is available in their house. This was found more pronouncing in Bahraich (96.1 per cent) followed by Mirzapur (95.2 per cent). However, about 82 per cent respondents in Loni and more than half of the responding in Banda revealed that potable drinking water is not available in their house. . More than half of the respondents reported that they have individual tap for drinking water. This was found more pronouncing in Banda followed by Loni and Bahraich. About 1/3$^{rd}$ respondents in Mirzapur had public stand post for drinking water while about 2/5$^{th}$ respondents in Bahraich had individual hand pumps for drinking water. It is to be noted that Banda is located in drought prone area of Bundelkhand. The water crisis during summer gradually increases due to less water availability of water in Ken River. Duration of water supply was reported fewer hours as about 1/3$^{rd}$ respondents revealed that water supply in their areas are 4 to 6 hours. This was found more pronouncing in Loni (67.1 per cent) followed by Mirzapur (61.6 per cent). More than 3/4$^{th}$ respondents in Banda revealed that water supply is less than 2 hours. Thus, water supply for longer hours was recorded high in Bahraich. About 2/3$^{rd}$ respondents reported that water supply in their house is through municipal tap. This was found more pronouncing in Banda (82.7 per cent) followed by Loni (69.4 per cent). About 2/5$^{th}$ respondents in Bahraich reported that they have hand pumps in their house. About 23 per cent respondents in Loni revealed that they are taking drinking water from bore wells. Lack of toilets, inadequate of toilets, dilapidated toilets, clogging of toilets, disposal of faecal sludge in area, flies and termites, long distance of toilets and poor maintenance of toilets are some of the sanitation problems.

Toilet coverage was reported 87.3 per cent. This was found more pronouncing in Loni (91.6 per cent) followed by Bahraich (88.3 per cent) and Banda (87.6 per cent). The toilet coverage was recorded low in Mirzapur (81.3 per cent). Again, 56 per cent respondents reported that they have individual separate household toilets. This was recorded high in Loni (72.8 per cent) followed by Banda (70.6 per cent). About 58 per cent respondents in Bahraich and 30 per cent respondents in Mirzapur reported that they have individual joint household toilets. About 9 per cent respondents revealed that they are defecating in open. This was recorded high in Mirzapur (13.1 per cent) followed by Banda (11.1 per cent) and Bahraich (10.7 per cent). It is to be noted that open defecation is more prevalent in the slums and backward areas of the cities. In Mirzapur, survey was also conducted in Vindhyachal region as Nagar Palika has its jurisdiction over Vindhyachal region. Access to public and community toilets was recorded high in Loni (8.3 per cent) followed by Mirzapur (5.5 per cent) and low in Bahraich (0.9 per cent). Most of the respondents reported that they flush toilets. However, traditional pit latrines were also recorded in Banda, Mirzapur and Loni. Lack of funds for toilet construction, lack of toilets in house, lack of space for toilet construction, old house and habitual for open defecation are some of the important reasons responsible for open defecation. However, reasons vary across the selected cities. Respondents were asked that whether community toilets have been constructed. About 16 per cent respondents revealed that community toilets have been constructed in their areas. This was found more pronouncing in Bahraich (24.3 per cent) followed by Mirzapur (22.1 per cent). Thus, majority of the respondents reported that community toilets have not been constructed in their areas. It is to be noted that community toilets have been constructed mainly in backward and slum areas of the cities. The respondents were asked about maintenance of community toilets in their areas. About 57 per cent respondents reported that community toilets are being maintained by ULBs. It was found more pronouncing in Mirzapur (87.5 per cent) followed by Loni (83.9 per cent). About 55 per cent respondents in Bahraich reported that Sulabh International is maintaining community toilets. Shramik Bharti is also maintaining community toilets significantly in Banda, Bahraich and Mirzapur. Majority of the respondents in Banda further reported that private organizations are maintaining community toilets.

Employees of ULBs and sanitary workers are mainly responsible for cleaning of community toilets. However, a significant proportion of respondents in Mirzapur and Bahraich reported that community is responsible for cleaning of community toilets. About half of respondents were found satisfied with cleaning of community/public toilets. This was found more pronouncing in Loni (92 percent). However, majority of respondents in Mirzapur and Bahraich were found dissatisfied with cleaning of community /public toilets. The respondents were asked that whether charges of community and public toilets are reasonable. About half of the respondents reported that user chargers of community /public toilets are reasonable. This was found more pronouncing in Loni (84 per cent). However, a large proportion of respondents in Banda, Bahraich and Mirzapur could not respond on the view point. The respondents were further asked that whether all family members of are using toilets. More than 3/4$^{th}$ respondents revealed that their all family members are using toilets. This was found more pronouncing in Loni followed by Mirzapur and Banda. However, about 2/5$^{th}$ respondents in Bahraich could not respond on the view point. The respondents were asked that who cleans these newly constructed toilets. Majority of the respondents reported that they themselves and their family members are cleaning newly constructed toilets. However, a significant proportion of respondents also reported that domestic servants and sweepers are cleaning these toilets. Satisfaction of sanitation services was recorded high in case of collectionof waste, sweeping of streets/roads, transportation of solid waste, water supply, cleaning of drainage and flow of water. However, dissatisfaction was recorded high in case of cleaning of public toilets, maintenance of sewerage, cleaning of drainage, flow of water (Singh,2018).

The overall analysis demonstrates that sanitation conditions in small cities are no better than other cities of the state. The institutional arrangements and infrastructural facilities are adequate for providing sanitation services in small and medium cities. The sewerage services were found partial in Mirzapur and Loni while sewer system in Banda is defunct. The facilities for sewage treatment are grossly in adequate in all the selected cities, even there is no such facility in Bahraich. Thus, most urban households are found depending on septic tanks which are also scientifically designed and constructed. There is no proper and scientific arrangement for regular desludging, treatment and disposal of faecal sludge in the selected cities, however, system has been developed in Loni for emptying of vacuum tank after desludging at certain points, directly connecting to sewer system for treatment at STP. Similarly, in Bahraich , attempts have been made to regulate the desludging of septic tanks through maintain a proper records of citizens. The citizens are hardly bothered about regular cleaning of septic tanks as they opt of desludging of septic tanks in case of overflow or blockages. All ULBs have suction machines for cleaning of septic tanks , however, the capacity of such machines and required equipments are not adequate. The people in small and medium cities are still defecating in open and use community / public toilets in absence of individual household toilets The public and community toilets were found adequate in Loni , however, in other selected cities , it was found grossly inadequate. The water supply was found worse in Banda as during summer, water sources based on surface water gradually shrink due to excessive mining, damming of river and high demand. Thus, sanitation services get set back in the city during summer. The door to collection solid waste has been introduced partially in the selected cities, however, in Bahraich , it was found better due to engagement of private firm for the cause.

## Conclusion

The overall analysis demonstrates that sanitation conditions in small cities are no better than other cities of the state. The institutional arrangements and infrastructural facilities are adequate for providing sanitation services in small and medium cities. The sewerage services were found partial in Mirzapur and Loni while sewer system in Banda is defunct. The facilities for sewage treatment are grossly in adequate in all the selected cities, even there is no such facility in Bahraich. Thus, most urban households are found depending on septic tanks which are also scientifically designed and constructed. There is no proper and scientific arrangement for regular desludging, treatment and disposal of faecal sludge in the selected cities, however, system has been developed in Loni for emptying of vacuum tank after desludging at certain points, directly connecting to sewer system for treatment at STP. Similarly, in Bahraich , attempts have been made to regulate the desludging of septic tanks through maintain a proper records of citizens. The citizens are hardly bothered about regular cleaning of septic tanks as they opt of desludging of septic tanks in case of overflow or blockages. All ULBs have suction machines for cleaning of septic tanks , however, the capacity of such machines and required equipments are not adequate. The people in small and medium cities are still defecating in open and use community / public toilets in absence of individual household toilets The public and community toilets were found adequate in Loni , however, in other selected cities , it was found grossly inadequate. The water supply was found worse in Banda as during summer, water sources based on surface water gradually shrink due to excessive mining, damming of river and high demand . Thus, sanitation services get set back in the city during summer. The door to collection solid waste has been introduced partially in the selected cities, however, in Bahraich , it was found better due to engagement of private firm for the cause.

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# EVALUATION OF CO-COMPOSTED FAECAL SLUDGE APPLICATION IN AGRICULTURE

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ABSTRACT

Water scarcity, increasing cost of inputs and poor soil quality are major reasons for decreasing agricultural productivity in India. It is therefore critical to optimize soil organic matter, which is vital for enhanced soil quality to improve productivity. Considering that some of the organic sources like farmyard manure, crop residues, green manure, etc. are dwindling as well as the negative implications of chemical fertilisers, we need to consider alternative sources. In this context, a study was conducted to evaluate the application of co-composted faecal sludge (FS) as an alternative; and to provide scientific evidence through field experiments about the potential for co-compost application in agriculture. An agricultural trial was conducted for two cropping seasons. The co-composted FS was one of the nutrient sources used in the trial. Nutrient-balanced final co-compost was produced as faecal sludge is rich in nitrogen; municipal wet waste is rich in carbon content. Randomised Block Design method was followed, and the application of five treatments with four replications per treatment was undertaken. Treatments comprised four types of nutrient sources – namely, treated faecal sludge, co-composted FS (co-compost), farmyard manure, chemical fertilizers and control. The findings of the study showed that the yield obtained from crops grown under co-composted FS was higher than the other four treatments. The parameters for crop growth and development were better for co-compost applied crops. Further, the produce grown under co-composted FS was free from pathogen contamination. The study showcased the potential of co-composted FS as a nutrient source vis-à-vis other sources considered for the trial. The study showed that reusing co-composted FS in agriculture can benefit the farming community by enhancing soil productivity there by increasing crop yield. The study also highlights the need for further research to assess the impact of co-composted FS application on crop nutrient content and weed menace.

*Keywords: co-composted faecal sludge, agriculture, soil productivity, agricultural trial.*

## 1 INTRODUCTION

The current situation of agriculture in India is characterized by water scarcity, increasing cost of inputs, nutrient deficiency and poor soil quality – all of which is leading to decreased agricultural productivity. Despite the growing use of fertilizers, the country is experiencing stagnation in agricultural productivity and degradation of soil quality [1]. It is, therefore, critical to improve soil productivity to meet growing food demand with decreasing cultivable land. Organic matter is vital for good soil productivity as it improves physical, chemical and biological properties of soil, therefore, referred to as "Life of Soil". Organic matter sources are dwindling resulting in search for alternate sources [2]. The most common organic matter sources are farmyard manure, crop residues, vermicompost, urban waste etc. Humanure (compost from human faecal material and urine) could also be considered as an alternate organic matter source; however, the main concern is the health risks associated with reuse. This can be mitigated by adopting protection measures, which include not just treating human waste but also combining treatment with other measures like selecting suitable crops, using safety gear to control human exposure and safe cooking practices [3]–[5]. The WHO 2006 Sanitation Safety Planning process provides reuse of wastewater, excreta and grey water, which would help mitigate the risks associated with human waste application in agriculture.

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The use of human waste on farmlands is not a new concept. Farmers have been recycling human excreta by applying it on agricultural fields for centuries, which closes the nutrient loop by mimicking nature – nutrients move from soil into living organisms through the intake of food and are subsequently recycled back to the physical environment by excreta application onto farmlands. However, with the introduction of water-borne sewage and due to unsafe disposal of faecal sludge and wastewater into the environment, this nutrient cycle, and in turn, the water cycle too is interrupted and replaced by a linear system that transports nutrients away from soil and into water bodies. This leads to the deficiency of nutrients in soil and accumulation of nutrients in aquatic ecosystems.

Though there are benefits of FS use with respect to crop yield and soil fertility, some health issues have also been reported after working with FS [6]. The main reason may be the viable helminths in FS despite a long drying period [7]. Hence it is important to ensure that farmers are educated regarding safe reuse practices during application. Further, there is a need for research to assess the effect of long- term application of FS on farmer/consumer health and the environment and the impact of FS application on crop growth, yield and quality in comparison with other soil conditioners [8].

In this context, a study was conducted to evaluate the application of co-composted FS as an alternative to soil conditioners (e.g. faecal sludge, farmyard manure, chemical fertilizers) in peri-urban settings; and to provide scientific evidence through field experiments about the potential for co-compost application in agriculture. The study was conducted at the Faecal Sludge Treatment Plant (FSTP) in Devanahalli, Bengaluru (Fig. 1), in order to recover and reuse the nutrients from treated FS to agriculture in nearby farmlands, thereby closing the nutrient loop with minimum environmental footprint.

Figure 1: Faecal Sludge Treatment Plant (FSTP), Devanahalli, Bengaluru, Karnataka, India.

There are many studies conducted worldwide that quantify pathogen reduction achievable by various health protection measures for reuse of human waste. But lesser attention is paid to the impact of its long-term application in agriculture. This study, conducted by an agricultural trial with two cropping seasons, therefore aims at assessing the impact of co-compost application in comparison with other treatments/nutrient sources like faecal sludge, farmyard manure, chemical fertilizers and control on crop growth and development and yield parameters.

## 2 CASE STUDY ON SAFE REUSE OF CO-COMPOSTED FAECAL SLUDGE IN AGRICULTURE AT DEVANAHALLI, BENGALURU

Devanahalli near Bengaluru became the first town in the country to get a first-of-its-kind town-scale faecal sludge treatment plant (FSTP) for the safe treatment and disposal of sludge collected from septic tanks and pit latrines. The plant is capable of treating human night soil without any human interference in an environment friendly and cost-effective manner. There is neither underground sewerage connection nor any organized septage treatment facility in the area which leads to washing of septage into existing open drains. Therefore, the faecal sludge treatment plant was setup. It was set up by Consortium for DWATS Dissemination (CDD) Society in collaboration with Devanahalli's Town Municipal Cooperation (TMC). The FSTP provides a safe delivery point for the waste. The objective of this project is to establish a pilot independent septage treatment unit and treat it to prescribed standards. The plant is successfully handling 100% of the sludge collected in Devanahalli today. The farmers in and around Devanahalli (Karnataka, India) have been using untreated FS on their farmlands. While FS is rich in nitrogen and moisture, there is a risk of pathogen contamination of the soil and crops. The main objective of the trial was to understand the effect of different treatments like faecal sludge, co-compost, farmyard manure, chemical fertilizers/recommended dose of fertilizers (RDF) and control on crop growth, development and yield parameters. A study was carried out at the Devanahalli FSTP site by CDD Society in collaboration with University of Agricultural Sciences, Bengaluru, to test the yield quality and quantity as well pathogen activation in co-composting of FS with Municipal Wet Waste (MWW). The premise available near the co-composting unit was used for undertaking field trials using different crops.

### 2.1 Materials and methodology

MWW was collected from households, hotels, and the vegetable market of Devanahalli town. Cesspool vehicles dislodge FS from septic tanks or soak pits and transport it to the town's FSTP. The FS undergoes an anaerobic treatment process and is laid onto drying beds. The FS slurry dries under sunlight, during which some pathogens get deactivated due to UV rays; but harmful pathogens like helminths eggs, E. coli, and faecal coliforms may still persist. These pathogens are then eliminated by co-composting of FS with MWW producing nutrient balanced co-compost/humanure, which is one of the inputs used for the field experiment conducted in the study area. The method of composting was by windrow method of co-composting dewatered faecal sludge (FS) with organic solid waste in 1:2 ratio (Fig. 2) to eliminate pathogen contamination [9].

Figure 2: Windrow method of co-composting faecal sludge with municipal wet waste.

(a)

(b)

Figure 4: (a) Second crop, sweet potato – field experiment at Devanahalli; and (b) First crop, field beans – tagged plant in the field.

The nutrient requirement of field bean was calculated by taking into account the soil nutrient content, recommended dose of fertilizer for field bean (POP) and the nutrient content of the treatments/organic sources used in the experiment. The entire requirement of Nitrogen (N) was provided through organic sources like faecal sludge, co-compost and farmyard manure (FYM) for T3, T4 and T5 blocks respectively. These organic sources were added three weeks prior to sowing of filed beans. The Phosphorous (P) and Potassium (K) requirement for these blocks were balanced/ met through inorganic fertilizer application. For the treatment T2, RDF of 25:50:25 kg/ha was applied and there was no FYM, faecal sludge and co-compost application. Here, inorganic fertilizers like Urea, Single Super Phosphate (SSP) and Muriate of Potash (MOP) were added as basal dose per plot. The 5 treatment details are as summarized below:

T1: Absolute Control (No addition of organic manures or inorganic fertilizers)

T2: Recommended dose of fertilizer (RDN) – 25:50:25 kg/ha (Chemical fertilizers)

T3: RDN through faecal sludge + balance P and K through (*inorganic fertilizers)

T4: RDN through co-compost + balance P and K through (*inorganic fertilizers)

T5: RDN through FYM + balance P through (*inorganic fertilizers)

RDN: Recommended dose of nitrogen
*Inorganic fertilizers = Urea – 46% N, SSP = 16% P2O5, MOP = 60% K2O

The final co-compost sample which was one of the inputs for the trial was tested for physical, chemical and microbial parameters.

The objective of the field experiment was to assess the long-term implications of different treatments like faecal sludge, co-compost, farmyard manure and recommended dose of fertilizers (RDF) on crop growth and development and yield parameters. For each treatment, five plants were randomly selected (5 x 20 = 100 plants in total). These plants were tagged and labelled with the treatment details. The field observations of growth and yield parameters are made for these tagged plants.

The plot wise yield data (KGs) of field beans for all the five treatments during nine harvests were collected and then the total yield was recorded. The growth and development parameters of field beans were collected 60 days after sowing. The data was collected from the randomly tagged five plants from each of the 20 plots.

A second crop was cultivated in the following Rabi season after the harvesting of field beans in the same field without altering the RBD. This was mainly to effectively utilize the residual moisture and nutrient content of the soil from the previous (Kharif) season. For this purpose, the root crop Sweet Potato was selected. Since Sweet Potato is a residual crop, treatments were not imposed again. The yield parameters of Sweet Potato like total root yield and weight of marketable and non-marketable roots were collected at the harvest phase. The field data for the growth parameters of Sweet potato like vine length and number of branches were collected from the tagged plants (5 plants per plot) and the results are plotted in the below graphs.

The edible part (field beans – pods, sweet potato – roots) of the produce after harvesting was analysed for pathogen contamination. The data from the field with regard to crop yield, growth and development was also recorded. The post-treatment data on yield parameters was collected at harvesting phase.

## 3 RESULTS AND DISCUSSIONS

### 3.1 Co-compost characteristics

The physical, chemical and microbial parameters and microbial parameters of co-compost are presented in Table 1.

Table 1: Characteristics of mature co-compost.

| Parameters | FCO standards | Final compost from the windrow |
|---|---|---|
| pH | 6.5–7.5 | 6.51 |
| Conductivity (dsm-1) | 8.2 | 0.9 |
| Particle size | Minimum 90% material should pass through 4.0 mm sieve | Passes |
| Moisture, percentage by weight, minimum | 25 | 30.2 |
| Bulk density | <1.0 | 0.77 |
| Total organic carbon, percent by weight, minimum | 12 | 16.5 |
| Total N, percent by weight, minimum | 0.8 | 0.7 |
| Nitrate Nitrogen % | ?? | 0.23 |
| Total P (as P2O5), percentage by weight, minimum | 0.4 | 0.24 |
| Total K (as K2O), percent by weight, minimum | 0.4 | 0.98 |
| C:N | <20 | 12.1 |

Table 2: Presence of pathogen in co-compost.

| Pathogens | Compost standards | Co-composted FS from the windrow |
|---|---|---|
| Helminth eggs | ≤ 3–8 eggs/gram of dry solids (Source: Strauss, 1991 [3]) | Negative |
| Faecal coliforms (MPN – Most Probable Number) | <1000 MPN/g (Source: CCME When compost contains only yard waste) | >1,600 MPN/g |

As per the analysis, the final mature compost meets most of the FCO standards (Table 1) and is free from pathogen contamination (Table 2).

The final compost obtained from the windrow method of composting is able to maintain the nutrient balance C:N ratio. Of all the excreted pathogen groups, representatives of helminth eggs are the most resistant and hence are often used as indicator organisms. The thermophilic phase of the composting ensures deactivation of these helminth eggs; pathogen die off at 60 degrees Celsius temperature. Preliminary research also suggests that some compost may have high faecal coliform counts due to bacteria of environmental origin and not of faecal origin. Thus, faecal coliforms may not be a reliable indicator of pathogen levels under all circumstances. The study also proposes to repeat the treatments with more number of samples/windrows to come to a definitive conclusion of the above study findings.

### 3.2 Results from application of soil conditioners

#### 3.2.1 First crop: Kharif season – field beans

The findings of the study from field experiments showed that the yield obtained from the crop (field experiment plots) grown under co-composted faecal sludge was comparatively higher than other treatments/nutrient sources (Fig. 5). The growth and development parameters like plant height, number of leaves, number of beans, weight of beans in grams, weight of bean seeds in grams etc. were slightly better for co-compost applied plots compared to other treatments (Fig. 6). The field beans final produce from all the five treatments was also sample tested for pathogen contamination. The results showed that the produce was free of E.coli and Faecal Coliforms.

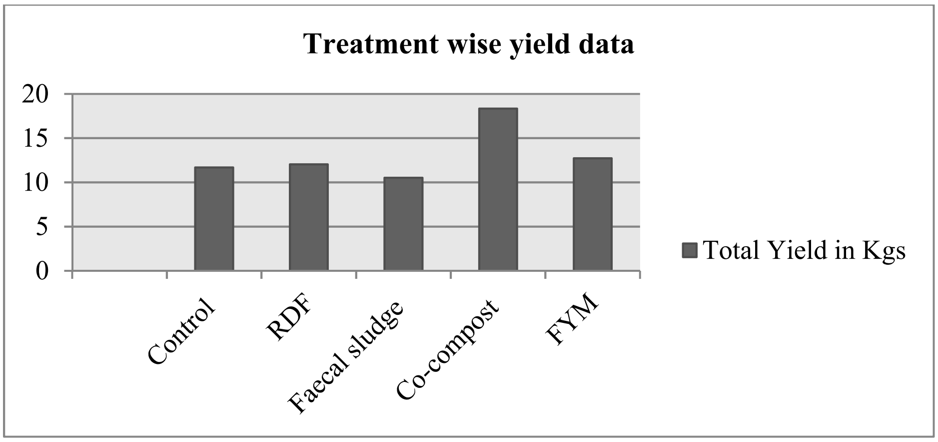


Figure 5: Treatment wise yield for field beans.

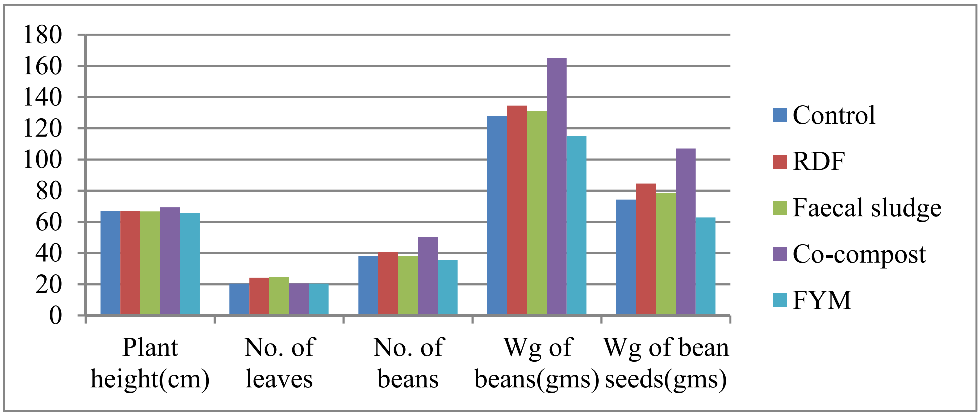


Figure 6: Treatment wise growth and development parameters for field beans.

The statistical analysis (ANOVA – One way) of the field results was conducted. The p-value was very close to the cutoff (0.05). Findings showed that the differences in yield among different sources of nutrients were slightly significant (p-value = 0.0632). The yield difference due to co-compost application was higher compared to other sources. But, the results for crop growth and development were not statistically significant.

3.2.2 Second crop: Rabi season – Sweet potato

The findings of the study from the field experiment showed that the sweet potato root yield and weight of marketable root obtained from the field experiment plots grown under co-composted faecal sludge was comparatively higher than other nutrient sources (Fig. 7). The growth and development parameters like vine length and number of branches etc. were slightly better for co-compost applied plots compared to other treatments (Fig. 8).

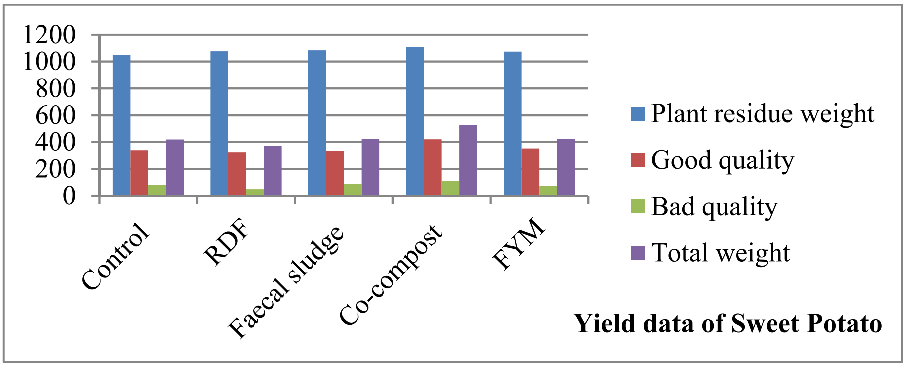


Figure 7: Treatment wise yield data of sweet potato.

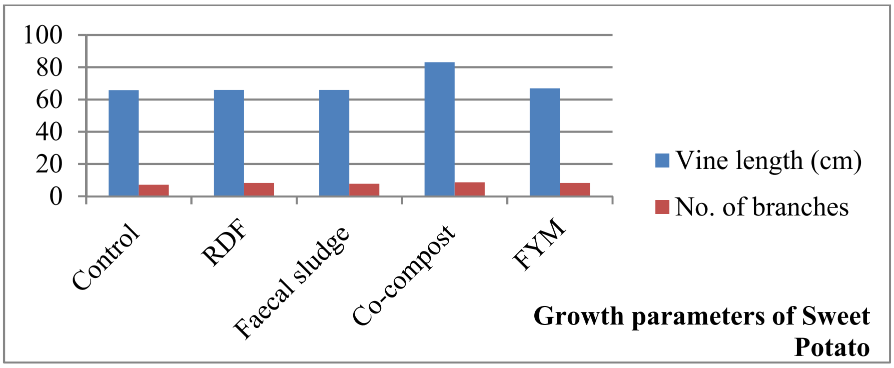


Figure 8: Treatment wise growth and development data of sweet potato.

The statistical analysis (ANOVA – One way) of the field results was conducted. The p-value was very close to the cutoff (0.05). Findings showed that the differences in yield among different sources of nutrients were slightly significant (p-value = 0.0614). The yield difference due to co-compost application was higher compared to other sources. But, the results for crop growth and development were not statistically significant. The Sweet Potato sample was also tested for pathogen contamination. The test report results showed negative for Helminths Egg presence both in the pulp part and the edible portion with skin. The study also proposes to repeat the field experiment for few more cropping seasons to come to a definitive conclusion of the above findings.

## 4 RECOMMENDATIONS AND CONCLUSIONS

Co-composting of faecal sludge with municipal wet waste will result in nutrient rich manure for application in agriculture. Co-composting proves to be safe for reuse of humanure and reduces the pressure on depleting natural resources for nutrients. Many studies have been conducted in India and outside which explain and quantify pathogen reductions achievable by various health protection measures. But there are not many studies with regard to its implication on crop growth and yield parameters. The findings of this research have given us the base to promote the use of human excreta-based soil inputs as they increase crop growth and yield.

Reusing co-compost in agriculture will greatly benefit the farming community by enhancing soil productivity, thereby increasing crop production. These will, in turn, have significant economic benefits by reducing expenses on public health and environment protection. The following health protection measures at each level of operation will reduce the health risks while ensuring human safety. Closing the nutrient loop by reusing human waste in food production has great potential in addressing sanitation and agriculture issues. Considering the nutrient significance of humanure and its role in combating the negative impact on the environment and public health (by reducing unsafe dumping on land and in waterbodies), human excreta-based soil inputs should be promoted for application in agriculture.

The need of the hour is to promote humanure application on the lines of city compost marketing. So that it would encourage famers to use humanure in agriculture. Below are some of the recommendations from the study:

- Acknowledging the unsafe faecal sludge disposal problem and promote the reuse of human excreta-based soil inputs
- There is a need to take measures to popularise humanure by providing direct incentives or subsidies on use of co-compost to farmers. The available assistance (subsidy) on the sale of compost from municipal solid waste should be considered for the sale of humanure also
- Marketing Development Assistance for the direct sale of humanure by compost manufacturers to farmers will make it more economical
- Humanure should also be co-marketed by tagging of cities with fertilizer marketing companies

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CENTRE FOR SOCIETY AND POLICY

Girija R (2019)

# HUMANURE APPLICATION IN AGRICULTURE: EMERGING POLICY CONCERNS AND RECOMMENDATIONS

**Girija R** [1]

*This Policy brief highlights the challenges in agriculture and provides recommendations with respect to the identified problem – hurdles in reusing humanure in agriculture. It presents evidence and experience, through research results and findings from the field on application of human excreta-based soil inputs in agriculture in order to make informed decisions.*

> "Well balanced loop – A human being excretes the same amount of nutrients that he/she takes up in his/her diet. It takes the same amount of fertilizer required to grow food for a person as the amount of nutrients a person excretes"
>
> – *Jönsson et al. 2004*

## 1. An Overview of Agriculture Sector in India

Decreased agricultural productivity in India is due to water scarcity, deficient rainfall, increasing cost of inputs, nutrient deficiency and poor soil quality. Despite the growing use of fertilizers, the country is experiencing stagnation in agricultural productivity and degradation of soil quality. It is, therefore, critical to optimize soil productivity and yield, in order to meet growing food demand with decreasing cultivable land. Organic matter is vital for good soil productivity as it improves physical, chemical and biological properties of soil; it is therefore, referred to as 'Life of Soil'. The most common organic matter sources are farmyard manure, crop residues, and vermicompost. Some of these organic matter sources are dwindling, resulting in the need to choose alternate sources. Humanure (compost from human faecal material and urine) could be considered as an alternate organic matter source (Girija, et al., 2019).

Many cities in India still depend on on-site sanitation infrastructure, such as septic tanks and pit latrines for sewage disposal, which require periodic emptying. However, the lack of designated places for disposing faecal sludge (FS) leads to unsafe dumping on land and in water bodies, which in turn leads to a negative impact on the environment and public health. If we can safely recover nutrients from human waste by reusing in agriculture, a lot of money spent on fertilizers could be saved, especially the cost of the import of phosphorous fertilizers. This can only be achieved by giving back to soil, nutrients consumed and then excreted by humans and animals — or releasing back into the environment by reusing in agriculture as soil amendments by closing the nutrient loop. However, the main concern are the health risks associated with reuse. The risk groups are farmers, who through usage, come into direct contact

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with the untreated FS on their farmlands; and the consumers consuming the contaminated produce. The WHO 2006 Sanitation Safety Planning process provides an incremental improvement plan for safe reuse of wastewater, excreta and greywater, which would help in mitigating the risks associated with human waste application in agriculture.

## 2. Policy Concerns of Reusing Humanure (co-composted faecal sludge) in Agriculture

Many farmers in peri-urban towns of India are using human excreta as manure and the main problem faced by them is that the food produced using human waste is not considered as "Organic". The compost quality standards provided by Fertiliser Control Order (FCO) are for organic compost and for Phosphate Rich Organic Manure (PROM) made from the feedstock, wet waste - vegetable market waste and yard waste. There are no set standards for manures originating from human faeces. There are differences between national and international norms for application of humanure in organic farming. The standard requirements of the National Programme for Organic Production (NPOP) of the Ministry of Commerce and Industry state that "Manures containing human excreta (faeces and urine) shall not be used for organic farming”. NPOP further states that if treated wastewater or faecal sludge is used for fertigation or as a soil conditioner, then the product is no longer ‘organic'. The International Federation of Organic Agriculture Movements (IFOAM) state that 'organic soil fertility management does not use human excrement on crops for human consumption without measures to protect humans from pathogens'. Under one of the requirements for soil fertilization, IFOM also states that ‘Human excrement shall be handled in a way that reduces the risk of pathogens and parasites and shall not be applied within six months of the harvest of annual crops for human consumption with edible portions in contact with the soil’.

If we interpret the above norms, the international norms (please refer the underlined) allow the use of humanure in organic farming, provided necessary safety measures are taken at each level of operation. In this context, a study was conducted to evaluate the application of humanure or co-composted faecal sludge in agriculture as an alternative. This study provides scientific evidences through field experiments about the potential for co-compost application in agriculture while ensuring safety.

## 3. Application of Co-Composted Faecal Sludge in Agriculture

The study was launched at the Faecal Sludge Treatment Plant (FSTP) in Devanahalli, Bengaluru, in order to recover and reuse nutrients from treated FS to agriculture. Under the study, a field experiment was conducted, and the methodology followed was ‘Randomised Block Design’ (RBD). This study conducted by the agricultural trials, therefore, aims at assessing the impact of co-compost application in comparison with other treatments/nutrient sources like faecal sludge, farmyard manure, chemical fertilizers and control on crop growth and development and yield parameters. The study involved co-composting of faecal sludge (FS) with Municipal Wet Waste (MWW) producing nutrient balanced co-compost/humanure, which is one of the inputs used for the field experiment conducted in the study area. The windrow method of co-composting dewatered faecal sludge (FS) with organic solid waste will eliminate pathogen contamination (Koné, et al., 2007). The sample test results showed that the final matured compost produced by co-composting dewatered faecal sludge (FS) with organic solid waste meet most of the Fertilizer Control Order (FCO) standards. The final co-compost was able to maintain the nutrient balance - C: N ratio - and is free from pathogen contamination.

The field trial included cultivating two crops – field beans during Kharif season followed by sweet potato during the Rabi season. The first crop, field beans, was grown under different nutrient sources - as mentioned above, through RBD. Field bean is a high growing crop, which grows above the ground; its edible parts will not come in contact with humanure. The second crop, Sweet Potato, is a residual crop, hence the treatments were not imposed again. Sweet potato is a root crop in which the edible parts will come in contact with the applied humanure (Girija, et al, 2019). Hence, these two crops were selected for the experiment i.e. to assess the pathogen contamination in both - high growing and root crops. Post-intervention, the final produce was assessed for pathogen contamination.

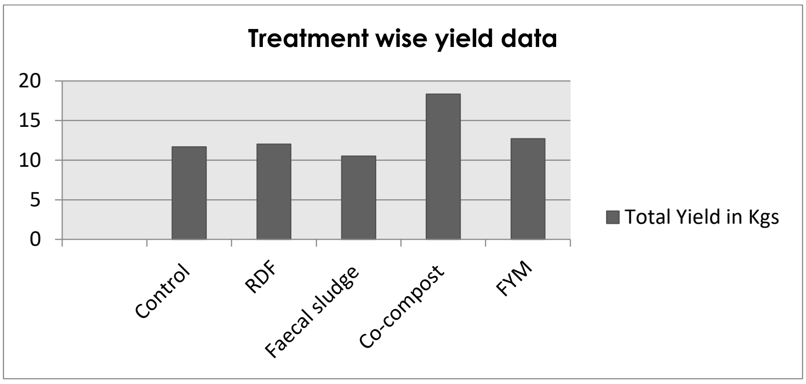


Figure 1: Treatment wise yield data of Field beans

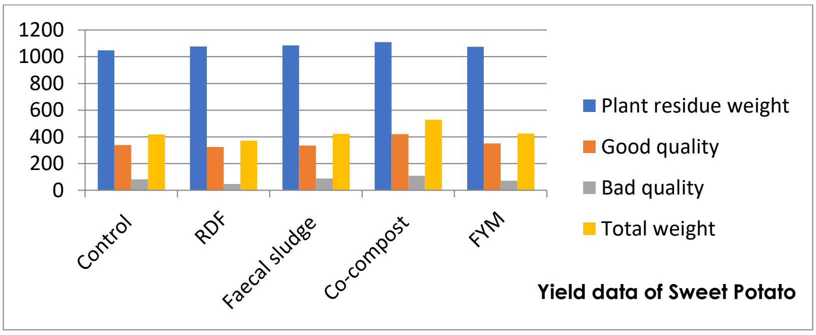


Figure 2: Treatment wise yield data of sweet potato

The findings from the field experiment showed that the differences in yield for both the crops among different sources of nutrients were slightly significant (Figure 1 and 2 – Source: Girija et. Al, 2019). The yield difference due to co-compost application was higher compared to other sources. But, the results for crop growth and development were not statistically significant. The final produce, field beans from all the five treatments were tested for pathogen contamination. The results showed that the produce was free of E. coli and Faecal Coliforms. The Sweet Potato sample was also tested for pathogen contamination. The test report results showed negative for Helminths Egg presence both in the pulp part and the edible portion with skin. The study also proposes to repeat the field experiment for few more cropping seasons to come to a definitive conclusion of the above findings (Girija et. Al, 2019).

## 4. Conclusions and Recommendations

Overall, it was found that the use of human excreta-based soil inputs in agriculture is an important alternative in farming as it enriches the nutrient content of the compost. Safe reuse of humanure in agriculture by following health protection measures will greatly benefit the farming community by enhancing soil productivity thereby increasing crop production. These will, in turn, have significant economic benefits, by reducing expenses on public health and environmental protection. The contents of the pits can be turned into valuable fertilizer, thereby a family's waste turns from being a liability in a septic tank to a growing asset. Human excreta-based soil inputs should be promoted for application in agriculture considering their nutrient significance. The paper proposes to repeat the field experiment for a few more cropping seasons to generate more evidence to support the argument.

Below are some of the recommendations from the study:

- The study findings showed that the final matured co-compost meets most of the Fertiliser Control Order (FCO) standards and is free from pathogens. Hence, this study would recommend including faecal sludge as one of the feedstocks under compost quality standards provided by FCO for organic compost.
- Providing Marketing Development Assistance for the direct sale of humanure by compost manufacturers to farmers will make it more economical.
- Humanure should also be co-marketed by tagging of cities with fertilizer marketing companies.
- The study findings showed that the humanure/co-compost reuse is safe for application in agriculture as the final produce (both high growing and root crops) is free from pathogen contamination. Hence, the study would recommend including humanure as an organic source under IFOAM organic soil fertility management and the produce grown by using humanure should be considered as ‘Organic’. This would encourage farmers to use human excreta-based soil inputs as it increases crop yield.
- Promote humanure application on the lines of city compost marketing, this would encourage famers to use humanure in agriculture.
- There is a need to take measures to popularise humanure by providing the direct incentive or subsidy on use of co-compost to farmers. The available assistance (subsidy) on the sale of compost from municipal solid waste should be considered for the sale of humanure.
- Sanitation and food are very often treated and practiced as two unrelated topics, but they are equally relevant to issues of under-nourishment and malnutrition. Closing the nutrient loop by reusing human waste in food production has great potential in addressing sanitation and agriculture issues. Mainstreaming nutrition in the WASH (Water, sanitation, and hygiene) discourse is thus the need of the hour.

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**Disclaimer**

This Policy Brief is a working draft that represents the views and recommendations of the author. The author alone is responsible for the views expressed in this paper. It should be noted that the document is being published for comments on its substantive merit and policy implications.

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# Accountability in Solid Waste Management: Critical Insights from a Waste Management Dispute in Kerala

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**Abstract**

Accountability serves a corrective purpose by making it feasible to address individual or group concerns and penalize misbehavior by the people and institutions in question. Based on the study of waste management in different regions of Kerala, the paper discusses and explores accountability and environmental concerns in solid waste management. Effective solid waste management systems are required to promote greater human health and safety. This is a qualitative - case study done with the help of secondary information obtained from different sources. The research work with a similar end was also reviewed to clarify the conceptual and descriptive parts of the study. The investigation analyzes how far decentralized waste management in Kerala aims to fix operational excellence in solid waste treatment. It also discusses the significant hurdles the area must overcome to achieve and retain this title.

**Keywords:** Accountability; Solid Waste Management; Environmental Concerns.

## Introduction

A democratic nation[1] like India must prioritize accountability (Merriam-Webster, n.d.) and openness, and it is essential for successful governance that citizens can demand these things from their government.[2] Even though accountability is difficult to grasp, knowing where it comes from can help citizens find ways to hold governments responsible. Fundamentally, accountability is synonymous with answerability; it refers to the duty to account for one's actions to specific people, groups, or organizations.[3] The most legitimate forms of government are those that uphold democratic ideals including accountability, representation, transparency, pluralism, and citizen participation in decision-making. When a government is unable to offer fundamental services, Citizens lose faith in it. As a result, the extent to which a government can perform its duties at any level typically determines a country's capacity to maintain democratic changes and ensure the welfare of its citizens.[4] Democracy is also dependent on the rule of law. All the following are reliant on responsible governments, equitable and open enforcement of the law, and adherence to universally recognized norms for human rights: Unbiased political and judicial systems safeguarding human rights, active civil society, public faith in the courts and police, and reform of the security sector.[5]

The study strongly advocates for more effective implementation of waste management rules in

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Kerala unless the administration accords high priority of the subject, the unfavorable condition may not be remedied. It is necessary to implement a strategic transformation through stringent oversight and the creation of specialized monitoring cells that establish accountability for deviation from laid down timelines by state and central governments. The main purpose of this study is to analyze the waste management performance of various districts, especially in the urban areas in Kerala. By examining the waste management system, this research attempts to analyze how to handle disaster like situations in Brahmapuram (Kerala). Due to the poor handling of plastic waste in Brahmapuram, the state is being portrayed in a negative light to the rest of the world. The state had 3,34,06,061 people, or 2.76 percent of India's population, according to the 2011 Census of India.[6] At 450 grams per person per day, the State produces around 15000 tons of trash daily. The center and northern regions of the State are anticipated to produce more waste in the future than the southern region. Kerala's rural communities may clearly see the effects of garbage generation in metropolitan areas. Highland Kerala's rural areas produce about 380 grams of carbon dioxide per person per day, compared to over 400 in cities nearby, 419 in municipalities, and about 545 in corporations. The continuum of uncollected rubbish along its corridors that run through cities and other areas also exhibits the ru-rban pattern[7] According to a comprehensive environmental evaluation based on the CEPI score (CEPI is an innovative global partnership working to accelerate the development of vaccines against epidemic and pandemic threats[8], the industrial cluster in the Greater Kochi Area (GKA) has been ranked as one of the most dangerously polluted places in the country with a score of 75.08 in 2012.[9] Still, there have been no significant changes.

According to the Indian Constitution[10], solid waste management is a state subject matter, and it is the main duty of state governments to make sure that suitable solid waste management practices are implemented in all the cities and towns in the state. The general responsibility of the Indian government is to develop policy directives and, when needed, offer technical support to the states and cities. Additionally, it aids in the development of human resources for local and state governments, and it serves as a conduit for securing outside funding for the execution of solid waste management projects[11] Externalities on the environment[12], biodiversity[13], and society have been negatively impacted by the lack of sanitation and waste disposal services. Therefore, it is crucial to develop environmentally friendly options for infrastructure and services that are suitable for Kerala while also enhancing institutional capabilities to design, plan, and manage them.[14]

## Methodology

This is a qualitative-case study done with the help of secondary information obtained from different sources. The research work with a similar end was also reviewed to clarify the conceptual and descriptive parts of the study. The analytical framework is built around the concept of accountability in solid waste management. Vance, Lowry, and Eggett (2013) describe the theory of accountability, it is important to distinguish between the two main applications of accountability, which are as a mechanism and as a virtue. In this sense, accountability is a positive attribute of an entity since it is seen as a virtue in which an individual exhibits a willingness to accept responsibility, a desirable trait among public officials, government organizations, or corporations. The concept of accountability is understood as a system wherein an individual may be obliged to defend their activities to a third party with the power to judge them and impose possible consequences on them.[15] To enhance solid waste management, the government has introduced several programs, such as MSW development (Municipal Solid Wastes) rules, the creation of a SWM (Solid waste management) manual, and JNNURM (Jawaharlal Nehru National Urban Renewal Mission was a massive city-modernization scheme launched by the Government of India under the Ministry of Urban Development) changes, but little progress has been made. For example, scientific treatment and sanitary disposal have not taken off, most PPP (public-private partnerships) initiatives have not yielded positive outcomes, and standard enforcement is a serious issue.[16] So the primary goal of this research is to examine the waste management performance of several districts in Kerala, particularly in metropolitan areas. This study examines the system to determine how to handle disaster-like scenarios in the Brahmapuram region of the Kochi district (Kerala). It must be realized that everyone is responsible for trash management, and there is no use in blaming one another. What is required is a shift in attitudes regarding the priority we place on waste management. The information came from peer-reviewed papers, meta-analyses, government or private sector databases, and datasets. This investigation also made use of information gathered by government ministries, as well as organizational records and statistics.

## Study Area

### *Waste Management and Accountability*

The legal system is a powerful tool of accountability since it is a major guarantor of the rule of law. Citizens and non-citizens can use the legal system to formally assert their rights and seek restitution, and a powerful, independent, and well-respected judiciary can serve as a check on the arbitrary exercise of state power.[17] However, those in poverty face significant obstacles to accessing the justice system and are more likely to be denied protections under the law pertaining to property, labor, and business. Legal empowerment techniques assist citizens demand accountability from officials while enhancing the accessibility of the legal system. These include giving citizens the knowledge and opportunities necessary to access institutions and services, as well as raising awareness of citizens' rights. However, state organizations and authorities might try to undermine this accountability.[18] To assess two or three distinct circumstances in Kerala, it is crucial to use these interpretations of accountability. In 2023, The ODF Plus ranking[19], which was done as part of the central government's Swachh Bharat Mission rural efforts for waste management[20], places Wayanad district top in the three-star category. The rating is a component of a strategy to improve rural residents' hygiene practices to make towns and villages cleaner, more attractive, and waste-free[21] Swachh Bharat Mission was introduced as a nationwide effort on October 2, 2014, across the entire nation. The initiative seeks to realize the goal of a "Clean India" by October 2nd, 2019.[22]


**Source:** Government of Kerala. Plastic and Other Non-Biodegradable Waste Management in Kerala (2023).https://swachhbharatmission.gov.in/sbmcms/writereaddata/Portal/Images/pdf/Kerala-Plastic_and_other_NBW.pdf

In 2022 the Swachh Bharat Mission (Urban) national ranking, the Kalpetta Municipality (Wayanad District in Kerala) achieved open defecation-free (ODF) ++ status, a first for the State, for its meritorious accomplishment in solid and liquid waste management. While only one urban local body (ULB) in the State has been chosen for ODF++ status, up to 35 ULBs have been chosen for ODF+ status, including four in the Thiruvananthapuram district, five in Ernakulam and Kannur, four in Alappuzha, Malappuram, and Kottayam, two in Idukki, three in Thrissur, and one each in the Pathanamthitta, Wayanad.[23] In the 14 districts of the State of Kerala, there are as many as 491 Model ODF Plus villages, 12 Aspiring ODF Plus villages, and 17 Rising ODF Plus villages, for a total of 520 ODF Plus villages. The State Administration is conducting various capacity-building exercises to train officials and speed up the implementation of activities across all ODF Plus verticals to speed up designating more villages as ODF Plus.[23]

The ODF Plus progress reported by the villages until the first of October 2022 will be used to determine the ratings for Panchayats and Districts. Below is a list of the weights for the various ODF Plus village categories.

ODF Plus (Model) Verified - 100%

ODF Plus (Model) - 80%

ODF Plus (Rising) - 60%

ODF Plus (Aspiring) - 40%.

**Source:** Ministry of Jal Shakti (2023). Categories of ODF Plus villages. https://sbm.gov.in/SSG2023/ODFPLus Ranking Delta Score.aspx

All households and institutions in the ODF Plus - Aspiring category, in addition to having access to sanitation through private latrines, also have plans for either solid waste management or liquid waste management; those in the ODF Plus - Rising category, on the other hand, have plans for both solid waste management and liquid waste management. All the following are present in those that have been designated as ODF Plus-Model where informational, educational, and communicational messages are distributed and presented.[24]

So, the efforts to rid the community of open defecation and manage solid and liquid waste with public support will contribute to outstanding success and this will help to achieve the central theme of accountability. Accountability is put up on clear intentions so if pollution-related problems do occur state should be able to limit related distractions through efficient remedies, like judicial and other redress mechanisms, sanctions, administrative fines and action, and civil liability. To protect the human rights of those who are impacted by hazardous chemicals, the government must maintain laws and ensure their rights including the right to participation, access to justice, and right to access to information that helps to maintain sufficient vigilance over the government which makes them more accountable. Attacks on environmental human rights activists are increasing, which may silence lawful protests and activism and will also force them to limit accountability that may endanger the environment, unsuitable developments, and indignity in addition to violating their human rights.[25]

In India, The Ministry of Environment and Forests has announced the revised Solid Waste Management Rules, 2016[26], which clearly outline the duties assigned to various classes of consumers after losing the struggle against the rising wave of municipal waste.

**WASTE MANAGEMENT RULES**

The Plastic Waste Management Rules, 2016

The Batteries (Management and Handling) Rules, 2001

The Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016

The Bio-Medical Waste Management Rules, 2016

The E-Waste (Management) Rules, 2016

The Water (Prevention and Control of Pollution) Act, 1974

The Construction and Demolition Waste Management Rules, 2016

The Solid Waste Management Rules, 2016

**Source:** Government of Kerala Local Self Government Department (2023).Waste Management Rules | Local Self Government Department (lsgkerala.gov.in)

The logistical chain for garbage evacuation would therefore need to be provided by cities and municipalities, with a system of cash reimbursement for the consumer in place. The regulations that were published 16 years ago utterly failed in the absence of such a system. Urban municipal organizations found it practical to simply transport waste to the suburbs, often using private companies that won lucrative long-term contracts.[27] Construction and demolition waste management rules violations are subject to the criminal penalties outlined in the Environment Protection Act of 1986 (29 of 1986). Swachh Surekha has given Kochi Corporation very bad ratings for the last five years. In terms of sanitary standards, the city falls short in areas like sufficient garbage collection, waste treatment facilities, and an adequate supply of public restrooms.[28]

The six functional aspects can be used to organize the actions involved in managing municipal solid wastes from the point of generation to final disposal: Waste generation, handling, storage, and processing at the source, collection, sorting, processing, and transformation, transfer and transport, and disposal are all included.[29] However, the Brahmaputra garbage dumping yard in the Kochi district of Kerala was discovered to be exploited improperly, generating several difficulties for the surrounding people and environment, according to the 2016 Kerala State Waste Management Report. Additionally, the 2016 Advocate Commissioners report made clear the alarming situation at the site, where there was a flagrant disregard for the 2016 Solid Waste Management Rule as well as numerous directives from the tribunal from time to time. The Advocate Commissioner's report, which was submitted back in 2016, included several recommendations for proper segregation and composting but no meaningful coercive measures have been adopted as expected.[30] The Kochi Corporation was hit with a heavy fine of Rs. 1 crore in a 2018 order by the National Green Tribunal (NGT) for disregarding the 2016 Solid waste management regulation which is applicable to every municipal authority responsible for the collection, segregation, storage, transportation, processing, and disposal of municipal solid. The Kerala State Pollution Control Board (KSPCB)[31] should receive two equal parts of the fine money, according to the tribunal's judgment, and the Central Pollution Control Board should receive the other half.[32] Also, The Kochi Corporation has been ordered to pay an environmental compensation of Rs. 10.05 crore by the Kerala State Pollution Control Board (PCB) because the municipal body disregarded the Solid Waste Management Rules, 2016, at its Brahmapuram plant. The evaluation period runs from April 9, 2019, until the end of October. Soon, a report on solid waste management based on inspections made by board representatives and the State Level Monitoring Committee (SLMC) was delivered to the National Green Tribunal (NGT).[33] However, the State High Court ruled in 2016 that the order should be suspended, stating that "the direction contained in the order that pollution control Board shall take steps to prosecute the officers of the petitioner will stand stayed." Again in 2021, another updated status report was submitted by the Chief Environmental Engineer of the Kerala State Pollution Control Board before the tribunal explaining various remarks about the same issue including that the administration fails to protect citizens. It states that despite repeated requests over the past two years, there has been no significant action taken to comply with the Solid Waste Management Rules, 2016 (SWM Rules) or handle solid waste. The samples unequivocally demonstrate that the environmental standards are not being met, as is evident from the State Pollution Control Board's report. The Municipal Corporation is still engaging in unlawful activity. Work on bio-mining has not yet begun. The right to a clean environment is just as important as the right to live in a community free of crime. The assessed compensation has not been paid out. The composting facility with windrows is in poor shape. The Chief Secretary's affidavit fails to provide evidence of any concrete steps that have been taken that are working. The situation is therefore not at all satisfactory. Maintaining law and order and defending the populace against crimes are equally important as upholding the environmental rule of law. The potential for public health harm exists when environmental standards are consistently broken, in addition to violating the rights of residents.[34] (So one question raised in that report is whether the officers handling the situation lack the necessary expertise or whether they will fulfill their constitutional duty to maintain a clean environment for the citizens.

In general, government entities and municipalities prioritize the issues they are currently facing rather than considering problems that will arise in the future because of environmental decline. According to their perspective, they will deal with difficulties when they arise rather than now. Because acting for the environment does not result in electoral benefits or guarantee a seat for the next election. The challenge now is: How can we alter this mindset? We think that long-term planning and implementation should be done with a positive attitude. The establishment of a framework is necessary because legislation and its efficient enforcement are essential to sustainability.[35] A similar waste management problem like the Kochi Corporation troubled the people of the Trivandrum district in 2011.

The Thiruvananthapuram Municipal Corporation (TMC) was unable to handle waste in an economically viable manner before 2011. Nearly 80% of waste generated in the district, was dumped at Vilappilsala, the place which is the city's dump. Following local protests over the site's lack of scientific waste management in 2011, the city was forced to close the Vilappilsala dumpsite. Following the shutdown, TMC used a decentralized strategy to deal with the crisis under the direction of the Kerala Suchitwa Mission, a technical support project run by the Local Self Government Department of the Keralan government. After the shutdown, TMC used a decentralized strategy to deal with the crisis under the direction of the Kerala Suchitwa Mission, a technical support program run by the Kerala Government's Local Self Government Department. The Mission oversees giving local self-governments in the state technical and managerial support for trash management. To carry out this Mission, TMC collaborated with private organizations and self-help organizations to collect and treat garbage created in the city door to door.[36]

But in the case of Brahmapuram Since 2012, the Kochi Corporation has been handling and transporting the municipal solid waste of five municipalities (Aluva, Angamaly, Kalamassery, Thrikkakara, and Tripunithura) and two panchayats (Cheranalloor and Vadavucode-Puthencruz).[37] 383 tonnes of trash are currently delivered to the plant each day. Since then, residents of nearby villages have demonstrated against the area's careless and illogical processing and disposal of waste.[38]

Most of the plastic garbage is being dumped into Brahmapuram, which then pollutes Kadambrayar and Chitrapuzha.Around nine of Brahmapuram's panchayats receive their water from Kadambrayar.[39] The Central Pollution Control Board specifically in its report "Comprehensive Report on Prevention and Control of Pollution in Kadambrayar River: An Action Plan for Rejuvenation" in 2018 states that Water for the industrial zones like KINFRA, Infopark Phase-1, Phase-2, Smartcity, Cochin Special Economic Zone (CSEZ), and for businesses like Nitta Gelatin India Ltd, Philips Carbon, Wonderla, Cochin Kadaalas, among others, comes from Kadambrayar is on the rivers in India that do not meet water quality criteria.[40] So it is clear that the corporation violated several laws, including the Water Prevention and Control of Pollution Act of 1974[41], the Environmental (Protection) Act of 1986[42], and the Municipal Solid Waste (Management and Handling) Rules of 2000[43], which mandates that municipal solid waste collection, storage, segregation, transportation, processing, and disposal take place only within the bounds of the relevant municipality.[44]

A Parliamentary Act established the National Green Tribunal[45] to carry out six laws, including the Environmental Protection Act, and to accomplish the Stockholm Conference's objectives. The NGT is a tribunal with the authority to hear cases on its own motion. On largely quantifiable environmental issues, the NGT has the authority to step in and resolve conflicts.[46] In 2018, the NGT ordered to start of a new plant with the order to file a case against the secretary of the municipal corporation and impose a penalty on the Kochi Corporation for violating the solid waste management rules in Brahmapuram. The verdict was postponed by the High Court. The High Court did not explain why the order was stayed in the stay order. There is no dispute that the corporation violates the law, whether intentionally or unintentionally, and that it is not exempt from liability for doing so. However, it was still unclear how the court could have permitted violations of such statutory requirements. There had been an effort to set up a solid waste treatment plant at Brahmapuram[47] however, the offense cannot be wiped out.

The world is sick of promises that are not kept. If future commitments are not supported by efficient accountability procedures at every level and translated into noticeable improvements in people's lives, they will lack credibility and are less likely to be carried through. Responsibility necessitates those persons in positions of responsibility have clearly defined responsibilities and performance criteria, allowing for an honest and unbiased evaluation of their actions. Public officials and organizations must be accountable by providing rational arguments to those who may be impacted by their decisions, oversight committees, the electorate, and the public.[48]

Accountability necessitates political vigor because those calling for accountability must be confident that they can do so safely, that officials will respond honestly, and that social needs and demands are taken seriously. This confidence must come from individuals, interest groups, civil society, the courts, the press, and opposition parties.[49]

The acknowledged active civil society and energetic political action, which have developed over a long historical process, maybe what makes the Kerala ethnicity unique. The state's social and political history demonstrates that the growth of its civil society and strong social ties was not a gift, but rather the result of numerous forces.[50] Now, Brahmapuram has demonstrated how inadequate public services, such as waste management, can cause a great deal of insecurity among the populace. The failure, however, has also been the ineffective regulation of damaging human activities from the perspective of the environment. Acceptance of the strong, inclusive political parties' active support and cooperation with a thriving civil society as the solution to this problem must be gained. By depending on the High Court, legal violations persisted for four priceless years. The abuse was not persuaded by the court either. Unfortunately, a fire that started at the location on March 2nd, 2023, lasted for eleven days and caused a lot of hardship for the locals of the city and surrounding areas. The fire, which spread swiftly through the debris thrown over a 40-acre area, also caused panic. Over a sizable area, smoke from the burning plastic trash had been released. The health and environmental problems caused by the fire and smoke, as well as the ineffective waste disposal system, have drawn harsh condemnation from several sources.[51] The annual burning of plastic waste at the Brahmapuram facility, according to city residents, has been going on for the past 11 years, but only this year did things get out of hand. According to opposition leaders, one of the contractors hired to handle the building waste ignited the fire on purpose. An inexperienced Bengaluru-based company was allegedly given a Rs 54 crore bio-mining contract at Brahmapuram by the state government, according to the opposition.[52] After four years, in 2023 the Division Bench of the court lifted the stay when it realized the magnitude of the disaster.[53] Kerala's ecological way of life has been called out by Brahmapuram, and it now takes priority over all else. Waste management is one of the most important public goods, hence government equipment that is geared towards providing private products must be redirected to creating public goods.[54]

Although the government has waste management regulations to handle disaster-like situations in Brahmapuram, the agencies were not properly mobilized in response to the Solid Waste Management Rules.[55] The Indian waste management system could undergo a significant change because of the Solid Waste Management Rules.[56] The regulations seem too perfect to be true in a nation with such massive waste management. As opposed to being a piece of information in the statute book, legislation is more about execution and enforcement. Strong accountability legislation would alter the mindset of government employees since it will increase transparency through more effective implementation of the RTI statute. The government might switch from inactive to active disclosure, and it might switch from process accountability to goal accountability. We need a friendly bureaucracy with informed and empowered people for successful administration, not just powerful legislation. There are several causes behind this relaxed mindset, including

- There is no sufficient supervision of policy implementation.
- There are no absolute standards of punishment for employees who violate the rules when they are carried out since, in most circumstances, fear of penalty—such as financial loss, loss of emoluments, demotion, and advancement in the service—works.
- Delays are brought on by excessive red tape and stubbornness.
- Because of widespread corruption, conflicts of interest, ignorance of policies, and the digital divide, beneficiaries suffer the most.
- For the system to run more efficiently
- Raising people's levels of digital and non-digital literacy so they are more aware of their rights and entitlements and can comprehend how to lodge complaints with the system.
- The bureaucracy's mid-career sensibilization, as it is frequently already overworked and may not be able to handle every case owing to time and resource limitations.
- Educating civil officials about their responsibilities and instilling in them a strong sense of ethics and integrity.
- The correct application of technology to assure accountability.

## Study Results

Strong accountability legislation would change the mindset of government personnel by increasing transparency through more effective Right to Information (RTI) (Govt of India, n.d.) implementation. The government may shift from passive to active disclosure, as well as from process accountability to goal accountability. We require a pleasant bureaucracy. Brahmapuram has shown how insufficient public services, such as garbage disposal, can engender widespread insecurity in the community. The failure, however, has also been the ineffective regulation of environmentally harmful human activities. Acceptance of the active assistance and cooperation of strong, inclusive political parties with a robust civil society as the solution to this challenge is required.

## Discussion

The present waste management laws, which include a wide range of concerns such as waste treatment at the source, garbage collection and disposal, septage treatment, and waste removal from public places, should be severely enforced. Workers from the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) (Government of India, n.d.-a), Kudumbashree, citizens' associations, Haritha Karma Sena (HKS), and youth clubs would be recruited to clean up rubbish in public spaces. Local bodies should keep the district administration informed of progress in implementing these types of action plans that help to increase the accountability of officials. Local governments cannot give up their duty to provide crucial services like waste management. Source-level waste segregation according to norms is critical to averting a repeat of the disaster that occurred at the Kochi waste dump. The National Green Tribunal's Principal Bench, chaired by Adarsh Kumar Goel, wrote: "Long stories of all-round failure of the administration are poor substitutes for good governance required to enforce environmental rule of law for protection of public health and the environment." The truth is that the administration is failing to protect residents' right to a clean environment, which is no less vital than the right to live in a crime-free environment. Despite repeated directives over the last two years, there has been no real activity to comply with the Solid Waste Management Rules, 2016 (SWM Rules) and solid waste handling of solid waste despite repeated directions in the last two years"(The Hindu, 2023a). Environmentalists who have been closely investigating the Brahmapuram disaster for a long time believe that decentralized garbage management, which has been successfully carried out in other parts of the state, is the only solution to Kochi's waste dilemma. Households can implement a composting system that is appropriate for them. Then there can be decentralized composting systems costing 10-15 cents in small pockets. This could handle approximately 65% of the garbage.

## Conclusion

Kadambrayar and Chitrapuzha became contaminated when most of the plastic waste was disposed of in Brahmapuram. Waste mismanagement has a direct impact on Article 21 of the Constitution, which states that everyone has the right to live in a clean environment, with access to clean water and air. Approximately nine panchayats in Brahmapuram obtained water from Kadambrayar. Therefore, the will to carry out worthwhile projects for the public, regardless of political differences, is more important than all of this. Projects should be combined with accountability to provide a sustainable remedy for this solution. Projects should prioritize Solid Waste Management services such as primary waste collection and transportation, source segregation and treatment at the decentralized level, resource recovery facility development and/or rehabilitation, and biodegradable waste management facility development. To increase the efficiency or accountability of officials, first information automation is necessary, which means officials should be compelled to post all information in the public domain so that anybody may access it, rather than acquiring it through RTI. Second, it is necessary to foster an attitude of sensitivity, which means public officials should participate in training sessions and awareness campaigns to help them understand the effects of their actions on the lives of others. Third, the general public's awareness is necessary, as people who are covered by socioeconomic programs view them as government-granted privileges. They should be made aware that they have the right and the ability to demand that they receive the benefits under a system. Finally, the grievance procedure needs to be made available. Anyone who does not receive their fair share of benefits under a program should be able to file a complaint and follow its development. These grievances ought to be made public as well. The role of media is also important, which helps investigative reporting by the media to identify the regions that have reaped the greatest rewards and others that have lagged.

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Working Paper 545

# Civic Activism in Urban Waste Management in Bengaluru City, India

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**Dipak Mandal and S Manasi**

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## Civic Activism in Urban Waste Management in Bengaluru City, India

**Dipak Mandal[1] and S Manasi[2]**

## Abstract

*This paper aims to examine the role of civic activism in urban waste management in Bengaluru city. It explores the present status of waste management in the city and civic involvement in improving the city environment by gradually turning it into an environmental movement. Lately, civic groups have played a significant role in community interests where the ecology and environment are central concerns. Given this backdrop, this paper documents initiatives taken by environment activists and their partnerships with the city corporation in promoting effective governance, specifically in managing the waste of the city. Furthermore, the paper also examines how the groups negotiate with the government and other agencies for the adaptation of sustainable initiatives and policies to manage the urban waste in the city.*

**Keywords:** urban waste-related movements; urban environmental movements; urban waste; civic groups

## Introduction

In recent years, different groups in urban areas have been showing rapidly increasing interest in social movements or civil society movements. Their interest has been reflected in participation of local activists in the urban governing process. Besides, urban politics has played a significant role in policymaking through participation and legal tools (Bitusikova, 2015). To raise their voice and bring attention to community interest, they employ methods related to urban mobilisation. Different types of urban mobilisation are carried out by many civil society organisations. For example, Resident Welfare Associations (RWA), neighbourhood development groups, religious-cultural and political oriented groups, local interest groups and protest organising groups (against the policies or decision for privatising the common resources). This community interest acts as a driving force in changing the urban system and can be described by the concentration of urban problems (Castells, 1983). With increasing urbanisation and the resultant population expansion and accretion of economic activity, the urban problems are securing central attention from the policymakers, urban planners and civil society organisations.

Environmental movements in the urban areas in India are seen much later compared to rural areas. But in recent days, various protests and agitations have been observed in the urban areas across the country as various studies found that rapidly growing urbanisation harms the environment (Kundu, 2007; Sridhar and Kumar, 2013). These agitators have drawn special attention to poor sewerage and sanitation facilities, lack of proper management of water bodies, urban waste, lakes and open space. In September 2019, various student groups protested in Chennai, Bengaluru, Mumbai, Kolkata, and Delhi responding to teen activist Greta Thunberg's call for action against climate change. The capital city of Delhi has seen various protests in 2019 and in earlier years against air pollution. Various social groups, activists, student organizations, and NGOs have participated and raised a slogan demanding the 'Right

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to Breathe'. Residents of Uruli Devachi and Phursungi in Pune, Maharashtra have continuously protested from 2015 against the illegal landfill in their area and in 2017 they held a strike and prevented the entry of garbage loaded truck into the landfill. A similar kind of protest was observed at Kodungaiyur area in Chennai against the dumping of garbage by local contractors as the residents face various health-related issues due to this landfill (EJ Atlas). Similarly, Bengaluru city has seen numerous protests organized by people, RWAs, activists, and NGOs against the city government for proper management of urban waste and protection of urban lakes. Some of the protests have drawn huge attention at the regional level as well as national levels, such as Mandur and Mavallipura waste-related protests and Bellandur and Varthur lake-related protests.

## Urban Environmental Movements in the City of Bengaluru

The city of Bengaluru is one of the fastest-growing million-plus cities in India as well as in Asia. This rapid growth and urbanization have led to a concentration of economic activities in the city. As per the census data 2011, 84.4 lakh people are living in this city with a population density of 4,381 persons per sq. km.[3] This unprecedented rapid urbanization and economic development in the past few decades have led to the rise in several environmental problems across the city. This city has become a platform of socio-economic-political and cultural transformation due to the increase in mobility. However, this diversity helps city dwellers to change their traditional ideas and accept the new policies and ideas (Sassen, 2002).[4] It makes the city environment a productive floor where the traditional and new civic engagement can spread easily. The ecology movements in India are the appearance of protest against the demolition of the two vital economics of natural processes and survival from the disorder of development, based mostly on market-oriented economy (Bandyopadhyay and Shiva, 1988).After the post-liberalization period, several multinational companies and economic activities have been concentrated in Bengaluru. The ecology movements are enlightening on how the resource demand of the present growth model has environmental damage and economic deficit built into them (Bandyopadhyay and Shiva, 1988; Karan, P. P. 1994). In India, most megacities face various issues, such as pollution, overpopulation, waste disposal, loss of biodiversity, reduced open spaces, urban lake pollution and public health-related issues. Given this backdrop, the objective of this paper is to document some of these initiatives/protests and a partnership that showcases civic activism in Bengaluru city and its influence on waste management and urban governance.

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# Waste Management Status in Bengaluru

The city generates more than 5,757 tonnes of solid waste per day and according to Bengaluru Master Plan 2031, the amount of waste generated per day will go up to 13,911 tonnes (The Times of India, December 1, 2017).[5] The Bruhat Bengaluru Mahanagara Palike (BBMP) is responsible for the collection, transportation, processing and disposal of municipal solid waste from the different originators. But, out of the total amount of waste, only 30 per cent of waste is collected by BBMP directly and 70 per cent of municipal solid waste is collected and transported through a contractor (Naveen & Sivapullaiah, 2016). Proper collection and management of municipal waste are taken care of by several Pourakarmikas, drivers, and supervisors engaged with the BBMP (see annexure 1).To manage this huge amount of municipal solid waste, BBMP has created several waste processing plants in different parts of the city. The role of this waste processing plant is to segregate the mixed waste and generate economic value from the waste after segregating it; only non-recyclable waste is eligible to go to a landfill (see annexure 2). With proper utilization of urban waste and to generate economic value from it, the city government has taken several policies regarding energy creation from the waste. On March 9, 2018, the BBMP signed a partnership agreement with a French company to set up a waste-to-energy plant. Earlier also, the BBMP had set up a few waste processing plants to generate energy from waste, but the power output (MW/Hour) was less due to a lack of infrastructure (annexure 3).

As mentioned earlier, 70 per cent of the total amount of solid waste is handled by the contractors. There are serious concerns as there is a lack of transparency and accountability, poor guidelines, and loopholes in agreements and arrangements. All this has resulted in poor management of waste.

**Table 1: Waste Management Status in the City of Bengaluru**

| Sl. No. | Waste Management Programme | Present Status |
|---|---|---|
| 1 | Segregation of waste at source | The segregation level has failed to cross 50% |
| 2 | Collection of sanitary waste separately | Yet to pick up speed |
| 3 | Dry Waste Collection Centres (DWCC) to directly collect dry waste door to door | On 65 wards; MoU is being negotiated for another 70 wards |
| 4 | New garbage tender/micro plans/cooperative societies | New tender and cooperative societies pending approval from the council |
| 5 | Moving Refuse Derived Fuel (RDF) backlog from the processing unit | In progress; expected to be completed in July |
| 6 | 2,000 bins on city streets; 250 semi-buried bins | 2,000 bins to be installed in a month; semi-buried bins to take six months |
| 7 | Clean-up marshals | Pending approval from the council |
| 8 | Shuchi Mitras | BBMP invited applications recently, two years after the proposal |
| 9 | Waste to energy plant | Five plants in the pipeline, work yet to begin |
| 10 | Bio-remediation in Mandur and Mavallipura | Only one bidder for tender for Mandur |
| 11 | Dedicated plant for construction and demolition waste | The tender process for three plants is in progress |
| 12 | Dedicated processing plant for animal waste | Choice of technology finalised, tender yet to be called |

*Source*: The Hindu, June 7, 2017

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Without proper disposal of solid waste, it pollutes the vital elements of the living environment like air, land, and water. On paper, there are several policies related to municipal solid waste (MSW) management, but on the ground, there are many problems with its implementation. This lack of proper management of urban waste creates various issues and as result, the government faced various types of protests organised by people and civil society.

**Table 2: Role of Protest/ Agitation on Waste Processing Plant**

| Sl. No. | Plant Location | Capacity (T/PD) | Current Situation |
|---|---|---|---|
| 1 | Chikkanagamangala | 500 | Destroyed in the fire; takes no waste |
| 2 | Doddabidarakallu | 200 | Overloaded with RDF and Compost; Takes no waste |
| 3 | Kannenahalli | 500 | Closed after protests |
| 4 | Seegehalli | 200 | Closed after protests |
| 5 | Subbarayanapalya | 200 | Closed after protests |
| 6 | Lingadheeranahalli | 200 | Takes 60 TPD, only functional plant |
| 7 | MSGP Plant, Chigarenahalli | 600 | 500 TPD |
| 8 | Mavallipura | 500 | 500 TPD |
| 9 | KCDC, HSR Layout | 70 | 200 TPD |
| 10 | Quarry Landfills- Bellahalli, Bagalur, and Mittaganahalli | - | Over 2000 TPD |

*Source*: The Hindu, April 8, 2017

## Review of Literature

According to UNEP and WHO's Health and Environment Linkages Initiative Report (HELI, 2009), rapid, unplanned and unsustainable patterns of urban development are making developing cities focal points for many emerging environmental and health hazards. As urban populations grow, the quality of the urban environment will play an increasingly important role in public health concerning issues ranging from solid waste disposal, provision of safe water and sanitation, and injury prevention to the interface between urban poverty, environment and health. Unsustainable patterns of transport and urban land use are a driver or the root cause of several significant and interrelated environments and health hazards faced by urban dwellers in developing countries. David Satterth waite (2007) discussed the environmental health burden of the urban population in low and middle-income countries. This paper used comparative methods for explaining the environmental problems, different types of hazards, and supply of basic amenities between low and middle-income countries. This paper argued that there is a negative relationship between income groups and environmental health burdens. Amitabh Kundu's (2012) paper talks about the process of demographic growth, economic growth and the quality of the micro-environment in and around the city of Delhi. After the 1990s, when India adopted globalization and opened a trade policy, Delhi's population rapidly increased. Due to this reason, the city faces many issues like residential problems, lack of basic services in urban areas, waste management problems, environmental degradation and so on. To solve these problems, the Delhi government took policy measures regarding the peripheralization (spatial configuration) of the city. Under this programme, the city government created a new residential zone in other core areas for reducing the overcrowded population in core areas. But this programme has had negative impacts on the regional economy, standard of living, and urban environment. He argued that transferring of environmental burdens in space and the process of degenerated peripheralization has a serious long-term cost implication for the regional economy.

R E Jones; J M Fly and H K Cordel's (1999) paper tries to find out whether urban residents are more concerned about environmental issues than rural residents or not. They found that urban people are more concerned about environmental issues. Also, they argued that local issues are more significant than national issues because people are closely related to local issues. They found that literate people, political awareness and high-income groups are more conscious of environmental issues and also demographic variables (religion, ethnicity, age, gender) have a higher impact on environmental issues. Xie and Ho's (2008) paper examined the role of the formal and non-formal organizations on urban environmentalism in two major cities in China, one in Xiangfan (now renamed Xiangyang) and another in Shanghai. In China, political conditions and cultural context have played a significant role in these movements. At the lower level (grassroots level) individual activity was more significant rather than organizational activity. The environmental activity in the central city, Xiangfan, is different from the eastern city of Shanghai. Shanghai is one of the more economically developed cities in China and also it is well connected globally. Thus, western tradition plays a major role in this city. Moreover, environmental NGOs have played a significant role in involving people in these movements. Brand, P. (2004) talks about the general theoretical perspective and the methodological approach of urban environmentalism and discusses the political economy and neo-liberalization for sustainable development of an urban area. This paper argued that neo-liberalization has promoted an open trade market and globalization. In this open trade market, the world's developed countries invest their money in an underdeveloped country and control the city’s economy. This process has increased the conflict between the international organization and the local governing body. This trend also increases geographical spatial segregation, poverty, and environmental burden. Yangpi Tong (2005) discussed the role of political ideology and local institutions on environmental movements in Taiwan and China. These two countries are closely related to a socialist ideology and that's why decentralization politics has played a significant role in any social movement. At the grassroots level, there are different groups due to different ideologies. In socialist countries, every social movement is controlled by the local governmental organisation. Under the decentralization policy, the local institution plays a major role in protecting the environment because people are closely related to this institution.

Another study by Enqvist *et al* (2014) shows that the citizen networks in Bengaluru function as a platform that enables interaction between diverse interest groups and acts as a watchdog that monitors urban ecosystems. A paper by Bob Hendriks (2009) focusing on governance networks and democracy shows a shift from a normative focus on participation and voice to political rights and influencing the rules of the game. Based on Nairobi's experience, the paper emphasises that international donors and support organizations should increasingly build community structures and innovative post-liberal citizen engagement mechanisms for influencing political rights independent of changes in governance network approach, support simultaneous conflict and cooperation strategies beyond the emergence and formation stages and increasingly offer real space and support to local solutions and innovations regarding co-governance rather than blueprint solutions.

Manasi and Deepa (2020) talk about arsenic contamination and environmental degradation of Hootgalli village in Mysore. This village is affected by water contamination (arsenic) due to industrial effluents. The major source of industrial effluent here is potassium nitrate which comes from the manufacturing sector. Potassium nitrate has increased the Biological Oxygen Demand (BOD) in the lake, water-borne diseases, and arsenic contamination in groundwater. A political leader identified those problems first and after that local people protested against the industrialists. The local people want two things- they want adequate drinking water and the shutting down of the industry. Vote bank politics and political ideology has played a major role in this movement. Another paper by Manasi has tried to focus on urban flooding and its causes; and urban conflict in Bengaluru. Before 1990, Bengaluru had 370 tanks and this number has rapidly decreased due to urbanization, industrialization, and encroachment of open space. Also, urbanization has decreased groundwater storage and infiltration rate. In the monsoon season of Koramangala, the lakes are reserved for rainwater and after that new grasses come up in that lowland. These new grasses are good for cattle as well as the environment. But, when the new policy and new construction came, this procedure was interrupted. The new policy and the construction organization hurt the system of water bodies in the Koramangala area. The local people and NGOs have protested against the Bengaluru Development Authority (BDA) and new construction. The Karnataka High Court said that BDA should involve local residential representatives in the Koramangala area development. After this protest Rs. 400 crore has been spent from 2006 to 2011 for re-modelling of the drain, rejuvenation of lakes, and there was also a Rs. 640 crore grant under the JNNURM programme.

According to Erin L Gordon (2012), the modern environmental movement was started in 1960 and 1970. The modern environmental movement covers broad and different areas of institutional oppression. Such oppression may include the consumption of ecosystems and natural resources into waste. It also includes pollution of air and water, weak infrastructure, exposure of organic life to toxic chemicals and several other focuses. Due to the rapid increase of urbanization and industrialization in the 20$^{th}$ century, the largest cities like Tokyo, São Paulo, Mexico City, Mumbai, and Kolkata faced many problems because of unplanned growth, lack of transport and infrastructure planning, lack of proper sanitation and sewerage facility and waste problem. All the above-discussed problems that highlight the intensity and dimensions of the problems on certain occasions led to agitations and environmental movements. The environmental movement can simply be defined as a social and political movement mainly concerning the conservation of the environment as well as improving the state of the environment (P P Karan, 1994). Generally, environmentalists favour the sustainable management of natural resources as well as the protection of the environment via changes in public policy and individual behaviour.

## Research Gap

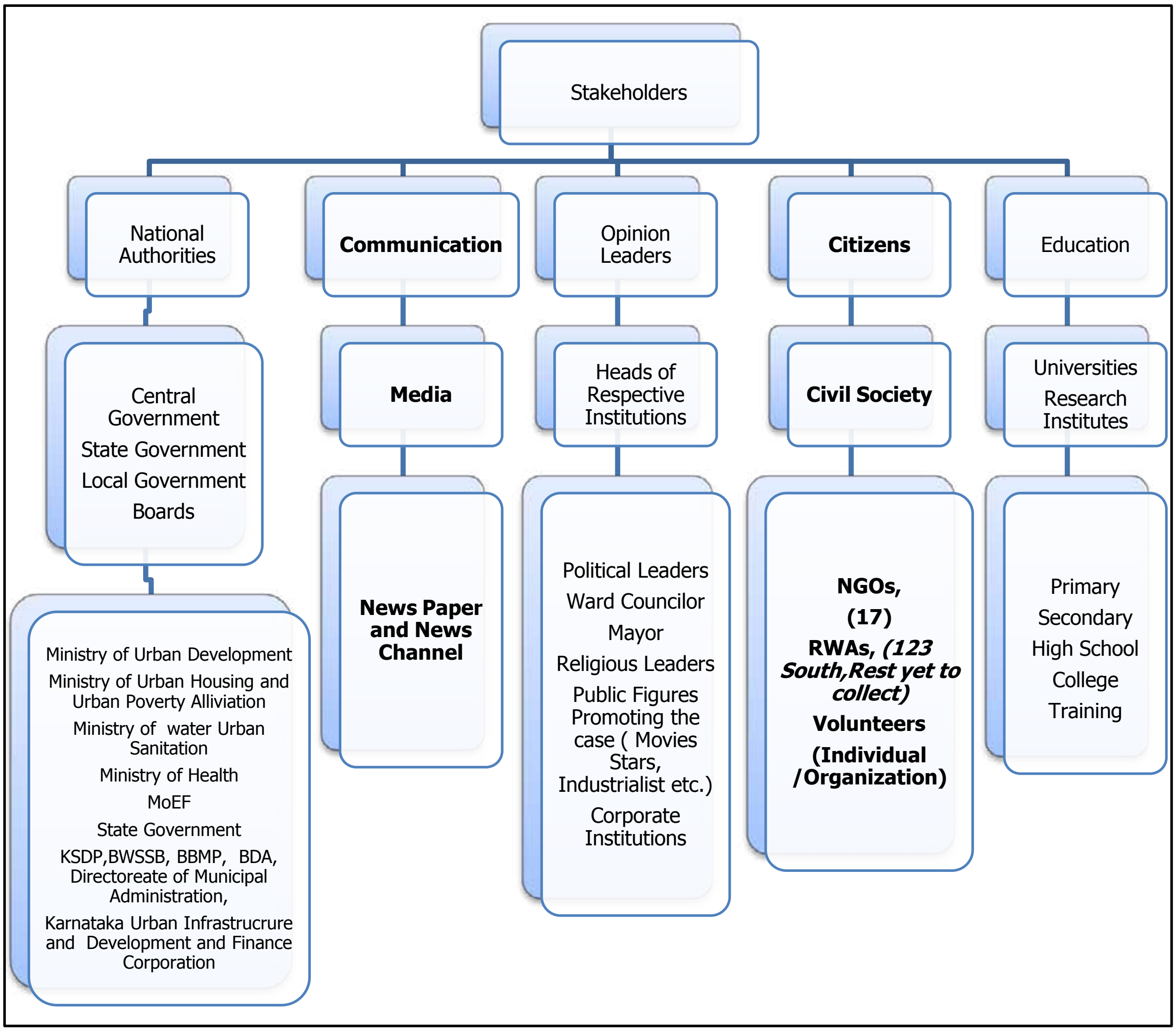
From the review of literature, it is quite clear that there are various MSW management related problems in terms of environmental challenges and governance. To solve the waste related problems, local governments promote a decentralised waste management system where the various stakeholders play an important role to solve the issues as well as bring changes in sustainable waste management. Sometimes they work together and other times as individuals to improve the waste management practices in the city. There are some studies that have discussed waste management, the negative impact on environment and health but there is rarely a study that has discussed the role of citizen group engagement in waste management in the city. The current study has filled this gap and discusses civic activism in urban waste management in Bengaluru City.

## Data and Methodology

The study has used both primary and secondary data to find out the waste management status as well as to examine the role of activity and mobilisation strategy of civic groups in urban environmental movements in the city. The collected data from the field survey have helped to identify the activity of civic groups, ward committees, policymakers and the BBMP for improving the city environment as well as solving the waste-related issues. For the collection of primary data, field visits, face-to-face in-depth interviews and group discussions with the Non-Governmental Organisations (NGOs), voluntary groups, and individuals who are engaged with urban waste management in the city were carried out.

***Actors Involved in Urban Environmental Movements*:** Several factors trigger urban environmental movements. It is observed that citizens, civil society, media, NGOs and Resident Welfare Associations (RWAs), and individual organizations are various institutional organizations that have been involved in collective action in demanding change, the more so when the threshold level is reached, affecting the quality of life. For instance, the agitation against the landfill protest in Mandur and Mavallipura waste processing plant in Bengaluru view is a perfect example, where people were agitated by a foul smell from a nearby agricultural field that was polluted with leachate. It is important to have a processing plant but the technology has to be in place to ensure there is no pollution as well.

**Figure 1: Stakeholder Engagement in MSW Management in Bengaluru**




*Source*: Prepared by Authors

The various stakeholders play an important role in MSW Management in Bengaluru. Additionally, increasing environmental awareness among the various stakeholders about the waste related issues have played a vital role in the formation of these civic groups. They focus primarily on their local problems which later spread locally to regional as well as global levels. Their functional areas range from participation in demonstration projects to monitoring and research, advocacy, environmental management, public discussion as well as cooperation and building networks among the other groups and governmental agencies towards sustainable MSW management in the city. However, in recent times, the range of their activities have broadened as rapid urbanisation, migration from rural areas and concentration of economic activities in cities have added various new challenges to waste related issues. Thereby, their activities now include public interest lobbying, participatory pressure groups, urban waste management related politics, environmental justice, ecological modernization, promoting environmental education, and capacity building programmes.

The paper has discussed three case studies to identify the role of various stakeholders and their impact on the city's waste management. The paper describes the location of the conflict, reasons, impact and people's views regarding the issue. Additionally, it discusses how these major protests have evolved into a movement to resolve the urban waste issues with the help of several initiatives taken by various stakeholders in this regard.

## Mandur Village Protest against Waste Dumping

The waste processing plant of Mandur is located 1.6 km from Mandur village. The surrounding area of this plant is occupied by agricultural fields, forests and plantation forests. Two Karnataka State reserve forests are located near this site; one is opposite to the plant while the other is located on the northern side of the plant. Eucalyptus and other mid-height trees densely dominate these two forests. This garbage dumping site has created several problems for the villagers. They are facing many health-related problems like skin diseases, respiratory problems, and water-borne diseases. Janardhan (resident of Mandur village) said: "During the night, the foul smell gets unbearable as the loaded trucks dump their garbage into the site". Also, he mentioned that "when we wake up in the morning, we see medium and lightweight garbage materials in front of our doorstep which is very disturbing". Another resident mentioned that "we get a foul smell 24 hours a day and our family members are not able to have food". Brush (resident of Mandur village) argued that "our agricultural land is affected due to this plant, scavenger birds, floating light particles of garbage; the stench is destroying our crops".

**The Conflict:** Bengaluru city generates around 4,000 tonnes of garbage per day and Mandur was getting nearly half of the total city garbage (Business Standard, June 3, 2014). On an average, more than 200 trucks dump unsegregated garbage every day. Due to the dumping of garbage, villagers faced several problems related to health and the environment. The garbage crisis threatened to go out of control and Mandur villagers started staging protests (DNA Bengaluru, December 10, 2012). A group of about 100 villagers staged a protest near Avalahalli police station where garbage lorries were parked on the roadside. When the villagers visited the BBMP officials on a Wednesday, the authority asked them to wait till Saturday evening for a letter. At their request, the villagers submitted letters to BBMP regarding their problems and requested them to close the landfill. Health minister Aravind Limbavali, BBMP commissioner Rajneesh Goel and Mayor Venkatesh Murthy promised the villagers that garbage would not be dumped in the landfill after January 29, 2013. Also, the officials promised to give it in a written format, which would be considered an agreement between the authorities and the villagers. But they did not get the letter from the authority by Sunday and they decided to protest again against the BBMP. On Monday, the communities living in and around Mandur observed a bandh, shop keepers downed shutters voluntarily, and the agitators forcibly locked the Mandur Gram Panchayat. However, the dumping of garbage continued and they used police protection for controlling the villagers. Gopal Rao, a social activist and resident of Mandur, said that "the communities were not ready to trust the BBMP's assurance this time. We believed them twice, but only got cheated. We are suffering every day. We will no longer put up with it, he said and added that they were ready to keep a vigil round the clock to prevent the entry of any garbage truck." (The Hindu, June 2, 2014).

Another villager, Murthy, said that "the government and the BBMP are giving more value to the garbage than to the lives of the villagers." He added, "Empty assurances over the years have only compounded our problems and villagers are affected by several diseases because of the air, water and soil pollution caused by the mounting of garbage in our backyard. Our field has been affected and crops have become emaciated. Why should we give the BBMP more time to get its act together?" (The Hindu, June 2014). Manjunath Rao, another resident of Mandur, said that "we will withdraw the protest only when the dumping of garbage ceases". On June 2, 2014, twenty-one protesting villagers of Mandur were arrested for allegedly throwing stones at police vehicles and garbage trucks. Additionally, a police officer said that, if the situation goes out of control, Section 144 under Cr PC may be imposed on the village to ensure garbage dumping (June 4, 2014, The Times of India). The villagers organised a stronger protest against the dumping of garbage in Mandur on Tuesday (5th June 2014) and raised various questions about the city's garbage disposal system. There were un-cleared garbage heaps in many areas due to a lack of proper management of city garbage. Angered by the arrest around 300 villagers, mostly women, staged a dharna in the landfill area on Tuesday and were determined not to allow garbage trucks inside.

**The strength of this movement and current status**: In 2005, BBMP took Mandur village as a garbage dumping site. Due to this landfill, villagers were getting a negative impact on their health, environment and socioeconomic status. Mandur villagers have been protesting to clean up their villages and stop garbage dumping since June 2012. Following this massive protest, BBMP Executive Engineer Nagaraj arrived at the spot and assured the protesters that the problem would be solved in a week. He also promised that steps would be taken to ensure that only a limited number of trucks carry the garbage to the unit daily (May 13, 2014, Deccan Herald). Chief Minister Siddaramaiah assured that garbage dumping would be stopped after November 2014 and regular health check-up camps would be held for the villagers. Also, he assured the residents that, "we will also take up odour control and spraying of repellents to tackle mosquitoes". At present, BBMP has stopped the dumping of garbage at this site.

**Diverse views:** Due to a hill of garbage dumping in this landfill, people are facing several problems. The villagers said that the Mandur's water is unfit for consumption and most of them bought drinking water even though they cannot afford it. The villagers were getting dengue, malaria, skin problems, and chronic diseases due to the garbage. Mandur resident Manjunath Rao said villagers had health problems due to the garbage and stray dogs attacked their cattle and children. Anand, one of the villagers of Mandur, said that in one week, six people died in the surrounding area due to this landfill. Students were not able to attend school because of the stench and had to move to another place. In the past, Mandur was famous for blue grapes and mangoes and 80 per cent of farmers were engaged in this field. But now, it has almost vanished because of the stench and insects coming from the plant. Another problem faced by farmers is the lightweight garbage from the landfill such as plastic, paper, and other lightweight particles get blown by the wind and pile up in their agricultural fields. Additionally, the garbage dumps have increased social isolation. One of the villagers said that "nobody wants to come here and even if they come, they do not want to stay. For the young men of Mandur it is not easy to get brides; besides, there is no celebration of any kind". Keeping these issues in mind and solving these problems, the local people led by Doreswamy protested against BBMP in June 2014.

**Scope for Dialogue:** Regular and permanent solutions are necessary for the treatment and management of the city's garbage. It requires proper management and segregation at the source which will help to generate economic value from the waste. Additionally, it can be a good opportunity for job creation, and generating resources from waste by following a systematic way of waste management (reuse, recycle, reproduce, recreate and revalue) which will help to bring a healthy and clean environment.

## Protest Against Mavallipura Landfills

Mavallipura is a medium village around 25-30 kilometres from the Central Business District of Bengaluru and its area is 303.17 acres. Mavallipura has good environmental assets; from the side, it is covered by natural forests (eucalyptus, babul, and other long and medium trees), ponds and agricultural fields. Avalahalli state forest and Karnataka Forest Research Centre are located near Mavallipura village. This waste processing unit has 46 acres of land which is located in a sensitive environmental zone. BBMP has an agreement with the Ramky Infrastructure Limited to manage this plant and around 700 tonnes of garbage is dumped into the plant daily.

**The Conflict:** The suffering of the people of Mavallipura began in 2003 when a local landowner H. Bailappa agreed to lease his land to dump solid waste. Due to the absence of safeguards, this area faced stench, air, water, and soil pollution. Residents started a systematic protest against the landfill under the leadership of the Dalit Sangharsh Samithi. In 2007, the government set up another agreement with Ramky Infrastructure Limited (RIL) for a waste processing plant for an operational period of 30 years. The area of this waste processing plant was 100 acres and it was surrounded by an agricultural field, natural forests and common grazing pastures. There are many more alarming factors for the location of these landfills. The Mavallipura landfills are located 2.5 kilometres away from the river Arkavathi and comprehensively violate an order of the Karnataka Department of Forest, Ecology, and Environment that protects the 1453 square kilometres watershed of Thippagondanahalli Reservoir across Arkavathi from polluting facilities. Another shocking feature of these landfills is that they are located 5.6 kilometres from the critical defence facility – Yelahanka Air Force Base. A study by KSPCB tells us that the leachate released from Bailappa's and Ramky's dumps has contaminated surface and groundwater significantly, particularly the Mavallipura tank which is part of a chain of lakes that ultimately discharge into the Thippagondanahalli Reservoir. Most of the villagers in Mavallipura are farmers or raise cattle to earn a living and if landfills converted their grazing land into waste dump sites, they will lose their daily earnings. Through it got permission from KSPCB to handle up to five hundred tonnes every day, the plant got almost 1000 tonnes of waste per day (July 13, 2012, Times of India). Nearly eighteen lakh tonnes of garbage were dumped at Mavallipura from 2007 to 2012. As per the agreement, the managing body should use a scientific strategy for waste segregation and recycling, but there is no safeguard boundary and scientific technology in the plant (Leo Saldanha, Environmental Support Group). On July 12, 2012, villagers, resident groups and Leo Saldanha protested against the Ramky Infrastructure Limited and BBMP and they also filed a Public Interest Litigation (PIL) in the High Court.

**Current Status:** When the case opened, the court gave a one-week deadline to the company for covering the dump yard and provide financial assistance to families affected by health problems and those who lost their family members due to the plant. The landfill was shut down in July 2014 following the direction of the Karnataka State Pollution Control Board. However, in practice, the plant is still functioning and during field visits, the study found that around twelve loaded trucks were entering the plant per hour around 11 am (on Sunday). Santosh, one of the residents of the village of Mavallipura, said that "on any other normal day, the number of trucks entering is much more in comparison to the weekend as most of the offices and workplaces are closed in the weekend".

**High Point of Protest:** Due to illegal waste dumping, villagers face several health-related issues and many of them suffer from gastrointestinal problems, dengue, malaria, and skin disorders. Women and kids were badly impacted due to waterborne diseases due to this plant. In 2011, 15-year-old Akshay died due to dengue and Muniraju and Rajanna due to kidney failure. In these families, there is no previous family history of the prevalence of such chronic diseases and the villagers have accused the plant run by Ramky Infrastructure Limited (Leo Saldanha, Bhargavi S. Rao and K R Mallesh; June 30, 2012). Narayanappa (aged 55 years), a well-known farmer, used to cultivate various types of horticultural products but he was facing problems as his land was getting untreated leachate and light particles from the plant. Additionally, being so close to the site, his family suffered heavily from the plumes of smoke that arose from the massive mountains of waste that burnt to reduce waste volumes. He suffered a serious asthmatic attack and died (ESG Report, 2012). In the middle of 2012, residents and community groups plied pressure on Ramky Infrastructure Limited to stop waste dumping and they formed a volunteer group to prevent the entry of garbage loaded trucks into a dumpsite. On August 23, 2012, the BBMP deployed 600 policemen to force open the landfill for allowing the entry of the garbage trucks. At that time 36-year-old Srinivas, one of the protesters, collapsed in shock and died. Following this, on August 24, 2012, several hundred protesters from 12 villages in the vicinity of the landfill staged a protest at the Yelahanka General Hospital where the body of Srinivas had been taken and declared that the body would not be cremated till the BBMP paid compensation to the relatives of the deceased. However, police personnel, without permission from Srinivas's family, brought the body to his village and tried to cremate it. When people protested against this move, several leaders were arrested. The protesters did not give up, and finally, at 5 pm, L Srinivas, deputy mayor of Bengaluru, arrived at the scene and promised Rs 1 lakh compensation to the bereaved family. He also promised a meeting with the community leaders on the question of the landfill on August 29, 2012.

## Residents' Demand

1. A resident of Mavallipura and twelve other villages in the north of Bengaluru are demanding a CBI inquiry into the city's garbage contract system.
2. They want to fully stop garbage dumping near their village because it's reducing the quality of the environment and health.
3. They want a medical facility and drinking water supply from BBMP.

## Protest Against Lingadheeranahalli Waste Processing Plant

This waste processing plant is located two kilometres from Turahalli forest and 0.7 km from Somapura Lake. The south and south-west area of this plant are occupied by forest and agricultural land and horticulture crops are grown and livestock reared for their livelihood. "The rest of the land is sold for settlements and the land price depends on the distance from the waste processing plant; if the distance is small, then the land price is also low and if the distance increases, then the land price also increases." (Avinash, one of the villagers of Mattekalpalya).

In 2010-11, BBMP bought the land from the local landlord for the homeless population. In 2013-14, BBMP modified their decision and converted the land into a waste processing site. One of the local villagers Manoj said that the BBMP used a fake address of this plant to keep their activity secret. The actual location of this plant is Banashankari sixth stage, fifth block, Mattekalpalya. Due to this plant, people are facing breathing problems, as the plant emits a very strong stench. Avinash (a resident) said that five to six years back, this area was rich with flora and fauna. Local discussions revealed that it was common to see peacocks, Eurasian eagle-owls, varieties of butterflies, and even leopards. However, they had all disappeared after the plant was established. One of the villagers mentioned that before the setting up on this plant, they supplied vegetables and fruits to different parts of Bengaluru city, and currently, they are struggling to earn any money from agricultural fields. This waste processing plant dumps their un-segregated debris near their agricultural fields, affecting soil properties and reducing soil fertility, besides increasing insect attacks on crops.

**The Conflict:** Bengaluru is known as one of the highest growing city in India and it produces four thousand tonnes of waste every day across 198 wards in the city. This situation has created huge pressure on the city development authority for proper management and disposal of waste. In early 2014, BDA considered Lingadheeranahalli as a waste-processing plant site and this unit has a fixed capacity to process two hundred tonnes of wet waste per day. The BDA has taken this plan without consulting residents and other civic groups (May 11, 2016, Deccan Herald). That's why the residents and those in Banashankari Sixth Stage protested outside the Lingadheeranahalli garbage processing plant. They argued that this plant will harm groundwater, forest, and the environment. People were demanding their "right to breathe"; they don't want to see another Mandur and Mavallipura. Every day about twenty-five trucks, (each truck carrying eight tonnes of garbage) from the south zone, enter the plant (May 11, 2016, Deccan Herald).Hundreds of residents took part in a protest. Ramaswamy, a local villager led the protest on May 10, 2016, from 10 a.m. to 5.30 p.m., and said that the problems of bad odour, mosquitoes, and contamination of underground water table were not addressed despite several promises from the BBMP (11 May 2016, The Hindu). They demanded that the BBMP shut down the plant as it is affecting their health and posing a threat to the flora and fauna of BM Kaval reserve forest and Turahalli forest. There are chances of diseases caused by insects and that the leachate reduces groundwater quality. Three persons from the surrounding villages had died due to air and water pollution (May 11, 2016, The News Minute). Devaraj, a resident of Mattekalpalya near the plant, said that he and his children were unable to eat peacefully due to the stench and mosquitoes if the problem continued; he plans to shift to another locality.

Under the Municipal Solid Waste Rule 2000, solid waste management cannot be taken up near lakes and forests. The BBMP does not have a No Objection Certificate (NOC) from the forest department nor has it applied for clearance from the State Environment Impact Assessment Authority. "If our land is affected and the groundwater contaminated, our lives will be destroyed," says Devaraj, a farmer of Mattekalpalya (Jan10, 2016, Deccan Chronicle). Also, there are no uses for proper technology and buffer zone maintenance between the plant and the residents or forests. Srinivas, a member of the resident welfare association (RWA) said that the existing plant has very outdated equipment, which is why disposal is not occurring properly and toxic water is released into the Somapura Lake. Ramprasad, a convener of 'Friends of Lakes' explains that if the right technology is used, the proximity of waste treatment plants is an issue that can be tackled (Jan 10, 2016, Deccan Chronicle). He also said that "look at the sewage treatment plant in Cubbon Park. It is in the heart of the city, but the areas around don't face problems".

**Current Status:** T S Mahesh, president of the Banashankari 6$^{th}$ Stage Resident Welfare Association, said that they filed PIL in the National Green Tribunal Court with the local group, against the BBMP and it was moved to the Karnataka High Court. Also, they submitted a petition to the BBMP last year and held a protest in June 2015. But to date, they had not got any response. He said, "We will continue to fight as the plant is affecting 25,000 houses and eight villages." After this protest, Sarfaraz Khan, BBMP Joint Commissioner for Health and Solid Waste Management, visited the spot and assured the residents that he would discuss the problems with the higher authorities. Still, this plant was active and daily 20-50 fully loaded trucks dumped city garbage into the waste processing plant (Manoj, resident of Banashankari 6$^{th}$ stage, 5$^{th}$ block).

**The opposing stands:** They argued that if the landfill and garbage processing unit are continuing in this area, then they will face the following problems:

- ✓ Groundwater will be contaminated in the layout.
- ✓ Exposure to hazardous waste can affect human health.
- ✓ Environmental pollution around the layout; children and the ageing population is more vulnerable to these environmental pollutants.
- ✓ Biodiversity will be affected. This area has forests and a lake, that's why there are many special animals and birds there. They will be affected by this plant.
- ✓ The cleanliness of the layout will be lost.

## Lessons learned from these three incidents

- A proper and systematic way of disposal of waste is very important to protect human health as well as the environment.
- Site selection, collection and treatment of leachate, and the cover of the dump area need to be taken into consideration for the dumping of waste into landfills.
- Need to educate citizens, environmental activists, and engineers on the impact of hazardous waste on the environment and human health.
- Need to monitor and observe the environmental and professional ethics in industrial units to deal with and handle the waste.

The four cases discuss the implications and networks that were formed to oppose impacts. Several such instances are booming across the country, specifically in Bengaluru to fight for justice.

# Role of Civic Groups in Waste Management

Most of the environmental non-governmental organisations (NGOs) in Bengaluru came after the economic reforms. The study found that there are two types of voluntary groups or NGOs existing in the city (see annex4). One group don't believe in any kind of protest and want to work with the government to improve the city's infrastructure, basic facilities, and environmental quality. Another group wants to work with people, identify their actual problems and want to bring some changes in society through a protest or agitation.

**Table 5: Nature of Environmental NGOs in Bengaluru**

| Sl. No | Name of the NGO/ Voluntary group /Blog | Formation year | Focus area | Activist/ non-Activist |
|---|---|---|---|---|
| 1 | Bangalore Environmental Trust* | 1987 | Urban waste | Activist |
| 2 | SAAHAS Zero Waste* | 2013 | Urban waste | Non- Activist |
| 3 | Sensing Local* | 2016 | Urban waste | Non- Activist |
| 4 | Hasirudala* | 2013 | Urban waste | Non-Activist |
| 5 | The Ugly Indian** | 2010 | Urban Waste | Activist |
| 6 | Environmental Support Group* | 1996 | Urban Waste | activist |
| 7 | CIVIC | 1992 | Urban waste, lakes and Governance | Activist |

Symbol index: * NGO, ** Voluntary Group,

*Source*: Prepared by the Author based on the nature of group activity

In the proper management of the city's municipal solid waste (MSW), various initiatives have been taken by civic groups as well as local government ranging from awareness creation, segregation at source, collection and transport and disposal of waste. The citizen groups and BBMP have organized various campaigns and training programmes to manage the MSW as well as improve the city environment. Some of these programmes include Kasa Muktha Bengaluru';[6] 'Wake up Clean up Bengaluru',[7] 'My Waste my Responsibility',[8] and 'Not in my Backyard'.[9] For example, in the last few years, various civic groups have organized several campaigns and public discussions with the help of BBMP to ban single-use plastic. In this campaign and training programme, different types of people such as traders, street vendors, and restaurant owners have participated and shared their knowledge of waste management practices. Additionally, eco-clubs have been set up in schools and colleges where the students can be made aware of better management of waste. The group called Solid Waste Management Round Table (SWMRT) is one of the pioneer civic groups enabled to educate teachers, staff and students about Trashonomics and the best strategy for waste management. In the city, there are more than two hundred groups actively engaged with MSW management and also on social media where they discuss the current issues, transparency and accountability in BBMP's waste management system (Kalra and Manasi, 2020).

Segregation of waste is one of the most important tasks in MSW management and '2bin1bag' by SWMRT is one of the most successful initiative programmes. In this programme, the organic and rejected waste is put in green and red bins accordingly and recyclable waste is mainly collected in a bag. Due to unplanned urban expansion, waste management is the major issue in the city and due to this, various groups and individuals protested and filed Public Interest Litigations (PIL) against the government's waste management practices. The city generates a majority of the mixed waste and segregation of waste is the major concern in waste management (Kalra and Manasi, 2020).For the better management of waste, in 2015, the Karnataka High Court passed an order for the citizens to adopt the idea of '2bin1bag'[10] to segregate the waste at the source (November 30, 2018,Business Line). As per the SWMRT report, more than two lakh households adopted this initiative and many civic groups have taken a positive initiative to implement it within the city. Also, there are various stakeholders engaged in MSW management such as RWAs, itinerant buyers, rag pickers, and NGOs like Hasirudala, Sahaas, BPAC, and Swachha. Sahaas has its recycling unit and also they have a dry waste collection centre (DWCC) across the city where people can put their dry waste and e-waste. Another NGO called Hasirudala plays an important role to manage the waste from bulk generators such as apartment complexes, hotels, marriage halls, and hospitals. One of the other major functional areas of Hasirudala is to secure and improve the social status, providing identity cards, and looking at the health condition of waste pickers and the waste workers. According to them, more than ten thousand waste pickers received their occupational identity card in Karnataka.

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[6] 'Kasa Muktha Bengaluru' (garbage free Bengaluru) was launched by then Chief Minister Siddaramaiah, then Ramalinga Reddy ( Bengaluru In- Charge Minister) and others in July 24, 2013 at Freedom Park. This programme offers training to the pourakarmikas and BBMP's contractors; creates volunteer groups for awareness campaign; audit and monitoring of BBMP's waste management practices.

[7] 'Wake Up Clean Up' seven days expo was organised by BBMP with the help of other government bodies and NGOs from February 3-10, 2013 to find the best solution for efficient SWM in the city

[8] 'My Waste My Responsibility' promotes complete waste segregation and uses of eco-friendly products

[9] 'Not in my Backyard' refers to waste disposal in a safe and responsible manner

[10] '2bins1bag' facilitates waste segregation at home where organic waste keep in green colour bin, blue colour bin is for dry waste and rejected waste for red colour bin

The processing of MSW is another major responsibility of BBMP and the city has eight waste processing units (The Hindu, July 5, 2017) as well as some biomethanisation units. For the proper management of MSW, many civic groups are favouring a decentralized waste processing system at the ward level as well as organic waste composting at the household level. The group called CIVIC has filed PIL many times in the court to implement the rule of ward committee formation in all 198 wards to solve the ward level garbage related issues. In the concern of the 'Zero Waste Initiative',[11] 'Green Wedding',[12] roof gardening and home composting are gaining attention in citizens' perception. 'Compost Santhe'[13] is one kind of decentralized waste processing initiative where it encourages the citizens to manage their household garbage. The compost from organic garbage helps for roof gardening as well as biogas generation (Kalra and Manasi, 2020). The BBMP has agreed and planned to install Compost Santhe units in all 198 wards. These units will facilitate the farmer to collect compost for their agricultural production. In the city, many municipal councillors and MLAs have come forward with the residents to implement this programme in their locality. Furthermore, this initiative has drawn attention in social media and newspapers where the people started a campaign called "Our Waste, Our Responsibility" to promote the Compost Santhe initiative. Another group called Daily Dump is well known for home composting and is the manufacturer of eco-friendly products. They organized various programmes about how to create wealth from waste, job creation in the field of the waste management system, and research on waste composting. They provide facilities like leaf composting, flower composting in the temple and religious festivals, and home organic composting units. They are playing a significant role to create awareness about vermin-compost, segregation of waste according to their nature and how to reduce the burden on the city's waste management system.

It would not be true to say that civic groups are always protesting against the local government. The city has seen various success stories regarding waste management where civic groups and the government work hand to hand to achieve goals such as the plastic ban campaign, '2bins1bag', 'Compost Santhe' and 'Zero Waste'. Although their activities have brought significant positive changes in waste management in the city, they are facing various challenges. The study observed that most of the NGOs raised questions about the waste collection strategy of the urban local bodies. BBMP has taken several policies for the collection of waste and segregation, but they mentioned that the ground reality shows the impact of these policies is negligible. The door-to-door collection did not happen properly as it mainly applies to those people who are staying on the ground and first floor, but for those who are staying on the above floors; this strategy has very little impact. It was observed that they dump their waste on the roadside when they go to their workplace. Segregation of waste is another major problem with the waste management system in Bengaluru. Pourakarmikas are collecting waste from different sources and contractors are simply dumping it into the waste processing plant or the landfill. Most of the respondents agreed strongly that the political nexus and corruption are playing a significant role in the city's waste management practices. Also, they mentioned that there is no issue in the government

[11] 'Zero Waste' focus on minimum waste generation and encourage people to reuse and recycle waste

[12] 'Green Wedding' to promote zero waste wedding where it includes items made from eco-friendly products, such as cutlery made from sugarcane fibers, invitation card made from recycled paper.

[13] 'Compost Santhe' promote for organic waste composting and build a network between compost producers and buyers to use the compost for farming

waste management policies but, because of the corruption and the political nexus, there is no proper impact of these policies on the ground. Lastly, human behaviour and people's mindset play a key role in the waste management system in every city. In the city, many citizens think that since they are paying their taxes to the government, it is their responsibility to manage the waste. On the other side, lack of knowledge, the rapidly growing population, and consumption habits increase the waste management problems in the city. In addition, the composting method needs some space as it attracts mosquitoes, rats and dogs by the stench and in urban areas most people do not have sufficient space to manage their waste. Also, cultural belief has a significant impact on the city's waste management process. One respondent mentioned that people had beliefs that if they keep garbage in their house then Laxmi (goddesses of wealth) would not come and 'Rahu and Ketu' (shadow planets considered inauspicious) would come at night time. Hence, they threw their garbage wherever they found space which had increased the black spots in the city.

## Conclusion

Environmental awareness and activism in Bengaluru are moving at a fast pace, implying a growth in responsible behaviour. However, Johan Enqvist *et al*, 2014 in their paper on Bengaluru, indicates that the networks' activities are influenced by internal tensions between inclusiveness and efficiency and between internal and external legitimacy. Hence, they suggest the development of a comprehensive framework for urban environmental stewardship to better describe the potential roles of citizens in governance across diverse social, political and ecological conditions and during different periods of urban change. Thus, there is a long way to go in upscaling the efforts to see significant impacts, but the efforts are commendable.

Civic activism plays an important role in the area of policy formation, and government activities, as they increase people's participation and environmental awareness. The engagement of various stakeholders in the decision-making process can enhance the strength of the goals and objectives of the decision. Many times, civic groups and the government work together to solve the problems. For example, single-use plastic is one of the major problems in urban waste management and to ban single-use plastic, the civic groups and government bodies worked together and earned huge attention from the citizens. Many times, individual stakeholders take the initiative to solve the problems by campaigning, discussing and filling PIL in court. To recognize the formal role of waste pickers and scrap dealers in waste management practices in the city, SWMRT filed an affidavit in Lok Adalat in 2012. Afterwards, BBMP issued an official letter to recognize their formal role and also provided ID cards to two thousand waste pickers.

Similarly, CIVIC (an NGO) has filed many PILs in court to implement the ward committee and decentralized the waste management system at the ward level. Afterwards, BBMP incorporated many of the suggestions and recommendations provided by CIVIC. Another organisation Saahas has influenced much of the government's decision-making process related to dry waste collection and composting of organic waste. Similarly, Hasiru Dala is working with BBMP for the social security and financial stability of pourakarmikas. In early 2020, BBMP incorporated inputs from Hasiru Dala in its SWM bye-laws. In December 2017, Karnataka High Court passed an order and directed the citizens to adopt the '2bin1bag' initiative to segregate the waste at the source. Finally, to prepare the draft of the Master Plan for Bengaluru, the individual experts, civic groups, and NGOs play a very crucial role to improve and modify the required changes which will, directly and indirectly, help to improve the waste management practices, city environment as well as improving the city governance.

Amidst all this, it should not be forgotten that solid waste management is not a short-term process; it is a continuous long-term process. It requires a comprehensive system, a decentralised waste management and a strict monitoring mechanism for implementing the rules and regulations. Additionally, people's awareness, motivation and participation are further required to strengthen the waste management practices in the city. To secure environmental sustainability, people should adopt the five ways (refuse, reduce, reuse, repurpose, and recycle) of effective waste management to properly manage the waste. Additionally, BBMP needs to further motivate and encourage eco-friendly approaches for the management.

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# Appendix

**Annexe 1: Details of Pourakarmikas in Bengaluru**

| Sl. No. | Description | Number |
|---|---|---|
| 1 | Pourakarmikas listed on the rolls | 32,000 |
| 2 | Pourakarmikas as per first audit by BBMP | 15,000* |
| 3 | Garbage vehicle drivers and helper | 11,000 |
| 4 | Supervisor | 1,000 |
| 5 | Compactor driver | 500 |
| 6 | Unaccounted workers | 5000 |

*Approximate figure;

*Source*: The Hindu, August 27, 2017

**Annexe 2: Waste Processing Plants and Their Capacity**

| Sl. No. | Name of the Waste Processing Plant | Capacity ( Tonnes per day) | Garbage intake now (Tonnes per day) |
|---|---|---|---|
| 1 | Kannahalli | 500 | 150 |
| 2 | Seegahalli | 200 | 50 |
| 3 | Lingadheeranahalli | 200 | 70 |
| 4 | Doddabidarakallu | 200 | 70 |
| 5 | Subbarayanapalya | 200 | 0 |
| 6 | Chikkanagamangala | 500 | 0 |
| 7 | Karnataka Compost Development Corporation (KCDC) | 300 | 200 |
| 8 | Mavallipura | 70 | 70 |

*Source*: The Hindu, Wednesday, July 5, 2017

**Annexe 3: Waste to Energy from Waste Processing Plant**

| Waste to Energy from Waste Processing Plant | | | |
|---|---|---|---|
| Sl. No. | Name of the Waste Processing Plant | Capacity (Tonnes per day) | Power Output (MW/Hour) |
| 1 | Giddenahalli | 500 | 9.66 |
| 2 | Gorur | 1000 | 13 |
| 3 | Bellahalli | 600 | 7 |
| 4 | Bellahalli | 1000 | 8 |
| 5 | Kannahalli | 500 | - |

**Giddenahalli project is being shifted to Mavallipura

*Source*: The Hindu, March 22, 2017

**Annex4: Classification of Activism**

| Sl. No. | Name of the specific model | Based on | Remarks |
|---|---|---|---|
| 1 | Participatory Activism | Membership organisation | Few events and many participants |
| 2 | Transactional Activism | Small advocacy organisation | Many events and few participants |
| 3 | Radical Activism | Usually on the loose organisational platform and individual activist | Few participants and militant strategies |
| 4 | Civic self-organisation | Individual, organisational effect | Many events, no organisation, and few participants |
| 5 | Episodic mass mobilisation | Short term events | Many participants, no organisation and very few events |

*Source*: Cisar, 2013

**Annexure 5: List of Environmental NGOs and Civic Group Working on Urban Waste in the City of Bengaluru**

| Sl No | NGO Name | Environmental Issues | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Urban Waste | Sanitation | Water Supply | Forest conservation | Lake conservation | Energy | Green Initiative | Recycling of waste | Rag Picker Issues | Awareness creation Capacity Building | Good Governance |
| 1 | Centre for sustainable development (CSD) | ✔ | ✔ | | ✔ | ✔ | ✔ | ✔ | ✔ | | ✔ | ✔ |
| 2 | Eco-Watch | ✔ | | | | ✔ | ✔ | ✔ | ✔ | | ✔ | |
| 3 | Bangalore Environmental Trust | ✔ | | ✔ | | ✔ | | | | | ✔ | ✔ |
| 4 | Bangalore Political Action Committee (BPAC) | ✔ | | | | ✔ | | ✔ | ✔ | | ✔ | ✔ |
| 5 | Solid Waste Management Round Table | ✔ | | | | | | ✔ | ✔ | ✔ | ✔ | ✔ |
| 6 | Saahas | ✔ | | | | | | ✔ | ✔ | | ✔ | ✔ |
| 7 | Youth for Parivarthan | ✔ | | | ✔ | | | | | | ✔ | |
| 8 | Environmental Support Group (ESG) | ✔ | ✔ | ✔ | ✔ | ✔ | | | ✔ | ✔ | ✔ | ✔ |
| 9 | Ugly Indian | ✔ | | | ✔ | | | | | | ✔ | |
| 10 | Hasirudala | ✔ | | | | | | ✔ | ✔ | ✔ | ✔ | ✔ |
| 11 | Yelahanka Eco Group | ✔ | | | | | | | | | ✔ | |
| 12 | Jannagraha | ✔ | ✔ | | | | | ✔ | | | ✔ | ✔ |
| 13 | ENDLESSLY GREEN (Blog) | ✔ | | | | | | | | | ✔ | |
| 14 | Sensing Local | ✔ | | | | ✔ | | | | | ✔ | |
| 15 | Swachha | ✔ | | | | | | | | | ✔ | |

Source: Compiled from the different sources

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# A Study On Relationship Between Recycling Plastic And Proper Disposal.

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***Abstract***

This paper covers the plastic recycling and disposal process which is carried out by chemical and the mechanical means where several technologies and steps are involved. India and the world have witnessed substantial growth both in the production and consumption of plastics. In absence of appropriate waste collection and segregation processes, the management of waste especially for the discarded plastic used for packaging has become a challenging task. Growing plastic pollution is affecting ecosystem as well as human health. This paper provides an overview to of all the challenges due to plastic pollution, for recycling and disposal, ways to mitigate, interplay of plastic recycling and disposal and awareness among the humans over the globe.



***Keywords: Recycling. Plastic Disposal, Environmental Pollution, Landfill, Green-house gases, Single-Use Plastic***

## INTRODUCTION

The plastic disposal and recycling in the global scale face significant challenges. Despite efforts to increasing recycling rates, a large portion of plastics waste still ends in the landfills, oceans or incineration. Improved waste management, infrastructure, awareness, and innovations in recycling technologies are crucial to address the issues. International cooperation is essential to develop sustainable solutions and reduce the environmental impact of plastic pollution. The first synthetic plastic was Bakelite, produced in 1907, that marked the beginning of the global plastics industry. However, rapid growth in global plastic production did not happen until the 1950s. In 1950 the global production of plastics was just 2 million tons over the next 70 years. However, annual production of plastics has increased nearly 230-fold to more than 460 million tons in 2022.

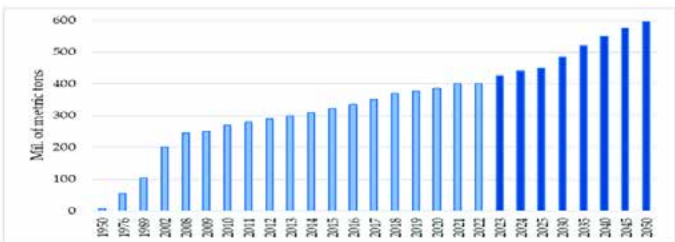


**Fig 1:** Production forecast of plastics worldwide from 1950 to 2050 in millions of metric tons

This overview will provide a general introduction to the issues regarding plastic disposal and recycling, awareness and how to avoid landfills due to plastic waste, ways to mitigate issues of plastic pollution, conservation of global ecosystem and human health.

## OBJECTIVES

- To reduce environmental impact such as pollution and ecological harm including aquatic life thereby mitigating climate change and conserve oceans.
- To conserve natural resources.
- To create closed loop system of recycling that leverages the recycling and ensures the reuse of post-consumer products to supply the material used to create the new version of same product.
- To protect ecosystems by minimizing the impact of plastic disposal on wildlife and human health.
- To reduce energy consumption compared to the production of the new virgin plastic.
- To facilitate sustainable resource management thereby alleviating the social and environmental burdens on the communities affected by the improper plastics disposal.
- To promote the more efficient use of space reducing the large volume of plastic in the landfills.
- To educate and create awareness among the public about responsible plastic disposal and recycling and foster international address the trans boundary movement of plastic waste
- To encourage the development of new technologies for efficient recycling, that facilitates long term sustainability of plastic use and disposal on a global scale.
- To adhere to waste management regulations and standards for environmental protection.

## MATERIALS AND METHODS

This paper were used of secondary data from the various sources like literature reviews, journals, articles, research papers etc. The entire study was carried out with the help of descriptive type of research methodology and Used of Statistical Techniques.

## RESULTS AND DISCUSSIONS

Plastics have become an unavoidable part of our daily life as it is convenient to use, having strength and durability. Being a non-biodegradable product, it also reduces the chance of decomposition of the product it contains. But this feature of plastic is the major cause for concern today. As plastics are almost not biodegradable, they accumulate in the environment once produced. So, it is very important to be aware of the problems associated with plastic waste and the means to dispose them properly. Plastics are derived from fossil fuels, such as petroleum and natural gas, which are non-renewable resources. By reusing and recycling plastics, we can conserve these valuable resources and reduce our dependence on them. Recycling of plastics consume lesser energy than their new counterparts contributing to conservation of resources. Plastic pollution in the oceans has turned out as a global concern. Improperly disposed plastics can find their way into water bodies, where they disrupt marine ecosystems, and contribute to the formation of large garbage patches. Reusing and recycling plastics helps prevent them from entering our oceans, mitigating the devastating impact on marine ecosystems. The process of recycling plastic consumes less energy compared to producing new plastic. Manufacturing plastic from raw materials requires significant amounts of energy, including extraction, refining, and processing. By recycling plastics, we can save energy and reduce greenhouse gas emissions associated with the production of new plastic. As recycling of plastics needs lesser resources and energy lesser amount of expenditure can be done to produce the same amount of product. However, the collection, sorting, processing, and manufacturing from recycled plastics can help the local economy. The best way of waste disposal will always ultimately remain one of the waste minimizations through best practice by both manufacturers and the general public ensuring maximum environmental benefit.

## RECYCLING AND DISPOSAL PROCESS

Plastic products if not disposed properly can cause a huge problem in the near and distant future. Studies suggests only 50% of the total plastic generated today gets a proper disposal. So, the goal should be production of as less amount of new plastic as possible. Depending on the quality and purity of the waste, the priority should be given to reuse, then reprocessing (mechanical recycling), then DE polymerization to the monomer, then conversion to a hydrocarbon feedstock and, at last resort, energy recovery (using as a fuel).

**PLASTIC DISPOSAL**

Mixed with other products plastic can be combusted in incinerator to generate heat and electricity.


**Fig 2**: Landfill **Fig 3**: Incinerator

These wastes to energy plants are a good alternative idea to dispose single use plastics. Landfill has become the most common and cheap form of plastic disposal it ranges between 40-60% of the total plastic disposal depending on the country. It is argued that it is the best way for carbon sequestration. However, even land filling has its own environmental hazards associated with it. It releases odorous components and greenhouse gases such as $CO_2$ and $CH_4$. It also contaminates the land and water by releasing leachable components trapped in plastics washed by rainwater. It is the biological degradation of waste especially organic waste to release $CO_2$. $H_2O$ and biomass.

These degradations are carried out by microorganisms. However, there are not much evidences suggesting effective degradation of plastics with biological agents. Incineration is used to burn the plastic in an incineration chamber at very high temperature but it produces huge quantity of temperature. Thus, following the 5R is the best possible way to tackle the issues with plastic. The 5R previously called 3R (Reuse, Reduce and Recycle) has added two more words -Refuse and Repurpose. The recycling process ensures that not only waste plastics are being reused but also new plastics are being prevented from production.

**PLASTIC RECYCLING**

In today's situation plastic recycling is very much needed. Plastic recycling ensures conservation of non-renewable fossil fuels (oil), reduction of the consumption of energy used in the production of new plastic, helps to reduce the amount of solid waste going to landfill and reduce the emission of greenhouse gases like carbon dioxide, carbon monoxide and methane into the atmosphereRecycling of plastics is a step-by-step process that starts with Collection, Sorting, Washing, Shredding, or grinding followed by Extrusion.

Collection is first stage of the recycling process, which involves the collection of waste materials from our homes, industries, and schools. For this stage it is important that everyone is correctly sorting their plastic ready for collection. These waste materials are collected by a local authority either directly or using a waste management contractor. Other collection opportunities include recycling centers, front of store or local recycling sites. The collection of plastic is the key for recycling system to operate well. The more plastic suitable for recycling that is collected the


**Fig 4:** Plastic recycling process

more material available to be reprocessed and used back into new products. Sorting is the second stage in recycling. It is done by sorting plastic from other materials and this is done at a Material Recovery Facility. From there this material shall then be taken to a Plastic Recovery Facility. The mixed recycling materials are then mechanically placed onto conveyer belts. Conveyer belts are used to maintain the constant flow of waste passing through the sorting facility. A series of techniques are used to separate the material ready for further processing. There are different types of sorting techniques. They are Manual picking, Trammels, Old corrugated cardboard screening, ballistic separator and magnet separator. Once, the material has been sorted, it will be transferred for reprocessing to a plastic re-processor for the next stage. Washing is the stage where the action of people can make a big difference. By simply rinsing the plastic simply can remove the food or other materials before they become dry and stick more severely and helps to ensure that the whole. During the washing process the plastic may go through a range of washing methods depending on the contamination and processors. The next stage is Shredding or Grinding. This is a critical stage in recycling plastic is where the plastics are shredded into plastic into smaller flakes. Shredding machines are used to ground the washed and sorted plastics into smaller pieces of plastic. Plastic can be shredded in different manner depending on the shredder such as - Hammer Mills and Shear Shredders. Extrusion is the final stage of plastic recycling. It is the process of melting down the plastic and forcing this through an extruder. The plastic is cut as it comes out of the extruder to form pellets. These pellets are sold onto manufacturers for making the new plastics.

## TYPES OF RECYCLING

The two broad categories of recycling process are Mechanical recycling and chemical recycling.
Mechanical recycling is a process to treat plastic scraps through a series of mechanical processes such as sorting, grinding, purification and revaluation without making significant changes in their chemical constitution. It is a cyclic process where the same type of plastic material undergoes rigorous sorting and following processes to turn into same flake or pellet sub stock. For example, the input can be a clean PET bottle and after mechanical recycling the output is also a same PET bottle of a lower quality. Most common recycled plastics are PET and HDPE over time these products become completely useless after several mechanical recycling. At that time chemical recycling can be used.

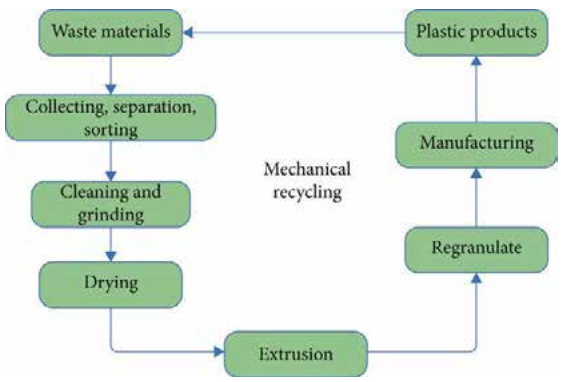


**Fig 5:** Steps of Mechanical Recycling

Chemical recycling is the process of recycling plastics through chemical change of polymer structure forming raw materials that can be used to manufacture new products. It can deal with the plastics that that may not be suitable for mechanical recycling. Chemical recycling can be done through Dissolution, precipitation, Pyrolysis and Gasification. In case of dissolution and precipitation the polymer is completely dissolved in an appropriate solvent. After that the polymer solution is then separated from the insoluble impurities and additives. The polymer is the precipitated again after the addition of an antisolvent. The solvent and antisolvent are then separated for reuse at the dissolution or precipitation stage of the process. Dissolution processes have been developed for recycling PS, PVC, nylon, PMMA, PE/PP cotton/PET mixed fibers, PLA/PET mixtures, and multilayer films. Pyrolysis refers to the process of converting plastics into solid, liquid, or gaseous fuels through thermal degradation of long-chain polymers into less complex molecules in the absence of oxygen. The process is divided into two parts.

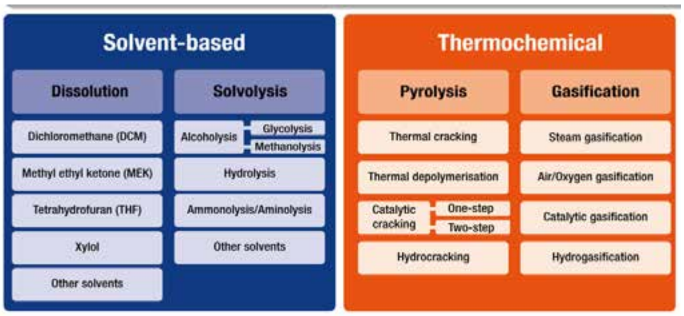


**Fig 6**: Types of Chemical Recycling

Firstly, the plastic is cleaned and cut into smaller pieces. Then the waste is pyrolyzed at >700°C. DE polymerization requires harsh pyrolysis conditions leads to complex mixture of hydrocarbons. A fraction of these hydrocarbons are very good to be used as a source of transportation fuel. Gasification is a method where the plastic is converted to synthetic gas or syngas which can be used for electric power generation or converted into fuel or chemical feed stocks such as methanol or ethanol which can be used for production of new products.

## ADVANTAGES OF PLASTIC RECYCLING

Plastic Recycling conserves the energy, processing the raw materials that come from the trees and the other natural resources takes more energy than recycling materials. Recycling of plastics reduces the water pollution and air pollution caused from land filling by reducing the need for conventional waste disposal and it reduces greenhouse gases emissions emitted from landfills. Recycling conserves the natural resources and the energy that would be required to produce plastic from scratch, Recycling of old and waste products into new products reduce the amount of waste that goes to the landfills, and recycling one ton of plastic can save 7.4 cubic yards of landfill space. Plastic Recycling helps in mitigating global warming and in reducing the pollution, The fossil fuels use that emit such harmful gases will be minimized. And, by recycling non-biodegradable waste, the air pollution and greenhouse gas emissions will be reduced.

## DISADVANTAGES OF PLASTIC RECYCLING

Plastic recycling can be harmful to the environment. When the plastic material is melted down, VOCs are released into the atmosphere, VOCs (volatile organic compounds) released from plastic recycling harm the environment. They, also present health risks to the people who use the recycled plastic, Plastic resin is manufactured from the petroleum and it can leech into the foods that are stored in the recycled plastic containers. Heat is required to melt the plastic. The process such as pyrolysis or incineration also generates carbon emissions, The harmful greenhouse gases contribute to the global warming and they are already taking showing harmful effects, As the plastic carries the potential health threats, much of recycled plastic will be less useful product.-After the plastic has been recycled once, it is very rarely suitable for the second round of recycling, So, the material will end up in the waste, If the plastic recycling continues in this way then the manufacturers will always have the same demand for new material. Plastic Recycling will produce the pollutants, including the chemical stews after breaking down the waste materials. This can hurt the environment, if not planned well, Plastic Recycling can increase low-quality jobs, These, include sorting the garbage, cleaning toxins and doing the other manual and the intensive labor, This can result in low morale, low income and poor quality of life in the community. Recycling tons of garbage will require separate factories causing more pollution and energy consumption to clean, sort, store and transport the waste materials, The need for extra bins for different kinds of trash will be needed, This, can equate to more trucks to pick them up, increasing the air pollution. Plastic Recycling can create more environmental problems, if not done right, recycling companies might abandon dump sites and leave the harmful chemicals to contaminate the land and the environment. Recycling is not always cost-efficient and it can result in net loss overall. Most importantly recycled plastic does not guarantee good quality products and thus more emphasis should be given on lesser generation and use of plastics in general. The recycled products are reusable just once or twice and then will end up in landfills giving people a false sense of security that plastics are being recycled.

**AWARENESS**

Recycling of plastics is being done more and more everyday but still it is not enough. The latest data from the Organization for Economic Co-operation and Development (OECD) a body made of 36 of world's richest countries serve as the warning of situation. The members of this club barely recycle 36% of their municipal waste on average. At an individual basis only seven countries 50% and regions such as OCED Europe were within 6b points of approved rate with 44%.


**Fig 7** :Plastic awareness rally

***Fig 8*** *:* Ban single use plastic

In the meantime, waste is gaining ground. The World Bank in 2018 warned that urban areas produce 2 billion tons of solid waste annually. They warned that this figure can increase by 70% by 2050 if we do not take serious actions. The World Bank itself urges countries to improve their waste management and control the generation of waste products.
Awareness of plastic recycling can be done through various games and activities for children.

- Draw the different recycling containers.
- Make toys out of waste.
- Prize for reusing and recycling waste.
- Cartoon promoting Recycling for children.
- Activities such as debates and presentation about plastic management and recycling.
- Videogames about recycling.

Awareness in adults can be done by various campaigns, workshops, and activities. Better salary to the people associated with recycling such as scrap collectors, cleaners and workers at recycling plants would encourage more people.

**GLOBAL SITUATION**

Germany has the highest Recycling Rate. It recycles about 99.8% of its plastic waste. There are norms of four bins across the country- Blue Bin for paper and cardboard, Yellow Bin for plastic and soft metals., Green or Brown Bin- for organic waste and Grey Bin- for general household. waste. Pfand is a deposit return scheme followed in Germany where whenever a person buys some product such as bottle and can in supermarket or kiosk, they pay a small amount on top of that price. When they return it they gets refunded. In 2016, France became the first country to ban the management of single use plastic cups, cutlery, and takeaway food boxes. In 2018, Great Britain's Royal Statistical Society statistic of the year was all about the plastic waste. Researchers calculated that about 21% of plastic waste has been incinerated, while about 79% is either landfills or polluting the environment. In 2018 Collins Dictionary named "single-use" citing a 4-fold increase in usage since 2013.
Plastic free July is a global movement that helps people be part of the solution to plastic pollution. Participants reduce their household waste and recycling by 21 kilos per person per year and contribute to a total saving of 940 million kilos of plastic waste each year. In India the use of plastic is fully decoupled from the consumption of finite resources. Reuse Model is applied which is relevant reducing the need for single use packaging. India produces 3.4 million tons of plastic waste in a year and only 30% of it is recycled. The theme for World Environment Day on 5 June 2023 will focus on solutions to plastic pollution under the campaign "Beat Plastic Pollution." The world is being inundated by plastic. More than 400 million tons of plastic are produced every year, half of which is designed to be used only once.

**RELATIONSHIP BETWEEN RECYCLING AND PLASTIC DISPOSAL**

The relationship between recycling and the plastic disposal lies in the fact that recycling mitigates the negative environmental impact of plastic disposal. It helps conserves resources, reduces energy consumption and minimizes pollution associated with the plastic production. Additionally, recycling contributes to circular economy, where materials are reused, and promoting sustainability. However, effective recycling requires the public awareness, proper infrastructure and the commitment from the individuals and the industries alike. Recycling plastics contributes significantly to nations by conserving the environment and minimizing the waste to landfills. It promotes the resource efficiency creating a circular economy and fostering sustainable practices. The recycling industry also generates job, contributing to the local economies. Moreover, embracing recycling helps nations reduce their carbon footprint, aligning with the global efforts to address the climate change. It encourages the innovation in the waste management and strengthens international cooperation in tackling the plastic pollution. Overall robust recycling practices contribute to a more environmentally conscious and economically sustainable future for nation. By adopting robust recycling practices, nation can contribute to the global efforts to address plastic pollution. Collaboration on the recycling initiatives can enhance the international environmental sustainability. It's important for nation to implement effective recycling programs, educate the public on the importance of recycling and invest in the infrastructure to maximize the contributions. Integrating plastic recycling process is very essential for maintaining the balance and health of all interconnected Earth Systems. It aligns with the broader goal of sustainable development and environmental stewardship.

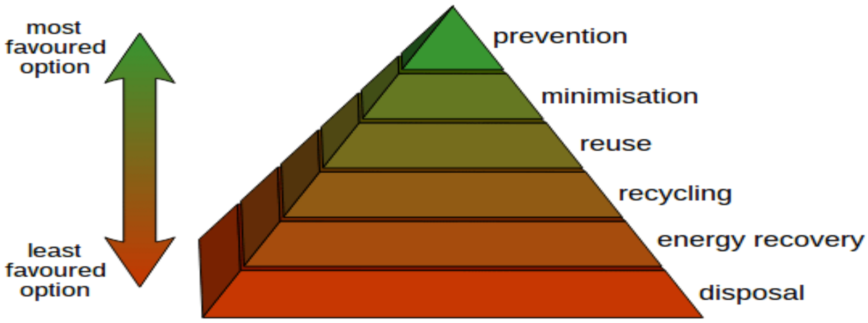


**Fig 9:** Plastic waste management methods and from most favoured to least favoured options

In the Earth system, the process of plastic recycling and disposal plays a crucial role in environmental sustainability. Plastic waste, if not properly managed, can have far-reaching impacts on various Earth systems. Inappropriate disposal of plastic waste can contaminate soil, affecting the geosphere and potentially harming ecosystems and agricultural productivity. Recycling helps mitigate this impact by reducing the need for new plastic production. Plastic pollution in oceans and water bodies is a significant concern. Recycling contributes to the preservation of the hydrosphere by minimizing the amount of plastic reaching water sources and ecosystems, thereby protecting aquatic life. The production of virgin plastics involves significant energy consumption and greenhouse gas emissions. Recycling helps decrease these emissions, contributing to a cleaner atmosphere and supporting efforts to mitigate climate change. Plastic waste poses threats to biodiversity when it enters ecosystems. Recycling reduces the demand for new plastic production, lessening the environmental impact on the biosphere and helping to protect flora and fauna. While the direct impact of plastic on ice and snow is limited, the overall reduction in energy consumption through recycling indirectly supports the preservation of polar ice caps and glaciers by mitigating climate change. Recycling plastic is integral to sustainable human activities. It reduces the need for landfill space, conserves resources, and supports a circular economy, contributing to a more harmonious coexistence between human activities and the Earth system. The extraction of raw materials for plastic production involves mining and drilling, impacting the lithosphere. Recycling helps minimize these activities, promoting a more sustainable use of Earth's geological resources. Plastic pollution affects the quality of soil and can disrupt ecosystems. Recycling prevents the accumulation of plastic waste in the pedosphere, preserving soil health and biodiversity. While plastic disposal may not directly impact the outermost layer of the Earth's atmosphere, the overall reduction in environmental pollution through recycling supports the health and sustainability of the entire Earth system.

## MAJOR CONTROVERSIES ON A GLOBAL SCALE

Several major controversies surround plastic recycling and disposal on a global scale, reflecting the challenges and debates in addressing plastic waste.

A significant controversy involves the export of plastic waste from wealthier nations to developing countries. This practice raises environmental justice concerns, as it can lead to improper disposal and environmental pollution in the receiving countries. Contamination of recyclable materials and difficulties in sorting different types of plastics pose challenges. Contaminated materials can compromise the quality of recycled products, and inadequate sorting processes can hinder the efficiency of recycling facilities. Many regions lack sufficient recycling infrastructure, hindering effective plastic waste management. The absence of collection systems, sorting facilities, and recycling plants contributes to increased reliance on land filling or incineration. The continued production and consumption of single-use plastic items, such as packaging and disposable utensils, exacerbate the plastic waste problem. Efforts to reduce reliance on these items face resistance from industries and consumers. Technological limitations in recycling certain types of plastics, particularly those with complex compositions or multi-layered packaging, present challenges. Innovations are needed to address these limitations and enhance overall recycling efficiency. Limited awareness and understanding among consumers about proper recycling practices contribute to contamination issues. Improving public education and incentivizing responsible disposal behavior are crucial aspects of addressing this controversy. The economic viability of recycling compared to the production of new plastics is a point of contention. Fluctuations in commodity prices can affect the profitability of recycling operations, impacting the sustainability of recycling programs. The fragmentation of plastic into microplastics poses environmental and health concerns. Controversies arise regarding the extent of the impact of microplastics on ecosystems and human health and the effectiveness of recycling in mitigating this issue. Divergent policies and regulations across countries and regions contribute to inconsistencies in plastic waste management. Harmonizing and enforcing effective regulations is challenging but essential for a unified global approach to plastic recycling. Addressing these controversies requires international collaboration, innovative technologies, improved infrastructure, and a shift in consumer behavior. It underscores the complexity of managing plastic waste on a global scale and the need for comprehensive, sustainable solutions.

## LIMITATIONS

While recycling and disposal methods play a crucial role in managing plastic waste, there are certain limitations and challenges associated with these approaches. Contamination of recyclable materials, especially in single-stream recycling systems, remains a significant issue. Mixed materials or improperly cleaned items can compromise the quality of recycled products. Some types of plastics are challenging to recycle due to their complex composition or multi-layered structures.

Technological limitations in processing these materials can reduce overall recycling efficiency. Recycling processes, particularly mechanical recycling, still require energy. While generally lower than producing virgin plastics, the energy consumption associated with recycling is a consideration in terms of overall environmental impact.

The market demand for recycled materials can fluctuate, impacting the economic viability of recycling operations. Dependence on market conditions can influence the success of recycling programs. Recycling can be economically challenging, especially when the cost of collection, sorting, and processing exceeds the value of the recycled materials. Economic considerations can influence the sustainability of recycling initiatives. Inadequate recycling infrastructure, particularly in developing regions, hinders effective waste management. Insufficient collection systems, sorting facilities, and recycling plants limit the scalability and success of recycling efforts.

The lack of standardized recycling symbols, labeling, and collection systems globally contributes to confusion among consumers and challenges in sorting and processing materials efficiently. Incomplete understanding and awareness among the public about proper recycling practices and the environmental impact of plastic waste can lead to improper disposal and contamination of recycling streams. While advanced recycling technologies show promise in addressing some limitations, the initial costs of implementing these technologies can be high, posing financial barriers to widespread adoption. In some cases, plastics that are not recycled end up in landfills or incineration facilities, contributing to environmental concerns.

Landfilling poses risks of soil and water contamination, while incineration can lead to air pollution and greenhouse gas emissions. Recognizing these limitations is crucial for developing more effective and sustainable strategies for plastic waste management. Addressing these challenges requires a holistic and integrated approach involving technology development, infrastructure improvement, policy implementation, and public engagement.

## MITIGATIONS

Mitigating the controversies surrounding plastic recycling and disposal requires a multifaceted approach involving various stakeholders. Implementing and enforcing international agreements or regulations to restrict or ban the export of plastic waste to developing countries, ensuring responsible disposal and preventing environmental injustices. Investing in advanced sorting technologies to improve the efficiency of separating different types of plastics. Automation and artificial intelligence can help reduce contamination and enhance the quality of recycled materials. Governments and industries should invest in building and upgrading recycling infrastructure, including collection systems, sorting facilities, and recycling plants, to create a robust and efficient waste management system. Enforcing Extended Producer Responsibility (EPR) policies, making manufacturers responsible for the entire lifecycle of their products, including collection and recycling. This encourages the design of products that are more easily recyclable. Implementing strict regulations on the production and use of single-use plastics. Encourage alternatives, such as reusable or compostable materials, and incentivize businesses to adopt sustainable packaging practices. Investing in research and development to overcome technological limitations in recycling complex plastics. Innovations in chemical recycling and advanced recycling technologies can improve the recyclability of a broader range of plastic materials. Conducting comprehensive public awareness campaigns to educate consumers about proper recycling practices, the environmental impact of plastic waste, and the importance of reducing single-use plastics. Providing economic incentives, such as tax breaks or subsidies, to businesses adopting sustainable practices and investing in recycling technologies. This can enhance the economic viability of recycling operations. Implementing regulations addressing the release of micro plastics into the environment. Encourage the development of technologies to capture and manage micro plastics, along with research on the long-term effects of micro plastics pollution. Fostering international collaboration and standardization of policies and regulations on plastic recycling and disposal. Facilitate knowledge sharing, technology transfer, and joint initiatives to address the challenges on a global scale. By combining these strategies, nations can work towards creating a more sustainable and effective approach to plastic recycling and disposal, ultimately mitigating the controversies associated with plastic waste management.


**Fig 10:** The principles of social ecology

## CONCLUSION

Plastic recycling and disposal are critical components of addressing the pervasive issue of plastic waste. While recycling offers a sustainable solution by reducing the need for new plastic production and minimizing environmental impact, it faces challenges such as contamination, technological constraints, and economic considerations. Efforts to improve recycling infrastructure, advance sorting technologies, and promote public awareness are essential. Additionally, the limitations of recycling highlight the importance of adopting a comprehensive waste management approach that includes reduction of single-use plastics, extended producer responsibility, and exploration of innovative disposal methods. A global commitment to standardized practices, collaborative research, and responsible consumer behavior is necessary for achieving a more sustainable and environmentally conscious management of plastic waste on a global scale.

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# Greener healthcare operations during COVID-19 pandemic: A data envelopment analysis approach

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ABSTRACT

This study examines internal greener operations in Indian healthcare during COVID-19 pandemic. Specifically, the research explores the interrelationships among three parallel healthcare lines: general care, emergency care, and biomedical waste (BMW) management to fulfill greener healthcare's targeted sustainable development goals. We use the three parallel stage data envelopment analysis (DEA) approach model to assess efficiencies of the overall system and the individual parallel stages. We collected panel data for cities in the state of Maharashtra, India during the second wave of pandemic in 2021. We find that the effectiveness of general and emergency medical services depends on the requirements of healthcare resources such as beds and equipment in times of pandemics. By contrast, the capacity of individual BMW treatment processes such as incineration, autoclave, shredder, and deep burial would have a bearing on the efficiency of both BMW management and the total system for greener operations. In the second phase, we evaluated the impact of context-specific exogenous factors using a regression model. We found that literacy level was the most important factor at all three parallel stages separately. Additionally, the total population and number of female vaccinated persons were significant across the system while population density and number of male vaccinated persons were inconsequential factors. Interestingly, the Wilcoxon rank-sum hypothesis test offered no evidence to suggest that performance of general care and BMW management, and emergency care and BMW management were equivalent. Implications of these findings for academic theory, practitioners, and policy makers are offered.

## 1. Introduction

Bio-medical waste (BMW) management is a critical healthcare sector issue (Govindan et al., 2021). Bio-medical waste or medical waste is "all waste materials generated at healthcare facilities, such as hospitals, clinics, physician's offices, dental practices, blood banks, veterinary hospitals, and medical research laboratories" (Makajic-Nikolic et al., 2016). The improper disposal and associated environmental burden of BMW widely impact the greener aspect of healthcare services (Rattan et al., 2022). Further, the hazardous nature of waste disposal results in air, water, and soil pollution and the spread of diseases, all affecting human health. Hence, the handling of BMW is critical for adequately utilizing healthcare facilities. BMW must be treated and disposed-off through authorized Common Biomedical Waste Treatment Facilities (CBWTF) or captive treatment facilities like deep burial. For a developing economy like India, CBWTF was utilized for waste treatment of around 90% of total BMW treated, with incineration process for around 60% of total BMW (Deepak et al., 2022).

Across developing countries, the BMW generation ranged from 0.1 kg/bed/day to 6.0 kg/bed/day in 2019 (Ansari et al., 2019). In India, the BMW increased from 0.24 kg/bed/day to 0.30 kg/bed/day from 2019 to 2021 [1]. The waste generation was between 0.13 kg/bed/day (in Rajasthan) to 0.82 kg/bed/day (in Tripura) among all Indian states in 2020. Interestingly, in 2021, the waste generation was between 0.12 kg/bed/day (in Andhra Pradesh) and 0.49 kg/bed/day (in Kerala). Hence, we speculate that less waste generation can be traced to activity levels of healthcare facilities in these states. However, there was a compound annual growth rate of around 7% BMW, but in contrast, only a 2.3% increase in number of beds and a 5.1% increase in healthcare facilities in 2021 compared to 2019 (see Fig. 1).

The increase in BMW was primarily due to the COVID-19 pandemic (Manupati et al., 2021). Hence, the Government of India developed COVID-19 waste-tracking software during the pandemic disruption, which tracked waste at the time of generation, collection and disposal. COVID-19 BMW comprised of around 15.2% and 10.5% of

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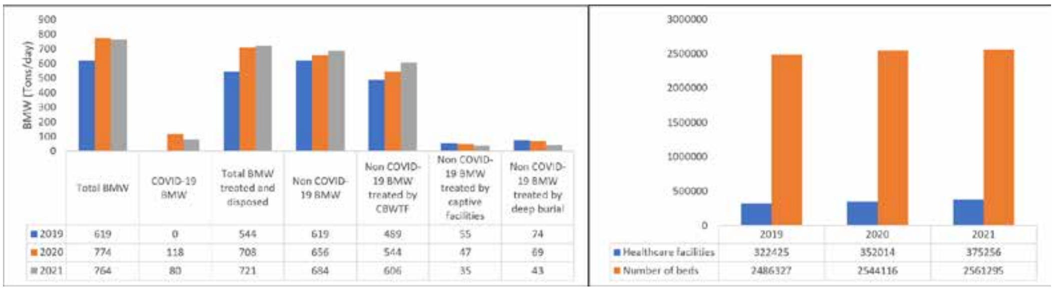


**Fig. 1.** Comparative BMW scenario and healthcare resources in India.

the overall BMW generated in India in 2020 and 2021, respectively. Interestingly, about 18% of total COVID-19 BMW was generated by the state of Maharashtra alone. While the rate of BMW generation increased exponentially, the number of healthcare facilities, beds, or BMW treatment capacity did not increase at the same rate. Further, there is a growing debate that sustainability in healthcare through waste reduction may only be achieved if patient safety is maintained (Xu et al., 2021; Azadi et al., 2022; Matin et al., 2022; Azadi et al., 2023a). Hence, there is a need to explore the efficiency with which BMW is managed, given the healthcare resources available for general and emergency care during the pandemic disruption. Overall, we propose integrating BMW management with healthcare operations for the most affected state (Maharashtra), which can significantly improve greener healthcare and sustainable development for India. While Maharashtra may not represent all states, a careful generalization of results for a larger population like India is possible based on the panel data during the pandemic.

Sustainable development for greener healthcare operations through efficiency measurement has been argued to be 'the need of the hour' (Thakur, 2021). We trace the importance of our study to the third sustainable development goal (SDG) on good health and well-being as proposed by the United Nations Development Programme (UNDP) (see Fig. 2). SDG-3 has 13 targets and 28 indicators to measure performance outcomes. In our study, we focus on the target of fighting communicable disease (Target 3.3) due to COVID-19. As per the Sustainable Development Report 2022, we identify that the countries need to fulfill SDG-3 globally. Specifically, fulfilling SDG-3 is challenging in India due to its vast population and limited access to healthcare. Further, in Fig. 2, the state of Maharashtra was severely impacted during the COVID-19 pandemic. We propose that investigation through Data Envelopment Analysis (DEA) can provide useful insights for inefficient cities in Maharashtra in terms of proper utilization of healthcare resources like hospital facilities, hospital beds, ventilators, Personal Protective Equipment (PPE) (Snigdha et al., 2023) and N95 masks (Tirkolaee et al., 2022). Also, policymakers can utilize the findings to implement timely policies relating to oxygen and ICU bed requirements for emergency healthcare lines. Secondly, we focus on reducing illnesses and deaths from hazardous chemicals (Target 3.9) due to BMW generated during COVID-19. While the mortality rate due to the generated waste is difficult to measure, estimating the BMW treatment capacity can help reduce human risks. Overall, the focus of sustainable development explored by SDGs can help build resiliency.[2]

The DEA methodology is chosen for analyzing the relative efficiency of the peer decision making units (DMUs) due to its distinctiveness among the several methods available for calculating DMU efficiency scores. DEA evaluates the relative efficiency of DMUs with same inputs to produce same outputs, identifies the efficient frontier, and suggests performance improvement for inefficient DMUs by increasing current output levels or decreasing current input levels (Charnes et al., 1978). At the very least, DEA distinguishes itself from other multi-criteria decision-making techniques as a non-parametric technique that does not require previous assumptions about the distribution of inputs/outputs (Arya and Yadav, 2018; Arya and Hatami-Marbini, 2023). Furthermore, no prerequisite knowledge of the weights attached to different variables is required for DEA. To determine the cause of inefficiencies in the cities' domain, standard DEA is also used to calculate the scale, pure technical, and overall technical efficiencies, respectively. Our goal is to uncover the variables that have a substantial impact on the efficiency scores attained in the first stage using a two-step strategy. We apply a DEA in the first stage and then use regression with fixed effects in the second stage (or step).

In general, there are studies where the production process of DMUs is treated as a black-box and studies that consider its internal structure. In black-box models, DMUs are viewed and calculated as a one-stage process corresponding to the traditional DEA method. In the literature, DEA has been used in numerous studies in several fields, such as banks (Favero and Papi, 1995; Arya and Singh, 2021), agriculture (Arya and Hatami-Marbini, 2023), healthcare (Heshmati et al., 2023), etc. In the conventional DEA (black-box) models, there is no detail about what is happening inside the production process, and the intermediate data connecting the initial inputs to the final outputs are ignored. This is well known as the main disadvantage of one-stage approaches. For example, Tone and Tsutsui (2009) argue that knowing how inputs and outputs are exactly connected would improve the discriminatory power of efficiency models without requiring unverifiable predictions. To cope with this problem, the black-box process can be broken down into a group of stages. The respective models for measuring the efficiency of this complex structure are called network DEA models.

In the literature, network DEA with parallel structures has been used in numerous studies (Färe et al., 2007; Kao, 2009; Cook et al., 2010; Bi et al., 2011; Kremantzis et al., 2022; Azadi et al., 2023b). Kao (2009) developed a parallel DEA model accounting for the performance of parallel components when determining the efficiency of forest management systems. The model treated each parallel production unit as an independent DMU. Cook et al. (2010) represented the overall efficiency of parallel network DEA structures using an additive weighted average of efficiencies of individual components. A parallel model was presented by Bi et al. (2011) for assessing the efficiency of several production lines under common weights. They found that the worst-performing line within the assessed production unit is enhanced to the greatest extent possible. A parallel network structure combined with a hierarchical one was proposed by Kremantzis et al. (2022) to measure the efficiency of several business schools at various universities. The parallel production systems presented by Kao (2009) and Bi et al. (2011) did not consider shared inputs and undesirable outputs, while Kremantzis et al. (2022) did not consider undesirable outputs (while considering shared inputs) in their parallel network DEA models respectively.

[2] UNDP Sustainable Development Goals (www.undp.org/sustainable-development-goals).

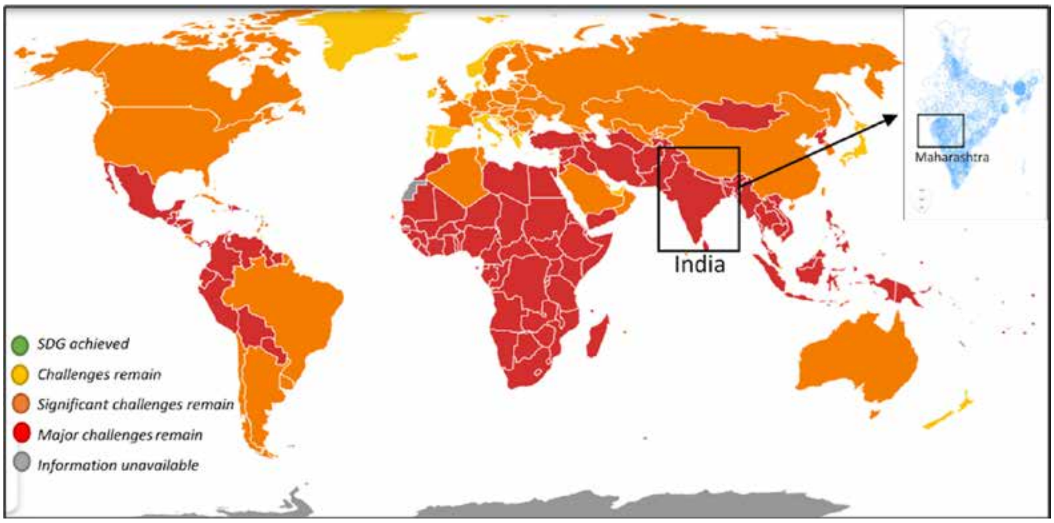


**Fig. 2.** Sustainable development report 2022 on good health and well being.

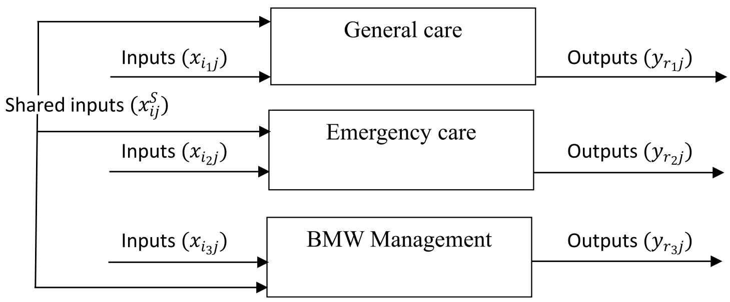


**Fig. 3.** Graphical representation of internal structure of healthcare.

Accordingly, we distinguish our methodology based on a standard network DEA model by incorporating various changes. We make the following contributions. First, a three-stage healthcare structure is proposed with shared inputs and undesirable outputs, which handles three parallel stages: *general care, emergency care,* and *BMW management* stages. (see Fig. 3). Traditional models do not provide information on the performance of general, emergency, and BMW administration efficiency by accounting for the internal structure of the healthcare stage. Second, we include shared inputs and undesirable outputs in the parallel stages. As a result, the best practices of healthcare's core efficiency in improving operations are also included in our modeling approach.

In network models, each DMU is examined in several stages, where the combined efficiency of each stage represents the overall performance. The literature on multi-stage development processes and their performance evaluation has recently increased (Kao, 2014; Despotis et al., 2016; Ma and Chen, 2018; Hatami-Marbini et al., 2018; Matin et al., 2022). However, due to their complex and uncertain internal processes, healthcare performance assessment presents significant challenges (Arya and Singh, 2021; Zhang et al., 2017). Our work is one of India's first research studies to evaluate relative and scale efficiency in a parallel three-stage model in the healthcare sector. Other India-specific studies focusing on hospital efficiency during COVID-19 include (Mishra et al., 2023). Based on our understanding of the Maharashtra, India healthcare ecosystem, we formulate the following research questions (RQs) to explore in our work:

RQ1. Through which techniques can efficiency ratings be evaluated? Specifically, which cities are most efficient for greener healthcare operations wherein the internal processes are connected in three parallel stages?

RQ2. Which parallel stage produces more BMW; is it general care or emergency care?

RQ3. Are there any notable variations in performance between general care, emergency care, and BMW management? What specific contextual factors significantly impact these efficiencies?

This is the first study that addresses all the research questions mentioned above in relation to the healthcare ecosystem of the Indian state of Maharashtra. The remainder of the paper is organized as follows. Section 2 provides the relevant literature review on sustainability in BMW management and applications of DEA in healthcare. Section 3 focuses on research methodology where we propose three stage parallel DEA approach and formulation. Section 4 provides the results and discussions for the selected cities in Maharashtra and compares the efficiencies by using a Wilcoxon rank-sum hypothesis test. Section 5 provides some interesting implications for sustainability. Finally, Section 6 discusses some limitations and possible extensions in the conclusion.

## 2. Literature review

We evaluate the two streams of research in biomedical waste management and data envelopment analysis in the healthcare sector to reveal the research gaps while assessing greener healthcare efficiency.

### 2.1. Biomedical waste management

Research on sustainability in healthcare is vast and spread across various engineering, environmental science, and management domains. Within this literature, the focus on greener healthcare with BMW management is relatively new but expanding. The research on greener healthcare with BMW management has focused on modeling techniques, performance outcomes, and ways to mitigate the impact of BMW (Govindan et al., 2021). Within this domain, studies have proposed an integrated approach for managing BMW (Deepak et al., 2022). For example, integrating the four color-coded bins, red, yellow, blue, and white, for BMW generation with BMW treatment scenarios can help reduce the environmental burden (Deepak et al., 2021). While low-temperature incineration is proposed as the best waste disposal technique (Manupati et al., 2021), digitization strategies and utilizing data from agencies such as Pollution Control Board are also proposed as ways to improve performance (Chauhan et al., 2021; Singh et al., 2022).

Specifically, meticulous data collection was done for COVID-19 BMW, which was categorized as infectious waste (Govindan et al., 2021). Tirkolaee et al. (2022) have highlighted the need to include data on demand parameters in healthcare while evaluating human risk and pollution due to COVID-19 BMW. Further, Çakmak Barsbay (2021) recommended that data-driven methods can improve hospital BMW management. This result is aligned with recommendations proposed by Sherman et al. (2020), stating that maintaining a healthcare database and applying relevant performance metrics can improve healthcare sustainability. Some recent studies in greener healthcare with BMW management are highlighted in Table 1. Based on the implications and research gaps, we identify that data analysis and utilizing performance measurement techniques can guide policymakers toward better decision-making. Hence, we collected data from reliable government sources and employed DEA as the relevant technique for our work.

### 2.2. Data envelopment analysis

DEA is a powerful approach for measuring the relative efficiencies of peer DMUs with common inputs and outputs (Charnes et al., 1978). In DEA, the performance of DMUs that produce multiple outputs by consuming multiple inputs is measured as the distance from the piece-wise linear efficient frontier (Tone and Tsutsui, 2009). A DMU is efficient if it lies on the efficient frontier. The reference set or peer group for the inefficient DMU is composed of efficient DMUs that provide a realistic target for inefficient DMUs for efficiency improvement (Doyle and Green, 1994). The DEA model, measured under Constant Returns to Scale (CRS) assumption, was first suggested by Charnes et al. (1978) to assess the relative efficiencies of DMUs. The efficiency of the $k$th observed DMU, i.e., $DMU_k$, is to be maximized in CCR (Charnes, Cooper, and Rhodes) DEA models subject to the constraints that the ratio of the weighted sum of outputs to the weighted sum of inputs of each DMU is less than or equal to unity. A DMU is completely efficient if and only if it is impossible to improve any input or output without worsening some other input or output. For more details, readers can refer to Charnes et al.'s (1978) article. The performance efficiency of a DMU measured by the CCR model is known as the overall technical efficiency. Charnes et al. (1978). Banker et al. (1984) extended the original CCR model and introduced the BCC (Banker, Charnes, and Cooper) model. The BCC model includes convexity constraint in CCR model, which represents the returns to scale. BCC model divides the overall technical efficiency into pure technical efficiency and scale efficiency. It is measured under Variable Returns to Scale (VRS) assumption. Scale efficiency of a DMU is defined as the ratio of overall technical efficiency and pure technical efficiency (Balk, 2001; Coelli et al., 2002; Kao and Hwang, 2011). It lies in $[0, 1]$. It literally illustrates how a DMU's scale size influences its efficiency. Thus, overall technical efficiency of a DMU can never exceed its pure technical efficiency (Banker et al., 1984). If a DMU's CCR and BCC efficiencies are one, it is operating at its most productive scale size. According to Zhu (2009), a sizable sample size is deemed necessary for the DEA model to have the ability to distinguish between exhibitors.

### 2.3. DEA in healthcare

Next, we review the recent studies that successfully employed DEA in healthcare settings for various configurations. In recent years, DEA is being used by service organizations, including healthcare services, as a data-driven tool for balanced benchmarking (Sherman and Zhu, 2013). Kohl et al. (2019) recently reviewed 262 papers of DEA applications between 2005 and 2016, focus on hospitals. They suggested that applying DEA to hospital settings can improve policy-making and management of health systems. We identify the input, output, control, and second-stage variables for some of these studies applying DEA in healthcare (see Table 2). For example, several studies used number of beds as input (Heshmati et al., 2023; Nedelea and Fannin, 2013; Jehu-Appiah et al., 2014). Similarly, COVID-19 contractions and mortality rates have been considered as outputs in a few studies (Isnain et al., 2022; Martínez-Córdoba et al., 2021). Variables relating to healthcare facilities, such as the number of healthcare workers (Alsabah et al., 2020; Top et al., 2020; Roth et al., 2019) or healthcare expenditures, have also been used as inputs (Ahmed et al., 2019; Jehu-Appiah et al., 2014).

As for the network DEA models, Matin et al. (2022) proposed an advanced network DEA model with a new directional distance function to evaluate the sustainability and resilience of blood supply chains. Azadi et al. (2023b) proposed a network DEA model based on a series structure with multi-periods and deep learning approach to predict sustainability of healthcare supply chains. Azadi et al. (2022) developed a network series range directional measure approach for evaluating the sustainability and resilience of healthcare supply chains with negative, undesirable, uncertain data. In response to the COVID-19 pandemic, Azadi et al. (2023a) developed a network DEA model aggregating the semi-oriented radial model, convexity assumption, and chance-constrained programming, to assess the sustainability and resilience of healthcare supply chains. They built a model that can handle data with integer values, negative data, stochastic data, ratio data, and undesired outputs. Zhang et al. (2023) proposed three parallel-series structure with undesirable outputs, but they did not considered shared inputs. Overall, the network DEA models are increasingly being adopted for efficiency analysis in the healthcare sector. However, there were limited studies that integrated BMW management with healthcare operations. Further, to the best of our knowledge, none of the studies employed parallel-stage DEA, MPI, and regression together to explore the possibilities of sustainable healthcare.

Various methods were integrated with DEA, such as Malmquist Productivity Index (MPI) for healthcare efficiency changes over time, and Ordinary Least Squares (OLS) regression, Tobit regression, and bootstrap truncated regression for second-stage regression. The control variables and second-stage variables for DEA were broader in scope including literacy rate (Alexander et al., 2003; Ahmed et al., 2019), hospital size (Roth et al., 2019; Mujasi et al., 2016), type of treatment (Roth et al., 2019), population density (Heshmati et al., 2023), gender (Heshmati et al., 2023; Martínez-Córdoba et al., 2021), and wages (Onder et al., 2022) (Table 2). Our study prefers the OLS regression since technical efficiency is a fraction data and not generated by any censoring process. Hence, OLS regression is more appropriate than Tobit regression. Further, the truncated regression and bootstrap method is computationally demanding and underperforms in presence of noise and for large samples (Banker et al., 2019). However, we validated our results using the bootstrap truncated regression.

**Table 1**
Healthcare sustainability evaluation with BMW management.

| Reference | Objectives (Country) | Methods (MCDM or not) | Findings | Implications | Research Gaps |
|---|---|---|---|---|---|
| Makajic-Nikolic et al. (2016) | Risk assessment of infectious medical waste management (Serbia) | Fault tree analysis and assess unreliability of system (×) | Injury at work and not using protective equipment were risks in waste management | Maintaining registers, monitoring risk indicators, training of employees, and increased awareness can minimize infections | Using medical waste management information system |
| Aung et al. (2019) | Evaluation of hospital waste management criteria (Myanmar) | Analytic Network Process (✓) | Dissemination and enforcement of technical guidelines and maintaining compliances | Enforce medical waste management laws and regulations | Direct observation methods and field studies |
| Manupati et al. (2021) | Evaluation of disposal alternatives of healthcare waste (India) | Fuzzy VIKOR (✓) | Incineration and integrated steam sterilization identified as best waste disposal techniques | Environment pollution while handling healthcare waste disposal | Environmentally feasible solution for waste disposal |
| Rizan et al. (2021) | Carbon footprint of hospital waste streams (United Kingdom) | Closed-loop and recycled content method (×) | Recycling and low-temperature incineration caused lowest carbon footprint | Disposal route with lowest carbon footprint and simplification of waste terminology | Determine landfill location |
| Thakur (2021) | Finding cleaner and sustainable healthcare services while fighting COVID-19 outbreak (India) | PESTEL, TISM and fuzzy MICMAC (✓) | Regular sanitization of contact points, social awareness, governments' investment policies, legal framework, and environmental policy | Collaboration to development frameworks and policies related to waste management during pandemic | Strategic planning |
| Chauhan et al. (2021) | Drivers of smart healthcare waste disposal planning and role of circular economy goals (India) | Decision making trial and evaluation technique (✓) | Digitally connected healthcare centers, waste disposal firms and providing pollution control board application to public | RFID labeling and GIS tracking of vehicles | Municipal solid waste disposal, transport management can be incorporated |
| Nketiah et al. (2022) | Incorporating place identity and natural bonding into norm activation model to forecast citizens' intention to recycle (China) | Partial least square structural equation modeling (×) | Openness to change, awareness of consequences, environmental concern, personal norms, and attitudes | Caution while developing waste management regulations containing place identity | Other psychological elements for recycling intention |
| Tirkolaee et al. (2022) | Design sustainable mask closed-loop supply chain network during COVID-19 for production, distribution and recycling of face masks (Iran) | Multi-objective Grey Wolf optimization algorithm with Non dominated sorting genetic algorithm II (×) | Customer demand of masks while evaluating cost, environmental pollution, and human risk | Objective trade-offs by supply chain managers | Employing uncertainty in models and integrating demand and inventory decisions |
| Deepak et al. (2022) | Environmental burden of existing biomedical waste management (India) | Lifecycle assessment based on abiotic depletion, global warming, ozone layer depletion, toxicity, oxidation, and acidification (×) | Integrated system reduces environmental burden | Segregate waste at point of generation, renewable energy sources to be used. Reliable to use incineration as a waste-to-energy plant | Integrate economic and social lifecycle assessment for sustainable waste disposal |
| Kurniawan et al. (2022) | Adding economic value to recycled waste through digital technology (Developing country) | Focus group discussions and data acquisition from waste banks (×) | Digital transformation promotes resource recovery of non-biodegradable waste | Creation of new jobs in waste recycling industry promoting digital society | Investigating market mechanisms, competition, and economic incentives to promote digitalization in waste recycling industry |
| Rattan et al. (2022) | Develop critical sustainability dimensions supporting sustainable development goals (India) | Exploratory and confirmatory factor analysis (×) | Ayurveda adds value to healthcare, provides equal access to patients, and promotes environmental sustainability | Need for greater connectivity between urban and rural healthcare settings. | Need for inclusion of public and private healthcare settings across the world |
| Snigdha et al. (2023) | Safe reusability of Personal Protective Equipment (PPE) clothing to reduce environmental and health hazards (Global) | Life-cycle inventory and Cradle-to-grave life-cycle assessment framework for disposable and reusable PPE body coveralls (×) | Reusable PPE improves environmental and health performance in all categories except water consumption. Replacing conventional electricity with solar energy for PPE manufacturing | Make environmentally informed decisions by medical textile industries, healthcare workers and policymakers | Focus on responsible consumption and production |
| Zhang et al. (2023) | Performance of government in promoting various sustainability sub-systems (China) | DEA (✓) | Overall improved efficiency, method heterogeneity and significant linkage inefficiency implies that the modelers should incorporate intermediate products | Inland provinces should promote their human capital and adopt advanced technology | Network meta/group frontier approach and a new concept of efficiency Foster-Greer-Thorbecke indicator. |

**Table 2**
Inputs and outputs used in the DEA literature for the health sector.

| Method | Inputs | Outputs | Control variables | Second stage IVs | Reference |
|---|---|---|---|---|---|
| DEA+MPI | Visits to doctor, healthcare time, cost of healthcare, Care opportunities, Available inpatient care places, Primary doctor visits, paid staff | Infected COVID-19 cases, Intensive cases, Weekly deaths | Gini coefficient, Population size, Population density, Gender, Land area, life expectancy, Age, GDP per capita | All control variables | Heshmati et al. (2023). |
| DEA+Tobit Regression | Price of labor, Price of physical capital, Price of borrowed funds | Total loans, Other earning assets | Liquidity, Bank's size, Solvency | All control variables | Sakouvogui and Guilavogui (2022) |
| DEA | Hospital beds, ICU beds, COVID-19 quarantine beds, Physicians, Nurses | COVID-19 cases, COVID-19 mortality | | | Isnain et al. (2022) |
| DEA+ Regression | Physicians, Nurses, Hospital beds, Health expenditure | Cases confirmed, Death rate | Location, Gender, Ideology, Age, GDP, Tourism, Unemployment rate | All control variables | Martínez-Córdoba et al. (2021). |
| DEA+Tobit Regression | Primary budget per capita, Physician, Nurses and midwives, Other health personnel | Visits to primary healthcare services per capita, Average follow-up per pregnant case, Average follow-up per infant, Infant mortality rate | Income per capita, University graduates | All control variables | İlgün and Şahin (2022) |
| DEA+Tobit Regression | Number of beds, Doctors, Nurses, and Non- medical workers | Total outpatient visits, Total number of discharges | | Hospital size, Bed occupancy rate, Average length of stay, Hospital type | Alsabah et al. (2020). |
| DEA+Tobit Regression | Per capita health expenditure, Purchasing power parities | Male and female disability adjusted life expectancy, Infant mortality rate | | Health expenditure, Female literacy, Nutrition, Immunization, Physicians per capita, Expenditure per GDP, Drug access, AIDS, Private to public ratio | Alexander et al. (2003) |
| DEA+Tobit Regression | Beds, Clinical staff, Nonclinical staff, Expenditure | Inpatient days, Outpatient visits, Deliveries, Laboratory services | Efficiency, Ownership | | Jehu-Appiah et al. (2014) |
| DEA+Tobit Regression | Capital, Beds, Labour, Medical staff | Outpatient visits, Inpatient days | Ownership, bed occupancy rate, Hospital size, OPD visits | Efficiency, Ownership, Bed occupancy rate, Hospital size, OPD visits | Mujasi et al. (2016) |
| DEA+OLS Regression | Nurses, Residents, Other clinical and Non-clinical labor, Staffed beds | Outpatient visits, Emergency visits, Inpatient surgeries, DRG-adjusted inpatient discharges, Clinical quality survival, Satisfaction with communication, cleanliness and quietness, Overall satisfaction, Recommend hospital | Size, Health care network, Group purchasing organization, Ownership status, Hospital location, Health record adoption | Percentage physicians employed per bed, Bed utilization, Size, Health care network, Group purchasing organization, Ownership status, Teaching hospital, Hospital location, Health record adoption | Roth et al. (2019) |
| DEA+OLS Regression | Physicians, Nurses, Beds | Discharges, Case mix index | | Percentage of Cesarean sections, outpatients surgical wards, Per capita public health expenditure | Mancuso and Valdmanis (2016) |
| DEA+ bootstrapped Truncated Regression | Number of Beds, Employees, Discharges | Readmission rate, Cost | Wage index, Location, Clinical quality, Experiential quality, Interaction of clinical and experiential quality | All control variables | Onder et al. (2022) |
| DEA+ bootstrapped Truncated Regression | Registered nurses, Licensed practical nurses, Other staff, hospital beds | Outpatient visits, Admissions, Post-admission days, Emergency visits, Outpatient surgeries, Total births | Government, Medicaid, Herfindahl–Hirschman index, Multihospital system, Income | Medicare health maintenance organization penetration | Nedelea and Fannin (2013) |

(*continued on next page*)

### 2.4. Research gaps

The literature review reveals that more research needs to be done despite the significance of evaluating healthcare, particularly in the context of the COVID-19 pandemic in India. On the other hand, the existing methodologies to assess healthcare efficiency need to consider the three-parallel structure of healthcare with shared and undesirable data features. Further, there is little investigation of sustainable development goals in healthcare settings, especially in the Indian context. Based on the identified research gaps, we target our study as follows. We apply three parallel-stage DEA models to evaluate the healthcare resources for sustainability with shared and undesirable data.

**Table 2** (*continued*).

| Method | Inputs | Outputs | Control variables | Second stage IVs | Reference |
|---|---|---|---|---|---|
| DEA+Tobit Regression | Total health expenditures in GDP, Physicians, Nurses, Hospital beds, Unemployment rate, Gini coefficient | Life expectancy at birth, 1/(infant mortality rate) | | Total health expenditures in GDP, Physicians, Nurses, Hospital beds, Unemployment rate, Gini coefficient | Top et al. (2020) |
| DEA+Truncated Regression | Health expenditure per capita, Purchasing power parity | Healthy life expectancy at birth, Infant mortality, Physicians, Hospital beds, Smoking prevalence (males), Primary completion rate | Physicians, Hospital beds, Smoking prevalence (males), Primary education, Income group, Population density | | Ahmed et al. (2019) |
| DEA | Administration and maintenance officers, Operational expenditures, Physicians, Nurses, Pharmacists, Doctors, Health workers | Income, Diagnoses and treatments, Inpatient discharges, Operations person-time | | | Cheng et al. (2023) |
| DEA | Raw material, Environmental, and Personal costs, Rate of inferior raw material, Employees' health and safety costs, Number of personnel, Number of patients, Number of beds | Number of errors in diagnosing COVID-19 disease, Number of discharged patients, Profit | | | Azadi et al. (2022) |
| DEA+MPI+ Regression | Number of facilities, Isolation beds, oxygen supported beds, ICU beds, Ventilators, Oxygen manifold available, Compatible BMW management facilities, Capacity of BMW management, Available PPE and N95 masks | Recovered people, Deceased people, BMW generated | | First and second dose vaccines, Males, Females, and transgenders vaccinated, Total population, Literacy rate, Population density | Our study |

The input-oriented model defines technical efficiency as the ability of a production plan to deliver the given level of outputs with fewer inputs (Favero and Papi, 1995). We focus on changes in scale efficiency measurement in DEA and MPI while evaluating the performance of healthcare facilities in cities by taking BMW into account. Scale efficiency in DEA assesses a manager's aptitude for deciding on the appropriate resource allocation to get the desired output levels (Kumar and Gulati, 2008). Thus, by evaluating scale efficiency and pure technical values, we can identify whether the DMU's inefficiency is due to technical problems or complete operating scale (activity levels). The analysis can also establish whether the scale is expanding or contracting. This will help understand whether the underlying healthcare process exhibits one of the three types of returns to scale: constant returns to scale (CRS), decreasing returns to scale (DRS), or increasing returns to scale (IRS).

Further, the temporal developments in efficiency and productivity using the month-wise panel data help us to identify unobserved patterns during the COVID-19 pandemic (Heshmati et al., 2023). We also apply the regression analysis to test the effects of exogenous variables on scale efficiencies (Roth et al., 2019). Some variables like vaccination, literacy rate, and population are little explored, given the Indian context. We demonstrate in our study that it is necessary to know whether a DMU is sustainable for internal and external changes for the purpose of better decision-making.

## 3. Methodology

### 3.1. Study context: The state of Maharashtra in India

We consulted reports generated by the public health department and pollution control board of the state of Maharashtra, India, as the source for our data.[3] During the peak of the first and second wave of the pandemic in 2020 and 2021, 100.85 tons/day and 203 tons/day of COVID-19 BMW were generated across India, respectively, of which the state of Maharashtra generated 17.5 tons/day and 19.02 tons/day respectively. (see Fig. 4). Maharashtra generated 0.25 kg/bed/day of BMW in 2021, and around 9% of the BMW was traced to the COVID-19 pandemic. Maharashtra continued to be ranked among the top three states that generated the maximum BMW levels in India in 2021. Similarly, while number of CBWTF reduced for treatment of COVID-19 generated BMW due to reduction of overall waste generation in 2021, exploration of city-wise capacity requirement remained challenging.

For our DEA efficiency analysis, we collected city-wise healthcare inventory information, COVID-19 statistics, and BMW characteristics in the state of Maharashtra, India, for ten months (January to October) of the pandemic disruption in 2021. These months were considered based on the following logic: Three months before the second wave (January to March), four months during the second wave (April to July), and three months after the second wave (August to October). We use this timeline because the second wave of the pandemic severely impacted a large population in India who were threatened with the possible infections of COVID-19 disease. There was a rush for emergency treatment and a dearth of facilities, hospital beds, oxygen inventory, ventilators, N95 masks, and PPE. Hence, the case fatality ratio kept on rising. Similarly, there was a challenge in matching COVID-19 BMW capacity with generated BMW for treatment in Maharashtra (see Fig. 5 for details). The capacity of COVID-19 BMW treatment included incinerators, autoclaves, shredders, deep burial, and others. The generation was in the form of incinerated and non-incinerated waste. We consider the total capacity and total treated COVID-19 BMW for the efficiency analysis. As discussed in the next section, we classify the inputs and

[3] Government of Maharashtra Department of Public Health, Maharashtra Pollution Control Board.

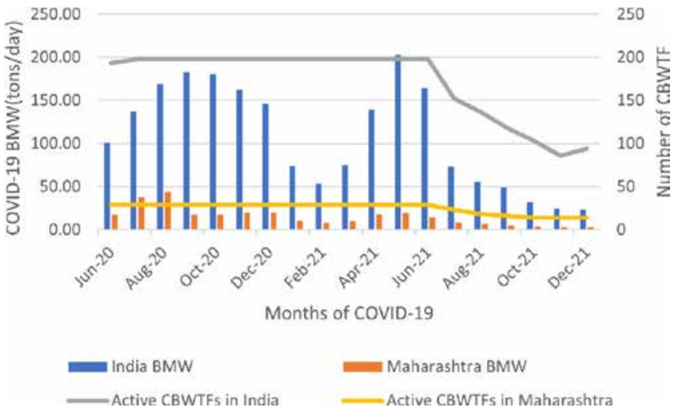


**Fig. 4.** Month-wise COVID-19 biomedical waste in India and Maharashtra.

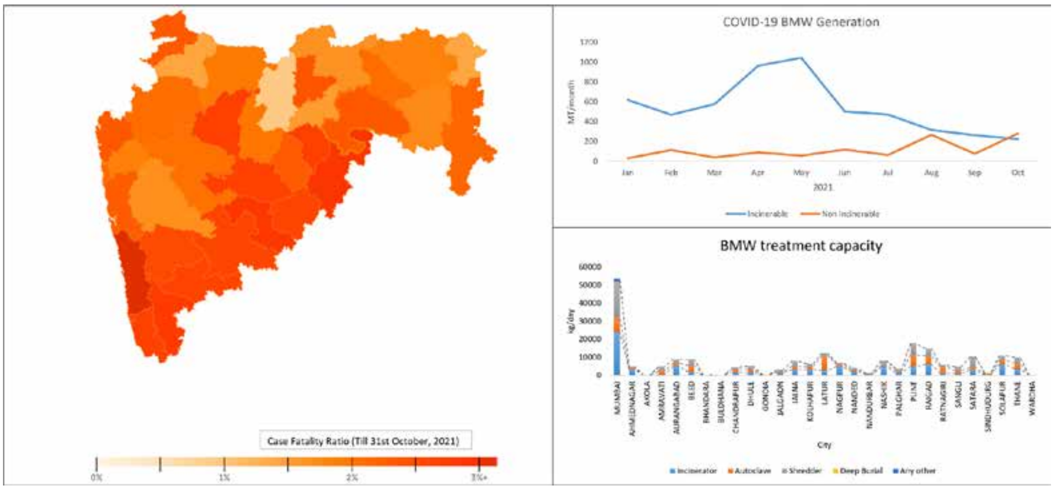


**Fig. 5.** District-wise case fatality ratio and BMW characteristics in Maharashtra.

outputs for general care, emergency care, and BMW management in the DEA model for analysis.

### 3.2. Variable selection

To delve into the operations, we are considering a parallel three-stage model in a situation where there are three subsequent stages in order to calculate the relative efficiencies of DMUs (Fig. 6 and proposed model). For our study, the DMUs are 29 cities within the state of Maharashtra. N95 masks and available PPEs are provided by the Indian Government and they do not segregate these items for general care, and emergency care. Further, the used N95 masks and PPEs are inputs to the BMW management process. Based on the requirement, decision-makers in hospitals segregate these items. Hence, N95 masks ($x^S_{i_3j}$) and available PPEs ($x^S_{i_4j}$) are considered as the shared inputs for general care, emergency care, and BMW management. The inputs for general care are number of facilities ($x^G_{i_1j}$) and total isolation beds ($x^G_{i_2j}$). The inputs for emergency care are oxygen supported beds ($x^E_{i_5j}$), total ICU beds ($x^E_{i_6j}$), number of ventilators ($x^E_{i_7j}$), and oxygen manifold available ($x^E_{i_8j}$). The inputs for BMW management are compatible BMW management facilities ($x^B_{i_9j}$), and the total capacity of BMW treatment ($x^B_{i_{10}j}$). Compatible BMW management facilities are those facilities which are compatible with treatment facilities at CBWTFs. Total BMW capacity includes the treatment processes like incinerator, autoclave, shredder, and deep burial for BMW treatment. The outputs for general and emergency care are recovered people from COVID-19 ($y^G_{r_1j}$, $y^E_{r_3j}$) (desirable outputs) and deceased people from COVID-19 ($y^{UN}_{r_2j}$, $y^{UN}_{r_4j}$) (undesirable outputs). The output for BMW management is Total BMW treated in kg/day ($y^B_{r_5j}$). The mathematical proposed DEA models for general care, emergency care, BMW management, and the overall system are provided in Section 3.3.

### 3.3. Proposed DEA model

Suppose that there is a group of $n$ homogeneous DMUs ($DMU_j$, $j = 1, 2, 3, \ldots, n$) and each DMU consists of three parallel stages (see Fig. 6). The first (general care) stage uses $m_1$ ($x^G_{i_1j}$, $i_1 = 1, 2, \ldots, m_1$) and $m_2$ ($x^G_{i_2j}$, $i_2 = 1, 2, \ldots, m_2$) inputs, and $m_3$ ($x^S_{i_3j}$, $i_3 = 1, 2, \ldots, m_3$) and $m_4$ ($x^S_{i_4j}$, $i_4 = 1, 2, \ldots, m_4$) shared inputs to generate $s_1$ ($y^G_{r_1j}$, $r_1 = 1, 2, \ldots, s_1$) outputs and $s_2$ ($y^{UN}_{r_2j}$, $r_2 = 1, 2, \ldots, s_2$) undesirable outputs. Several methods have been put forth in conventional DEA to include undesirable outputs in a DMU's production process. These approaches were characterized as direct and indirect approaches by Scheel (2001). Direct approaches incorporate undesired outputs into the efficiency

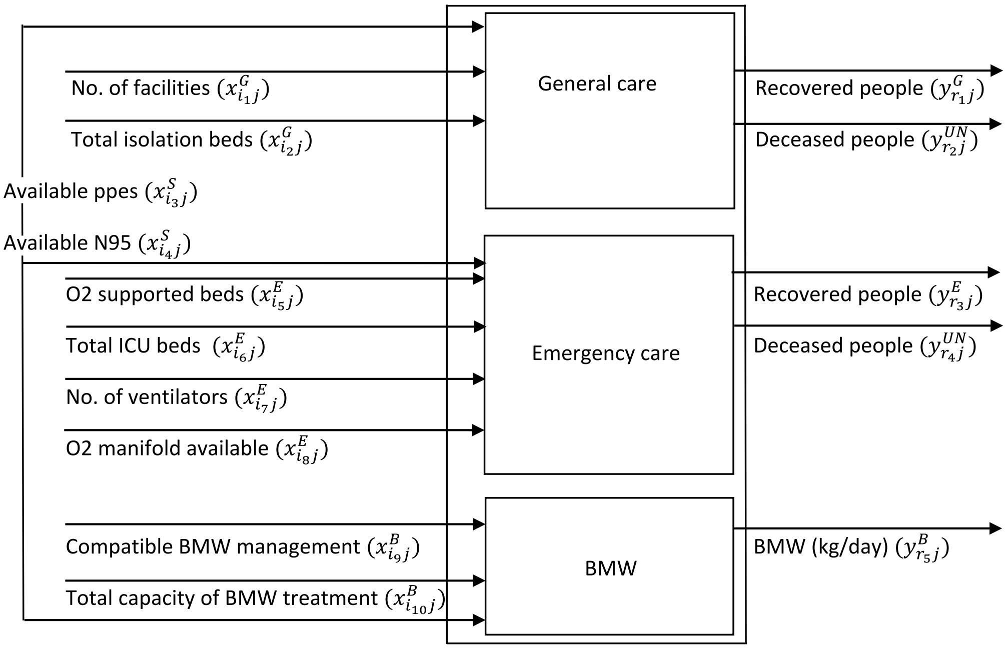


**Fig. 6.** Internal structure of healthcare system.

model without any data transformation. In contrast, indirect approaches convert undesirable output data by a monotone decreasing function to make it desirable output after the transformation (Seiford and Zhu, 2002). In the healthcare sector, the direct approach is more appropriate since it is more acceptable to add undesirable outputs like deceased people directly into the DEA model and examine its impact on the healthcare sector (Retzlaff-Roberts et al., 2004).

In this paper, the efficiency scores are obtained independently for individual stages, and the overall system using all stages is connected in parallel (Cook et al., 2010; Ma and Chen, 2018). We have referred to the proportions of shared inputs for parallel stages as $\alpha_1$, $\alpha_2$, and $\alpha_3$, respectively. As far as the shared input percentages are concerned as per World Health Organization, 40% of the COVID-19 patients had mild symptoms, while 60% of the COVID-19 patients had moderate, high, and critical symptoms.[4] However, during the resource rationalization of N95 masks and PPEs due to shortage of supply, general care departments were asked to limit the use of these resources.[5] Hence, we assume that $\alpha_1$=30% of resources for general care and $\alpha_2$=70% of resources for emergency care, and $\alpha_3 = \alpha_1 + \alpha_2$ for BMW Management (disposed N95 masks and PPEs). We scale these ratios accordingly for our developed model. $E^G_k$ denotes $DMU_k$'s relative efficiency for general care, which can be calculated via the following CCR model in the input orientation.

$$E^G_k = \max \sum_{r_1=1}^{s_1} v^G_{r_1k} y^G_{r_1k}$$

$$\sum_{i_1=1}^{m_1} u^G_{i_1k} x^G_{i_1k} + \sum_{i_2=1}^{m_2} u^G_{i_2k} x^G_{i_2k} + \sum_{i_3=1}^{m_3} (\alpha_1) u^S_{i_3k} x^S_{i_3k} + \sum_{i_4=1}^{m_4} (\alpha_1) u^S_{i_4k} x^S_{i_4k} + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k} y^{UN}_{r_2k} = 1,$$

$$\sum_{r_1=1}^{s_1} v^G_{r_1k} y^G_{r_1j} - \Big(\sum_{i_1=1}^{m_1} u^G_{i_1k} x^G_{i_1j} + \sum_{i_2=1}^{m_2} u^G_{i_2k} x^G_{i_2j} + \sum_{i_3=1}^{m_3} (\alpha_1) u^S_{i_3k} x^S_{i_3j} + \sum_{i_4=1}^{m_4} (\alpha_1) u^S_{i_4k} x^S_{i_4j} + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k} y^{UN}_{r_2j}\Big) \le 0, \tag{3.1}$$

where $u^G_{.k}$ and $v^G_{.k}$ are the (.)th input and the (.)th output weights of $DMU_k$, respectively. $DMU_k$ is efficient if $E^{G*}_k = 1$, where $E^{G*}_k$ be the optimal value of the above model; otherwise, it is called inefficient.

Second system (emergency healthcare) uses $m_5$ ($x^E_{i_5j}$, $i_5 = 1, 2, \ldots, m_5$), $m_6$ ($x^E_{i_6j}$, $i_6 = 1, 2, \ldots, m_6$), $m_7$ ($x^E_{i_7j}$, $i_7 = 1, 2, \ldots, m_7$), $m_8$ ($x^E_{i_8j}$, $i_8 = 1, 2, \ldots, m_8$) inputs, and $m_3$ ($x^S_{i_3j}$, $i_3 = 1, 2, \ldots, m_3$), $m_4$ ($x^S_{i_4j}$, $i_4 = 1, 2, \ldots, m_4$) shared inputs to produce $s_3$ ($y^E_{r_3j}$, $r_3 = 1, 2, \ldots, s_3$) outputs and $s_4$ ($y^{UN}_{r_4j}$, $r_4 = 1, 2, \ldots, s_4$) undesirable outputs. $E^E_k$ denotes $DMU_k$'s relative efficiency for emergency care, which can be calculated as follows:

$$E^E_k = \max \sum_{r_3=1}^{s_3} v^E_{r_3k} y^E_{r_3k}$$

$$\sum_{i_5=1}^{m_5} u^E_{i_5k} x^E_{i_5k} + \sum_{i_6=1}^{m_6} u^E_{i_6k} x^E_{i_6k} + \sum_{i_7=1}^{m_7} u^E_{i_7k} x^E_{i_7k} + \sum_{i_8=1}^{m_8} u^E_{i_8k} x^E_{i_8k} + \sum_{i_3=1}^{m_3} (\alpha_2) u^S_{i_3k} x^S_{i_3k} + \sum_{i_4=1}^{m_4} (\alpha_2) u^S_{i_4k} x^S_{i_4k} + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k}$$

$$y^{UN}_{r_4k} = 1,$$

$$\sum_{r_3=1}^{s_3} v^E_{r_3k} y^E_{r_3j} - \Big(\sum_{i_5=1}^{m_5} u^E_{i_5k} x^E_{i_5j} + \sum_{i_6=1}^{m_6} u^E_{i_6k} x^E_{i_6j} + \sum_{i_7=1}^{m_7} u^E_{i_7k} x^E_{i_7j} + \sum_{i_8=1}^{m_8} u^E_{i_8k} x^E_{i_8j} + \sum_{i_3=1}^{m_3} (\alpha_2) u^S_{i_3k} x^S_{i_3j} + \sum_{i_4=1}^{m_4} (\alpha_2)$$

$$u^S_{i_4k} x^S_{i_4j} + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k} y^{UN}_{r_4j}\Big) \le 0 \ \forall j. \tag{3.2}$$

where $u^E_{.k}$ and $v^E_{.k}$ are the (.)th input and the (.)th output weights of $DMU_k$, respectively. $DMU_k$ is efficient if $E^{E*}_k = 1$, where $E^{E*}_k$ be

[4] Rational use of personal protective equipment (PPE) for coronavirus disease (COVID-19): interim guidance, 19 March 2020 (No. WHO/2019-nCoV/IPC PPE_use/2020.2). World Health Organization.

[5] https://www.mohfw.gov.in/pdf/GuidelinesonrationaluseofPersonalProtectiveEquipment.pdf.

$$E_k^{O1} = \max\ (W_1 E_k^G + W_2 E_k^E + W_3 E_k^B), \tag{3.4}$$

$$\text{here } W_1 + W_2 + W_3 = 1, \tag{3.5}$$

$$W_1 = \frac{\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1k}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2k}^G + \sum_{i_3=1}^{m_3} (\alpha_1) u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} (\alpha_1) u_{i_4k}^S x_{i_4k}^S + \sum_{r_2=1}^{s_2} v_{r_2k}^{UN} y_{r_2k}^{UN}}{\begin{array}{c}\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1k}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2k}^G + \sum_{i_3=1}^{m_3} u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} u_{i_4k}^S x_{i_4k}^S + \sum_{r_2=1}^{s_2} v_{r_2k}^{UN} y_{r_2k}^{UN} + \sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5k}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E x_{i_6k}^E \\ + \sum_{i_7=1}^{m_7} u_{i_7k}^E x_{i_7k}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8k}^E + \sum_{r_4=1}^{s_4} v_{r_4k}^{UN} y_{r_4k}^{UN} + \sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9k}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}k}^B\end{array}} \tag{3.6}$$

$$W_2 = \frac{\begin{array}{c}\sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5k}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E x_{i_6k}^E + \sum_{i_7=1}^{m_7} u_{i_7k}^E x_{i_7k}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8k}^E + \sum_{i_3=1}^{m_3} (\alpha_2) u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} (\alpha_2) u_{i_4k}^S x_{i_4k}^S \\ + \sum_{r_4=1}^{s_4} v_{r_4k}^{UN} y_{r_4k}^{UN}\end{array}}{\begin{array}{c}\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1k}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2k}^G + \sum_{i_3=1}^{m_3} u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} u_{i_4k}^S x_{i_4k}^S + \sum_{r_2=1}^{s_2} v_{r_2k}^{UN} y_{r_2k}^{UN} + \sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5k}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E x_{i_6k}^E \\ + \sum_{i_7=1}^{m_7} u_{i_7k}^E x_{i_7k}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8k}^E + \sum_{r_4=1}^{s_4} v_{r_4k}^{UN} y_{r_4k}^{UN} + \sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9k}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}k}^B\end{array}}, \tag{3.7}$$

$$W_3 = \frac{\sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9k}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}k}^B + \sum_{i_3=1}^{m_3} (\alpha_3) u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} (\alpha_3) u_{i_4k}^S x_{i_4k}^S}{\begin{array}{c}\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1k}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2k}^G + \sum_{i_3=1}^{m_3} u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} u_{i_4k}^S x_{i_4k}^S + \sum_{r_2=1}^{s_2} v_{r_2k}^{UN} y_{r_2k}^{UN} + \sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5k}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E x_{i_6k}^E \\ + \sum_{i_7=1}^{m_7} u_{i_7k}^E x_{i_7k}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8k}^E + \sum_{r_4=1}^{s_4} v_{r_4k}^{UN} y_{r_4k}^{UN} + \sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9k}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}k}^B\end{array}}, \tag{3.8}$$

**Box I.**

the optimal value of the emergency care model; otherwise, it is called inefficient.

The third (BMW management) stage uses $m_9$ ($x_{i_9j}^B$, $i_9 = 1, 2, \dots, m_9$), $m_{10}$ ($x_{i_{10}j}^B$, $i_{10} = 1, 2, \dots, m_{10}$) inputs, $m_3$ ($x_{i_3j}^S$, $i_3 = 1, 2, \dots, m_3$) and $m_4$ ($x_{i_4j}^S$, $i_4 = 1, 2, \dots, m_4$) shared inputs to generate $s_5$ outputs ($y_{r_5j}^B$, $r_5 = 1, 2, \dots, s_5$). $E_k^B$ denotes $DMU_k$'s relative efficiency for BMW management, which can be calculated as follows:

$$\begin{aligned} E_k^B &= \max \sum_{r_5=1}^{s_5} v_{r_5k}^B y_{r_5k}^B \\ &\sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9k}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}k}^B + \sum_{i_3=1}^{m_3} (\alpha_3) u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} (\alpha_3) u_{i_4k}^S x_{i_4k}^S = 1, \\ &\sum_{r_5=1}^{s_5} v_{r_5k}^B y_{r_5j}^B - (\sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9j}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}j}^B + \sum_{i_3=1}^{m_3} (\alpha_3) u_{i_3k}^S x_{i_3j}^S \\ &\quad + \sum_{i_4=1}^{m_4} (\alpha_3) u_{i_4k}^S x_{i_4j}^S) \leq 0 \ \ \forall j. \end{aligned} \tag{3.3}$$

where $u_k^B$ and $v_k^B$ are the (.)th input and the (.)th output weights of $DMU_k$, respectively. $DMU_k$ is efficient if $E_k^{B*} = 1$, where $E_k^{B*}$ be the optimal value of the above model; otherwise, it is called inefficient.

The healthcare system's overall efficiency ($E_k^{O1}$) with three parallel stages (see the equations given in Box I): Thus, we get the following fractional overall CCR (parallel) model using (3.4), (3.6)–(3.8) and all the constraints from three stages (see the equation given in Box II): The model (3.9) has been transformed into the following output multiplier CCR model for overall system:

$$\begin{aligned} E_k^O &= \max \sum_{r_1=1}^{s_1} v_{r_1k}^G y_{r_1k}^G + \sum_{r_3=1}^{s_3} v_{r_3k}^E y_{r_3k}^E + \sum_{r_5=1}^{s_5} v_{r_5k}^B y_{r_5k}^B \\ &\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1k}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2k}^G + \sum_{i_3=1}^{m_3} u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} u_{i_4k}^S x_{i_4k}^S \\ &\quad + \sum_{r_2=1}^{s_2} v_{r_2k}^{UN} y_{r_2k}^{UN} + \sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5k}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E x_{i_6k}^E + \sum_{i_7=1}^{m_7} u_{i_7k}^E \\ &x_{i_7k}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8k}^E + \sum_{r_4=1}^{s_4} v_{r_4k}^{UN} y_{r_4k}^{UN} + \sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9k}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}k}^B = 1, \\ &\sum_{r_1=1}^{s_1} v_{r_1k}^G y_{r_1j}^G - (\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1j}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2j}^G + \sum_{i_3=1}^{m_3} (\alpha_1) u_{i_3k}^S x_{i_3j}^S \\ &\quad + \sum_{i_4=1}^{m_4} (\alpha_1) u_{i_4k}^S x_{i_4j}^S + \sum_{r_2=1}^{s_2} v_{r_2k}^{UN} y_{r_2j}^{UN}) \leq 0 \ \ \forall j, \\ &\sum_{r_3=1}^{s_3} v_{r_3k}^E y_{r_3j}^E - (\sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5j}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E x_{i_6j}^E + \sum_{i_7=1}^{m_7} u_{i_7k}^E x_{i_7j}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8j}^E \\ &\quad + \sum_{i_3=1}^{m_3} (\alpha_2) u_{i_3k}^S x_{i_3j}^S + \sum_{i_4=1}^{m_4} (\alpha_2) \\ &u_{i_4k}^S x_{i_4j}^S + \sum_{r_4=1}^{s_4} v_{r_4k}^{UN} y_{r_4j}^{UN}) \leq 0 \ \ \forall j, \\ &\sum_{r_5=1}^{s_5} v_{r_5k}^B y_{r_5j}^B - (\sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9j}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}j}^B + \sum_{i_3=1}^{m_3} (\alpha_3) u_{i_3k}^S x_{i_3j}^S \\ &\quad + \sum_{i_4=1}^{m_4} (\alpha_3) u_{i_4k}^S x_{i_4j}^S) \leq 0 \ \ \forall j. \end{aligned} \tag{3.10}$$

$DMU_k$ is efficient in overall system if $E_k^{O*} = 1$ and it is also stage efficient, where $E_k^{O*}$ be the optimal value of the above model; otherwise, it is inefficient.

Real-world applications have periods, and applying DEA independently to each period is inappropriate for these situations. While the DEA approach only gives us information on managerial efficiency, MPI (Caves et al., 1982) is used for efficiency changes over time and is becoming a popular method among researchers in various fields (Barros, 2005; Kim et al., 2021; Achi, 2023; Dutta et al., 2020). The MPI (3.11) was further broken down by Färe et al. (1992) to identify two contributing factors of productivity change (tfpch): efficiency change or the catching-up effect (effch), and technical change or frontier shift (techch).

$$MPI^{t,t+1}(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \left[ \frac{D^t(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D^t(x^t, y^t)}{D^{t+1}(x^t, y^t)} \right]^{1/2} \tag{3.11}$$

where $D$ denotes the distance function, $MPI^{t,t+1}(x^t, y^t, x^{t+1}, y^{t+1})$ denotes the MPI over $t$ and $t+1$ periods, $x^\cdot$ and $y^\cdot$ are the inputs and outputs respectively. Efficiency change is the first expression and technical change is the second expression on the right-hand side. Efficiency change is a term used to indicate how technical efficiency has changed over time, or, to put it another way, how rapidly inefficient

$$E_k^{O1} = \max\ (W_1E_k^G + W_2E_k^E + W_3E_k^B), \tag{3.4}$$

$$\text{here } W_1 + W_2 + W_3 = 1, \tag{3.5}$$

$$W_1 = \frac{\sum_{i_1=1}^{m_1} u^G_{i_1k}x^G_{i_1k} + \sum_{i_2=1}^{m_2} u^G_{i_2k}x^G_{i_2k} + \sum_{i_3=1}^{m_3}(\alpha_1)u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4}(\alpha_1)u^S_{i_4k}x^S_{i_4k} + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k}y^{UN}_{r_2k}}{\begin{array}{c}\sum_{i_1=1}^{m_1} u^G_{i_1k}x^G_{i_1k} + \sum_{i_2=1}^{m_2} u^G_{i_2k}x^G_{i_2k} + \sum_{i_3=1}^{m_3} u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4} u^S_{i_4k}x^S_{i_4k} + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k}y^{UN}_{r_2k} + \sum_{i_5=1}^{m_5} u^E_{i_5k}x^E_{i_5k} + \sum_{i_6=1}^{m_6} u^E_{i_6k}x^E_{i_6k}\\ + \sum_{i_7=1}^{m_7} u^E_{i_7k}x^E_{i_7k} + \sum_{i_8=1}^{m_8} u^E_{i_8k}x^E_{i_8k} + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k}y^{UN}_{r_4k} + \sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9k} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}k}\end{array}} \tag{3.6}$$

$$W_2 = \frac{\begin{array}{c}\sum_{i_5=1}^{m_5} u^E_{i_5k}x^E_{i_5k} + \sum_{i_6=1}^{m_6} u^E_{i_6k}x^E_{i_6k} + \sum_{i_7=1}^{m_7} u^E_{i_7k}x^E_{i_7k} + \sum_{i_8=1}^{m_8} u^E_{i_8k}x^E_{i_8k} + \sum_{i_3=1}^{m_3}(\alpha_2)u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4}(\alpha_2)u^S_{i_4k}x^S_{i_4k}\\ + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k}y^{UN}_{r_4k}\end{array}}{\begin{array}{c}\sum_{i_1=1}^{m_1} u^G_{i_1k}x^G_{i_1k} + \sum_{i_2=1}^{m_2} u^G_{i_2k}x^G_{i_2k} + \sum_{i_3=1}^{m_3} u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4} u^S_{i_4k}x^S_{i_4k} + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k}y^{UN}_{r_2k} + \sum_{i_5=1}^{m_5} u^E_{i_5k}x^E_{i_5k} + \sum_{i_6=1}^{m_6} u^E_{i_6k}x^E_{i_6k}\\ + \sum_{i_7=1}^{m_7} u^E_{i_7k}x^E_{i_7k} + \sum_{i_8=1}^{m_8} u^E_{i_8k}x^E_{i_8k} + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k}y^{UN}_{r_4k} + \sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9k} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}k}\end{array}}, \tag{3.7}$$

$$W_3 = \frac{\sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9k} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}k} + \sum_{i_3=1}^{m_3}(\alpha_3)u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4}(\alpha_3)u^S_{i_4k}x^S_{i_4k}}{\begin{array}{c}\sum_{i_1=1}^{m_1} u^G_{i_1k}x^G_{i_1k} + \sum_{i_2=1}^{m_2} u^G_{i_2k}x^G_{i_2k} + \sum_{i_3=1}^{m_3} u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4} u^S_{i_4k}x^S_{i_4k} + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k}y^{UN}_{r_2k} + \sum_{i_5=1}^{m_5} u^E_{i_5k}x^E_{i_5k} + \sum_{i_6=1}^{m_6} u^E_{i_6k}x^E_{i_6k}\\ + \sum_{i_7=1}^{m_7} u^E_{i_7k}x^E_{i_7k} + \sum_{i_8=1}^{m_8} u^E_{i_8k}x^E_{i_8k} + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k}y^{UN}_{r_4k} + \sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9k} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}k}\end{array}}, \tag{3.8}$$

**Box I.**

the optimal value of the emergency care model; otherwise, it is called inefficient.

The third (BMW management) stage uses $m_9$ ($x^B_{i_9j}$, $i_9 = 1,2,\dots,m_9$), $m_{10}$ ($x^B_{i_{10}j}$, $i_{10} = 1,2,\dots,m_{10}$) inputs, $m_3$ ($x^S_{i_3j}$, $i_3 = 1,2,\dots,m_3$) and $m_4$ ($x^S_{i_4j}$, $i_4 = 1,2,\dots,m_4$) shared inputs to generate $s_5$ outputs ($y^B_{r_5j}$, $r_5 = 1,2,\dots,s_5$). $E^B_k$ denotes $DMU_k$'s relative efficiency for BMW management, which can be calculated as follows:

$$\begin{aligned}
E_k^B &= \max \sum_{r_5=1}^{s_5} v^B_{r_5k}y^B_{r_5k}\\
&\sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9k} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}k} + \sum_{i_3=1}^{m_3}(\alpha_3)u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4}(\alpha_3)u^S_{i_4k}x^S_{i_4k} = 1,\\
&\sum_{r_5=1}^{s_5} v^B_{r_5k}y^B_{r_5j} - (\sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9j} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}j} + \sum_{i_3=1}^{m_3}(\alpha_3)u^S_{i_3k}x^S_{i_3j}\\
&\quad + \sum_{i_4=1}^{m_4}(\alpha_3)u^S_{i_4k}x^S_{i_4j}) \le 0 \ \ \forall j.
\end{aligned} \tag{3.3}$$

where $u^B_{.k}$ and $v^B_{.k}$ are the (.)th input and the (.)th output weights of $DMU_k$, respectively. $DMU_k$ is efficient if $E^{B*}_k = 1$, where $E^{B*}_k$ be the optimal value of the above model; otherwise, it is called inefficient.

The healthcare system's overall efficiency ($E^{O1}_k$) with three parallel stages (see the equations given in Box I): Thus, we get the following fractional overall CCR (parallel) model using (3.4), (3.6)–(3.8) and all the constraints from three stages (see the equation given in Box II): The model (3.9) has been transformed into the following output multiplier CCR model for overall system:

$$\begin{aligned}
E_k^O &= \max \sum_{r_1=1}^{s_1} v^G_{r_1k}y^G_{r_1k} + \sum_{r_3=1}^{s_3} v^E_{r_3k}y^E_{r_3k} + \sum_{r_5=1}^{s_5} v^B_{r_5k}y^B_{r_5k}\\
&\sum_{i_1=1}^{m_1} u^G_{i_1k}x^G_{i_1k} + \sum_{i_2=1}^{m_2} u^G_{i_2k}x^G_{i_2k} + \sum_{i_3=1}^{m_3} u^S_{i_3k}x^S_{i_3k} + \sum_{i_4=1}^{m_4} u^S_{i_4k}x^S_{i_4k}\\
&\quad + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k}y^{UN}_{r_2k} + \sum_{i_5=1}^{m_5} u^E_{i_5k}x^E_{i_5k} + \sum_{i_6=1}^{m_6} u^E_{i_6k}x^E_{i_6k} + \sum_{i_7=1}^{m_7} u^E_{i_7k}\\
&x^E_{i_7k} + \sum_{i_8=1}^{m_8} u^E_{i_8k}x^E_{i_8k} + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k}y^{UN}_{r_4k} + \sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9k} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}k} = 1,\\
&\sum_{r_1=1}^{s_1} v^G_{r_1k}y^G_{r_1j} - (\sum_{i_1=1}^{m_1} u^G_{i_1k}x^G_{i_1j} + \sum_{i_2=1}^{m_2} u^G_{i_2k}x^G_{i_2j} + \sum_{i_3=1}^{m_3}(\alpha_1)u^S_{i_3k}x^S_{i_3j}\\
&\quad + \sum_{i_4=1}^{m_4}(\alpha_1)u^S_{i_4k}x^S_{i_4j} + \sum_{r_2=1}^{s_2} v^{UN}_{r_2k}y^{UN}_{r_2j}) \le 0 \ \ \forall j,\\
&\sum_{r_3=1}^{s_3} v^E_{r_3k}y^E_{r_3j} - (\sum_{i_5=1}^{m_5} u^E_{i_5k}x^E_{i_5j} + \sum_{i_6=1}^{m_6} u^E_{i_6k}x^E_{i_6j} + \sum_{i_7=1}^{m_7} u^E_{i_7k}x^E_{i_7j} + \sum_{i_8=1}^{m_8} u^E_{i_8k}x^E_{i_8j}\\
&\quad + \sum_{i_3=1}^{m_3}(\alpha_2)u^S_{i_3k}x^S_{i_3j} + \sum_{i_4=1}^{m_4}(\alpha_2)\\
&u^S_{i_4k}x^S_{i_4j} + \sum_{r_4=1}^{s_4} v^{UN}_{r_4k}y^{UN}_{r_4j}) \le 0 \ \ \forall j,\\
&\sum_{r_5=1}^{s_5} v^B_{r_5k}y^B_{r_5j} - (\sum_{i_9=1}^{m_9} u^B_{i_9k}x^B_{i_9j} + \sum_{i_{10}=1}^{m_{10}} u^B_{i_{10}k}x^B_{i_{10}j} + \sum_{i_3=1}^{m_3}(\alpha_3)u^S_{i_3k}x^S_{i_3j}\\
&\quad + \sum_{i_4=1}^{m_4}(\alpha_3)u^S_{i_4k}x^S_{i_4j}) \le 0 \ \ \forall j.
\end{aligned} \tag{3.10}$$

$DMU_k$ is efficient in overall system if $E^{O*}_k = 1$ and it is also stage efficient, where $E^{O*}_k$ be the optimal value of the above model; otherwise, it is inefficient.

Real-world applications have periods, and applying DEA independently to each period is inappropriate for these situations. While the DEA approach only gives us information on managerial efficiency, MPI (Caves et al., 1982) is used for efficiency changes over time and is becoming a popular method among researchers in various fields (Barros, 2005; Kim et al., 2021; Achi, 2023; Dutta et al., 2020). The MPI (3.11) was further broken down by Färe et al. (1992) to identify two contributing factors of productivity change (tfpch): efficiency change or the catching-up effect (effch), and technical change or frontier shift (techch).

$$MPI^{t,t+1}(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \left[\frac{D^t(x^{t+1}, y^{t+1})}{D^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D^t(x^t, y^t)}{D^{t+1}(x^t, y^t)}\right]^{1/2} \tag{3.11}$$

where $D$ denotes the distance function, $MPI^{t,t+1}(x^t, y^t, x^{t+1}, y^{t+1})$ denotes the MPI over $t$ and $t+1$ periods, $x^{\cdot}$ and $y^{\cdot}$ are the inputs and outputs respectively. Efficiency change is the first expression and technical change is the second expression on the right-hand side. Efficiency change is a term used to indicate how technical efficiency has changed over time, or, to put it another way, how rapidly inefficient

$$E_k^{O1} = \max \frac{\sum_{r_1=1}^{s_1} \upsilon_{r_1k}^G y_{r_1k}^G + \sum_{r_3=1}^{s_3} \upsilon_{r_3k}^E y_{r_3k}^E + \sum_{r_5=1}^{s_5} \upsilon_{r_5k}^B y_{r_5k}^B}{\begin{gathered}\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1k}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2k}^G + \sum_{i_3=1}^{m_3} u_{i_3k}^S x_{i_3k}^S + \sum_{i_4=1}^{m_4} u_{i_4k}^S x_{i_4k}^S + \sum_{r_2=1}^{s_2} \upsilon_{r_2k}^{UN} y_{r_2k}^{UN} + \sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5k}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E \\ x_{i_6k}^E + \sum_{i_7=1}^{m_7} u_{i_7k}^E x_{i_7k}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8k}^E + \sum_{r_4=1}^{s_4} \upsilon_{r_4k}^{UN} y_{r_4k}^{UN} + \sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9k}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}k}^B\end{gathered}}$$

$$\frac{\sum_{r_1=1}^{s_1} \upsilon_{r_1k}^G y_{r_1j}^G}{\sum_{i_1=1}^{m_1} u_{i_1k}^G x_{i_1j}^G + \sum_{i_2=1}^{m_2} u_{i_2k}^G x_{i_2j}^G + \sum_{i_3=1}^{m_3} (\alpha_1) u_{i_3k}^S x_{i_3j}^S + \sum_{i_4=1}^{m_4} (\alpha_1) u_{i_4k}^S x_{i_4j}^S + \sum_{r_2=1}^{s_2} \upsilon_{r_2k}^{UN} y_{r_2j}^{UN}} \le 1 \ \ \forall j,$$

$$\frac{\sum_{r_3=1}^{s_3} \upsilon_{r_3k}^E y_{r_3j}^E}{\begin{gathered}\sum_{i_5=1}^{m_5} u_{i_5k}^E x_{i_5j}^E + \sum_{i_6=1}^{m_6} u_{i_6k}^E x_{i_6j}^E + \sum_{i_7=1}^{m_7} u_{i_7k}^E x_{i_7j}^E + \sum_{i_8=1}^{m_8} u_{i_8k}^E x_{i_8j}^E + \sum_{i_3=1}^{m_3} (\alpha_2) u_{i_3k}^S x_{i_3j}^S + \sum_{i_4=1}^{m_4} (\alpha_2) \\ u_{i_4k}^S x_{i_4j}^S + \sum_{r_4=1}^{s_4} \upsilon_{r_4k}^{UN} y_{r_4j}^{UN}\end{gathered}} \le 1 \ \ \forall j,$$

$$\frac{\sum_{r_5=1}^{s_5} \upsilon_{r_5k}^B y_{r_5j}^B}{\sum_{i_9=1}^{m_9} u_{i_9k}^B x_{i_9j}^B + \sum_{i_{10}=1}^{m_{10}} u_{i_{10}k}^B x_{i_{10}j}^B + \sum_{i_3=1}^{m_3} (\alpha_3) u_{i_3k}^S x_{i_3j}^S + \sum_{i_4=1}^{m_4} (\alpha_3) u_{i_4k}^S x_{i_4j}^S} \le 1 \ \ \forall j. \tag{3.9}$$

**Box II.**

DMUs can catch up with more efficient ones. The technical change reflects how the technological frontier has changed over time. There are significant distinctions between efficiency and technical change in the healthcare sector where facilities may struggle to control their operational size and may experience severe resource constraints when investing capital-intensive medical equipment. In other words, these distinctions will guide decision-makers to concentrate resources for healthcare sustainability. For more details, readers can refer to Färe and Grosskopf's (1996) article.

In order to determine how the efficiency scores produced in the first stage are correlated with specific environmental variables, we conducted regression analysis with fixed effects as the second stage in the two-step approach to DEA. We estimated a regression equation that is utilized to find a correlation between the efficiencies calculated in the first stage. This helps to establish a valid inference and the significant determinants of the scale efficiencies computed in the first stage of the DEA. We run a regression using data from January 2021 to October 2021 on a balanced panel of 29 cities, with scale efficiency as the dependent variable (3.12). The following specification equation applies to the second-step model:

$$\begin{aligned} Scale_{it} = {} & \beta_0 + \beta_1 \text{ First dose vaccine}_{it} + \beta_2 \text{ Second dose vaccine}_{it} \\ & + \beta_3 \text{ Males vaccinated}_{it} \\ & + \beta_4 \text{ Females vaccinated}_{it} + \beta_5 \text{ Transgenders vaccinated}_{it} \\ & + \beta_6 \text{ population}_{it} \\ & + \beta_7 \text{ literacy rate}_{it} + \beta_8 \text{ population density}_{it} \\ & + \text{ month Dummies} + \text{ DMUs Dummies } + \varepsilon_{it} \end{aligned} \tag{3.12}$$

To eliminate the unwanted error, we also took into account fixed effects and dummy factors. The number of people who received the COVID-19 first dose and second dose vaccines, respectively, is represented by the first dose and second dose vaccines.

## 4. Results and discussion

We start by analyzing the first research question (RQ1). The question focuses on the technique for efficiency ratings and identifying the cities which are efficient for greener healthcare operations. We apply the proposed DEA model to answer these questions. To evaluate the efficiency ratings, first, we identify the count of IRS, CRS, and DRS for the 29 cities (DMUs) according to scale efficiencies (see Fig. 7). The VRS model measures the scale efficiency for each of the sample cities. From the VRS model, we analyze whether a city's healthcare operations indicated IRS, CRS, or DRS (Jehu-Appiah et al., 2014). If output increases by more than the proportional input change, there is IRS. If output increases by less than the proportional change in inputs, there is DRS, and finally, in case output increases the same as proportional change, there is CRS. Based on such findings, those units with IRS should have increased the use of input resources to achieve higher performance levels. In contrast, units with DRS should have decreased their utilization rate (Bahrami et al., 2018). From the overall efficiency, the state performed well in April, May, and June, the peak months of the pandemic. However, since these results are black-box in nature, they do not reveal the true state of affairs for individual parallel stages. Further examination shows that the minimum and maximum number of efficient cities are between 4 and 7 for general care, 3 and 10 for emergency care, 5 and 8 for BMW management, and 9 and 13 for overall efficiency, respectively. Interestingly, in general, and emergency care, IRS are favorable numbers from January to May and unfavorable from June to October. However, BMW's IRS count rose between January and October.

The results depict that general and emergency care performed poorly after May, while BMW management performed well from January to October, with performance improvement over the period of the months. Emergency care performed better than general care from January to May and marginally better from June to October. Hence, we can conclude that the facilities and utilization in emergency care were adequate. In response to our inquiry with experts, it was revealed that city municipal corporations were managing BMW management administration quite well. This is revealed in the results as well. However, general care and emergency care did not improve over time. Hence, general and emergency treatment should be enhanced for sustainable utilization of resources since inefficient medical care indirectly impact BMW management. Overall, we identify that hospitals in particular cities did not focus on general treatment during the pandemic and instead focused on emergency care. From this observation, we can also infer that if an individual exhibit mild COVID-19 symptoms, they should move to COVID care centers (quarantine centers) where better general care can be provided. This will help in saving resources for emergency care and reduce undesirable outputs that impact sustainability for BMW management.

For five cities in January, the efficiency index was equivalent to 1, indicating that they performed at a rate of efficiency that is close to 100% of the sample average (see Table 3). The pure technical efficiency (BCC) indicator gauges a city's output as a result of how well its managers managed to arrange the inputs into the greener healthcare process.

In comparison to the rest of the dataset, a disproportionately high number of cities (12) perform input-to-output conversion at a 100% relative efficiency. According to the data at hand and the scale efficiency index, only five cities for each operational management structure are

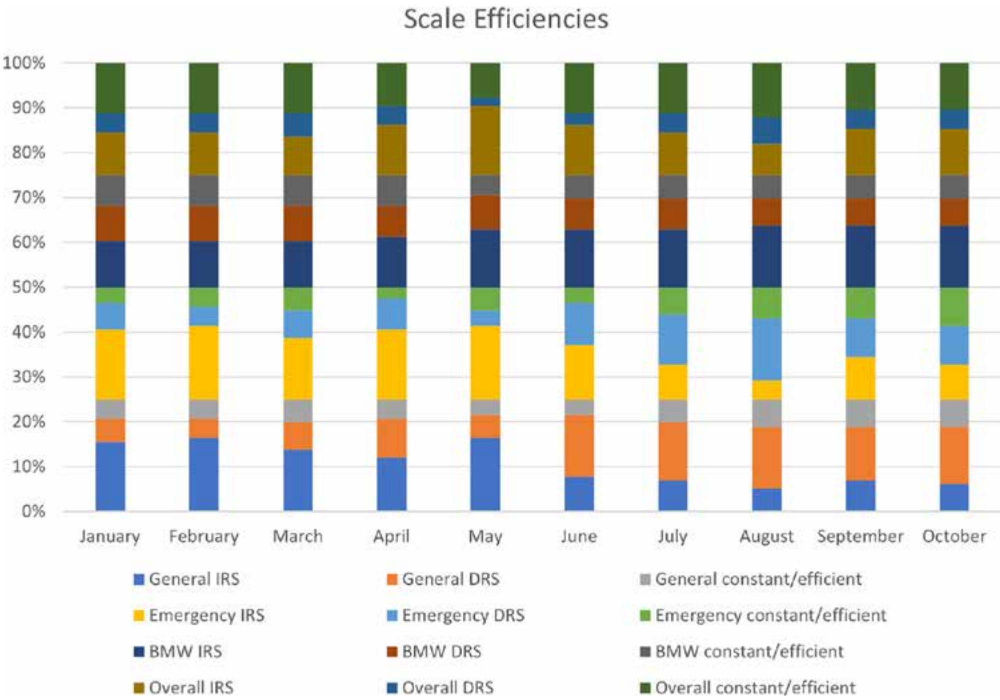


**Fig. 7.** Scale efficiencies across months in 2021.

**Table 3**
Number of efficient cities.

| Model | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct |
|---|---|---|---|---|---|---|---|---|---|---|
| General care | | | | | | | | | | |
| CCR | 5 | 5 | 4 | 5 | 4 | 4 | 6 | 7 | 7 | 7 |
| BCC | 12 | 12 | 11 | 10 | 11 | 9 | 11 | 11 | 11 | 10 |
| Scale | 5 | 5 | 6 | 5 | 4 | 4 | 6 | 7 | 7 | 7 |
| Emergency care | | | | | | | | | | |
| CCR | 4 | 5 | 4 | 3 | 4 | 4 | 6 | 7 | 7 | 7 |
| BCC | 11 | 12 | 11 | 11 | 12 | 10 | 11 | 11 | 11 | 10 |
| Scale | 4 | 5 | 6 | 3 | 5 | 4 | 6 | 7 | 7 | 9 |
| BMW management | | | | | | | | | | |
| CCR | 7 | 7 | 7 | 7 | 5 | 5 | 6 | 6 | 6 | 6 |
| BCC | 12 | 12 | 12 | 13 | 13 | 12 | 12 | 12 | 12 | 12 |
| Scale | 7 | 8 | 7 | 7 | 5 | 5 | 6 | 6 | 6 | 6 |
| Overall | | | | | | | | | | |
| CCR | 13 | 13 | 11 | 10 | 9 | 12 | 12 | 14 | 12 | 12 |
| BCC | 18 | 18 | 17 | 15 | 16 | 17 | 17 | 18 | 17 | 17 |
| Scale | 13 | 13 | 13 | 10 | 9 | 13 | 12 | 14 | 12 | 12 |

completely scale efficient. The CCR/BCC index ratio is used to calculate this indicator. Therefore, the empirical findings tend to point to the scale of operations and input/output configuration as the primary causes of cities' inefficiency rather than the efficiency of their management teams' methods for allocating inputs to the healthcare process.

The findings from the remaining months confirm this outcome. The CCR efficient cities are expanded rather than BCC from the months of July to October. Based on this, decision-makers in general and emergency care have only been concerned with input/output configuration and the size of their activities. Uniquely, BMW management findings suggest that management teams' performance in terms of how they are organizing inputs in the waste management process, rather than their input/output configuration and size, is the primary cause of cities' inefficiency. When all models are taken into account in January, we get 13, 18, and 13 efficient cities for CCR, BCC, and scale, respectively. Based on these observations, we are unable to determine which types of treatment (general care, emergency care, BMW management) the cities are providing well for greener healthcare, but the internal structure appears to be doing so.

Next, we show the cities' average technical, pure technical, and scale efficiency for all months in Table 4. Overall, we observe that there is significant variation in the minimum and maximum efficiency measures every month. Further, the mean efficiencies are not stable over time. There is also a large variation between minimum and mean efficiencies. The standard deviation across months also remains high across months. For example, the mean efficiency for CCR model in the month of May is 64.8%, the minimum efficiency is 29.7% and the standard deviation is 23.1%. This shows that the performance of cities shows a statistically significant change over the months of the second wave of pandemic. While the standard deviation is slightly higher for general care as compared to emergency care, it is the highest for BMW management across months. This suggests that some cities are performing really poorly in terms of BMW management.

From January to May, technical efficiency estimates (CCR index) indicate that general care for cities retain the top spot in care, operating at 68.7% efficiency in January to 64.8% efficiency in May. For example, January results suggest that inefficient general care hospitals could reduce their inputs by 31.3%, if they were as efficient as the five efficient general care hospitals listed in Table 3, while generating the specified output levels. Emergency care is closely behind with an average overall efficiency rating of 67.8% in January and 64.6% in May. This demonstrates the significant impact of resources for emergency care and the micro and macro environmental knowledge on hospitals' operations. This means that in the pertinent market, general and emergency cares are likely to maintain high levels of capabilities and best medical practices. Interestingly, from June to October, CCR for emergency care is better than CCR for general care. This shows a shift of efficient hospitals' resources towards emergency treatments. Finally, BMW management appears to have limited adaptation to local

**Table 4**
Month-wise efficiencies for the model.

| Month | Model | General care | | | | Emergency care | | | | BMW management | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Mean | Std.Dev. | Min | Max | Mean | Std.Dev. | Min | Max | Mean | Std.Dev. |
| January | CCR | 0.399 | 1 | 0.687 | 0.216 | 0.385 | 1 | 0.678 | 0.206 | 0.052 | 1 | 0.552 | 0.307 |
| | BCC | 0.416 | 1 | 0.774 | 0.218 | 0.416 | 1 | 0.794 | 0.212 | 0.145 | 1 | 0.67 | 0.316 |
| | Scale | 0.529 | 1 | 0.891 | 0.115 | 0.556 | 1 | 0.857 | 0.122 | 0.355 | 1 | 0.811 | 0.207 |
| February | CCR | 0.402 | 1 | 0.688 | 0.208 | 0.4 | 1 | 0.68 | 0.204 | 0.052 | 1 | 0.575 | 0.307 |
| | BCC | 0.417 | 1 | 0.782 | 0.216 | 0.417 | 1 | 0.797 | 0.211 | 0.15 | 1 | 0.691 | 0.31 |
| | Scale | 0.56 | 1 | 0.885 | 0.12 | 0.596 | 1 | 0.857 | 0.127 | 0.343 | 1 | 0.818 | 0.213 |
| March | CCR | 0.394 | 1 | 0.7 | 0.213 | 0.394 | 1 | 0.692 | 0.209 | 0.052 | 1 | 0.579 | 0.307 |
| | BCC | 0.406 | 1 | 0.786 | 0.214 | 0.406 | 1 | 0.806 | 0.214 | 0.151 | 1 | 0.691 | 0.313 |
| | Scale | 0.567 | 1 | 0.896 | 0.122 | 0.56 | 1 | 0.866 | 0.138 | 0.342 | 1 | 0.826 | 0.208 |
| April | CCR | 0.327 | 1 | 0.674 | 0.219 | 0.339 | 1 | 0.664 | 0.203 | 0.051 | 1 | 0.582 | 0.316 |
| | BCC | 0.332 | 1 | 0.766 | 0.228 | 0.345 | 1 | 0.777 | 0.221 | 0.13 | 1 | 0.671 | 0.337 |
| | Scale | 0.619 | 1 | 0.887 | 0.117 | 0.556 | 1 | 0.865 | 0.132 | 0.349 | 1 | 0.859 | 0.178 |
| May | CCR | 0.297 | 1 | 0.648 | 0.231 | 0.31 | 1 | 0.646 | 0.226 | 0.051 | 1 | 0.556 | 0.301 |
| | BCC | 0.33 | 1 | 0.755 | 0.246 | 0.31 | 1 | 0.758 | 0.241 | 0.136 | 1 | 0.666 | 0.333 |
| | Scale | 0.393 | 1 | 0.878 | 0.17 | 0.393 | 1 | 0.87 | 0.162 | 0.33 | 1 | 0.824 | 0.179 |
| June | CCR | 0.305 | 1 | 0.662 | 0.204 | 0.342 | 1 | 0.681 | 0.198 | 0.051 | 1 | 0.568 | 0.308 |
| | BCC | 0.311 | 1 | 0.76 | 0.225 | 0.346 | 1 | 0.776 | 0.222 | 0.132 | 1 | 0.667 | 0.33 |
| | Scale | 0.54 | 1 | 0.886 | 0.148 | 0.573 | 1 | 0.892 | 0.134 | 0.332 | 1 | 0.834 | 0.177 |
| July | CCR | 0.315 | 1 | 0.706 | 0.224 | 0.356 | 1 | 0.724 | 0.213 | 0.052 | 1 | 0.583 | 0.311 |
| | BCC | 0.325 | 1 | 0.787 | 0.222 | 0.356 | 1 | 0.789 | 0.217 | 0.132 | 1 | 0.671 | 0.327 |
| | Scale | 0.528 | 1 | 0.904 | 0.139 | 0.608 | 1 | 0.924 | 0.119 | 0.338 | 1 | 0.851 | 0.17 |
| August | CCR | 0.4 | 1 | 0.747 | 0.207 | 0.403 | 1 | 0.754 | 0.202 | 0.052 | 1 | 0.591 | 0.309 |
| | BCC | 0.423 | 1 | 0.817 | 0.192 | 0.423 | 1 | 0.816 | 0.194 | 0.135 | 1 | 0.675 | 0.323 |
| | Scale | 0.548 | 1 | 0.916 | 0.121 | 0.617 | 1 | 0.928 | 0.113 | 0.339 | 1 | 0.855 | 0.163 |
| September | CCR | 0.423 | 1 | 0.754 | 0.204 | 0.457 | 1 | 0.792 | 0.174 | 0.052 | 1 | 0.599 | 0.309 |
| | BCC | 0.442 | 1 | 0.819 | 0.191 | 0.459 | 1 | 0.829 | 0.178 | 0.138 | 1 | 0.679 | 0.32 |
| | Scale | 0.545 | 1 | 0.922 | 0.12 | 0.657 | 1 | 0.959 | 0.082 | 0.339 | 1 | 0.858 | 0.16 |
| October | CCR | 0.422 | 1 | 0.747 | 0.2 | 0.454 | 1 | 0.782 | 0.17 | 0.052 | 1 | 0.603 | 0.313 |
| | BCC | 0.44 | 1 | 0.813 | 0.19 | 0.456 | 1 | 0.824 | 0.178 | 0.138 | 1 | 0.679 | 0.32 |
| | Scale | 0.555 | 1 | 0.921 | 0.118 | 0.66 | 1 | 0.954 | 0.083 | 0.339 | 1 | 0.862 | 0.16 |

circumstances with an efficiency from 55.2% in January to 60.3% in October. From a managerial perspective, this indicates that bio-medical operations are improving. However, managers could still produce the specified output levels while averaging a 39.7% reduction in their inputs after October. For pure technical efficiency index (BCC), the efficiencies lie between 75.6% (May) to 81.9% (September) for general care, 75.8% (May) to 82.4% (September) for emergency care, and 66.6% (May) to 69.2% (February) for BMW management. Since the overall technical efficiency index for each city is lower than its pure technical efficiency index, it suggests that the input/output configuration and not the management teams' ability to manage the inputs in the hospitals' operations is the primary cause of cities' inefficiency. The scale efficiency results are also interesting. While the trend followed is similar to CCR results with general care better than emergency care and BMW management from January to May, emergency care takes the top spot from June to October. The scale efficiency ranges from 81.1% for BMW in January to 95.9% for emergency care in September. From the perspective of a practitioner, we identify that the peak of the pandemic in April, May, and June resulted in efficiency loss across stages. However, emergency care was the quickest to recover and improve hospital operations further through appropriate utilization of resources. The evidence presented above points to a general picture that can be explained as follows: general and emergency care is delivered with relatively high levels of efficiency because they combine the benefits of services provided by hospitals and governments together with their adaptability to regional conditions. BMW management has the highest degree of adaptability and freedom, but there are no local opportunities to take advantage of. Finally, cities working under BMW supervision appear to have relatively low-efficiency scores as a result of their relatively poor capacity for local area adjustments.

Additionally, according to average efficiencies (see Table 5), technical efficiency for medical care (average of general and emergency care) is 70.53%, which is better than the 57.88% efficiency for BMW management. According to the interpretation of these two results, medical care appears to "waste" fewer resources than BMW. Also take note of the fact that the scale efficiency index is greater than the pure technical efficiency index for both BMW and medical care as reported in Table 3, indicating a productivity weakness for these sectors. Therefore, improving the procedures by which inputs are converted into outputs should be the operational objective for both categories of care (medical care and BMW) in our sample. The pooled standard deviation for CCR model is 19.97% with BMW management having a standard deviation of 30.89%. Hence, BMW management should also give special attention to scale size minimization.

**Table 5**
Average efficiencies for the model.

| | CCR | BCC | Scale |
|---|---|---|---|
| Overall | 0.6631 | 0.7529 | 0.8785 |
| Pooled Std. dev. | 0.1997 | 0.1907 | 0.0866 |
| General care | 0.7013 | 0.786 | 0.8986 |
| Emergency care | 0.7093 | 0.7966 | 0.8972 |
| Medical care | 0.7053 | 0.7913 | 0.8979 |
| BMW management | 0.5788 | 0.6761 | 0.8398 |

Next, we answer the second research question (RQ2) to identify which parallel stage between general and emergency care produces more BMW. We apply Spearman's correlation and Wilcoxon rank-sum hypothesis testing to answer this question. Table 6 calculates the efficiency correlation coefficients for general care, emergency care, and BMW management at 1% significance level. Efficiency in the healthcare sector for both general care and emergency care is correlated at 0.887. General care and BMW management have a correlation of 0.317, and emergency care and BMW have a correlation of 0.403. First, we identify a strong association between general and emergency care efficiency. Second, we identify that the BMW is more correlated with emergency care as compared to general care.

Additionally, using Wilcoxon rank-sum hypothesis testing, the means of the general care, emergency care, and BMW management efficiencies are compared at a 0.05 significance level. Between general care and emergency care, the *p*-value is 0.906. We disprove the null hypothesis and come to the conclusion that there is sufficient data to

**Table 6**
Correlation results: General care, emergency care, and BMW management.

| | | General care | Emergency care | BMW management |
|---|---|---|---|---|
| General care | Spearman's correlation | 1 | .881** | .426** |
| | Sig. (2-tailed) | | 0 | 0 |
| | N | 290 | 290 | 290 |
| Emergency care | Spearman's correlation | .881** | 1 | .455** |
| | Sig. (2-tailed) | 0 | | 0 |
| | N | 290 | 290 | 290 |
| BMW management | Spearman's correlation | .426** | .455** | 1 |
| | Sig. (2-tailed) | 0 | 0 | |
| | N | 290 | 290 | 290 |

** Correlation is significant at the 0.01 level (2-tailed).

**Table 7**
Month-wise MPI for the model.

| Month | General care | | | Emergency care | | | BMW management | | | Overall | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | effch | techch | tfpch | effch | techch | tfpch | effch | techch | tfpch | effch | techch | tfpch |
| 2 | 1.005 | 1.018 | 1.023 | 1.005 | 1.011 | 1.016 | 1.049 | 0.733 | 0.769 | 1.001 | 0.918 | 0.919 |
| 3 | 1.017 | 1.041 | 1.059 | 1.018 | 1.039 | 1.058 | 1.008 | 1.201 | 1.21 | 1.001 | 1.127 | 1.129 |
| 4 | 0.956 | 1.23 | 1.175 | 0.957 | 1.219 | 1.166 | 0.983 | 1.539 | 1.514 | 0.975 | 1.356 | 1.322 |
| 5 | 0.952 | 1.279 | 1.217 | 0.959 | 1.253 | 1.202 | 0.959 | 1.021 | 0.979 | 1.017 | 1.021 | 1.038 |
| 6 | 1.035 | 0.958 | 0.992 | 1.072 | 0.907 | 0.972 | 1.019 | 0.472 | 0.481 | 1.012 | 0.604 | 0.611 |
| 7 | 1.062 | 0.987 | 1.048 | 1.061 | 0.976 | 1.036 | 1.032 | 0.876 | 0.904 | 1.025 | 0.919 | 0.942 |
| 8 | 1.073 | 0.925 | 0.993 | 1.051 | 0.932 | 0.98 | 1.02 | 0.649 | 0.662 | 1.03 | 0.784 | 0.808 |
| 9 | 1.01 | 0.989 | 0.999 | 1.062 | 0.927 | 0.984 | 1.015 | 0.814 | 0.826 | 1.036 | 0.877 | 0.909 |
| 10 | 0.993 | 0.996 | 0.989 | 0.989 | 0.987 | 0.976 | 1.004 | 0.845 | 0.849 | 0.994 | 0.917 | 0.912 |
| Mean | 1.011 | 1.041 | 1.052 | 1.019 | 1.021 | 1.04 | 1.01 | 0.859 | 0.868 | 1.01 | 0.926 | 0.936 |

demonstrate that emergency care and general care are similar in terms of efficiency scores. Between general care and BMW management, the $p$-value is 0.003, and between emergency care and BMW management, it is 0.005. We conclude that there is no indication that the results in terms of efficiency measures between BMW management and general care, as well as between BMW management and emergency care, are equal based on these data, which indicates that they are statistically significant. In both these approaches, we conclude efficiency of BMW management is much more related to emergency care. Thus, BMW generation and disposal are more dependent on emergency treatment as compared to general treatment.

To answer the third research question (RQ3) related to variations in performance, we use Malmquist Index to account for changes in city productivity. This is done because, over the course of ten months, cities' capacity to produce outputs may have increased because of their ability to use inputs and outputs effectively, pushing the production frontier either upward or downward. The Malmquist productivity Index (tfpch) is further broken down into efficiency change (effch) and technical change (techch) (see Table 7). When taking into account the overall model, the productivity index in the cities has fallen by 0.64%. This is due to a 0.74% decline in technological advancement and a 0.1% increase in efficiency. This makes it impossible for us to determine the cause of the productivity index's decline. Hence, we calculate the productivity indices for general, emergency, and BMW treatment in accordance with internal operations. The cities' productivity indicator has risen by 0.52% overall in general care. This is due to 0.41% rise in technological advancement and a 0.11% increase in efficiency. The emergency care productivity index has risen by 0.4%. This is due to 0.21% rise in technological advancement and a 0.19% increase in efficiency. On further exploration, we identify that there was efficiency improvement in general care and emergency care post the peak of the pandemic in the months from June to October. There was a lack of technological advancement in medical care as compared to the duration from January to March. However, this did not result in an overall loss of efficiency. BMW's productivity indicator has fallen by 1.32%. This can be ascribed to a 1.41% decline in technological advancement and an increase in efficiency of 0.1%. Hence, we identify that the lack of technological advancement in BMW management over the duration of pandemic reduced overall efficiency and impacted sustainable growth.

In general care, City 23 (Ratnagiri) has the highest MPI of 1.68%, which is significantly higher than the state's average of 0.52%, according to Table 8, which details the MPI for specific cities. Technology change accounts for the majority of the contribution (1.03%), with efficiency increase accounting for the remaining 0.6%. Only 3 cities have an MPI of less than 1%, on average. All other towns have an MPI of more than 1%. Similarly, we discover that City 23 has the highest MPI of 1.7% for emergency care, which is significantly higher than the state average of 0.4%, for individual cities in emergency care. Technology change accounts for the majority of the contribution (1.27%), with efficiency increase accounting for the remaining 0.38%. Interestingly, City 1 (Mumbai) and not City 23, receive the main contribution from efficiency improvement, which is 0.71%. For emergency care, there are 5 cities with MPI of less than 1%, on average. In BMW management, City 10 (Dhule) has the highest MPI at 0.931 (a decline of 0.69%), which is significantly higher than the overall average of 0.868 (a decrease of 1.32%). Interestingly, City 7 (Bhandara) and not City 10, receive the main contribution from efficiency improvement, which is 0.88%. The productivity indicator for City 7 in BMW is 0.89, which represents a 1.1% decline. The primary factor for City 7 is productivity improvement through better input/output configuration. The shift in the technological frontier has reduced by 1.82%. Interestingly, City 1 has the least decline of technology change, which is 1.19%. Thus, the management efforts for BMW are much better in Mumbai as compared to other cities. Overall, none of the cities have MPI of more than 1% for BMW management.

For the second part of RQ3 related to contextual factors impacting efficiencies, we constructed a regression equation that may be utilized to infer the important determinants of the efficiencies computed in the first stage of the DEA (see Eq. (3.12)). For general care, literacy rate, transgenders vaccinated, and males vaccinated are statistically significant while other variables are not significant (see Tables 9 and 10). R square value is identified as 0.619. For emergency care, only the literacy rate is statistically significant while other variables are not significant. The R square value is 0.56, which is lesser than that for general care. For BMW management, literacy rate and transgenders vaccinated are statistically significant, while other variables are not significant. R square for BMW management is 0.598. For the overall model, administered first dose vaccines, females vaccinated, and the

**Table 8**
City-wise MPI for the model.

| Cities | General care | | | Emergency care | | | BMW management | | | Overall | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | effch | techch | tfpch | effch | techch | tfpch | effch | techch | tfpch | effch | techch | tfpch |
| 1 | 1.056 | 1.014 | 1.072 | 1.071 | 1.004 | 1.075 | 1.007 | 0.891 | 0.897 | 1.053 | 0.847 | 0.892 |
| 2 | 1 | 1.077 | 1.077 | 1 | 1.065 | 1.065 | 1 | 0.875 | 0.875 | 1 | 0.938 | 0.938 |
| 3 | 1.021 | 1.045 | 1.067 | 1.036 | 1.01 | 1.047 | 1 | 0.826 | 0.826 | 1 | 0.922 | 0.922 |
| 4 | 1.023 | 1.018 | 1.041 | 1.023 | 1.018 | 1.041 | 0.986 | 0.875 | 0.863 | 1.023 | 0.954 | 0.976 |
| 5 | 0.969 | 1.025 | 0.993 | 0.989 | 1.01 | 0.999 | 0.93 | 0.885 | 0.823 | 1 | 0.837 | 0.837 |
| 6 | 0.997 | 1.029 | 1.025 | 1.019 | 1.025 | 1.044 | 0.977 | 0.881 | 0.861 | 1.019 | 0.944 | 0.962 |
| 7 | 1.028 | 1.032 | 1.061 | 1.004 | 1.007 | 1.011 | 1.088 | 0.818 | 0.89 | 1 | 1.069 | 1.069 |
| 8 | 1.016 | 1.042 | 1.058 | 1.016 | 1.016 | 1.032 | 1 | 0.799 | 0.799 | 1 | 0.862 | 0.862 |
| 9 | 0.974 | 1.042 | 1.014 | 0.98 | 1 | 0.98 | 0.973 | 0.887 | 0.863 | 0.985 | 0.888 | 0.875 |
| 10 | 1.016 | 1.052 | 1.068 | 1.027 | 1.04 | 1.068 | 1.072 | 0.869 | 0.931 | 1.016 | 0.957 | 0.971 |
| 11 | 0.954 | 1.045 | 0.997 | 0.955 | 1.041 | 0.994 | 0.989 | 0.827 | 0.819 | 0.984 | 0.882 | 0.868 |
| 12 | 1.039 | 1.017 | 1.057 | 1.056 | 0.999 | 1.055 | 1.012 | 0.879 | 0.889 | 0.999 | 1.01 | 1.009 |
| 13 | 1.023 | 1.039 | 1.063 | 1.038 | 1.016 | 1.055 | 1.001 | 0.894 | 0.895 | 1.038 | 1.01 | 1.048 |
| 14 | 1.044 | 1.024 | 1.069 | 1.039 | 1.009 | 1.048 | 1.021 | 0.883 | 0.902 | 1.017 | 0.881 | 0.896 |
| 15 | 1.003 | 1.041 | 1.044 | 1.013 | 1.025 | 1.039 | 0.974 | 0.873 | 0.85 | 1.01 | 0.859 | 0.867 |
| 16 | 1.007 | 1.05 | 1.057 | 1.039 | 1.024 | 1.063 | 1.03 | 0.838 | 0.863 | 1.017 | 1.015 | 1.032 |
| 17 | 0.987 | 1.044 | 1.03 | 0.995 | 1.013 | 1.008 | 0.999 | 0.846 | 0.845 | 1.001 | 0.908 | 0.909 |
| 18 | 1.021 | 1.058 | 1.079 | 1.015 | 1.028 | 1.043 | 1.031 | 0.872 | 0.899 | 1.016 | 0.981 | 0.996 |
| 19 | 0.975 | 1.034 | 1.008 | 0.996 | 1.005 | 1.001 | 1.017 | 0.881 | 0.896 | 0.991 | 0.971 | 0.962 |
| 20 | 1.001 | 1.033 | 1.034 | 1.001 | 1.03 | 1.031 | 1.081 | 0.833 | 0.901 | 1.002 | 0.935 | 0.937 |
| 21 | 1.014 | 1.044 | 1.059 | 1.014 | 1.043 | 1.058 | 1.02 | 0.867 | 0.884 | 1 | 0.936 | 0.936 |
| 22 | 1 | 1.033 | 1.033 | 1 | 0.965 | 0.965 | 1 | 0.848 | 0.848 | 1 | 0.86 | 0.86 |
| 23 | 1.06 | 1.103 | 1.168 | 1.038 | 1.127 | 1.17 | 1.036 | 0.836 | 0.867 | 1.012 | 0.972 | 0.984 |
| 24 | 1.048 | 1.039 | 1.089 | 1.051 | 1.026 | 1.078 | 1.027 | 0.865 | 0.888 | 1.023 | 0.974 | 0.996 |
| 25 | 1.041 | 1.047 | 1.09 | 1.059 | 0.991 | 1.05 | 1.016 | 0.879 | 0.893 | 1.041 | 0.898 | 0.935 |
| 26 | 1.022 | 1.09 | 1.114 | 1.022 | 1.09 | 1.114 | 1 | 0.844 | 0.844 | 1 | 0.867 | 0.867 |
| 27 | 1.022 | 1.029 | 1.052 | 1.046 | 1.005 | 1.052 | 0.982 | 0.886 | 0.87 | 1.049 | 0.884 | 0.928 |
| 28 | 0.962 | 1.054 | 1.014 | 1.008 | 1.017 | 1.024 | 1.021 | 0.833 | 0.85 | 1 | 0.867 | 0.867 |
| 29 | 1 | 0.996 | 0.996 | 1 | 0.983 | 0.983 | 1 | 0.844 | 0.844 | 1 | 0.988 | 0.988 |
| Mean | 1.011 | 1.041 | 1.052 | 1.019 | 1.021 | 1.04 | 1.01 | 0.859 | 0.868 | 1.01 | 0.926 | 0.936 |

**Table 9**
OLS regression results: General care, emergency care, and BMW management.

| | DV: scale efficiency of general care | | | | DV: scale efficiency of emergency care | | | | DV: scale efficiency of BMW management | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Estimates | std error | t stat | *p*-value | Estimates | std error | t stat | *p*-value | Estimates | std error | t stat | *p*-value |
| Intercept | −0.171 | 0.519 | −0.331 | 0.741 | −0.937 | 0.551 | −1.702 | 0.09 | −0.359 | 0.537 | −0.667 | 0.505 |
| First dose vaccine | −2.95E−08 | 6.00E−08 | −0.492 | 0.623 | 1.50E−08 | 6.37E−08 | 0.235 | 0.814 | −2.47E−08 | 6.22E−08 | −0.397 | 0.692 |
| Second dose vaccine | 6.68E−08 | 9.15E−08 | 0.73 | 0.466 | 1.17E−07 | 9.71E−08 | 1.206 | 0.229 | 7.58E−08 | 9.48E−08 | 0.8 | 0.425 |
| Males vaccinated | 2.58E−07 | 1.30E−07 | 1.98 | 0.049 | −9.73E−08 | 1.38E−07 | −0.705 | 0.482 | 2.34E−07 | 1.35E−07 | 1.739 | 0.083 |
| Females vaccinated | −1.86E−07 | 1.29E−07 | −1.439 | 0.151 | 1.29E−07 | 1.37E−07 | 0.943 | 0.347 | −1.57E−07 | 1.34E−07 | −1.176 | 0.241 |
| Transgenders vaccinated | 0 | 0 | −2.424 | 0.016 | 0 | 0 | −1.251 | 0.212 | 0 | 0 | −2.548 | 0.011 |
| Total population | 2.71E−08 | 2.88E−08 | 0.942 | 0.347 | 4.06E−08 | 3.06E−08 | 1.327 | 0.186 | 3.78E−08 | 2.99E−08 | 1.265 | 0.207 |
| Literacy rate | 0.015 | 0.007 | 2.25 | 0.025 | 0.024 | 0.007 | 3.36 | 0.001 | 0.017 | 0.007 | 2.455 | 0.015 |
| Population density | −0.001 | 0 | −1.332 | 0.184 | −0.001 | 0 | −1.297 | 0.196 | −0.001 | 0 | −1.314 | 0.19 |
| R square | 0.619 | | | | 0.56 | | | | 0.598 | | | |

total population are statistically significant, with an R square value of 0.611. The year and city fixed effects are regarded as exogenous, while all other variables are considered as endogenous. The second-stage estimation biases are addressed using the bootstrap method (Simar and Wilson, 2007; Tewari and Arya, 2023). According to the findings, we are getting similar results as the OLS regression. Therefore, our model results are significant and valid.

Based on these results, we identify that the literacy rate needs to be improved to improve the scale efficiency for individual stages of healthcare operations. Hence, a city is much more exposed to inefficient healthcare delivery during the pandemic, if the population is less literate compared to other cities. Secondly, vaccinating the transgenders in the cities also helps to improve the efficiency of general care and BMW management. This finding is unique as the transgender population is generally neglected for healthcare treatment during such calamities. Another non-intuitive finding is that the scale efficiencies for general care depend on the vaccinated male population. Specifically, a larger proportion of males are the working population in India. Hence, improving vaccine dosage for the gender may have a greater number of recovered people in the model. For the overall model, it is clear that administering the first dose of vaccine can improve the scale efficiencies of the cities. Interestingly, vaccinated female population can improve the overall efficiency. Globally 70% of the healthcare workforce comprises women (Sindhwani et al., 2022). Also, the households in India are run by women and they stimulate the growth of parallel healthcare

**Table 10**
OLS regression results: Overall system.

| | DV: scale efficiency of overall system | | | |
|---|---|---|---|---|
| | Estimates | Standard error | t stat | *p*-value |
| Intercept | 0.638 | 0.353 | 1.805 | 0.072 |
| First dose vaccine | 9.94E−08 | 4.09E−08 | 2.433 | 0.016 |
| Second dose vaccine | 6.51E−08 | 6.23E−08 | 1.045 | 0.297 |
| Males vaccinated | 6.46E−08 | 8.85E−08 | 0.729 | 0.467 |
| Females vaccinated | −2.06E−07 | 8.78E−08 | −2.347 | 0.02 |
| Transgenders vaccinated | −8.57E−05 | 7.17E−05 | −1.196 | 0.233 |
| Total population | 6.52E−08 | 1.96E−08 | 3.325 | 0.001 |
| Literacy rate | 0.002 | 0.004 | 0.471 | 0.638 |
| Population density | 2.79E−05 | 0 | 0.088 | 0.93 |
| R square | 0.611 | | | |

stages together. Strangely, larger population size has a positive impact on scale efficiency, which may be due to the stability and regulations of larger cities in terms of resource utilization.

## 5. Implications for sustainability

We highlight some policy insights to city officials for sustainable development. For example, the City 1 (Mumbai) and City 21 (Pune) did not have an efficient overall system because neither general care, emergency care, or BMW management were efficient. These are urban metropolitan cities and, therefore, were significantly impacted due to the pandemic. However, even though these cities are generating the maximum incinerable and non-incinerable BMW, they are much better at handling the changes for healthcare resources and BMW capacity during the pandemic duration. On the contrary, City 2 (Ahmednagar) and City 22 (Raigad) were efficient for all the parallel stages and the overall system. Specifically, these cities are near Mumbai, and the resources exceed the requirements. While the patient count and generated BMW was low, there was enough capacity to fulfill the needs. It is pleasing to observe that City 3 (Akola), City 8 (Buldhana), and City 29 (Wardha) are efficient at managing the overall system and the BMW management. However, they are inefficient at providing general and emergency care. This is true as these cities are not as developed for healthcare as the metro cities. City 11 (Gondia) appears inefficient at the BMW management stage, in contrast to being efficient at general care, emergency care, and the overall system. Interestingly, this is the only city that used deep burial for BMW disposal. Hence, city officials must switch to incineration and autoclave for better BMW management. These specifics are essential for improving operational efficiency at all three stages.

### 5.1. Managerial implications

Next, we propose some non-intuitive managerial implications. We propose that literacy rate is more significant than population density when access to healthcare and BMW management can impact the health and well-being of individuals. Hence, city officials must fulfill the location-specific literacy levels, especially in dense populations, to improve reach and fulfill the healthcare requirements. The policy level outcomes can then be applied to other dense locations in other countries in the African region or Southeast Asian region where good health and well-being remain a significant challenge. Secondly, since BMW management is more correlated to emergency care, policies across the globe need to categorize BMW based on the nature of treatment as well. Thus, countries with better SDG-3, like Spain, Italy, and Japan, can utilize this finding to empirically investigate the importance of BMW management in the overall healthcare ecosystem. Finally, the gender-specific vaccination outcome can be used in some countries in Southwest Asia and Africa, where there is a low representation of females and transgender in decision-making and a lack of universal health coverage (Sindhwani et al., 2022).

The SDG of good health and well-being cannot be over-emphasized for healthcare sustainability. We identify that general and emergency care are interrelated. The hospital management needs to take care of policies during emergencies, where limited healthcare resources are managed better based on the inputs and outputs, as shown in our model. Since hospital beds and dedicated healthcare facilities were limited, restricted access to these services for general care could have improved the cities' overall efficiency. During the emergency, the limited number of oxygen beds, ICU beds, and ventilators further constrained the state from optimal utilization. However, the state of Maharashtra rose to the challenge by better managing human resources, streamlining the communication channels, and providing data access to everyone. Further work can be undertaken to analyze the role of the available data using big data analytics for measuring improved healthcare sustainability (Wang et al., 2018).

The SDG of reducing illness and deaths from hazardous chemicals is addressed using BMW management. The efficiency of BMW management is lower than general and emergency care. However, the cities show increasing returns to scale over the months. While around 80% of treated COVID-19 BMW is incinerated, the non-incinerated COVID-19 BMW through deep burial is much more harmful to sustainability. The capacity for handling waste through incinerators, autoclaves, shredders, and deep burial is not uniform across cities. Hence, on several occasions, the BMW was transported across cities for treatment or disposal. This further increased the hazard risks due to the handling and transit of infectious waste. The depletion of shared healthcare resources like available N95 masks and PPE also resulted in over-exposure of society to hazardous BMW in the cities (Chen et al., 2021). Overall, we see that around 50% cities in Maharashtra were much more efficient in managing healthcare operations than others.

## 6. Conclusions

Most healthcare systems are complex and involve intertwined processes connected to real-world problems. This study takes three parallel systems into account to assess the performance of healthcare in India. In the system, general care, emergency care, and BMW management operations are connected in parallel. Besides the direct inputs and outputs, we include shared variables (Available N95 masks and PPEs) in three stages and the undesirable variable (deceased people) data. Therefore, the proposed models (3.1)–(3.10) handle a lot of complexity that can somewhat depict the real-world scenario. The proposed models enable us to evaluate the stage-wise (general care, emergency care, and BMW management) and overall healthcare efficiencies to promote sustainable development.

The result shows that the scale efficiency measures of general care vary in $[0.393, 1]$, emergency care varies in $[0.393, 1]$, and BMW varies in $[0.33, 1]$ ranges, respectively. This analysis would provide an excellent opportunity to streamline internal operations further to increase healthcare sector efficiency in India. Based on the results, we propose relevant policy insights to city officials and managerial insights to healthcare authorities. Further, OLS regression analysis suggests that only the literacy rate is significant in all three stages separately (general care, emergency care, and BMW management). These findings also indicate that when internal system operations are considered, the coordination of the system is evaluated much better. The Wilcoxon rank-sum hypothesis test is suggested to compare the means of general care, emergency care, and BMW management efficiencies. While taking into account the general care and emergency care efficiencies as statistically equal, there is insufficient proof to argue that the efficiencies between general care and BMW management, and emergency care and BMW management, are not equal. The suggested evaluation method, therefore, can help decision-makers significantly improve the operational effectiveness and efficiency of the Indian healthcare system.

The results and discussions can provide valuable and up-to-date information for city managers to identify weaknesses and sources of inefficiency in utilizing healthcare resources. This will allow them to take appropriate corrective actions, develop sustainable healthcare sector growth policies, and keep up with technological advancements. All these considerations can help healthcare sectors to improve their rankings. Additionally, evaluating the healthcare sector's efficiency helps investors and governments decide which cities to cooperate with and how best to use and invest their infrastructure for the most significant health improvements in cities.

Future researchers can utilize the findings to develop advanced DEA models like series-parallel, assembly, disassembly, hierarchical, or dynamic models by involving multiple stakeholders like hospitals, city officials, and the healthcare workforce. Other methods can be explored to treat undesirable outputs and shared inputs in the model. The model can also incorporate the severity index of patients based on the population dynamics while evaluating efficiency. Other exogenous variables like lockdown restrictions and quarantine measures of the government can be tested through regression analysis. Also, the research can be extended to other countries having different healthcare and BMW management requirements. Our study would thus provide helpful methodological background and insights for country-specific research.

## CRediT authorship contribution statement

**Rohit Sindhwani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Data curation, Conceptualization. **Alka Arya:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Jayanth Jayaram:** Writing – review & editing, Visualization, Supervision, Project administration, Investigation, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

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Article

# Precising E-waste Generation for Economic Recycling

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**Abstract**

With enhanced technological advancements, digital transformation and globalisation, there has been a significant rise in the amount of electronic waste (e-waste), posing a threat to the global economy and environment. The study deploys a grey prediction model to forecast the amount of e-waste generation by 2026 in India. The precise data generated can be further used to calculate operation costs, workforce requirements, collection time, warehouse and landfills needed for economical recycling of e-waste.

**JEL Codes:** A1, C8, Q5

**Keywords**

E-waste, forecasting, grey modelling, economic recycling

## I. Introduction: E-waste Issues in Emerging Economics

In the past few years, the electronic market has been one of the most vigorously growing markets in lower-middle income countries. The augmented demand and consumption of electronic products are caused owing to rapid financial growth (Dwivedy & Mittal, 2010). This growth is integrated with technological advancement, population growth, urbanisation, descending price trends and consumer behaviour of replenishing electronic products with new ones. Due to this, the production of electronic products is aggravated, resulting in an increasing amount of e-waste generation (Kumar & Dixit, 2018). As a result, e-waste has turned out to be the fastest-growing waste stream globally (Panchal et al., 2021).

E-waste often encompasses several precious and toxic materials, and if e-waste is not managed appropriately, it could lead to a shortage of natural resources as well as serious economic and environmental problems. The United Nations has mentioned that around 53 million tons of e-waste were produced globally in 2019, with a comparable projection rate to attain 74 million tons by 2030. It has also been anticipated that e-waste could grow with the aid of 2 million tons every year and reach 111 million tons by 2050 (Forti et al., 2020). Although, as per the Global E-waste Monitor Report (2017), only 20 per cent of the e-waste generated worldwide was collected for recycling.

A massive volume of e-waste generation and disposal has been a plaguing issue in most developing nations such as India, China, Vietnam, Nigeria and others (Ikhlayel, 2018). India was the 3rd among 177

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countries in e-waste generation and was responsible for almost one-third of the global e-waste production (Forti et al., 2020). However, most of the e-waste is illegally disposed of or treated in the informal sector, and they directly or indirectly affect the environment and economy. In order to deal with the expanding quantum of e-waste generation, there is a significant need to implement an efficient e-waste management system.

E-waste management consists of all individual activities required to manage e-waste from its inception to its final disposal, such as generation, allocation, collection, storage, recycling, recovery and incineration (Khatun & Dhara, 2022). To design and develop an efficient e-waste management system, along with effective collection and recycling of respective electronic products, depend upon multiple factors such as country size, technology innovation, collection process, recycling behaviour, handling and recycling methods (Petridis et al., 2016). The level of involvement of formal and informal players in collecting and recycling e-waste, law enforcement and government funding for waste management are also essential factors. However, estimating e-waste generation is always a top priority and essential input for developing, operating and optimising e-waste management systems. Panchal et al. (2021) also claim that for effective e-waste management, there is a requirement for reliable country-level data on e-waste generation. A precise estimation of e-waste generation is always pivotal for policymakers and e-waste organisations to develop an efficient and economical collection, storage, recycling and disposal strategy. Presently, in India, there is an absence of accurate data for the amount of e-waste generation in the future.

From this point of view, the study has utilised a grey prediction model to forecast the overall amount of e-waste generated by 2026 in India. The study outcomes will help in planning and developing an efficient and cost-effective strategy for e-waste recycling. Figure 1 shows the graphical illustration of the proposed research work.

The rest of the article is structured as follows: Section II, we present a literature review on e-waste forecasting. Section III explains the data and methodology utilised in the study. Then, Section IV describes the empirical result of the study. Finally, Section V provides research implications and concludes the article.

## II. Review of Literature

Over the past two decades, researchers have utilised multiple methods to estimate e-waste generation. One of the most commonly utilised methods in e-waste estimation is ‘market supply’, in which sales data of electronic products is combined with the product lifespan to estimate e-waste generation. Based on this method, the total amount of electronic products sold in a particular year becomes e-waste after the completion of their average lifespan (Petridis et al., 2016). First, in the Indian context, Jain and Sareen (2006) utilised the market supply method to estimate the amount of e-waste generation from televisions and personal computers in Delhi. In addition, multiple studies use similar methodologies to predict e-waste amounts from different electronic products (Barman et al., 2017; Kumar & Srihari, 2007). The procedure of e-waste estimation from the market supply method is strongly dependent upon assessing the average lifespan of electronic products. Lifespan considered for this methodology is either constant or follows some distribution function. However, the lifespan depends upon various factors, such as user behaviour, innovation and social-economic factors, which may vary from region to region (Petridis et al., 2016).

Furthermore, some researchers are using mathematical models to predict e-waste amounts. For example, Dwivedy and Mittal (2010) developed a logistic model to determine the number of obsolete computers in India by 2026. Ahmed et al. (2014) predicted the e-waste generated across Indian industrial sectors

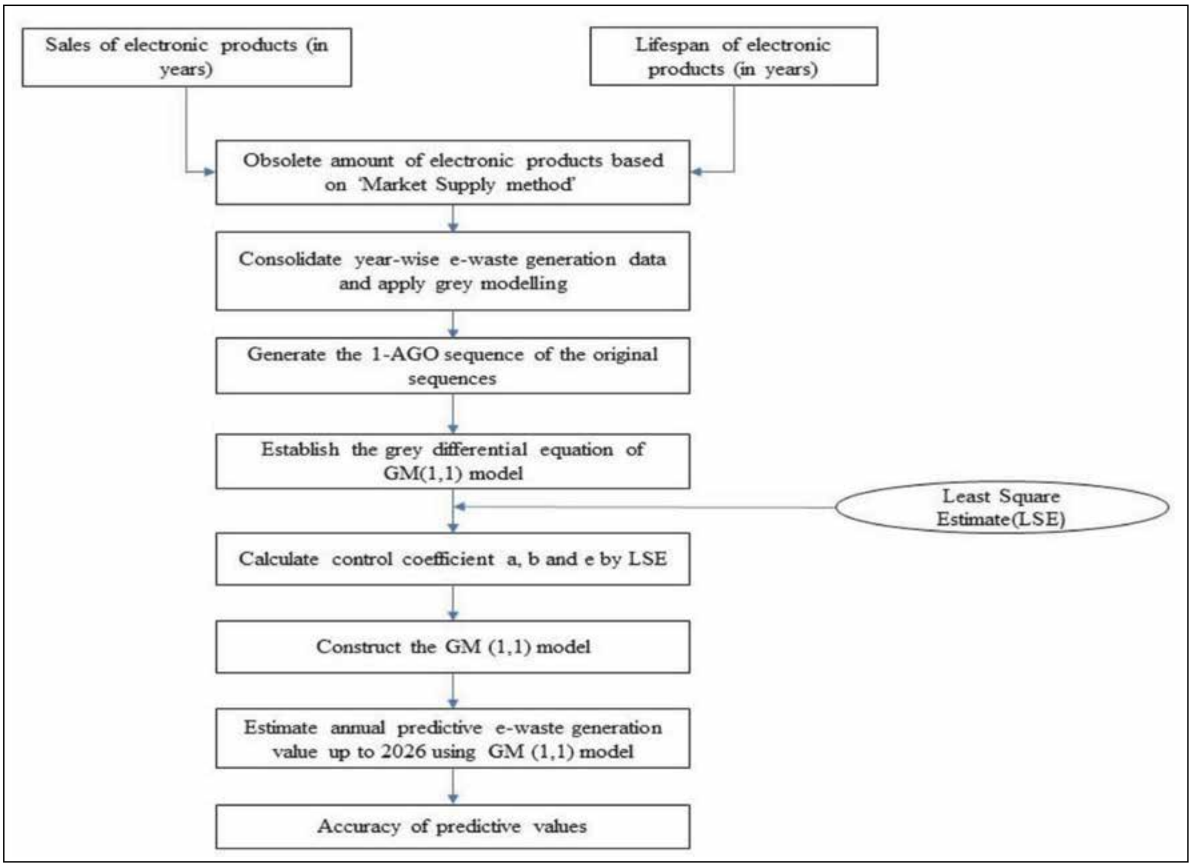


**Figure 1.** Proposed Research Methodology.

using regression analysis. A distinct approach was taken by Pant (2013), who developed a mathematical equation to estimate the amount of e-waste generated from seven electronic items by incorporating population statistics, product lifespan and sales data in the model. However, due to the lack of availability of sales data for all electronic products, it is not easy to approximate the overall amount of e-waste generation at the country level using these models.

On the other hand, Kiran et al. (2021) preferred to adopt a different approach, using discrete grey modelling, to assess the amount of e-waste produced from electronic items that include televisions, cellular phones and personal computers in the Indian context. Similarly, Kazancoglu et al. (2021) adopted grey modelling and predicted the volume of e-waste collected within the context of Turkey. Mmreki et al. (2018) also used grey modelling to evaluate the amount of e-waste generated in Botswana city. Among all these studies, the grey modelling methodology provides meaningful insights and more accurate results with small-sized and limited data points. Furthermore, grey modelling is more suitable to use when chaotic and complex conditions and discrete data points are available for the forecast.

Moreover, it may be noted that the current Indian scenario reflects a messy situation, owing to its regulations, coupled with the fact that there are limited data points to predict e-waste amount. Therefore,

**Table 1.** Year-wise Summary of E-waste Generation Studies within the Indian Context.

| Authors | Data | Methodology | Findings |
|---|---|---|---|
| Jain and Sareen (2006) | Personal computers and television | Market supply method | Forecasting the amount of e-waste generated from televisions and personal computers in Delhi |
| Kumar and Shrihari (2007) | Computers, televisions, refrigerators, phones and washing machines | Market flow method and sensitivity analysis | Identify the total amount of e-waste generated in Mangaluru from five electronic items |
| Dwivedy and Mittal (2010) | Personal computers | Logistic model and time-series analysis | Estimate the volume of e-waste produced from personal computers in India by 2026 |
| Kothari et al. (2011) | Personal computers | Grey relational model | To forecast the number of discarded computers |
| Pant (2013) | Seven electronics items (desktop, laptops, washing machine, televisions, refrigerators, ACs and microwave oven) | Time-series and factor analysis | A mathematical equation was developed for estimating e-waste amount via incorporating population statistics, lifespan and sales data in the model |
| Dasgupta et al. (2017) | Desktop, notebooks, refrigerators, television and washing machines | System dynamic approach | Predict the volume of e-waste produced from five electronic items |
| Barman et al. (2017) | Laptop, desktop, mobile phone and printers | Market supply | To access the volume of e-waste produced within Guwahati city |
| ivek et al. (2019) | Mobile phones | Hot trend exponential smoothing and ARIMA | Estimated number of mobile phones undergo recycling and scrap by 2020 in India |
| Kostha et al. (2021) | Mobile phones | Sales-stock lifespan model | To determine the amount of e-waste produced from obsolete mobile phones in Delhi |
| Panchal et al. (2021) | 21 electronic items defined by the Central Pollution Control Board (CPCB) | #x2018;Market Supply method' | Estimate e-waste flow from 21 electronic items within India from 2017 to 2021 |
| Kiran et al. (2021) | Mobile phones, personal computers and television | Discrete grey modelling | Utilising the grey modelling method to forecast the e-waste amount generated from cellular phones, television and computers |

in this study, we have utilised the grey prediction model for predicting e-waste amount. Table 1 shows some relevant studies on e-waste forecasting within the Indian context.

## III. Data and Methodology

In this study, we have used two different statistical data sets. First, the e-waste amount report by the Central Pollution Control Board (CPCB) from 21 electronic items (Appendix, Table 1.1), and second, the e-waste amount report by the Global E-waste Monitor from 54 electronic items. E-waste generation from these electronic items is estimated by CPCB using the 'Market Supply Method'. The Global E-waste Monitor has been using the 'Weibull distribution-based sales stock lifespan model' to estimate e-waste generation using the dynamic lifespan of the product. The CPCB has used the 'time step delay' or 'market supply method' using a fixed lifespan of the product. The equation utilised in the market supply method is defined below (Li et al., 2015; Wang et al., 2013).

$$W(n) = \mathrm{POM}(n - L^{\mathrm{avg}})$$

$W(n)$ = E-waste generated in the particular year $n$
POM = Electronic item put on market
$L^{\mathrm{avg}}$ = Average lifespan of products

For e-waste estimation, CPCB utilised sales data of electronic products put on the market by 1,606 producers, who registered under Extended Producers Responsibility (EPR) (Biswas & Singh, 2020). However, the actual number of sales data put on the market annually by these producers and sales data for each item is not available. In such a situation, utilising the market supply method is not viable for estimating the future trend. Therefore, we have used the grey modelling method for estimating the overall trend of e-waste generation. Grey modelling is a more practical and viable option when there is a messy situation, and limited data points are available for forecasting.

In order to build a data set for the amount of e-waste generation from 21 electronic products reported by the CPCB, we have performed counter-calculation using e-waste collection target for producers in EPR (Appendix, Table 1.2) and percentage of collection target for each consecutive years after the implementation of E-waste Management Rule, 2016 (Table 2). Table 3 showcases the estimated amount of e-waste generation from 21 electronic products reported by the CPCB.

As per CPCB, in 2017–2018, India generated about 0.70 million metric tons (Mt) of e-waste. Within the span of a year, in 2018–2019, this figure spiralled up to 0.85 Mt, followed by 0.90 Mt in 2019–2020, 1.06 Mt in 2020–2021 and 2.07 Mt in 2021–2022 (Figure 2).

However, e-waste amounts reported by CPCB are based on only 21 electronic items and sales data put by only registered producers in EPR. Moreover, this data does not include the imported number of electronic products. Therefore, the actual amount of e-waste generation in India is more than the estimated amount reported by CPCB. In such a situation, we have used another statistical data set reported by the Global E-waste Monitor. Their methodology to estimate e-waste amount is based on 54 electronic

**Table 2.** Year-wise Collection Targets under Extended Producer Responsibility.

| No. | Year | Collection Target |
|---|---|---|
| 1. | 2017–2018 | 30% of total e-waste generation |
| 2. | 2018–2019 | 30% of total e-waste generation |
| 3. | 2019–2020 | 40% of total e-waste generation |
| 4. | 2020–2021 | 40% of total e-waste generation |
| 5. | 2021–2022 | 50% of total e-waste generation |

**Table 3.** Estimated Amount of E-waste Generated (Reported by the Central Pollution Control Board (CPCB)).

| S. No. | EEE Code | 2017–2018 | 2018–2019 | 2019–2020 | 2020–2021 | 2021–2022 |
|---|---|---|---|---|---|---|
| A. | *Information technology and telecommunication equipment* | | | | | |
| 1. | ITEW 1 | 2,100 | 2,710 | 2,542.5 | 2,877.5 | 3,146 |
| 2. | ITEW 2 | 110,143.33 | 113,960 | 95,542.5 | 85,837.5 | 67,516 |
| 3. | ITEW 3 | 6,983.33 | 8,033.33 | 8,235 | 10,527.5 | 1,500 |
| 4. | ITEW 4 | 3,203.33 | 6,003.33 | 4,732.5 | 3,640 | 606 |
| 5. | ITEW 5 | 743.33 | 1,423.33 | 1,377.5 | 1,797.5 | 264 |
| 6. | ITEW 6 | 26,323.33 | 27,770 | 28,037.5 | 34,847.5 | 35,296 |
| 7. | ITEW 7 | 710 | 1,363.33 | 1,875 | 3,420 | 3,204 |
| 8. | ITEW 8 | 0 | 0 | 0 | 0 | 0 |
| 9. | ITEW 9 | 483.33 | 1,240 | 1,945 | 2,277.5 | 2,828 |
| 10. | ITEW 10 | 70 | 70 | 65 | 110 | 60 |
| 11. | ITEW 11 | 0 | 0 | 0 | 0 | 0 |
| 12. | ITEW 12 | 893.33 | 1,306.66 | 1,185 | 1,140 | 1,124 |
| 13. | ITEW 13 | 0 | 0 | 0 | 0 | 0 |
| 14. | ITEW 14 | 73.33 | 73.33 | 102.5 | 247.5 | 358 |
| 15. | ITEW 15 | 17,666.66 | 60,703.33 | 49,640 | 52,865 | 30,916 |
| 16. | ITEW 16 | 10 | 3.33 | 12.5 | 37.5 | 62 |
| B. | *Consumer electrical and electronics* | | | | | |
| 17. | CEEW1 | 205,086.66 | 228,460 | 249,867.5 | 224,690 | 201,616 |
| 18. | CEEW2 | 191,530 | 237,756.66 | 256,437.5 | 357,540 | 1582,806 |
| 19. | CEEW3 | 92,623.33 | 121,703.33 | 150,397.5 | 174,932.5 | 168,930 |
| 20. | CEEW4 | 83,490 | 103,553.33 | 133,135 | 205,052.5 | 183,412 |
| 21. | CEEW5 | 34,283.33 | 29,250 | 13,150 | 10,355 | 0 |
| 22. | **Total (Mt)** | **0.704** | **0.857** | **0.905** | **1.063** | **2.070** |

products (Annex 1: list of items considered in global e-waste, Forti, 2020) and also included imported amount.

According to the Global E-waste Monitor report, in 2015, India generated about 1.97 Mt of e-waste (Biswas & Singh, 2020). Within the span of a year, in 2016, this figure spiralled up to 2.22 Mt, followed by 2.53 Mt in 2017, 2.86 Mt in 2018, and 3.23 Mt in 2019 (Biswas & Singh, 2020). As per ASSOCHAM's (2019) report, in 2020, the e-waste generated was around 5.20 Mt (Shenoy, 2019). Based on the input data, developed Figure 3 reflects the stupendous rise from 2015 to 2020. The dotted blue line (Figure 3) highlights trends of e-waste generation within India over time in a linear progression.

After consolidated annual e-waste amount reported by both the organisation, we have applied the grey prediction model on both data sets to estimate the overall trend of e-waste generation and also perform a comparative analysis on the predictive values obtained from the analysis.

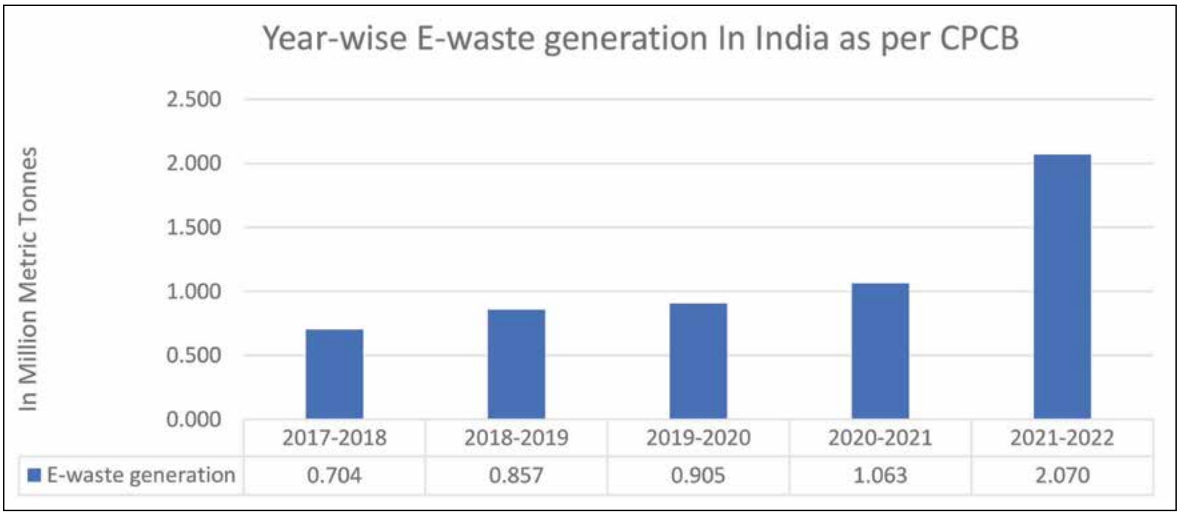


**Figure 2.** Year-wise E-waste Generation in India (Based on the Central Pollution Control Board (CPCB) Report).

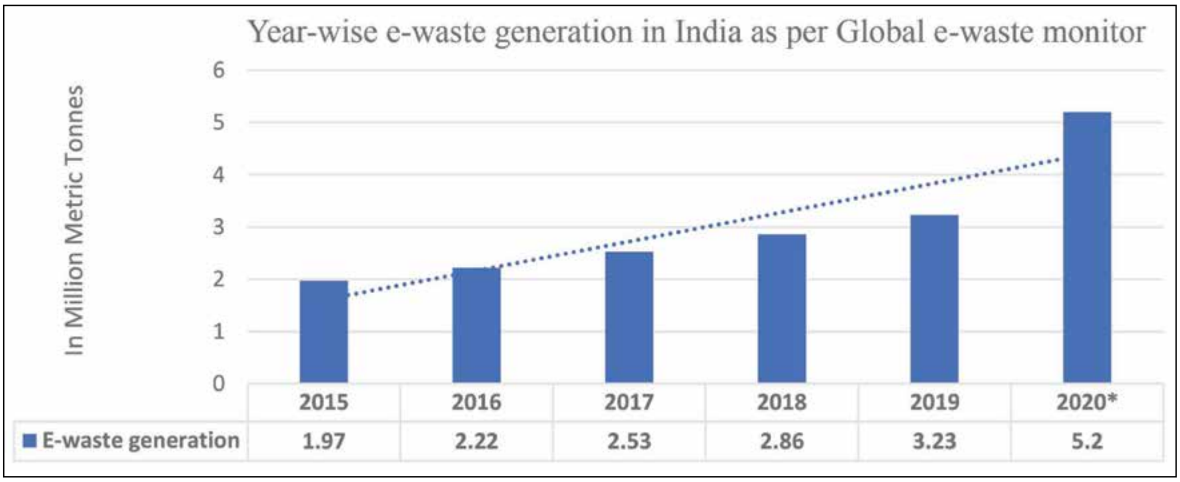


**Figure 3.** Year-wise E-waste Generation in India Based on Global E-waste Report (Biswas & Singh, 2020, Centre for Science and Environment).

**Note:***Approximate data of e-waste amount in India (Shenoy, 2019).

## *Methodology: Grey Prediction*

In 1982, the grey system theory was initially propounded by Ju-long Deng (Kazancoglu et al., 2021). The model works efficientl when only some variables are present (Bao et al., 2015). For the grey rolling model GM (1,1), Guo et al. (2015) postulated the use of actual data set $\left(x_1^0, x_2^0\right)$ to compute predicted data $\left(x_3^0\right)$.

To perform GM (1,1) modelling for prediction, six main steps are required, and those are defined below:

1) The first step involves using the initial data points. Whereas $x^0$ represents the original data points:

$$x^0 = (\{x^0(1), x^0(2), \ldots x^0(n)\}, \; n \geq 4 \tag{1}$$

Based on Equation 1, the subsequent one is computed using Equation 2:

$$x^0(i:k) = \{x^0(i), (i+1), \ldots x^0(k)\} \tag{2}$$

Equation 3 is shown below:

$$x^0(i:k) = \{x^0(1), x^0(2), x^0(3) \ldots x^0(k)\}, \; i = 1 \tag{3}$$

Accumulating Generation Operation (AGO) is carried out on this sequence (Equation 3) that resulted in the following sequence ($x_1$).

2) In the second step, using AGO, $x_0$ series changes monotonically to increase the $x_1$ series. To calculate $x_1$, sigma function is used in the equation, which is shown below:

$$x_k^1 = \sum_{i=1}^{k} (x^0 i), \; i = 1, 2, \ldots, n \tag{4}$$

3) In this step $Z_k^1$ is calculated after finding the $x_k^1$. Then, the generated mean sequence $Z_k^1$ of $x_k^1$ is computed using the below defined formula:

$$Z_k^1 = 0.5\left[(x_k^1) + \left(x_{(k-1)}^1\right)\right], \; k = 1, 2, 3, \ldots, n \tag{5}$$

4) Then, the parameter value of both $a$ and $b$ are estimated using the least square method; and the following equation is defined in accordance (below). Moreover, after structuring the required grey model, the output of the grey equation would be computed by means of both $a$ and $b$ parameters.

$$b = x_{(k)}^0 + aZ_k^1 \tag{6}$$

$$x_{(2)}^0 = aZ_2^1 + b$$

$$x_{(3)}^0 = aZ_3^1 + b$$

The output of Equation 6 is put into Equation 7 for further analysis.

$$x_{(n)}^0 = aZ_n^1 + b \tag{7}$$

Further, to find the value of both $a$ and $b$ parameters, the following matrices need to be structured while utilising the following formula:

$$\begin{array}{lll} x_2^0 & -Z_2^1 & 1 \\ x_3^0 & -Z_3^1 & 1 \\ Y = x_n^0 & \mathrm{B} = -Z_n^1 & 1 \end{array} \tag{8}$$

Then, the matrix methodology is used to determine the value of both parameters (i.e., $a$ and $b$)

$$a = (a, b)^T = \left(B^T B\right)^{-1}\left(B^T Y\right) \tag{9}$$

5) To determine the predicted values of the starting data point at ($K + 1$), there is a need to calculate grey differential equation.

$$x^1_{(K+1)} = \left[x^0_1 - \frac{b}{a}\right]e^{-ak} + \frac{b}{a} \quad (12)$$

Further, inverse AGO method is used to control the calculated data, as shown in Equation 10.

6) In this step, predicted value is calculated using parameter values and initial data points, as reflected in the following equations of the GM $(1,1)$ model.

$$x^0_{(K+1)} = \left[x^1_{(K+1)} - x^1_{(1)}\right],\ K = 1,2,3,\ldots,n \quad (11)$$

$$x^0_{(K+1)} = \left[\left\{(x^0(1)\left(1-e^a\right)\right\} - \frac{b}{a}e^{-ak}\right],\ K = 1,2,3,\ldots n$$

7) Finally, we perform an error analysis to identify errors among the predicted and actual values of the data. Herein, we use error analysis to measure the accuracy of GM (1,1) prediction model. The following equation is adopted to measure the average percentage error, where $\hat{x}^0_k$ shows predicted value of model and $x^0_k$ shows initial value of data.

$$e(K+1) = \left|\frac{x^0_k - \hat{x}^0_k}{x^0_k}\right| \times 100\%$$

*The fundamental assumption of the model is:*

- Due to data limitations, illegal flow and secondhand/reused electronic items data are not considered in the estimation model.
- Data on population growth and GDP are also not included in the model.

## IV. Empirical Results

First, we have applied grey modelling on the values of e-waste reported by the CPCB (Table 3). The process of calculating e-waste generation using GM (1,1) has been elaborated systematically below.

'$X_0$' represents a non-negative data series for e-waste generation reported by CPCB in previous consecutive years, and are given as (in tonnes):

$$X_0 = (776423, 945390, 998285, 1172200, 2283640)$$

Then new $X_1$ series is calculated, which effectively is a cumulative addition of $X_0$ series, which is AGO.

$$X^1 = (776423, 1721813, 2720098, 3892298, 6175938)$$

From the following sequences, $Z^1_k$ of $X^1_k$ is found as:

$$Z^1_k = (1249118.3, 2807055.8, 3306198.3, 5034118.3)$$

Using least square method, the value of $a$ and $b$ has been obtained.

$$\mathbf{Y} = \begin{vmatrix} 945390 \\ 998285 \\ 1172200 \\ 2283640 \end{vmatrix} \mathbf{B} = \begin{vmatrix} -1249118 & 1 \\ -2807056 & 1 \\ -3306198 & 1 \\ -5034118 & 1 \end{vmatrix}$$

Then we calculated $\left(B^T.B\right)^{-1}$ for using Equation 8.

$$\left(B^T.B\right) = \begin{vmatrix} 4.57131\text{E}+13 & -12396490 \\ -12396490 & 4 \end{vmatrix}$$

$$\left(B^T.B\right)^{-1} = \begin{vmatrix} 1.3708E-13 & 4.2E-07 \\ 4.2E-07 & 1.5661 \end{vmatrix}$$

$$a = -0.3493,\ b = \ 236379,\ e = \ 2.7183$$

$$x^1_{(K+1)} = \left(776,423 - \frac{236,379}{-0.3493}\right) e^{-(-0.3493)(k)} - 236,379$$

**Table 4.** Predicted Volume of E-waste Generated Based on the Central Pollution Control Board (CPCB) Reported Amount (Tonnes).

| 2022–2023 | 2023–2024 | 2024–2025 | 2025–2026 |
|---|---|---|---|
| 3,262,224.2 | 4,583,264.5 | 6,439,261 | 9,046,844.8 |

**Table 5.** Actual Versus Predicted E-waste Volume and Error Analysis (Based on the Central Pollution Control Board (CPCB) Reported Amount).

| Year | Actual Value ($X_k^0$) | Predicted Value ($X_k^1$) | Error | Relative Percentage Error |
|---|---|---|---|---|
| 2017–2018 | 776,423 | 776,423 | 0 | 0% |
| 2018–2019 | 945,390 | 837,277.3 | 108,112.60 | 11.43% |
| 2019–2020 | 998,285 | 1,176,333.5 | 178,048.52 | 17.83% |
| 2020–2021 | 1,172,200 | 1,652,690.7 | 480,490.71 | 40.99% |
| 2021–2022 | 2,283,640 | 2,321,949.1 | 38,309.11 | 1.67% |
| 2022–2023 | – | 3,262,224.2 | – | – |
| 2023–2024 | – | 4,583,264.5 | – | – |
| 2024–2025 | – | 6,439,261 | – | – |
| 2025–2026 | – | 9,046,844.8 | – | – |

**Table 6.** Predicted Volume of E-waste Generated Based on Amount Reported by Global E-waste Monitor (Million Metric Tons).

| 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|
| 7.10 | 8.83 | 10.98 | 13.67 | 17.00 | 21.15 |

**Table 7.** Actual Versus Predicted E-waste Volume and Error Analysis (Based on Amount Reported by Global E-waste Monitor).

| Year | Actual Value ($X_k^0$) | Predicted Value ($X_k^1$) | Error | Relative Percentage Error |
|---|---|---|---|---|
| 2015 | 1.97 | 1.97 | 0 | 0% |
| 2016 | 2.22 | 2.3847 | –0.16475 | 7.42% |
| 2017 | 2.53 | 2.9664 | –0.43643 | 17.25% |
| 2018 | 2.86 | 3.6900 | –0.83001 | 29.02% |
| 2019 | 3.23 | 4.5900 | –1.36008 | 42.10% |
| 2020 | 5.20 | 5.7096 | –0.50969 | 9.80% |
| 2021 | – | 7.1024 | – | – |
| 2022 | – | 8.8348 | – | – |
| 2023 | – | 10.9898 | – | – |
| 2024 | – | 13.6704 | – | – |
| 2025 | – | 17.0049 | – | – |
| 2026 | – | 21.1529 | – | – |

**Table 8.** Accuracy of the Prediction Model on Both Data Sets.

| | Predicted Values of the Central Pollution Control Board (CPCB) Data | Predicted Values of Global E-waste Monitor Data |
|---|---|---|
| Average relative error | 17.98% | 21.42% |
| Accuracy | 82.01% | 78.87% |

Once the value of constants $a$ and $b$ are calculated, the predicted values for each year have been calculated using the abovementioned forecast equation. Table 4 reflects the predicted values of e-waste generation from 2022 to 2026 as per the analysis performed on CPCB reported amount.

On the other hand, Table 5 shows both the actual and predicted volume of e-waste generated in India up to 2026; it also shows the error analysis between these values.

Based on the findings in Table 4, India will generate about 8.20 Mt by 2026. However, this prediction is based on only 21 electronics items considered by CPCB, and 1,606 producers put their electronic products on the market. The actual amount of e-waste is more than 8.20 Mt. Thus, a similar methodology is applied on the values reported by Global E-waste Monitor and estimated the predicted values. Table 6 shows the predicted values of e-waste generation from 2021 to 2026.

After calculating traditional error analysis for both data set forecasting, the average relative error is found to be 17.98 per cent for CPCB data forecasting and 21.42 per cent for Global E-waste Monitor data forecasting.

$$\text{Accuracy} = 100 - \text{ARPE}, \tag{13}$$

Then, the overall accuracy of the prediction model is calculated using Equation 13, which is shown in Table 8.

The prediction result showcases that around 21.15 Mt of e-waste will be generated by 2026. However, the current e-waste management practices to handle e-waste issues are solely based on the data reported by the CPCB, and the actual amount of e-waste generation in India is about 200 per cent more than CPCB reported amount. Thus, there is a need to upscale their e-waste collection targets and recycling rate to handle e-waste-related issues effectively. Moreover, the prediction result indicated that there is about 23 per cent increment in the e-waste amount annually. Consequently, to control this phenomenal increase, there is indeed a necessity to explore alternate solutions. Based on yearly predicted increments in e-waste generation, various required resources can be planned in an economic way for e-waste collection, classification, workforce requirement, warehouse development, repairing, dismantling and needed landfills.

## V. Conclusions and Implications

Technology's advancement, everchanging nature and reduced life cycles of electronic products have made e-waste a growing concern to the global economy. Nations, especially lower-middle income countries, require a robust framework to efficiently take social, economic and environmental advantages of e-waste recycling. Therefore, the study has deployed a grey prediction model to forecast the e-waste volume generated in India till 2026. The forecasting results demonstrate that the amount of e-waste generation in 2021 will be 7.1 Mt and with a similar projection rate it will reach up to 21.15 Mt in 2026.

Such yearly precising of generated e-waste can help in the efficient planning and processing of e-waste. Precise strategies can be formulated for managing the flow of e-waste while minimising its adverse effects. This study contributes to achieving environmental and economic objectives by forecasting the e-waste generation to prevent recovery losses. The study also contributes to the knowledge development process of extant research. In future research, precise data generated can be further used to calculate operation cost, workforce requirement, collection time, warehouse and landfills needed for e-waste collection and processing.

### *Implications*

- The process of setting collection targets primarily depends upon the market supply method. Lack of data availability of all electronic items and imported number of electronic products, limiting their ability to set appropriate collection targets or e-waste strategy. Therefore, utilising predictive grey modelling in such conditions offers significant utility to efficiently assess the trend flow.
- Precise annual e-waste estimation can help policymakers and stakeholders to develop an efficient e-waste strategy.
- Comparative analysis between predicted values of both data sets will be used to estimate new collection targets and upgradation in their operational efficiency.
- Moreover, the predicted value can be utilised to calculate the amount of recovered material and the economic potential of extracted material.

## Appendix

**Table 1.1.** Item Considered by the Central Pollution Control Board (CPCB) in E-waste Generation with Their Average Lifespan.

| S. No. | Electrical and Electronic Equipment (EEE) Item | EEE Code | Average Life (Years) |
|---|---|---|---|
| A. | *Information technology and telecommunication equipment* | | |
| 1. | Centralised data processing: mainframe, minicomputers | ITEW 1 | 10 |
| | | | 5 |
| 2. | Personal computing: personal computers (central processing unit with input and output devices) | ITEW 2 | 6 |
| 3. | Personal computing: laptop computers (central processing unit with input and output devices) | ITEW 3 | 5 |
| 4. | Personal computing: notebook computers | ITEW 4 | 5 |
| 5. | Personal computing: notepad computers | ITEW 5 | 10 |
| 6. | Printers including cartridges | ITEW 6 | 8 |
| 7. | Copying equipment | ITEW 7 | 5 |
| 8. | Electrical and electronic typewriters | ITEW 8 | 6 |
| 9. | User terminals and systems | ITEW 9 | 10 |
| 10. | Facsimile | ITEW 10 | 5 |
| 11. | Telex | ITEW 11 | 9 |
| 12. | Telephones | ITEW 12 | 9 |
| 13. | Pay telephones | ITEW 13 | 9 |
| 14. | Cordless telephones | ITEW 14 | 7 |
| 15. | Cellular telephones (feature phones and smartphones) | ITEW 15 | 5 |
| 16. | Answering systems | ITEW 16 | 5 |
| B. | *Consumer electrical and electronics* | | |
| 17. | Television sets (including sets based on liquid crystal display (LCD) and light emitting diode (LED) technology) | CEEW1 | 9 |
| 18. | Refrigerator | CEEW2 | 10 |
| 19. | Washing machine | CEEW3 | 9 |
| 20. | Air conditioners excluding centralised air conditioning plants | CEEW4 | 10 |
| 21. | Fluorescent and other mercury-containing lamps | CEEW5 | 2 |

**Source:** CPCB (Central Pollution Control Board) (2016).

**Table 1.2.** Category-wise Collection Targets as Reported in Producer Extended Producers Responsibility (EPR) Plans.

| S. No. | EEE Code | 2017–2018 | 2018–2019 | 2019–2020 | 2020–2021 | 2021–2022 |
|---|---|---|---|---|---|---|
| A. | *Information technology and telecommunication equipment* | | | | | |
| 1. | ITEW 1 | 630 | 813 | 1,017 | 1,151 | 1,573 |
| 2. | ITEW 2 | 33,043 | 34,188 | 38,217 | 34,335 | 33,758 |
| 3. | ITEW 3 | 2,095 | 2,410 | 3,294 | 4,211 | 750 |
| 4. | ITEW 4 | 961 | 1,801 | 1,893 | 1,456 | 303 |
| 5. | ITEW 5 | 223 | 427 | 551 | 719 | 132 |
| 6. | ITEW 6 | 7,897 | 8,331 | 11,215 | 13,939 | 17,648 |
| 7. | ITEW 7 | 213 | 409 | 750 | 1,368 | 1,602 |
| 8. | ITEW 8 | 0 | 0 | 0 | 0 | 0 |
| 9. | ITEW 9 | 145 | 372 | 778 | 911 | 1,414 |
| 10. | ITEW 10 | 21 | 21 | 26 | 44 | 30 |
| 11. | ITEW 11 | 0 | 0 | 0 | 0 | 0 |
| 12. | ITEW 12 | 268 | 392 | 474 | 456 | 562 |
| 13. | ITEW 13 | 0 | 0 | 0 | 0 | 0 |
| 14. | ITEW 14 | 22 | 22 | 41 | 99 | 179 |
| 15. | ITEW 15 | 5,300 | 18,211 | 19,856 | 21,146 | 15,458 |
| 16. | ITEW 16 | 3 | 1 | 5 | 15 | 31 |
| B. | *Consumer electrical and electronics* | | | | | |
| 17. | CEEW1 | 61,526 | 68,538 | 99,947 | 89,876 | 100,808 |
| 18. | CEEW2 | 57,459 | 71,327 | 102,575 | 143,016 | 791,403 |
| 19. | CEEW3 | 27,787 | 36,511 | 60,159 | 69,973 | 84,465 |
| 20. | CEEW4 | 25,047 | 31,066 | 53,254 | 82,021 | 91,706 |
| 21. | CEEW5 | 10,285 | 8,775 | 5,260 | 4,142 | |
| 22. | Total | 232,927 | 283,617 | 399,314 | 468,880 | 1,141,820 |

**Source:** Khetriwal (2019).

To estimate item-wise e-waste amount in a year:

$$\text{E-waste generated by an item in a year} = \frac{(\text{Amount of item collection in year} \times 100)}{(\text{Percent of collection target in the year})}$$

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Research article

# A computer vision-based system for real-time component identification from waste printed circuit boards

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A B S T R A C T

With an exponential increase in consumers' need for electronic products, the world is facing an ever-increasing economic and environmental threat of electronic waste (e-waste). To minimize their adverse effects, e-waste recycling is one of the pivotal factors that can help in minimizing the environmental pollution andto increase recovery of valuable materials. For instance, Printed Circuit Boards (PCBs), while they have several valuable elements, they are hazardous too; and therefore, they form a large chunk of e-waste being generated today. Thus, in recycling PCBs, Electronic Components (ECs) are segregated at first, and separately processed for recovering key elements that could be re-used. However, in the current recycling process, especially in developing nations, humans manually screen ECs, which goes on to affect their health. It also causes losses of valuable materials. Therefore, automated solutions need to be adopted for both to classify and to segregate ECs from waste PCBs. The study proposes a robust EC identification system based on computer vision and deep learning algorithms (YOLOv3) to automate sorting process which would help in further processing. The study uses a publicly available dataset, and a PCB dataset which reflect challenging recycling environments like lighting conditions, cast shadows, orientations, viewpoints, and different cameras/resolutions. The outcome of YOLOv3 detection model based on training of both datasets presents satisfactory classification accuracy and capability of real-time competent identification, which in turn, could help in automatically segregating ECs, while leading towards effective e-waste recycling.

## 1. Introduction

In the past few years, with population growth, urbanization, technological advancement, and human reliance on electronic products, e-waste has increased significantly (Kumar and Dixit, 2018; Yadav et al., 2022). Statistics reveal that around 500 million computers were discarded in the United States between 1997 and 2007, and over 1.2 billion mobile phones were produced globally in a year (Kiddee et al., 2013). Printed Circuits Boards (PCBs), composed of multiple Integrated Circuits (ICs) interconnected via copper traces, are extensively used in all electronic products, and serve as the central part of these products.

With technological advancement, there has been a simultaneous upgradation in the function and structure of electronic products. This has led to a heterogeneous mix of material and multi-layered structure of circuit boards (Lu et al., 2022) comprising over 60 different elements. For instance, they include costly materials like gold (Au), silver (Ag), and copper (Cu); in fact, there are exclusive earth elements, with relatively higher concentrations in Waste PCBs (WPCBs) than in natural ores (Hubau et al., 2019; Lu et al., 2022). WPCBs, in turn, contain multiple toxic and hazardous materials (e.g., cadmium (Cd), and mercury (Hg), along with organic components like brominated flame retardants (BFRs) (Charitopoulou et al., 2021). Improper treatment or open burning of WPCBs results in losses of natural resources, significantly generating hazardous gases such as carbon monoxide (CO), and hydrobromic acid (HBr), severely affecting human health and environment (Guo et al., 2020). Therefore, it is imperative to efficiently recycle and manage WPCBs in an eco-friendly manner to extract valuable materials and components.

The differences in material composition of various components in PCB prove that there is a requirement for dismantling and separating WPCB components before material recovery (Lu et al., 2022; Silva et al., 2021). In the absence of a systematic process and the high cost of fully

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automated pre-processing, these tasks are manually performed by human labor in developing countries. Manual processing for such operations is a time-consuming, tedious, and unreliable option. Furthermore, it subsequently affects the workers' health and delimits the processing capacities (Massiris Fernández et al., 2020; Wu et al., 2022). In contrast, due to a lack of archaic technologies and poor treatment processes, most WPCBs are directly exported from developing nations to developed nations for further processing, where WPCBs are manually treated by workers via crude manner (e.g., acid leaching, open burring etc.) or illegally dumped into the waste site (Chatterjee, 2012). Thus, from a holistic point of view, such activities do tend to lead to a shortage of natural resources, while causing severe economic and environmental damage (Wang and Huo, 2023).

To maximize the WPCBs recycling outcome and minimize manual processing, some automated approaches were developed to liberate electronic components (ECs) from bare boards, such as electro-chemical process, electro-mechanical separation, magnetic separation, gravity separation and thermal desoldering (Kaya, 2019; Otsuki et al., 2020; Ueda et al., 2021; Vermeșan et al., 2019). Through these automated approaches, ECs present on bare boards are extracted to make them convenient for further processing (Kaya, 2019). However, utilizing these methods for dismantling and segregating ECs is not an efficient method as they require abrupt movement during this processing that indirectly affects the original functionality of the components and processing time required for disassembling (Kopacek, 2017). Moreover, e-waste consists of multiple tiny or complex electronic components; if they are not sorted appropriately, results in minimizing the proportion of precious metals compared to overall e-waste weights and makes the current recycling processes incapable of recovering them (Soomro et al., 2022). Thus, to enable full recovery of precious materials, there is a need to identify the components from WPCBs that contain valuable materials and segregate them. It may also be noted herein that related studies on identifying and isolating ECs from WPCBs into specific categories are limited thus far. Therefore, this study attempts to fill such a research gap by focusing on identifying and segregating valuable ECs from WPCBs for further recycling them efficiently.

With the introduction of Industry 4.0, emerging technologies are supporting in e-waste treatment, specifically in the classification and sorting process (Castiglione et al., 2023; Dong et al., 2022; Kazancoglu et al., 2021). Classifiers based on deep learning algorithms and cloud computing technology are integrated to develop an intelligent municipal waste management system that can 'intelligently' classify e-waste right during garbage collection. In turn, this reduces the overall cost of collection, classification, and monitoring (Wang et al., 2021). Today, with the advancement in deep learning algorithms, Computer Vision Technology (CVT) based applications to provide operation excellence in various domains (Zhang et al., 2023).

Especially in the field of e-waste management to enable earlier classification and sorting, including "Region-based Convolutional Neural Networks" (R–CNN) and Convolutional Neural Networks (CNN), along with other classification methods, such as "Principal component analysis" (PCA) or Support Vector Machine (SVM) (Lu et al., 2022; Lu and Chen, 2022; Sharma et al., 2023). Firstly, Gundupalli et al. (2018) developed a simulated dataset prepared from locally generated e-waste to classify their material into metallic and non-metallic fractions, and their model based on a thermal imaging-based technique is capable of classifying fractions with 84–96% accuracy. Nowakowski and Pamuła (2020) developed an object classification system using the CNN model to identify various categories of e-waste for the collection process and their system can classify with an accuracy of around 90–97% for specified categories of e-waste. More recently, Liang and Gu (2021) proposed a multi-task learning model that simultaneously recognizes and localizes waste with higher accuracy and faster speed. Johnson et al. (2022) developed a roboCRM system that utilized CVT and a robotic manipulator to identify and classify reusable batteries from waste streams.

However, due to slower computing capacity and time-consuming processes, they are limited numbers of applications for e-waste segregation in real time. Thus, there is a necessity to prepare a highly sophisticated method to collect and segregate EC waste. You Only Look Once (YOLO) seems to be an appropriate method whose algorithm helps transform the object classification and localization process into a single regression problem. It is believed to help in better object detection speed than CNN (Redmon et al., 2016). In fact, if one were to compare the earlier YOLO versions (i.e., YOLOv1 and YOLOv2), it may be noted that its latest version (i.e., YOLOv3) does significantly enhance both detection speed and accuracy, specifically for smaller objects, that too in real-time (Chand and Lal, 2022; Chen et al., 2021; Li et al., 2020). YOLOv1 is the first version of the YOLO model released in 2015 by Joseph Redmon to overwhelm the problem of the R–CNN model of two-stage detection, which makes the object detection process slower and more complex (Aly et al., 2021). However, the major drawback to this version is not capable of identifying smaller objects in a cluster. Then, YOLOv2 is introduced to address the shortcomings of the YOLOv1 model, in which they introduce an anchor mechanism found within the Faster R–CNN. Anchors make it easier for the model to predict the bounding boxes, it makes the YOLOv2 model better, faster, and stronger in comparison to YOLOv1 (Srivastava et al., 2021). Regardless, YOLOv2 has certain limitations such as it utilizing the SoftMax function to evaluate the conditional probability of classes that impose the assumption that every bounding box conation only labels. But in reality, a given object can have multiple labels, that create problems of overlapping. To solve the multi-level problem, the YOLOv3 model was introduced, which uses independent logistic classification for each class and makes them efficient for real-time processing (Mao et al., 2022). Therefore, we have chosen YOLOv3 for your proposed research work.

Since ICs are a significant source of precious metals and contain valuable materials within WPCBs, we propose deploying the YOLOv3 object detection algorithm to segregate ICs from WPCBs. Specifically, deploying the YOLOv3 model in this context helped identify and classify ICs into distinct categories based on real-time processing while verifying its effects and efficiency with high speed and precision. Moreover, the competence of the proposed methodology can help minimize the requirement of manual processing and losses of precious material, thereby providing overall sustainability in the WPCBs treatment.

The rest of paper is structured as follows: the following section briefly describes the status quo of CVT in WPCB processing. Section 3 explains datasets, research methodology of YOLOv3 development, and performance indices utilized for object detection model. Section 4 delivers its implementation outputs; while section 5 highlights the research implications and concludes the paper along with study limitations and future scope.

## 2. Review of literature

Several studies in the past have proposed automated methods for handling e-waste. For instance, Weinert et al. (2017) promoted the use of 'deep learning' for developing automated systems for classifying e-wastes. Meanwhile, it may be noted that many researchers have implemented CVT for optical inspection of PCBs. In this process, various other methods have also been adopted to help in determining and analyzing defects that relate to manufacturing. Putera and Ibrahim (2010) for instance, applied image-processing techniques, coupled with mathematical morphology tools. They attempted to pinpoint specific manufacturing defects, arising from PCBs, especially during an automated inspection in assembly lines. Notably, computer vision applications for PCB classification have recently emerged. In fact, generally, two approaches are most frequently used for this problem; first for identifying PCBs level, where types of PCBs are present, and are separated from the waste stream. The second is to identify various components from the WPCBs for further processing of the components.

### 2.1. PCB identification

In this approach, the researcher explores various methodologies using CVT to develop an automated Classification system for segregating WPCBs into specific types for further processing. Pramerdorfer and Kampel (2015b) proposed an automatic classification method, using local feature matching and geometric verification to classify WPCBs from waste steam into specific categories without using any competent level details. However, one of the most compelling feature extraction methods has been developed by David Lowe, known as the "Scale Invariant Feature Transform (SIFT)," which can handle all invariants from the images (Lowe, 1999). Pramerdorfer and Kampel (2015b) also compared performance of different featuring techniques like Binary Robust Invariant Scalable Keypoints (BRISK), Fast Retina Keypoints (FREAK), SIFT, and Speed Up Robust Feature (SURF). The outcome of their experiment showcases up to 100% accuracy for the object detection process under controlled pose and illumination dataset. In contrast, Soomro et al. (2022) built a public PCB dataset to propose a robust PCB classification system, using deep learning and computer vision techniques that are capable of classifying WPCBs into specific categories under working environments and recycling conditions. However, such kind of works related to competent-level identifications from WPCBs, and real-time detection of components still need to be explored.

### 2.2. Competent level identification

For the competent level identification of WPCBs to facilitate the recycling process, Li et al. (2013) adopted an automated PCB recycling system for analyzing materials. The system comprised sensors equipped with cameras, lasers, and spectrometers. However, this approach may not be suitable for applying on a broader range of PCBs, as not all are modelled with comparable bordering features. Li et al. (2014) also tried to read the labels of ICs for further analysis, adopting Optical Character Recognition (OCR), along with analogized distinct OCR engine performances.

Li et al. (2016) further extended their work and proposed another technique that identifies the PCB components by combining regions based on similar feature sets (e.g., color/pixel intensity and edges). They were later used to remove the background. Lu et al. (2022) developed an automatic solution to classify various ECs from WPCBs, using the YOLOv3 algorithm. Their model shows satisfactory classification accuracy on the self-made dataset. Nevertheless, a major problem related to their model was that it couldn't capture practical scenarios required for the recycling environment, such as orientation, motion blur, and indoor and semi-outdoor conditions. However, it may be noted that owing to significant variations in PCB structures, to find a robust and generic solution that performs ECs identification in real-time and recycling is still an open research problem. Therefore, to accomplish the issues as mentioned above, the study proposes an automated and generic solution to identify ECs from WPCBs using the YOLOv3 object detection algorithm. The aim herein is to identify components in a suitable environment and real-time for further recycling process.

## 3. Research methodology

### 3.1. Study design and datasets

Awan et al. (2021) had proposed a few data analysis steps for utilizing a machine learning model, which we chose to adopt for our study. Fig. 1 captures the competent ICs detection model in the form of a flowchart. It may be noted herein that the two images dataset of WPCBs, PCB-DSLR and Domestic WPCBs, were at first collected and labeled with a roboflow tool, which further used to validate and train the YOLOv-3 model. After the convergence of loss value and mapping (matching the features of objects found within the bounding boxes), the training of a competent detection model (YOLOv3) was performed. Then, we used different images that were collected from the domestic WPCBs database, and evaluated, as well as measured the operational performance of the object detection model using various indices such as precision, recall and detection speed. Table 1 elaborates upon the detailed descriptions of

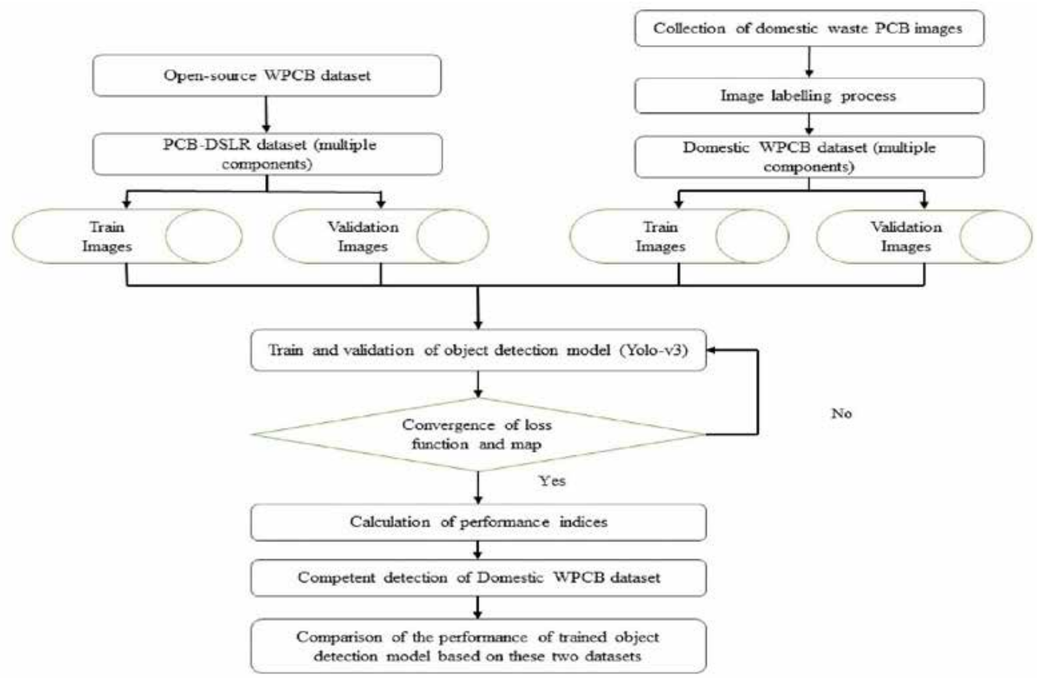


**Fig. 1.** Flowchart of research work.

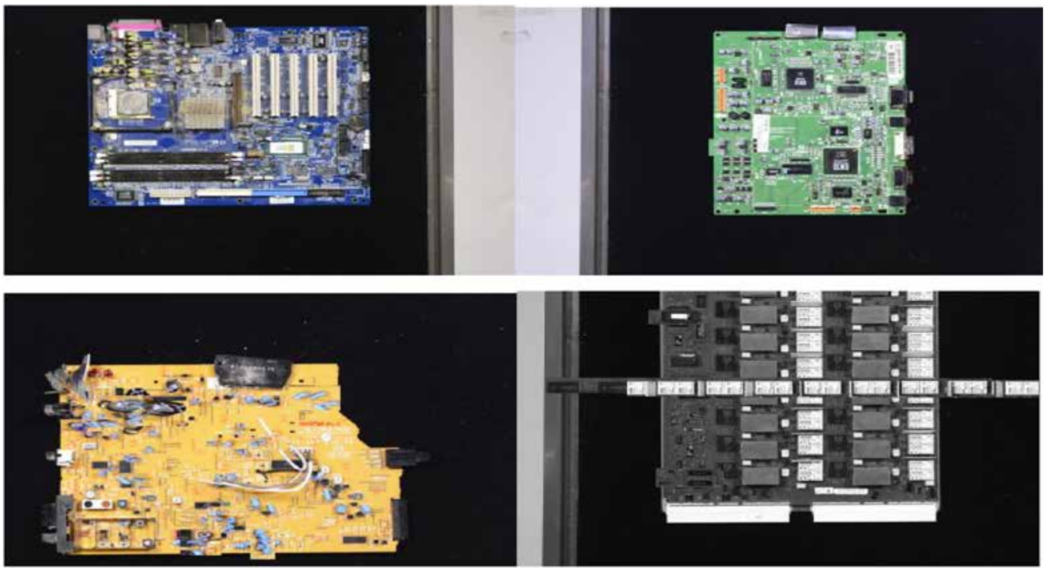

**Fig. 2.** Samples Waste PCBs images from PCB-DSLR dataset (Pramerdorfer and Kampel, 2015a).

**Table 1**
Description of both the datasets used in the experimentations.

| | PCB-DSLR dataset (Pramerdorfer and Kampel, 2015a) | Domestic WPCB dataset |
|---|---|---|
| Number of images | 748 | 248 |
| Categories of IC | Five (SOIC. SSOP, TSSOP, TVSOP, QFN) | Two (IC_1, IC_2) |
| Place of waste generation | Austria | India |
| Dataset type | Single objects | Single and multiple objects |

both datasets that have a distinct number of images, orientations, and numbers of components within the images (see Fig. 2).

### 3.1.1. PCB-DSLR dataset

The PCB-DSLR dataset is a publicly available, consisting of 748 images of 165 different PCBs. In addition, each image contained waste PCB images of a resolution of 4928 x 3280 pixels and information related to accurate segmentation of the depicted PCB and bounding boxes of all IC chips (Pramerdorfer and Kampel, 2015a). To build the dataset, each WPCB extracted from the waste stream is placed on an image acquisition system consisting of a black conveyor belt for carrying the waste stream and capturing the images of each WPCB using a professional DSLR camera. According to the dataset's description, it consists of five unique types of ICs: SOIC, SSOP, TSSOP, TVSOP, and QFN. More precisely, 165 different types of PCBs in the dataset, where 11 PCBs contain no kind of such IC, 42 PCBs contain at most 3 ICs (25.5%), 84 PCBs contain at most a combination of 9 ICs (50.9%), and the remaining 137 PCBs consists at most 19 ICs (83.0%) which is the combination of above mentioned five unique ICs (Pramerdorfer and Kampel, 2015a).

### 3.1.2. Domestic WPCB dataset

Furthermore, to build an object detection model appropriate for competent identification of WPCBs in every condition, 100 more waste PCBs were manually collected from recycling centers, repair shops or dumping yard stations and followed the steps utilized by Mao et al. (2022) in their research work for dataset building to object detection model. Then, each collected WPCB was placed on a white sheet or cardboard, and a mobile camera was used to capture the image of WPCBs under the recycling conditions such as indoor light or natural sunlight. Herein, some images contain a single PCB, and some contain multiple objects as a broken part of the single PCB. Each image was captured at a resolution of 416 x 416 pixels with different backgrounds, blur effects, orientations and lighting conditions and later added to the new dataset sequentially. The final dataset utilized for the analysis consists of 348 new images and sample images from the own build dataset represented in Fig. 3. The primary purpose of building our dataset is to provide the form of a simulation closer to real-world examples found in recycling conditions.

As shown in Fig. 3 (b), we employed an open-source labelling tool named Roboflow to make borderlines for ICs (IC_1 and IC_2) within the WPCBs images and annotated them. Herein, IC_1 are those circuits that are in working condition or can be used further; IC_2 is those that were not useable or recycled further. Thus, to identify IC_1 and IC_2 from domestic WPCB for the annotation process, we have marked circuits as IC_1: if the quality of the circuit is in good condition in a visual way or code written on the circuit is not damaged and for IC_2: color and code written on the circuit is damaged or not capable to read. In this way, we have distinguished circuits into IC_1 and IC_2 to make borderlines during the annotation process.

Notably, the annotation process of components generates an additional file in a textual format that contains the size, position, and names of each annotated object. During YOLOv3 training, these image annotations operated as the ground truth for detecting IC, and this annotated image data was further stored in the XML format. In contrast, images within both datasets were randomly divided into two classes: the training dataset (70% of images) and the testing dataset (30% of images).

Further, to identify ICs from WPCB images, we considered a transfer learning process in which pre-trained object detection algorithms were utilized. However, a significant problem that comes across in IC detection is a few short learning problems, as PCB contains multiple and distinct types of IC within the PCB, making it difficult for the model to detect every individual IC. Therefore, one needs to have a more extensive sample database for the model's training process. We used a data augmentation process to enhance the performance of the object detection algorithm (YOLOv3) on both datasets. The data augmentation process also involved the black box approach (process to convert the

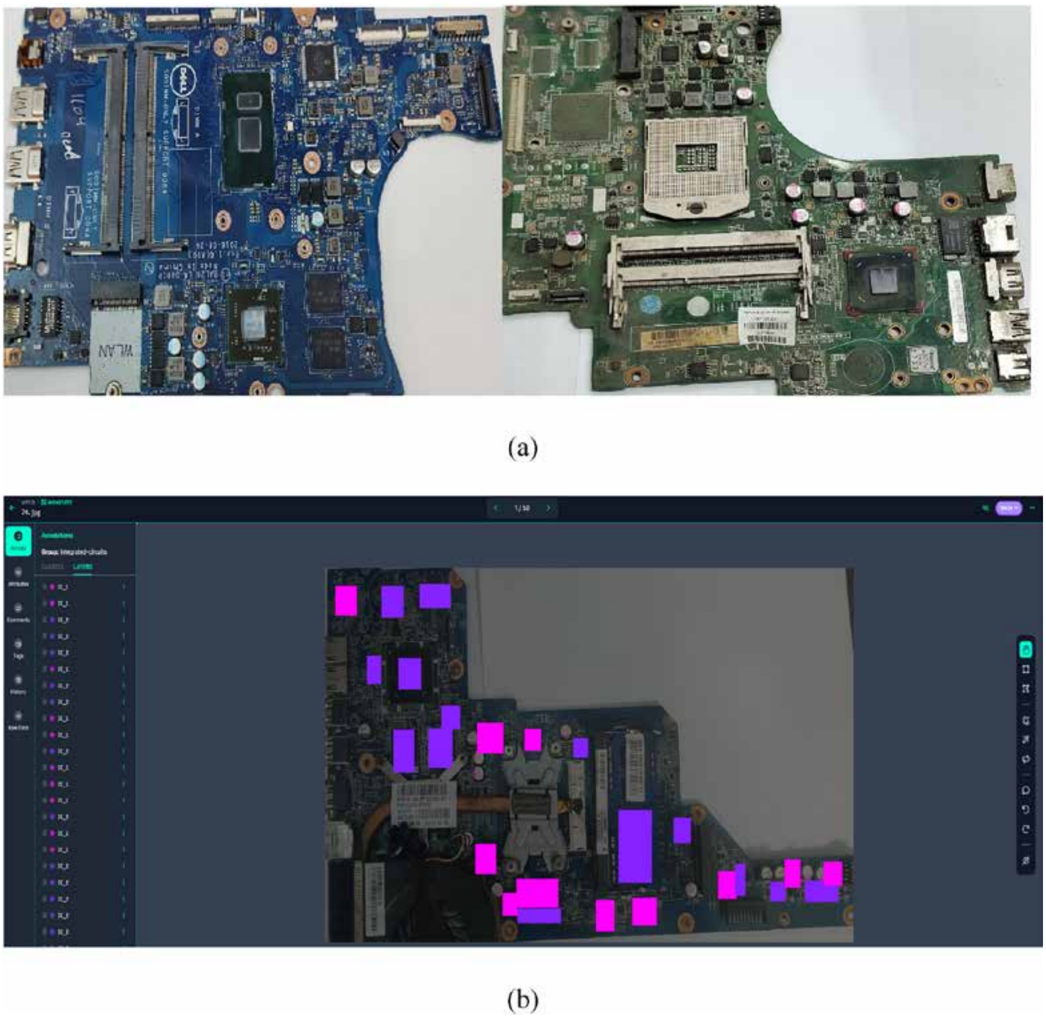

**Fig. 3.** (a) Sample Waste PCBs images from own locally developed dataset, and (b) Sample image of domestic WPCB dataset with the associated ground-truth annotations.

image into a hyper-vibrant image format), the white box approach (to convert the image into dull format), affine image transformation, etc.

In contrast, incorporating real-time affine image transformations into YOLOv3 training allows randomly flipping images into vertical and horizontal directions. Overall, it will enhance the diversity of WPCB images used for the training process and improve training effectiveness. Data augmentation of images by image generator process in real time is already feasible in Keras by using simple commands such as "Resizing", "Rescaling", "Random flip", etc. In other words, we applied a data augmentation technique to the images of the training data after each epoch while utilizing the augmented data to develop new inputs for the YOLOv3 model for each epoch, to preventing over-fitting. As a result, the diversity of images is increased without increasing the number of waste images.

#### *3.1.3. Reason to build new dataset*

The foremost reason to build a new dataset is to propose a CVT-based system that is capable of identifying ICs in terms of the following recycling conditions:

- F095 Invariant to motion blur.
- F095 Invariant to indoor and outdoor conditions such that a diffuser and special polarized filter are not required for the further process; normal lighting conditions are sufficient.
- F095 Invariant to cast shadows in PCBs that are not flat so much (i.e., PCBs fitted with connectors, heat sinks, unremoved part of the casing, etc.).
- F095 Invariant to adequate change in terms of viewpoint/perspective as well as rotary motion of the object.

### *3.2. YOLOv3*

Fig. 4 (a) showcases the basic working procedure of the YOLOv3 model via a systematic diagram, where the whole system is divided into two major parts: Feature extractor and detector; both are multi-scale. Whenever a new WPCB image comes in, it goes through via a feature extractor first so that it can obtain the various feature embedding in the image at three or more different scales. Then, these features are fed into three or more branches of the detector to obtain the bounding boxes and class information to identify the various objects.

The overall network architecture of the YOLOv3 model is illustrated in Fig. 4 (b). As it may be noted from this figure, the YOLOv3 model

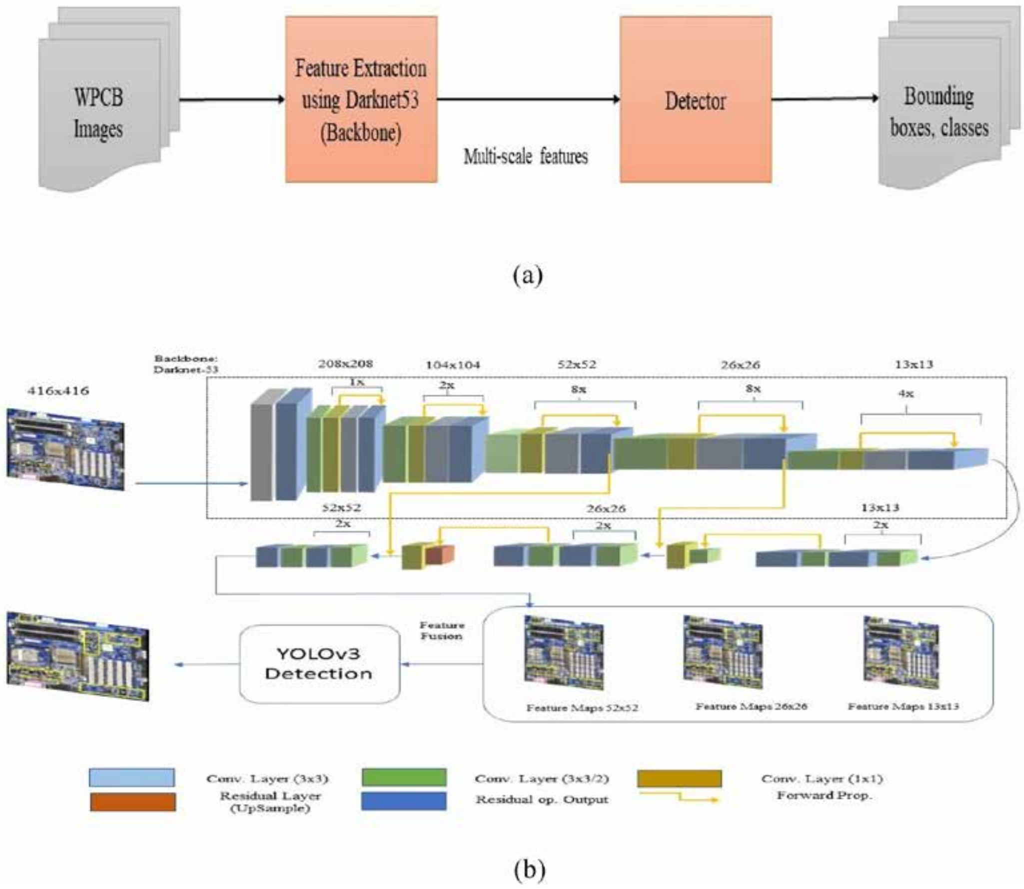


**Fig. 4.** (a) Basic architecture and (b) Network architecture of YOLOv3 model.

divides the images of the objects from the dataset into the $S \times S$ grids. Notably, if the object center with ground truth fits into a grid, then the grid should be able to detect this object. Importantly, each grid anticipates its confidence scores, bounding boxes, and class conditional probabilities. An object's confidence score may be defined as:

$$Confidence\ Score = p_r(object) \times IoU_{pred}^{truth},\ p_r(object) \in (0,1) \tag{1}$$

$$IoU_{pred}^{truth} = \frac{Area(B_{pred} \cap B_{truth})}{Area(B_{pred} \cup B_{truth})} \tag{2}$$

where, $p_r(object)$ refers to the index that represents an object within the grid. Thus, when an object is within the grid, it may be perceived as $p_r(object) = 1$; otherwise $p_r(object) = 0$. On the other hand, $IoU_{pred}^{truth}$ shows how analogous an object could be to the ground-truth object. It may be achieved by dividing overlap area of ground-truth and predicting bounding box by the union area. Further, it may be noted that in the object detection process, "class-specific confidence score" (*CSCS*) of each bounding box needs to be achieved by clustering the class conditional probability $p_r(class_i / object)$, (Equation (3)) (Mao et al., 2022). *CSCS* is generally performed to assess the accuracy of both localization and object detection. Importantly, if multiple bounding boxes recognize a similar object simultaneously, then it is advisable to adopt non-maximum suppression to get an optimal bounding box. Specifically, in this case, every single grid estimates nine pre-selected bounding boxes via k-mean clustering.

$$CSCS = p_r(class_i) \times IoU_{pred}^{truth} \tag{3}$$

YOLOv3 utilizes Darknet 53 as the primary tool to draw out features from images. Fig. 4 (b) displays the YOLOv3 network structure that includes 53 layers of the convolutional network coupled with 23 residual layers. Within the network, there are three different sizes of convolution kernels (i.e., 1 × 1, 3 × 3, and 3 × 3/2). Specifically, they are utilized within existing convolutional layers and help draw out image features in sequence. Moreover, existing residual layers inside the network are further utilized to avoid the gradient problem. In fact, they also ensure convergence of the YOLOv3 model. Furthermore, YOLOv3 utilizes feature maps and feature pyramid networks of varying scales for multi-scale detection to find the various levels of feature maps. We primarily used 3 feature maps with distinct scales (i.e., 52 × 52, 26 × 26, and 13 × 13) via 3 times down sampling in fusion. This was done for detecting different parts of the same objects concurrently, thereby implying that YOLOv3 can indeed detect even fine-grained characteristics of the objects.

For instance, the 13 × 13 scale size can identify more oversized objects as this scale size can effectively result in high-down sampling multiples. Interestingly, however, it still somewhat retains a sizeable receptive feature map field. The scale 52 × 52, on the other hand, is possibly more suited for detecting more diminutive entities (Cheng et al., 2020). Then blending these feature maps, we can measure the loss value and loss function of the bounding boxes and assess the model's performance. The loss function value of the YOLOv3 model may be defined by equations (4)–(7) (Redmon and Farhadi, 2018) and it is the summation of three different scores that co-ordinate prediction score (refer to the objectness score prediction for bounding boxes responsible for predicting objects), IoU score (indicating bounding boxes with no objects) and classification error score (penalize class prediction for bounding boxes which predicts the objects). Finally, we back-propagate the loss values of each bounding box for calculating the optimal network parameters and achieving both classification and localization of best-bounding boxes in the training process.

$$Loss = Error_{coord} + Error_{Iou} + Error_{cls} \tag{4}$$

$$Error_{coord} = \lambda_{coord}\sum_{i=1}^{s^2}\sum_{j=1}^{B} I_{ij}^{obj}\left[(u_i-\widehat{u_i})^2+(v_i-\widehat{v_i})^2\right]+\lambda_{cord}\sum_{i=1}^{s^2} \times \sum_{j=1}^{B} \mathrm{I}_{ij}^{obj}\left[(\sqrt{\mathrm{w_i}}-\sqrt{\widehat{\mathrm{w_i}}})^2+\left(\sqrt{\mathrm{h_i}}-\sqrt{\widehat{\mathrm{h_i}}}\right)^2\right] \tag{5}$$

$$Error_{Iou} = \sum_{i=1}^{s^2}\sum_{j=1}^{B} I_{ij}^{obj}(c_i-\widehat{c_i})^2+\lambda_{nobj}\sum_{i=1}^{s^2}\sum_{j=1}^{B}\mathrm{I}_{ij}^{obj}(c_i-\widehat{c_i})^2 \tag{6}$$

$$Error_{cls} = \sum_{i=1}^{s^2}\sum_{j=1}^{B} I_{ij}^{obj}\sum\nolimits_{c\in class}\left(p_{ri}(c)-\widehat{p_{ri}(c)}\right)^2 \tag{7}$$

In these equations, $Error_{Iou}$, $Error_{cls}$, and $Error_{coord}$ refer to, *IoU*, classification errors, and coordinate predictions, respectively. $\lambda_{coord}$ refers to the coordinate error's weight, while $s^2$ marks number of grids within input image, and B represents number of bounding boxes that are triggered by each grid. Further, the model's $\lambda_{coord}$ parameters (i.e., both *S, and B*) were set to 5, 13 and 9, respectively. It may be noted that the model's $I_{ij}^{obj}$ is 1 in case an object is into the $j_{th}$ bounding box in grid; otherwise, $I_{ij}^{obj}$ is to 0. ($u_i$, $v_i$, $\mathrm{w_i}, \mathrm{h_i}$) refers to the coordinates of the object center, along with width and length of bounding boxes at true values; while, ($\widehat{u_i}, \widehat{v_i}, \widehat{\mathrm{w_i}}, \widehat{\mathrm{h_i}}$) serve as the center coordinates, along with both length and width of the predicted bounding boxes.

Further, in equation (6), $\lambda_{nobj}$ refers to the weight of the *IoU* error. $c_i$ *and* $\widehat{c_i}$ represent both the predicted and true confidence. The $Error_{cls}$ of grid *i* may be defined as the total of the classification error of all items within the grid; it has been evaluated, using equation (7), where, $p_{ri}(c)$ represents the true probability of the targeted object is truly centered on grid *i*, and does belong to class c, wherein $\widehat{p_{ri}(c)})$ is the predicted probability.

### 3.3. Performance indices of the object detection algorithms

In most cases, two indices are generally utilized to measure the performance of an object detection models: precision [$p(r)$] and recall (r). The calculation rationale of these indices is shown below:

$$p(r) = \frac{TP}{TP+FP} \tag{8}$$

$$(r) = \frac{TP}{TP+FN} \tag{9}$$

where *TP, FP* and *FN* refer to numbers of both true and false positives, coupled with false negatives. Precision represents how IC ratios from WPCB images were aptly predicted. Recall refers to predicted IC's accuracy ratio, vis a vis how they matched to the right categories (Tan et al., 2021). Frame per second (FPS) rate helps in understanding how promptly a model could process images, while generating its output (Mao et al., 2022).

Average precision *(AP)* was more balanced than random sampling regarding complete document collection. Primarily, it is a performance index that is frequently utilized for object detection algorithms. *AP* value may be defined as a space below the precision curve *[p(r)]* on recall *(r)*. Similarly, mean average precision *(mAP)* is equal to the mean *AP* sums of all detection categories. In fact, it aims to estimate the average detection accuracy across several target objects, owing to which it is frequently viewed as the complete performance indices of the object detection model (Mao et al., 2022). These values are expressed by equations (10) and (11).

$$AP = \int_0^1 p(r)dr \tag{10}$$

$$mAP = \sum_{k=1}^{NC}\frac{AP_k}{NC} \tag{11}$$

In equations, p(r) is defined as a recall function (r); $AP_k$ is considered as the average precision of the Kth class object, and *NC* is the number of object classes. During the training process, at the different *IoU* threshold values, the object detection model showcases distinct ***mAP*** values. Therefore, it is pivotal to select an adequate threshold value at which the highest mAP and the perfect accuracy of the model is attained. We used Python 3.5 and Keras 2.2.0 frameworks at the backend for implementing the various object detection algorithms. All the analyses were performed using a computer with an Intel(R) Core (TM) i5-8250U CPU @ 1.60 GHz, 64 GB RAM and a Radeon 530. This configuration allows the training of the YOLOv3 model with an average iteration speed of 2.9s.

## 4. Results and discussion

### 4.1. Performance of YOLOv3 model trained on PCB-DSLR

Fig. 5 (a) displays the changes in the ***mAP*** value at threshold value 0.5, along with the average loss in the object detection model during the training process, utilizing the PCB-DSLR dataset. Specifically, the figure illustrated that the loss function value at the starting point was high enough when the training process was ongoing. Then, the loss function value started to flatten after 150 iterations, indicating that the model began to converge. At a threshold value of 0.5, ***mAP*** value for the object detection model achieved around 70.60%, while the average loss function value of the model was around 0.035 after finishing the whole training process (i.e., 850 iterations). The overall time taken by the model for the training process was about 14 h. As the value of ***IoU*** threshold of the model assesses the number of objects forecasted within the bounding boxes and consequentially outcomes in the different ***mAP*** values, the consequences of change values within the ***IoU*** threshold values are documented (Table 2).

Further, the object detection model (YOLOv3) achieved a mAP of 70.70% at a threshold value of 0.5, a mAP of 65.35% at a threshold value of 0.6, and a mAP of 59.32% at a threshold value of 0.7; at this moment, all the model's training and configuration conditions were maintained. The training process outcome indicated that the model's ***mAP*** value is decreased when we use a stricter ***IoU*** threshold value for the PCB-DSLR dataset. As the ***IoU*** value increased, training the object detection model on the PCB-DSLR dataset made it challenging to align with the bounding boxes of the objects. This decrease in mapping alignment was attributed to the fact the more significant ***IoU*** threshold, resulting in an exponential increase in the number of positive training samples. This led to overfitting during the training process (Mao et al., 2022).

In contrast, the detection speed of the model was about 40 FPS, illustrating that the model was indeed capable of identifying 40 distinct objects within a second. It represents high detection performance that is sufficient for automated processing of ICs. The highest-yielding value of model is at threshold value of 0.5, which is 70.60%. Table 3 shows each ICs type's AP values within the PCB-DSLR dataset. The model attained the highest AP values for SOIC-20 and QFN-20 ICs. As the total number of these ICs within the images was lesser in comparison to other ICs, it

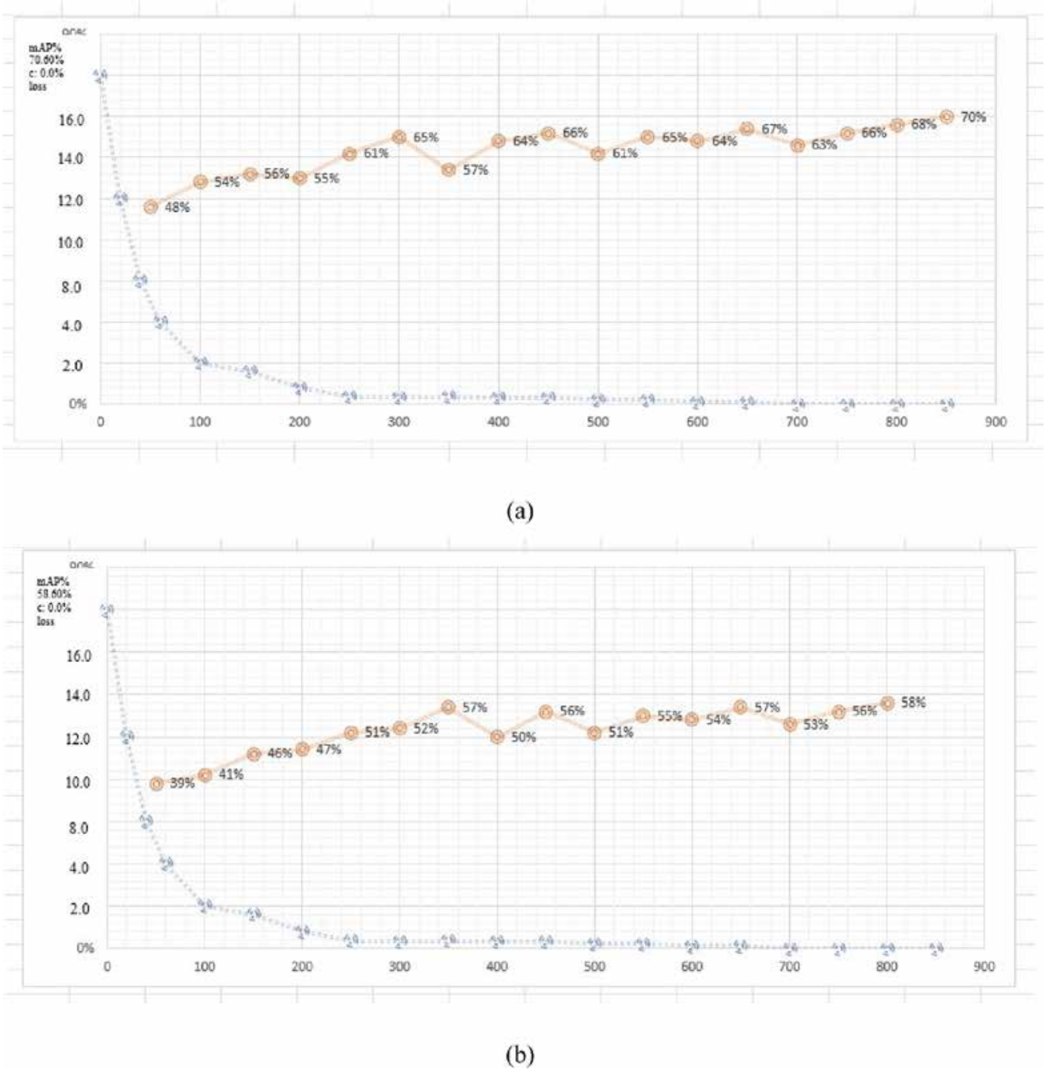


**Fig. 5.** The associated YOLOv3 loss function (blue curve) and mAP@0.5 value with respect to number of iterations (orange curve) (a) PCB-DSLR dataset and (b) Domestic-WPCB dataset.

**Table 2**
Impact of different *IOU* values on PCB-DSLR and Domestic WPCB trained YOLOv-3 model.

| IOU threshold | PCB-DSLR dataset | | | Domestic WPCB dataset | | |
|---|---|---|---|---|---|---|
| | *mAP* (%) | Recall (%) | Detection speed (FPS) | *mAP* (%) | Recall (%) | Detection speed (FPS) |
| **0.5** | 70.60 | 76 | 40 | 58.60 | 64 | 40 |
| **0.6** | 65.35 | 70 | | 53.05 | 55 | |
| **0.7** | 59.32 | 65 | | 51.45 | 53 | |

**Table 3**
Average precision of the object detection model for each IC class of PCB-DSLR and Domestic WPCB dataset.

| PCB-DSLR dataset | | | Domestic WPCB dataset | | |
|---|---|---|---|---|---|
| Types of ICs | AP (%) | *mAP@0.5 (%)* | Types of ICs | AP (%) | *mAP@0.5 (%)* |
| SOIC-20 | 79.10 | 70.60 | IC_1 | 75.60 | 58.60 |
| SSOP-20 | 59.85 | | IC_2 | 41.06 | |
| TSSOP-20 | 67.54 | | | | |
| TVSOP-20 | 71.95 | | | | |
| QFN-20 | 74.56 | | | | |

resulted in a higher *AP* value. Moreover, during the model's training stage, the learning process laid more emphasis on the critical feature of these ICs that resulted in higher *AP* value (Melinte et al., 2020).

Fig. 6 (a) shows sample images of the PCB-DSLR dataset that were used to measure the testing performance of the object detection model. The dataset's images of waste PCBs have diverse orientations and aspects, e.g., oblique, portrait, and landscape. These datasets also consist of images of different shapes. The trained object detection model can detect multiple ICs from the images of the test dataset. Fig. 6 (b) shows the sample images of the locally developed Domestic WPCB datasets that were utilized for the detection process, with multiple ICs present in an image.

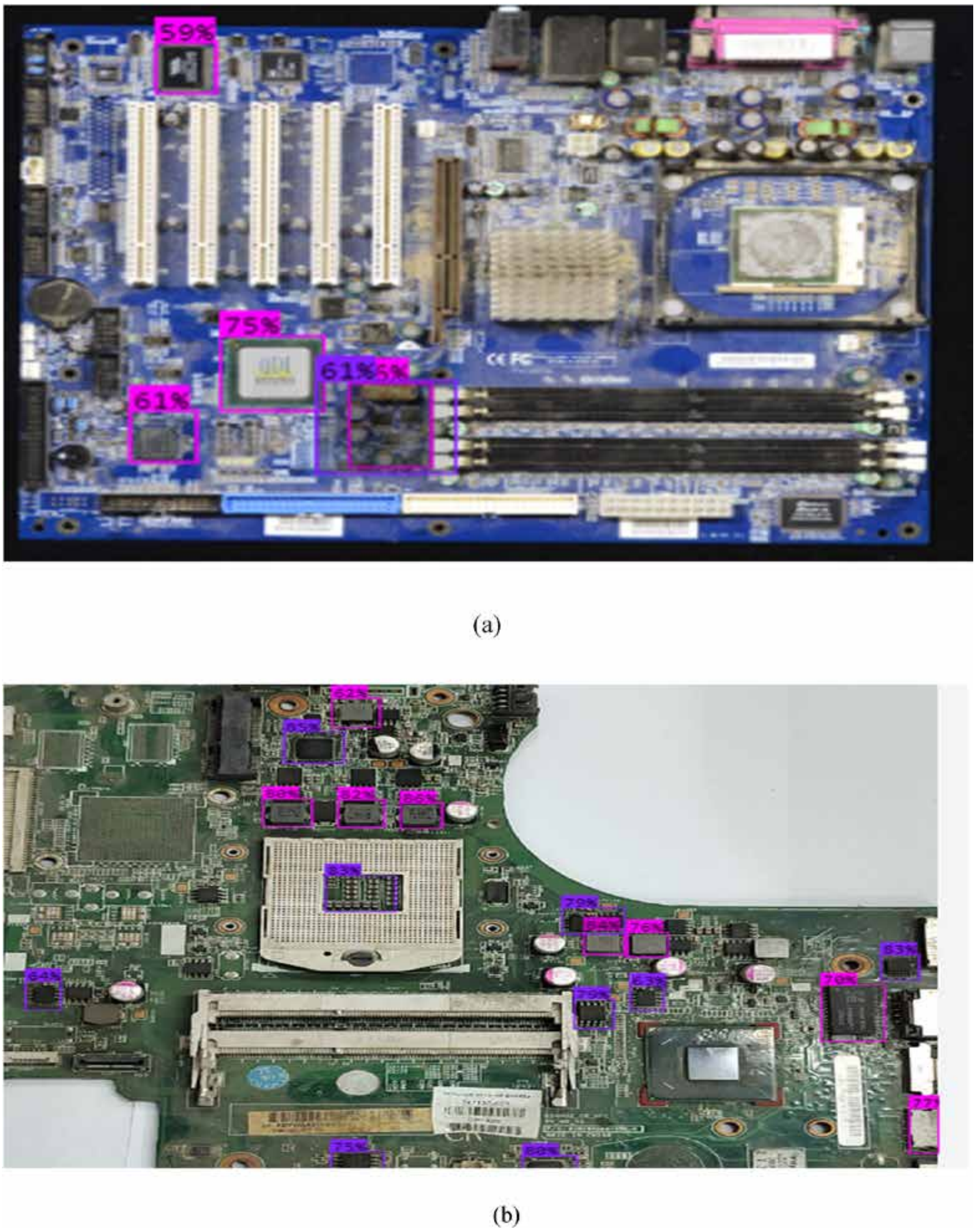


**Fig. 6.** YOLOv3 detection results on testing images of (a) DSLR-PCB dataset, and (b) Domestic-PCB dataset with a confidence score of various ICs.

### 4.2. Performance of YOLOv3 model based on domestic WPCB

A PCB piece comprises about 30 percent of metallic components, of which, many are high-value materials (e.g., gold, silver, and copper). Importantly, although these high-value materials describe less than 1 of the PCB weight, they illustrate 80 to 88 percent recycling value (Awasthi et al., 2017). Li et al. (2004) evaluated that 1 ton of WPCBs has about 284 gms of gold. Fig. 5 (b) elaborates upon the object detection model's reliability in terms of training the Domestic WPCb dataset. It effectively showcases that the model's loss function value flattened after 250 iterations, alluding to the fact that the model would begin convergence. The object detection model achieved about 58.6% of *mAP* at a 0.5 threshold value, and the average loss function value was approximately 0.082 after 800 iterations. The overall time taken by the model for the training process was about 11 h. Table 2 shows the impact of various *IoU* threshold values on the object detection model's *mAP* values. The results broadly indicate that the model had achieved a mAP value of 58.60% at the threshold value of 0.5, a mAP value of 53.05% at the threshold value of 0.6, and a mAP value of 51.45% at the threshold value of 0.7. As opposed to the training process on the WPCBs dataset, the mAP values of the model had minimally lessened when the model used a stricter threshold value. Interestingly, the performance of this model seems relatively weaker than the trained model utilizing the WPCBs dataset. This is because WPCBs seem to have a bigger image repository that features a greater number of essential attributes. Importantly, all the models' recall value was beyond 79% on the domestic WPCBs dataset; this value decreased approximately by 5% when the threshold value of *IoU* changed from 0.5 to 0.7. This result is seen to be reliable with the more significant IoU threshold value, resulting in over-fitting and lower accuracy (Mao et al., 2022). On the other hand, the model's object detection speed was nearly 40 FPS, which is fast enough for identifying objects in real-time (20 FPS is the minimum value required for object detection in real-time).

The maximum *mAP* value of the model was around 58.60% at 0.5 threshold value. The model's *AP* value on both classes is showcased in Table 3; the maximum AP value by the model was attained for IC_1. This was possible because IC_1 had more prominent features. IC_2 on the other hand, has lesser numbers than IC_1; however, there was greater variance in features within the training images, resulting in lower AP thereof. Fig. 6 (a) shows sample images from domestic WPCBs dataset which was utilized for the testing process to identify ICs. The trained object detection model successfully detected multiple ICs from the images. However, the model had a low *mAP* value for IC_2 and a good recall value. The main reason is that the false positive object may be classified more or blurriness within the images that effectively resulted in a lower *mAP* value. Specifically, the trained object detection model had limitations when detecting multiple objects from a single image due to multiple bounding boxes that were generated for the single object. Therefore, to enhance the accuracy of the proper classification for IC_2 and minimize the effect of blurriness, there is a need to utilize other sensors with computer vision algorithms, such as near-infrared (NIR) and thermal imaging, to improve the visibility quality of the distinct objects. On the other hand, the issue of multiple bounding boxes can be solved by raising the *IoU* value. Regardless, increasing this value might decrease the obtained *mAP* value as well as impact the identification of other ICs.

Fig. 6 (b) represents the testing results of ICs detection from the domestic WPCBs dataset using the Domestic dataset-trained object detection model. It consists of two distinct ICs manually labeled based on the ICs' condition and quality: IC_1 is those circuits that were in working condition and were reusable; IC_2 is those that were not useable. Both ICs were effectively localized and classified. In comparison to the outcome presented in Fig. 5(b), this outcome demonstrates that the object detection model trained using domestic WPCBs would perform better in place of the model trained using the PCB-DSLR dataset in terms of interoperability or recycling working conditions. The outcome of the model can be attributed to two aspects: First, the object detection model that has been proposed is apt for implementation within realistic environments or recycling conditions. Secondly, an object detection model that is trained to utilize an image dataset comprising images of both working conditions, wherein laboratory and recycling environment, would enable better performance than a model that is trained using a single dataset of laboratory conditions for the use case that has been considered in the study. This implies that finalizing a solution to a realistic environment or recycling condition would be desired if the recycling plant were to utilize the most efficient object detection solution for conveyor-carried e-waste streams.

Furthermore, the object detection model based on domestic WPCB training performs well; they have certain limitations during the identification process of ICs from WPCBs. On the other hand, for using this model in a real-world environment or recycling conditions, it is necessary to further classify the ICs into distinct classes rather than two classes to ensure they function effectively. For instance, standard classes of ICs or recycling-based ICs for further processing. Further work is also required to examine the impact of integrating additional sensors with CVT that would help us to improve the detection rates of ICs. Moreover, future studies should also explore developing an automatic robotic system that could improve the sorting process of ICs.

## 5. Conclusions

ICs detection and segregation from WPCBs help in extracting valuable materials and fulfilling the requirement of useful natural resources. Using an automatic ICs disassembler integrated with a vision-based ICs detection would minimize the involvement of manual labor associated with the recycling process and the amount of e-waste that goes into being dumped. Therefore, some open-source WPCB datasets were proposed for ICs or PCB classification and detection, and the most widely used PCB-DSLR dataset contains images of singular WPCBs under laboratory conditions. However, the major drawback of this dataset is the absence of recycling conditions or real-world working conditions. Subsequently, the outcome of this database showed that there is a necessity to build your own waste database that is capable of providing a practical environment, especially if one chooses to utilize a computer vision-based detection methodology.

Thus, this study develops a new dataset: Domestic WPCBs that contain images of WPCBs collected from recycling centers, repair shops or dumping yard stations and captured under recycling conditions such as without any restriction on background, camera, orientation, lighting, and perspective to provide simulated practical conditions. Then, we trained and evaluated the comparative performance of PCB-DSLR and Domestic WPCBs dataset-trained object detection model, and found that the object detection model trained, using Domestic WPCBs performed relatively weaker in terms of precision, but sufficiently better to perform in the recycling conditions. Furthermore, the study's outcome showed that the object detection model trained using both datasets was sufficiently fast enough for real-time ICs detection. In contrast, the Domestic WPCBs-based trained object detection model could detect ICs from new images or datasets, whereas the PCB-DSLR-trained object detection model could not. These outcomes illustrate that for efficiently identifying ICs from WPCBs within the actual environment or recycling conditions, a trained object detection model with a dataset containing recycling conditions is needed.

The proposed Domestic WPCBs-based object detection model can be adapted and deployed in recycling facilities to identify ICs in real time to efficiently recycle and reduce the amount of valuable material that undergoes incarceration or is landfilled. On the brighter side, the conversion of this object detection model (YOLOv3) into TensorFlow lite or ONNX format provides the capability to implement it on mobile devices, which reduces the requirement of relying on heavily automated machines for dissembling.

Moreover, significant issues for classifying ICs are the distinct design and manufacturing complexities of PCBs, which effectively make it challenging to train object detection models and use them for detecting ICs from new WPCB images. Nevertheless, when this drawback was blended with the fact that various electronic products produce diverse WPCBs, along with multiple ICs of distinct shapes and sizes, making it difficult to detect thereby, our proposed approach seem to yield remarkable improvement in the detection process. Regardless, Domestic-WPCBs dataset-trained object detection model could further be improved. Therefore, studies in the future may examine the effects of blending additional sensors (e.g., thermal imaging, Radio frequency identification (RFID), etc.) for providing additional benefits to the object detection model such as the capability of detecting components during the days and even in the dark without being affected by illumination conditions and identifying the components even the minute changes in the structures. This possibly may improve the detection accuracy of ICs, along with a Domestic WPCBs-trained object detection model coupled with an automatic disassembler system with an aim to further enhance the recycling process. The study has used only two categories of ICs for the training of object detection models that might be affecting the performance of the model. Therefore, future research studies may focus in the context of multiple-level classification of ICs for the training of the model.

## Authors contribution

Himanshu Sharma: conceptualization, software, validation, investigation, resources, data curation, writing—original draft, writing—review and editing, visualization, supervision, and project administration. Harish Kumar: conceptualization, writing—original draft, and writing—review and editing, supervision, and project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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# Modeling third-party reverse logistics for healthcare waste recycling in the post-pandemic era

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**ABSTRACT**

The COVID-19 pandemic has increased the demand for life-saving devices known as 'ventilators,' which help critically ill patients breathe. Owing to the high global demand for ventilators and other medical equipment, many Indian nonmedical equipment companies have risen to meet this demand. This unexpected demand for ventilators during the COVID-19 pandemic, similar to that for other EOL electronic medical devices, has become a severe problem for the nation. Consequently, the healthcare industry must efficiently handle EOL ventilators, which can be outsourced to 3PRLPs. 3PRLPs play a vital role in a company's reverse logistics activities. This study emphasises the 3PRLP selection process as a complex decision-making problem and the optimisation of order allocation to qualified 3PRLPs. As a result, this study proposes a two-phase hybrid decision-making problem. First phase combines the two multi-attribute decision-making methods to select 3PRLPs based on their assessed SPS and Second phase, the evaluated SPS was utilised as one of the objectives of a multi-objective linear programming model to allocate orders to the selected 3PRLPs. To solve the proposed model, both classical and modern approaches were used. The results show that the proposed framework can be successfully implemented in the current scenario of the healthcare industry.

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## 1. Introduction

The healthcare industry is one of the largest industries in the world. It includes hospitals, medical devices, clinical trials, outsourcing, medical tourism, and health insurance, all of which provide goods and services to patients. India's healthcare sector is expanding rapidly due to improved coverage, expanded services, and increased spending by both public and private sectors. Following the global identification of the COVID-19 pandemic, the healthcare industry has grown rapidly by increasing health facilities, government funding, possible reimbursement reform, and building resiliency in supply chains (Burgos and Ivanov 2021; Byrne, Barber, and Lim 2021). According to statistics (World Health Organization 2021), COVID-19 cases in India rapidly increased, of which 80% of the cases were minor, and more than 5% required intensive care units (ICU) with mechanical ventilation (Möhlenkamp and Thiele 2020). Since then, a total of 44.6 million cases have been reported as infected and 529 thousand deaths.

Mechanical ventilation provides breathable air movement to patients whose lungs have been damaged, who are unable to breathe adequately (Iyengar et al. 2020). As a result, every country needed to increase its ventilator capacity during the pandemic by manufacturing a large number of units. All medical-device manufacturers meet this demand by producing a large number of ventilators. However, most medical device manufacturing companies lack financial muscles to significantly increase ventilator production within a short period (Sharma, Verma, and Aggarwal 2020). During the COVID-19 pandemic, many Indian non-medical equipment companies, such as automobile companies, collaborated with them to produce life-saving breathing devices (Dearborn 2020; Pandey 2020; Sharma, Verma, and Aggarwal 2020).

As the number of COVID-19 cases increased, the production of Electrical and Electronic Equipment (EEE) in the waste stream resulted in the unsustainable management of e-waste, also known as electrical and electronic waste. Waste Electrical and Electronic Equipment

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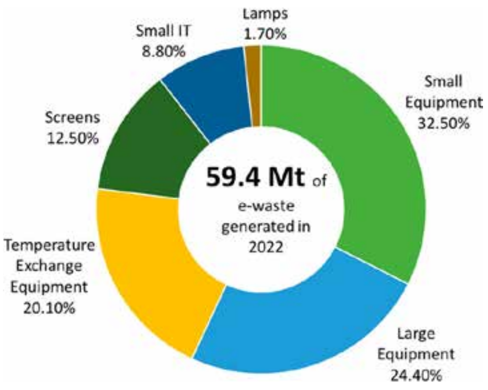


**Figure 1.** E-waste generation per EEE category.

**Table 1.** Distribution of E-waste categories.

| Category | E-Waste Quantity (Mt) | Percentage of Total E-Waste |
|---|---|---|
| Small Equipment | 19.4 Mt | 32.5% |
| Small IT | 5.2 Mt | 8.8% |
| Large Equipment | 14.5 Mt | 24.4% |
| Screens | 7.4 Mt | 12.5% |
| Temperature Exchange Equipment | 11.9 Mt | 20.1% |
| Lamps | 1.0 Mt | 1.7% |

(WEEE) directives classify EEE into small equipment, large equipment, temperature exchange equipment, screens, lamps, and small IT (Forti et al. 2020; Shittu, Williams, and Shaw 2021). Each product within the six e-waste categories is defined in Table A1 in Appendix A because each has a different lifetime profile. This means that each category has different waste quantities, economic values, and potential environmental and health impacts if incorrectly recycled. As a result, the collection and logistical processes, as well as recycling technology, differ for each category of EEE (Shittu, Williams, and Shaw 2021; Li et al. 2023)

The global quantity of electronic waste (e-waste) generated in 2022 across six categories is depicted in Figure 1, with a cumulative total of 59.4 million metric tons (Mt).[1] Based on the information collected from the report of *TheRoundup.org* on global e-waste statistics percentage[2], it is evident that a significant proportion, precisely 75% of which is mainly covered by only three categories of EEE: small equipment, which includes household appliances, other small medical devices, and toys which is the largest of the three EEE categories accounting for 19.4 Mt (32.5%). The remaining e-waste categories collectively constitute a smaller portion of the global e-waste composition, and are detailed in Table 1.

Medical electronic waste, also known as e-medical waste, accounts for 8% of the total e-waste generated; however, this is expected to increase to more than 20% in the near future (*Management of medical, electronic waste involves no easy solutions and Business Standard Editorials 2019*; Perkins et al. 2018). Over the last decade, global e-waste production has increased by 2 Mt/y. The statistics related to e-waste from 2014 to 2030 could increase from 44.4 Mt to 74.7 Mt, in which only 17.4% of e-waste is known to be collected and appropriately recycled (Forti et al. 2020).

As developing countries have limited regulatory oversight of e-waste processing, the informal processing of end-of-life (EOL) medical electronics products may cause serious health and pollution issues (Shittu, Williams, and Shaw 2021). As a result, many developed countries ship discarded electronic equipment to less developed countries, where they are dismantled and burned, emitting toxin fumes and other hazardous materials such as lead, cadmium, chromium, brominated flame retardants, and Polychlorinated Biphenyls (PCBs), thereby harming the environment and human health (Dutta et al. 2022; Shittu, Williams, and Shaw 2021).

During the COVID-19 pandemic, there has been a worldwide surge in ventilator demands. The total number of ventilators in India, including those from government and private hospitals, is 57,000.[3] There was a need for approximately 1.1–2.2 lakh ventilators until the end of May 2020, when COVID-19 was expected to peak. The global market demand for ventilators increased rapidly to 5000–7000 ventilators per week when COVID-19 was at its peak, in April 2020.[4] This clearly indicates that the market size for ventilators will continue to grow at a 7.5% annual rate in the coming years.[5]

These ventilators are similar to EOL electronic medical devices that may have a limited operational life. As a result, when they reach the end of their useful life, they may generate a large amount of medical e-waste, which may have a negative impact on the environment and human health (Shittu, Williams, and Shaw 2021). If disposed improperly after use during a pandemic, it may pose significant environmental challenges, making it crucial to address EOL management practices. *As* reported in May 2021, approximately 7,000 centre-allocated ventilators were sitting idle, and approximately 1,900 were not received in good condition and stopped working after two hours. Previously, similar incidents were also reported.[6] These incidents demonstrate the need for effective management of EOL ventilators (Jauhar et al. 2023; Murugesan, Jauhar, and Sequeira 2022; Sengazani Murugesan et al. 2020).

Immediate production of ventilators may eventually lead to landfilling in the future, harming human health and the environment. In other words, if these medical devices are not correctly disposed of, this will be another emerging e-waste problem in all advanced countries (Iyengar et al. 2020; Shittu, Williams, and Shaw 2021; Trivedi, Pandey, and Trivedi 2022). This demonstrates the critical importance of EOL ventilators during a pandemic. Medical device manufacturers may benefit financially from the disposability of medical equipment and materials. To address this issue, as part of their sustainability development, all healthcare companies must incorporate Reverse Logistics (RL) activities and strategies into their supply chain systems that prioritise the proper disposal and management of these medical devices. This can include the responsible disposal, recycling, reuse, and refurbishment of EOL ventilators (Trivedi, Pandey, and Trivedi 2022). This can help to reduce the amount of e-waste generated and prevent hazardous materials from entering the environment (Pratap et al. 2022; Prajapati et al. 2022a).

### 1.1. Motivation of the study

In addition to e-waste management, healthcare facilities can be outsourced to some e-waste management companies, referred to as Third-Party Logistics (3PLs), a type of outsourcing service provided by companies specialising in logistics and supply chain management. 3PL companies offer a range of services, such as transportation, warehousing, inventory management, order fulfillment, and other logistics-related services to businesses that require these services but do not have the resources, expertise, or infrastructure to manage them in-house.

In the context of reverse logistics, 3PL companies can provide services for the collection, transportation, disposal, or recycling of end-of-life products. This can include services such as product takeback, sorting, disassembly, and material recovery. By outsourcing these services to 3PL companies, businesses can improve their reverse logistics processes, reduce costs, and ensure compliance with the environmental regulations.

Third-Party Reverse Logistics Providers (3PRLPs), or third-party reverse logistics providers, are specialised 3PL companies that specifically focus on reverse logistics processes. They offer services such as product-return management, recycling and disposal, and product refurbishment or remanufacturing. By outsourcing these processes to 3PRLPs, businesses can improve their sustainability practices, reduce waste, and promote circular economic principles.

These 3PRLPs can assist in the collection, transportation, and disposal of e-waste generated from medical devices such as ventilators. By partnering with 3PRLPs, healthcare organisations can ensure that the e-waste generated from ventilators is disposed of in an environmentally sustainable manner while adhering to relevant laws and regulations. Moreover, partnering with 3PRLPs can also help healthcare organisations identify opportunities to recycle or refurbish ventilator components, thereby reducing the amount of e-waste generated. Furthermore, these recycled or refurbished components can be sent to manufacturing companies as raw materials for the production of new ventilators.

3PRLPs can offer logistics and transportation services to organisations for the movement and management of goods and materials. This includes warehousing, inventory management, transportation, and distribution, which could reduce costs, improve efficiency, increase flexibility, and provide access to specialised expertise (Zhang, Li, and Li 2023). 3PLs have the necessary expertise, technology, and infrastructure to manage complex logistics operations, which can help healthcare organisations improve their supply chain performance and responsiveness. However, it is worth noting that 3PLs may not be able to offer the same level of expertise and efficiency in managing the reverse logistics of medical equipment and materials as 3PRLPs. While they may be able to transport medical waste and equipment, they may not possess the specialised knowledge and experience required to dispose of these materials in an environmentally sustainable manner or identify opportunities for recycling and refurbishing.

In such cases, partnering with 3PRLPs may be more appropriate for healthcare organisations seeking to reduce waste and optimise their supply chain. 3PRLPs have specific experience and knowledge in managing the disposal, recycling, and reuse of medical equipment and materials, which can be crucial for healthcare organisations seeking to reduce waste and optimise their supply chain. Additionally, 3PRLPs can offer value-added services, such as refurbishment and repair of medical equipment, which may not be within the scope of services offered by 3PLs. Thus, collaboration between the 3PRLPs and manufacturing companies can help reduce the environmental impact of medical equipment waste and create a more sustainable supply chain system in the healthcare industry. This study makes the following main contributions to fulfil the shortcomings of earlier studies:

- Identifying the potential causes of the surge in ventilator production during the COVID-19 pandemic and emphasising the importance of EOL ventilator management can be outsourced to 3PRLPs.
- We propose a three-phase hybrid decision-making framework for selecting 3PRLPs in the healthcare industry to promote sustainability and waste reduction, considering all economic, social, environmental, quality, and risk criteria.
- Developing a multi-objective, multi-product, multi-period, and multi-scenario mathematical model to

address order allocation for manufacturing ventilators from recycled raw materials that maximises sustainability and quality while minimising delivery time, defect rate, delivery, and product loss value.
- Classical and modern approaches were used to successfully solve the proposed mathematical model in the current healthcare industry scenario.
- Implementing the proposed framework in India, focusing mainly on the production of breathing devices and ventilators during the COVID-19 pandemic, and analyzing the results.

### 1.2. Objectives of the study

The primary goal of this study was to close the gap in the healthcare industry by identifying 3PRLPs and allocating orders for recycled or refurbished raw materials to 3PRLPs. As a result of RL activities, the pollution caused by rudimentary recycling and unsafe disposal of EOL ventilators in the environment can be reduced. RL practices indirectly promote the role of 3PRLPs, which focus on their business strategies to achieve sustainability at lower costs and higher quality performance (Islam and Huda 2018; Sarkis, Helms, and Hervani 2010). In this sense, the criteria for evaluating 3PRLPs are contradictory, making the selection process more challenging (Aguezzoul 2014; Büyüközkan and Ifi 2012; Efendigil, Önüt, and Kongar 2008; Jayant et al. 2014; Kannan et al. 2009; Prakash and Barua 2016a).

Such 3PRLPs' evaluation and selection in the healthcare industry can be regarded as a Multi-Attribute Decision-Making (MADM) problem because it can easily convert qualitative environmental and social factors into quantitative parameters (Stephen et al. 2016; Stević et al. 2020; Venkatesh et al. 2015). Other factors with uncertainty, such as quality, quantity, and timing of return, are thought to be important for RL and should thus be considered. The performance of the 3PRLPs for EOL ventilators was evaluated. The results were combined with the Multi-Objective Optimization (MOO) problem with uncertainty to establish an order allocation model to obtain an optimal solution while considering several different goals. Consequently, the following research questions were addressed in this study.

- How can RL activities be incorporated into the health care industry?
- How can we propose group decision making for selecting 3PRLPs with green, economic, social, and environmental factors in the healthcare industry?
- How should an (MOO) model be formulated to allocate orders to EOL ventilators?
- Can both traditional and modern methods be used with the MOO model?

This paper is divided into six sections. Section 2 presents a systematic review of previous research activities in the healthcare industry and 3PRLPs selection with order allocation. Section 3 discusses the case study considered in this study, which was inspired by real-world applications during the pandemic era. Section 4 presents the proposed framework used to solve real-world problems. The first phase presents research on this problem, followed by the integration of GBWM and TOPSIS to evaluate the sustainable performance score of each 3PRLP. The final phase defines the multiobjective programming problem formulated to obtain a set of Pareto-optimal solutions using classical and modern techniques. Section 5 examines the outcomes of various classical and modern approaches. Section 6 presents the managerial implications of the study. Section 7 concludes the paper with key findings and offers suggestions for future research as well as the limitations of the study.

## 2. Literature review

The current study is better understood by examining previous research in the area of sustainable 3PRLPs and order allocation in the healthcare industry. To provide context and background, this section presents a comprehensive review of the related literature on supplier selection, sustainable supplier selection, sustainable supply chain management, post-pandemic logistics scenarios, and applications of decision-making approaches in the healthcare sector.

In the post-pandemic era, limited attention has been paid to healthcare supply chain management. As a result, there is a strong need to investigate the challenges embedded in Healthcare Supply Chain Management (HSCM), particularly in the aftermath of the COVID-19 crisis, to provide potential solutions to material managers to reduce inefficiencies and achieve supply chain success. Therefore, the literature review in this study discusses supplier selection and order allocation in healthcare, and the role of RL and its practices in healthcare.

### 2.1. Supplier selection in healthcare industry

An efficient supplier selection process is critical to the success of any business organisation (Nayak et al. 2023). The choice of a supplier is typically an MCDM problem. Depending on the nature of the problem or the problem's solution space, MCDM is classified as Multi-Attribute Decision-Making (MADM) or multi-objective decision-making (MODM). Because of their ability to evaluate different alternatives based on certain conflicting criteria, the authors have mostly used different MCDM methods to address this problem. MADM or MCDM methods, such as the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Best Worst Method (BWM), Technique for Order Of Preference By Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Complex Proportional Assessment (COPRAS), Visekriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Data Envelopment Analysis (DEA), and others, divide complex problems into smaller parts, which are then analyzed and combined to provide a solution to the overall complex problem (Singh and Pant 2021). In other words, they assist the Decision Maker (DM) by considering many different criteria and reaching a compromise solution based on these conflicting parameters.

Supplier selection is a critical aspect of supply chain management in various industries, including the health care sector. In the healthcare industry, the timely delivery of high-quality materials and services is essential to meet the needs of patients. Therefore, selecting the right suppliers is crucial to ensure the availability of necessary medical supplies and equipment. The process of selecting suppliers in the healthcare industry is similar to that of other industries (Bali et al. 2022), and it is still a critical issue when using the same criteria as other industries.

The selection of suppliers or 3PRLPs is a common issue in supply chains. Timely delivery of sufficient quantities of high-quality materials is always a concern, as this will meet customers' needs. The authors mostly used multi-criteria decision-making (MCDM) models to evaluate suppliers or 3PRLPs. Many authors have attempted to evaluate and select healthcare suppliers by using various MCDM techniques. Table 2 shows previous studies undertaken to select suppliers in HSCM.

This study attempts to shed light on 3PRLPs selection in the healthcare industry sector following the COVID-19 outbreak using the BWM-TOPSIS approach. BWM was used as a weighting method to determine the weights of the criteria, while TOPSIS was used to rank the alternatives based on the same criteria. The BWM has received considerable attention in recent years because of its ability to produce more consistent comparisons and unique optimal solutions with very limited information. It has been used in various fields, including the automotive industry, agriculture, transportation, water resource management, health and education, and supply chain management (Ahmad et al. 2017; Gupta 2018; Hafezalkotob et al. 2018; Almahdi et al. 2019; Bai, Zhu, and Sarkis 2022; Kazançoglu et al. 2023; Wu, Gao, and Barnes 2023; Zhou et al. 2023).

The TOPSIS method ranks the 3PRLPs after identifying the weights of all sustainable criteria. This method is based on the idea of determining a compromise solution closest to the Positive Ideal Solution (PIS) that maximises beneficial attributes and farthest from the Negative Ideal Solution (NIS) that minimises non-beneficial attributes. TOPSIS, compared to other MADM methods, is comprehensive, transparent, easy to compute, straightforward, and works on 'closeness to the ideal concept (Singh et al. 2020a; Singh, Verma, and Pant 2020b). As a result, the combination of BWM and TOPSIS can enables the inclusion of the performance score of 3PRLPs in a ranking index, making the results more reliable and realistic (Gupta and Barua 2017; Lo et al. 2018; Yucesan et al. 2019).

## 2.2. Supplier selection and order allocation in healthcare industry

In recent years, organisations have considered environmental, social, and economic factors when selecting suppliers to achieve long-term business sustainability and maintain their market position (Singh et al (2023). Thus, in recent decades, Sustainable Supplier Selection (SSS) has received considerable attention, emphasising the importance of reverse supply chain management. The authors began to discuss RL integration of supplier selection and order allocation. For instance, a study stating that supplier selection and order allocation are the two most important stages in supply chain management and proposed a four-phase methodology for a meat supply chain using fuzzy AHP -TOPSIS, $\varepsilon$–constraint, and LP-metrics solution method, and then again applying the TOPSIS method to reveal the best Pareto optimal solution (A. Mohammed et al. 2018). The issue of sustainable supplier selection and order allocation was addressed by developing an inclusive multi-objective mixed-integer linear programming model and solving it using the $\varepsilon$-constraint method and Benders decomposition algorithm (Moheb-Alizadeh and Handfield 2019). Another study that included uncertainty in global supplier selection and order allocation used hybrid fuzzy MCDM methods and incorporated the results into a multi-choice goal programming model for the automotive industry (Ali et al. 2022). Under the current environmental issues and government requirements, the authors presented an integrated decision-making model to solve the partner selection using the Taguchi loss function with BWM and obtained the Pareto solution using Particle Swarm Optimization (PSO) and TOPSIS in a leading Chinese LED lighting manufacturer (Wu, Gao, and Barnes 2022). In extension to (A. Mohammed et al. 2018), the authors considered the G-silent multi-tier Supplier

**Table 2.** Application of MADM techniques for supplier selection in HSCM.

| *Researchers (year)* | *Techniques* | *Criteria* | | | | | *Order Allocation* | *Application* | *Country* |
|---|---|---|---|---|---|---|---|---|---|
| | | *Economic* | *Environment* | *Social* | *Risk* | *Quality* | | | |
| (*Mehralian et al.* 2012) | Fuzzy TOPSIS | √ | √ | √ | √ | √ | × | Medicine supplies in pharmaceutical industry | Iran |
| (*Alinezad, Seif, and Esfandiari* 2013) | Quality Function Deployment (QFD), Fuzzy AHP | √ | × | √ | × | √ | × | Medicine supplies in pharmaceutical industry | - |
| (*Ghadimi and Heavey* 2014) | Fuzzy Inference System (FIS) | √ | √ | √ | × | × | × | Miniature spring component for medical devices | Shannon, Ireland |
| (*Venkatesh et al.* 2015) | TOPSIS | √ | × | × | × | √ | × | Blood bags | India |
| (*Pourghahreman and Rajabzadeh Qhatari* 2015) | TOPSIS, PROMETHEE | √ | × | √ | × | √ | × | Medicine supplies in pharmaceutical supply chain | Iran |
| (*Malik, Abdallah, and Hussain* 2016) | ANP | × | √ | × | × | × | × | Healthcare supplies | UAE |
| (*Che and Chang* 2016) | ANP, DEA and PSO | √ | × | × | × | √ | × | Sphygmomanometer manufacturing | Taiwan |
| (*Bahadori et al.* 2020) | Artificial Neural Network (ANN) and fuzzy VIKOR | √ | × | × | × | √ | × | Medical equipment and consumer goods | - |
| (*Akcan and Güldeş* 2019) | AHP, TOPSIS, ELECTRE, GRA, and SAW | √ | × | √ | × | √ | × | Healthcare supplies | Turkey |
| (*Stević et al.* 2020) | MARCOS | √ | √ | √ | × | × | × | Cataract eye surgery equipment | Bosnia and Herzegovin |
| (*Mahmoudi, Javed, and Mardani* 2022) | Fuzzy Ordinal Priority Approach (FOPA) | × | √ | × | × | √ | × | Three different case studies in the post COVID-19 pandemic era | - |
| (*Pamucar, Torkayesh, and Biswas* 2022) | Measuring attractiveness through a categorical based evaluation technique (MACBETH) and Combinative Distance-based Assessment (CODAS) | √ | √ | √ | × | √ | × | Medical face mask and face shields | Turkey |

Selection and Order Allocation (SS/ OA) problem use the Fuzzy Multi-Objective Mixed Integer Linear Programming Model (FMOMILPM) for the food industry (Ahmed Mohammed et al. 2023).

In these papers, the authors integrated classical and modern optimisation methods with MADM methods to consider supplier selection and order allocation simultaneously in the context of a sustainable supply chain. Table 3 summarises the literature on integrating 3PRLPs selection with order allocation in various industries.

## *2.3. Challenges in decision-making and integration of methods*

Because a series of Pareto solutions is obtained by these multi-objective optimisation algorithms, it is very difficult for Decision Makers (DMs) to select the best one(s). DM preferences are often subjective, based on the features of an object or person, regardless of the current needs and goals of the Decision Maker (DM). Additionally, psychological measurements of people typically describe differences between individuals or states over time, raising concerns about how to arrive at a final decision without the decision maker's preferences and subjective measures (Chiu and Lai 2022). Therefore, this study attempts to integrate modern optimisation methods, such as Non-Dominated Sorting Genetic Algorithm II & Non-Dominated Sorting Genetic Algorithm III (NSGA II and NSGA III), with MADM methods, namely TOPSIS. The integration of NSGA and MADM techniques has been gaining increasing attention in recent years as an effective approach for solving complex decision-making problems (Chiu and Lai 2022; Kabadayi and Dehghanimohammadabadi 2022; Khettabi, Benyoucef, and Amine Boutiche 2022; Lu et al. 2023; Xu et al. 2020; Zare et al. 2023).

**Table 3.** Application of various techniques for the selection of sustainable 3PRLPs and order allocation.

| *Researchers (year)* | *Technique used for 3PRLP selection* | *Reverse activities* | *Multi-objective model* | *Technique used for MOO model* | *Order allocation* | *Application* | *Country* |
|---|---|---|---|---|---|---|---|
| (*Moghaddam 2015*) | AHP | √ | √ | Monte Carlo simulation and Fuzzy goal programming | √ | Global Manufacturing industry | |
| (*Prakash and Barua 2016b*) | FAHP and FTOPSIS | √ | × | - | - | Electronic industry | - |
| (*Prakash and Barua 2016a*) | FAHP and VIKOR | √ | × | - | - | Electronic industry | India |
| (*Jauhar and Pant 2017*) | DEA with DE and MODE | √ | × | - | - | Automotive industry | India |
| (*Zarbakhshnia, Soleimani, and Ghaderi 2018*) | FSWARA and FCOPRAS | √ | × | - | - | Automotive industry | Iran |
| (*Govindan et al. 2019a*) | COPRAS and BWM | √ | × | - | - | Electronic industry | India |
| (*Govindan et al. 2019b*) | ELECTRE I and SMAA | √ | × | - | - | Automotive remanufacturing industry | India |
| (*Zarbakhshnia et al. 2020*) | FAHP and GMOORA | √ | × | - | - | Manufacturing industry | - |
| (*Chen et al. 2021*) | MPMADM | √ | × | - | - | Automotive industry | - |
| (*Mohammadkhani and Mousavi 2022*) | CRITIC and VIKOR | √ | × | - | - | Electronic industry | India |
| (*Jauhar, Amin, and Zolfagharinia 2021*) | DEA, DE, and Multi-objective Programming | √ | √ | $\varepsilon$-constraint and weighted sum aproach | √ | Cellphone industry | Canada |
| Current Study | GBWM and TOPSIS | √ | √ | $\varepsilon$-constraint, NSGA-II and NSGA-III | √ | Healthcare industry | India |

This integrated approach is distinguished by its ability to handle complex problems with multiple objectives and criteria while also considering the preferences of different decision-makers, which NSGA algorithms alone cannot do (Shao, Barnes, and Wu 2022). Compared to other techniques, the integrated approach offers several advantages: (1) providing a more comprehensive evaluation of potential solutions, which can lead to better decision-making; (2) consideration of multiple objectives, which is especially important in complex problems with conflicting objectives; (4) exploration of a wider range of potential solutions, increasing the likelihood of finding the optimal solution; and (4) incorporating the DMs' preferences and priorities into the evaluation process, ensuring that the selected solution aligns with their goals and objectives. Furthermore, compared to most studies that only prefer MADM methods, the proposed approach ensures an optimum result for the quantities of products to be allocated to suppliers, while providing a structured and systematic approach to selecting the best Pareto optimal solution (Bektur 2020).

According to the literature review in Table 3, very few studies have integrated 3PRLPs selection and order allocation in the RL of the healthcare industry. This suggests that integration is a critical aspect of healthcare supply chain management. By adopting appropriate decision-making methods, healthcare companies can select the best suppliers and allocate orders efficiently, thus ensuring the delivery of quality care to patients. In recent years, various issues concerning logistics and supply chains in the post-pandemic scenario have been addressed, which are discussed in the next section.

### 2.4. Role of RL practices in the healthcare industry

RL encompasses the principles of reducing, reusing, remanufacturing, and recycling to manage EOL products, posing a challenge for industries in promoting sustainability (Dabees et al. 2023). In response, businesses are increasingly embracing sustainable supply chain management systems (SSCM) to address their environmental impact. Notably, recent research has highlighted RL activities within the forward and reverse logistics networks in the e-commerce sector. For example, scholars have introduced a mixed-integer nonlinear programming (MINLP) model to optimise cost, revenue, and sustainability across a closed-loop supply chain goods flow (Prajapati et al. 2022b). Another study innovatively tackled the complexities within e-commerce platforms, suppliers, manufacturers, third-party logistics, retailers, and customer tiers (Prajapati et al. 2022a). Employing techniques such as the block-based genetic algorithm, fit-fly algorithm, and CPLEX, they devised a forward and reverse logistics network design (FRLND) that integrates consumer pickup and timely delivery windows (Daultani et al. 2022). Additionally, the authors harnessed discrete event simulations to explore the effects of delivery time flexibility on last-mile distribution vehicle mileage (Pereira Marcilio Nogueira et al. 2022). Similarly, other organisations, such as the healthcare industry, are motivated by environmental, economic, and social concerns to engage in procurement. The healthcare industry is concerned with providing eco-friendly and health-friendly equipment and medicines to patients, because patient care is their primary goal.

To achieve the goal of a healthy-friendly environment in health centres, waste generated in laboratories, operating rooms, facilities, cafeterias, and old medical devices must be properly disposed or recycled. Ignoring the waste generated can result in contamination or infection in other patients. Lee et al. (2002) identified the sources, types, and amounts of medical plastic waste produced by six to eight city hospital departments and three animal hospitals in Massachusetts, as well as methods to increase the recycling potential of medical plastic waste. Gurgur (2013) developed a chance-constrained programming model for supplier selection and quantity allocation for a hospital in need of new and refurbished healthcare products and equipment. The authors used a simulated annealing method to determine the best solutions for a variety of scenarios.

Mishra et al. (2020) proposed a combined MCDM and Fuzzy Set Theory (FST) approach for selecting the safest and healthiest facility in hazardous waste recycling organisations. According to the literature, RL is also important in the healthcare industry, but researchers have not paid much attention to this area, as summarised in Tables 2 and 3. Furthermore, the increased demand for ventilators during the COVID-19 pandemic in 2020 has generated a large amount of e-waste globally. This will be a serious issue in the near future and must be addressed.

In recent years, various issues concerning logistics and supply chains in post-pandemic scenarios have been addressed. Ivanov (2020) demonstrated a simulation model for epidemic outbreak analysis in the global supply chain. Sharma, Verma, and Aggarwal (2020) attempted to create a framework for improving SSC survivability following the COVID-19 pandemic. Choi (2021) discussed the topics of risk analysis in logistics by reviewing prior publications and proposing research agendas to overcome logistics challenges during and after COVID-19. Burgos and Ivanov (2021) investigated the impact of COVID-19 on the food retail supply chain, and proposed several directions and practical implementation guidelines to improve food retail SC resilience. Chowdhury et al. highlighted various disruptions of SCM. (2021). The supply chain disruptions of sustainable supplier selection and order allocation for multinational enterprises during the COVID-19 era are given attention by proposing a novel nRa-NSGA-II algorithm for solving a multi-stage multi-objective optimisation model (Shao, Barnes, and Wu 2022). Following the COVID-19 pandemic, Kenan and Diabat (2022) developed a mathematical model for the blood supply chain, and Lee, Ko, and Moon (2022) developed a two-stage stochastic programming model that presents uncertainties in an e-commerce supply chain network. Some researchers have presented strategic discussions on the post-COVID-19 pandemic supply chain 4.0 (Frederico 2021; Ivanov and Dolgui 2021; Soares, Ferreira, and Murari 2021; Sultana et al. 2022; Alabi and Ngwenyama 2023; Datta, Jauhar, and Paul 2023). Furthermore, researchers have worked on designing emergency logistics networks during natural disasters or accidents. These studies aim to ensure smart transportation and logistics system planning for multi-depot pickup and delivery vehicle routing problems under time-window constraints (Wang et al. 2020; 2022; 2023; Wang et al. 2021a; Wang et al. 2021b).

### 2.5. Research gaps and contributions

In response to the COVID-19 pandemic, there has been a worldwide surge in ventilator demand; however, less attention has been paid to the production of these ventilators. This could result in the use of a large number of unused or obsolete ventilators in the near future, leading to e-waste. This study fills this gap by proposing a decision-making approach for 3PRLPs selection in the healthcare industry, followed by optimal allocation of orders to 3PRLPs for recycled or refurbished raw materials. Similarly, other business organisations consider sustainability factors in this growing business. Considering the extensive literature review and objective questions, the following knowledge gaps can be identified.

- Most studies have examined logistics and supply chain disruption due to COVID-19, but the huge accumulation of instant medical devices (ventilators) and their waste management in the supply chain are not taken into consideration.
- The majority of prior research has assessed 3PRLPs based on economic, environmental, social, and quality factors. However, the use of risk factors in the healthcare sector has not received significant consideration.
- The inclusion of multiple objectives during order allocation in an MOO model involving a mixture of maximising the sustainability scores of suppliers while

minimising the defect rate and product loss value is very limited.

- Most prior research has not accounted for the use of classical and modern optimisation approaches in the MOO model for the healthcare industry.
- The integration of optimisation methods and MCDM is less prevalent for selecting the most suitable solutions for a set of Pareto optimal solutions. This is usually left to the decision maker.

This study aims to bridge the above research gaps by proposing a framework that can assist in selecting 3PRLPs and optimising order allocation, leading to a reduction in e-waste and promoting environmental responsibility in the healthcare industry.

### 2.6. Limitations of the existing research

Every research endeavour has limitations arising from aspects such as research design, methodology, and data sources. It is crucial to acknowledge these limitations to foster further improvements in the research framework. Although this study has numerous advantages, it is not immune to limitations. The limitations of this study are as follows.

- Obtaining a real life-based dataset for this research problem poses a challenge. Consequently, the authors relied on data from published papers to implement the proposed framework.
- The study did not address the presence of missing values in the dataset when incorporating DM opinions on criteria pairwise comparisons.
- The model is formulated such that only one post-pandemic product is considered; no other e-waste product is considered before or after the pandemic.

These limitations underscore areas in which future research could potentially refine and enhance the proposed framework, ensuring its applicability and robustness in addressing the complexities of the subject matter.

## 3. Problem statement

This section illustrates the use of a hybrid GBWM-TOPSIS method inspired by a real-world case study of the healthcare industry during the COVID-19 pandemic, as depicted in Figure 2. As the COVID-19 pandemic is uncontrollable, a wide range of medical devices, including diagnostic tests, Personal Protective Equipment (PPE), sterilisers, air purifiers, disinfectant devices, and noninvasive remote monitoring devices, are in high demand for the diagnosis, prevention, and treatment of COVID-19. However, among all these medical devices in the healthcare industry, the demand for ventilators is expected to grow exponentially in the global market because they are the most needed devices. Its primary function is to provide artificial respiration by mechanically moving breathable air into and out of the lungs to keep critically ill patients breathing.

Many Indian nonmedical equipment companies are rushing to convert their manufacturing into the production of various types of low-cost ventilators as an alternative to automating the manual to increase their ventilator capacity in a large number of units. However, because these low-cost ventilators have a short lifespan, this demand may result in the generation of e-waste in the future.

It is possible to reduce medical e-waste generation using recycled raw materials to manufacture ventilators. With advancements in the healthcare industry, plastics have proven to be one of the few versatile materials that have made health care simpler and less painful, such as disposable syringes, intravenous blood bags, and small and large medical equipment (Li et al. 2023). PVC is the most common plastic material used in the manufacturing of medical devices, followed by PE, PP, PS, and PET. PVC is a high-quality, temperature- and corrosion-resistant compound that can be recycled for a wide range of new soft PVC applications.

As a result, in addition to other materials and parts, EOL e-medical devices contain a significant amount of plastic. Under strict government environmental rules and regulations, this plastic is collected and sent to the 3PRLP centre for reverse logistics activities. Recycling using plastic from EOL ventilators was also considered in this study for the production of new e-medical devices. This has the potential for significant success in terms of sustainability. This recycled plastic is obtained from the best-chosen 3PRLPs, and orders are expected to be placed in the healthcare industry to produce new e-medical devices. As these are medical supplies, the materials and equipment used in this study must meet stringent healthcare criteria. Thus, supplier selection is critical.

## 4. Proposed research framework

The primary goal of this study was to highlight the process of 3PRLPs selection in the healthcare industry because it is the most neglected topic in the healthcare industry literature review. Figure 3 presents an empirical example of how model integration can be used to solve the problem of sustainable 3PRLPs selection and order allocation in three phases.

The first phase involves the formation of an expert group that defines the set of criteria, their sub-criteria, and alternatives (3PRLPs) for evaluation based on these

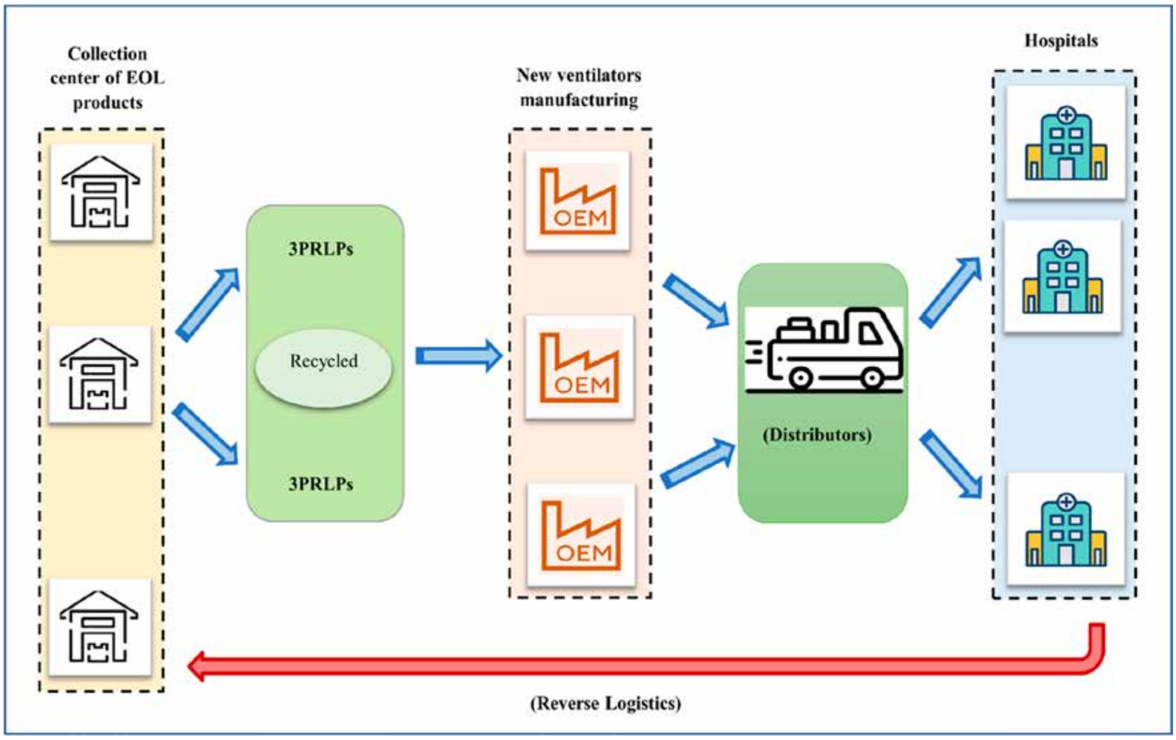


**Figure 2.** RL operation of EOL ventilators, mainly focusing on plastics.

criteria. Following the definition of the problem, the sustainable performance scores of each of the 3PRLPs were evaluated using a group-based decision-making method. In the second phase, the weights at each level of the hierarchy were calculated using only the GBWM method, and then the weights were used in TOPSIS to evaluate the performance of the 3PRLPs. Finally, an MOO model is developed to determine the best order allocation for each qualified supplier using the $\varepsilon$-constraint as the classical approach, and NSGA-II and NSGA-III as the modern approach. A set of Pareto solutions was obtained for the MOO model using different approaches. One of the Pareto solutions from the Pareto front is often selected by the decision-maker based on the importance of the objectives. In this study, the solution was determined using the TOPSIS method. TOPSIS is particularly suitable for this task because the scale of the comparisons is quantitative, and the method allows for direct application to the data, resulting in a compromise solution and enabling the weighting of the criteria. A detailed description of the steps involved in MADM and optimization methods can be found in Appendix B.

### 4.1. Phase I: Identifying criteria and hierarchical structure

The model proposed in this study was demonstrated in a real-world decision problem during the COVID-19 pandemic. To conduct a comprehensive assessment, three DMs from various backgrounds were asked to formulate a decision-making problem.

#### 4.1.1. Identifying the criteria/ sub-criteria and alternatives (3PRLPs)

The three decision-makers are expected to identify, select, and evaluate alternatives. First, the 3PRLPs responsible for delivering raw materials (recycled plastic) for manufacturing e-medical devices were identified. As the original equipment manufacturer (OEM) is located in northern India, only 15 3PRLPs from this region were chosen. Second, criteria for evaluating sustainable 3PRLPs were developed through a review of the relevant literature and a series of expert discussions. The process of selecting sustainable 3PRLPs in the healthcare industry is similar to that in other sectors.

As a result, the criteria used in other sectors can also be used in the healthcare sector. However, it is necessary to place greater emphasis on environmental and social criteria in this study because the generated e-waste will have a negative impact on the environment and workers' health (Jauhar et al. 2022). To evaluate the 15 3PRLPs, a total of 27 sub-criteria were grouped into four main sustainability criteria. Table 4 includes the definitions of each criterion and sub-criterion as well as references to which these criteria have been used previously.

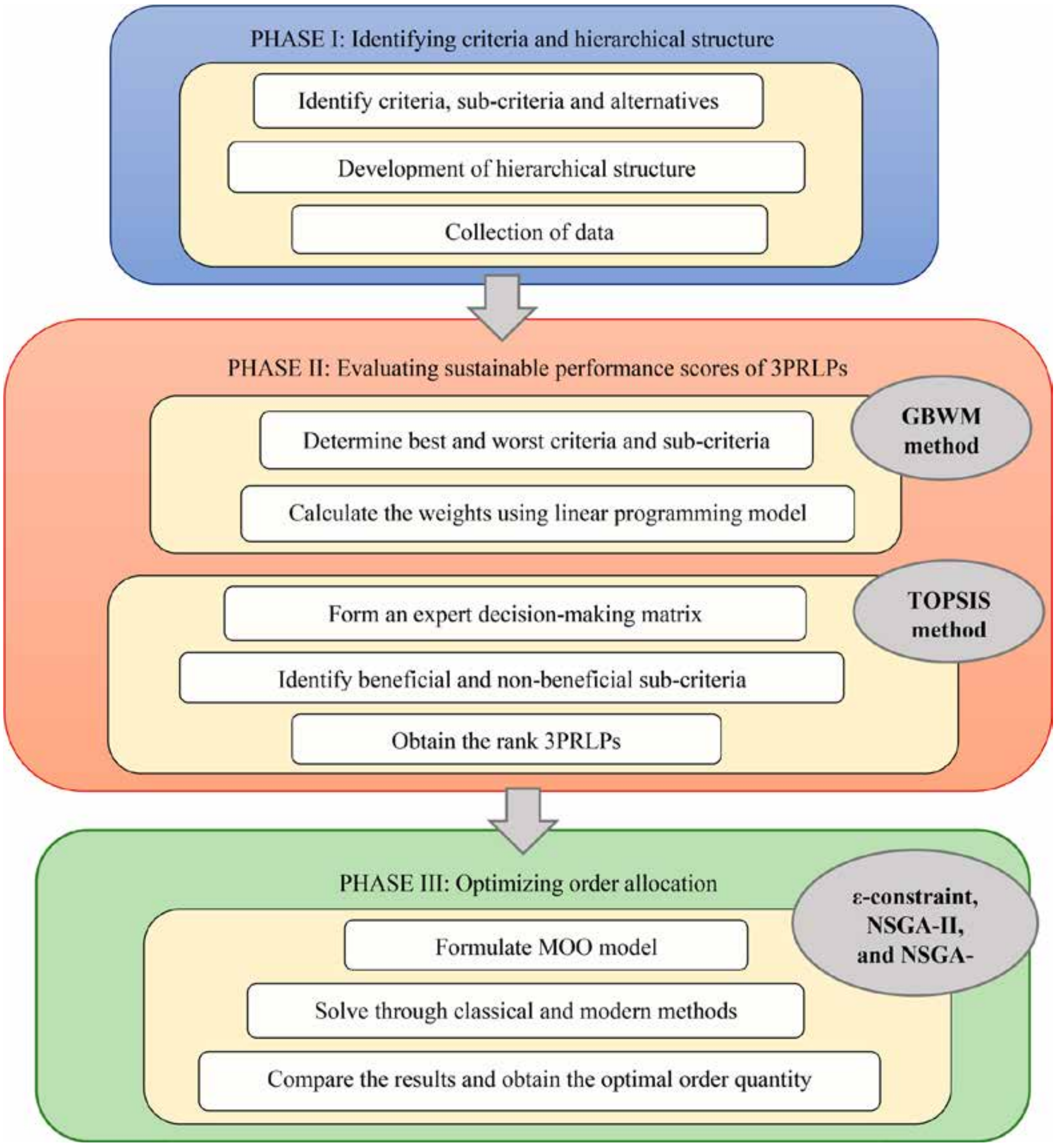


**Figure 3.** Proposed research framework.

### 4.1.2. Collection of data

To obtain a comprehensive view, a panel of three DMs with diverse backgrounds was engaged in formulating the decision-making problem. A Google form was designed and information was collected from these DMs. The form featured a pairwise comparison questionnaire encompassing all the criteria and sub-criteria. This allowed us to assess the importance of various combinations through pairwise comparisons on a 5-point rating scale.

The team of three DMs included a college professor; a researcher familiar with supply chain management, reverse logistics, and MCDM techniques; and a professional from industry with more than 20 years of experience. The information gathered from these three DMs prioritises each criterion and sub-criteria based on their knowledge and expertise. This valuable understanding is crucial for the next phase, helping to set weights and calculate sustainable performance scores for each 3PRLPs.

### 4.1.3. Development of hierarchical structure

As shown in Figure 4, the problem discussed was presented in a four-level hierarchical structure. Each level was evaluated relative to the highest level. The top level of this structure defines the desired function, which is the selection of sustainable 3PRLPs. The second level presents the main criteria that must be considered when ranking the sustainable 3PRLPs. In the third level, the activities involved in each criterion are presented as sub-criteria.

**Table 4.** Continued.

| Main Criteria | Sub-Criteria | Nature | Preferred | Description | References |
|---|---|---|---|---|---|
| | Eco-design production ($C_{25}$) | Quantitative | Max | The ability of 3PRLPs to design and develop green products compliance with environmental management standards developed by ISO. | Saen, R. F., 2010; Mavi, Goh, and Zarbakhshnia 2017; Zarbakhshnia, Soleimani, and Ghaderi 2018 |
| | Environmental protection certification ($C_{26}$) | Quantitative | Max | The ability of 3PRLPs holding certificates compliance with environment laws and regulations. | Zarbakhshnia, Soleimani, and Ghaderi 2018; Govindan et al. 2019a, 2019b |
| | Pollution control ($C_{27}$) | Qualitative | Max | The standards established by the 3PRLPs that helps in reducing the harmful environmental impacts or reduce the pollution emission into the environment. It also refers to quantification of the amount of environmental threatening waste being produced per manufactured unit of product. | Govindan et al. 2019a |
| | Environmental expenditure ($C_{28}$) | Quantitative | Max | Refers to the efforts made by the 3PRLPs towards green production improvement and environmental management. | Efendigil, Ölnüt, and Kongar 2008; Saen, R. F., 2010; Mavi et al 2017; Govindan et al. 2019a |
| Social ($C_3$) | Health & safety ($C_{31}$) | Qualitative | Max | Implementation of measures by the 3PRLPs concerning the protection of health and life of employees. | Mavi, Goh, and Zarbakhshnia 2017; Zarbakhshnia, Soleimani, and Ghaderi 2018; Govindan et al. 2019a |
| | Voice of OEMs ($C_{32}$) | Qualitative | Max | Requirements of all important information about the 3PRLPs to OEM at higher quality of interactions. | Mavi, Goh, and Zarbakhshnia 2017; Zarbakhshnia, Soleimani, and Ghaderi 2018 |
| | Respect for local rules ($C_{33}$) | Qualitative | Max | The ability of 3PRLPs to fulfill the all the government compliance with legal and other regulations and the adoption of organizational policies. | Mavi, Goh, and Zarbakhshnia 2017 |
| | Flexible working arrangements ($C_{34}$) | Qualitative | Max | Refers to the flexibility in working schedules of the employee that could potentially promote the employee satisfaction and an increased efficiency and product quality. | Mavi, Goh, and Zarbakhshnia 2017; Govindan et al. 2019a |
| | Employment stability ($C_{35}$) | Qualitative | Max | Refers to the importance given to the employees as without their cooperation the company cannot achieve its goals. | Zarbakhshnia, Soleimani, and Ghaderi 2018; Govindan et al. 2019a, 2019b |
| | Rights of employees ($\boldsymbol{C_{36}}$) | Qualitative | Max | Refers to respecting of all rights and interests of employees within the organization. | Zarbakhshnia, Soleimani, and Ghaderi 2018; Govindan et al. 2019a |
| | Data destruction ($C_{37}$) | Qualitative | Max | Refers to the reliability of data destruction in the device memory of any old patient. | - |
| | Training ($C_{38}$) | Qualitative | Max | Refers to the continuous training and education of employees to acquired required skills and knowledge about the new standards and guidelines by the government for paying attention to their health and safety in order to avoid any fatal incident. | Govindan et al. 2019a |
| | Promotion & awareness ($C_{39}$) | Qualitative | Max | Refers to the efforts of the 3PRLPs for creating awareness about the importance of 3R's through the platforms of media. | |
| Risk ($C_4$) | Operational risk ($C_{41}$) | Qualitative | Min | Refers to the risk related to the internal operations of 3PRLPs that prevent to perform the operations satisfactorily. | Govindan, Sarkis, and Palaniappan 2013; Mavi, Goh, and Zarbakhshnia 2017; Zarbakhshnia, Soleimani, and Ghaderi 2018 |

**Table 4.** Continued.

| Main Criteria | Sub-Criteria | Nature | Preferred | Description | References |
|---|---|---|---|---|---|
| | Financial risk ($C_{42}$) | Qualitative | Min | Refers to the risk related to the liquidity or capital of 3PRLPs due to any changes in the economic environment. | Govindan, Sarkis, and Palaniappan 2013; Mavi, Goh, and Zarbakhshnia 2017; Zarbakhshnia, Soleimani, and Ghaderi 2018 |
| | Organizational risk ($C_{43}$) | Qualitative | Min | Refers to the risk faced from the OEMs including material strategic, reputational, regulatory, legal, security, and legal liability risk. | Govindan, Sarkis, and Palaniappan 2013; Mavi, Goh, and Zarbakhshnia 2017 |
| | Security risk ($C_{44}$) | Qualitative | Min | Refers to the risk related to internal and external factors affecting the security of the supply chain, logistics, and transportation management. | Govindan, Sarkis, and Palaniappan 2013 |

Economic factors (C1) had seven sub-criteria, environmental factors (C2) had eight, social factors (C3) had nine, and risk factors (C4) had four (C4). At the final level, 15 3PRLPs were presented as alternatives that must be ranked using all the sub-criteria presented in the previous level.

### 4.2. Phase II: Evaluating sustainable performance score of 3PRLPs

The Sustainable Performance Score (SPS) of each 3PRLP was crucial for further analysis. Thus, this phase involves weight elicitation and SPS calculation.

#### 4.2.1. Determining weights by GBWM

The selection of sustainable 3PRLPs is a critical decision process in SSCM, because it includes many qualitative and quantitative factors. A hybrid MCDM approach was used during this phase. The DMs identify the best and worst criteria for making pairwise comparison vectors after grouping the criteria and sub-criteria. The weights of all the sustainable criteria are then determined using a BWM-based group decision-making method instead of classical weight elicitation methods such as AHP. These weights were then used in the TOPSIS method to calculate the closeness coefficient of each 3PRLP. Finally, the ranking is determined using the TOPSIS results. Criteria weights were calculated using the GBWM. On a preference scale of 1–9, the DMs were asked to compare their identified best criteria to the other criteria. Table 5 shows the BO (best-to-others) vector. Similarly, comparisons were made to rate others based on the worst criteria. Table 6 lists the OW (Others-To-Worst) vector.

Based on BO and OW, a set of weights in percentages (30, 50, 20) is assigned for each DM based on their knowledge and experience. In this case, the industrial expert (DM2) is assigned a higher weight owing to

**Table 5.** BO vectors.

| Decision Makers | Best | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|---|
| DM1 | $C_2$ | 3 | 1 | 3 | 6 |
| DM2 | $C_1$ | 1 | 2 | 3 | 6 |
| DM3 | $C_2$ | 3 | 1 | 2 | 6 |

**Table 6.** OW vectors.

| Decision Makers | DM1 | DM2 | DM3 |
|---|---|---|---|
| Worst | $C_4$ | $C_4$ | $C_4$ |
| $C_1$ | 5 | 6 | 5 |
| $C_2$ | 6 | 5 | 4 |
| $C_3$ | 4 | 6 | 4 |
| $C_4$ | 5 | 6 | 5 |

their extensive real-world exposure. The faculty member (DM1) holds an intermediate weightage, adept at combining theoretical knowledge with practical insights. The researcher (DM3) was assigned a relatively lower weight, aligning with their focus on theoretical exploration. These percentages collectively represent the proportion of the impact of each DM input on the overall decision-making process. At each level of the hierarchy, the weights of all the criteria and sub-criteria were calculated using the same procedure. The problem is then solved using LINGO software by formulating it as in Eq. (2). Table 7 displays the integrated results for the three DMs. The environmental criteria come first, followed by the economic criteria. In the sub-criteria, recyclability is preferred over all other criteria, whereas disposal is considered the least preferred. Next, TOPSIS was used to consolidate 3PRLP sustainability performance data.

#### 4.2.2. Ranking 3PRLPs by TOPSIS

The selection of 3PRLPs is both difficult and complicated. The MCDM method is effective in solving decision problems while providing suggestions for relevant improvements in a specific area. The TOPSIS method was used in this study to assess the long-term performance of 3PRLPS. The initial decision matrix

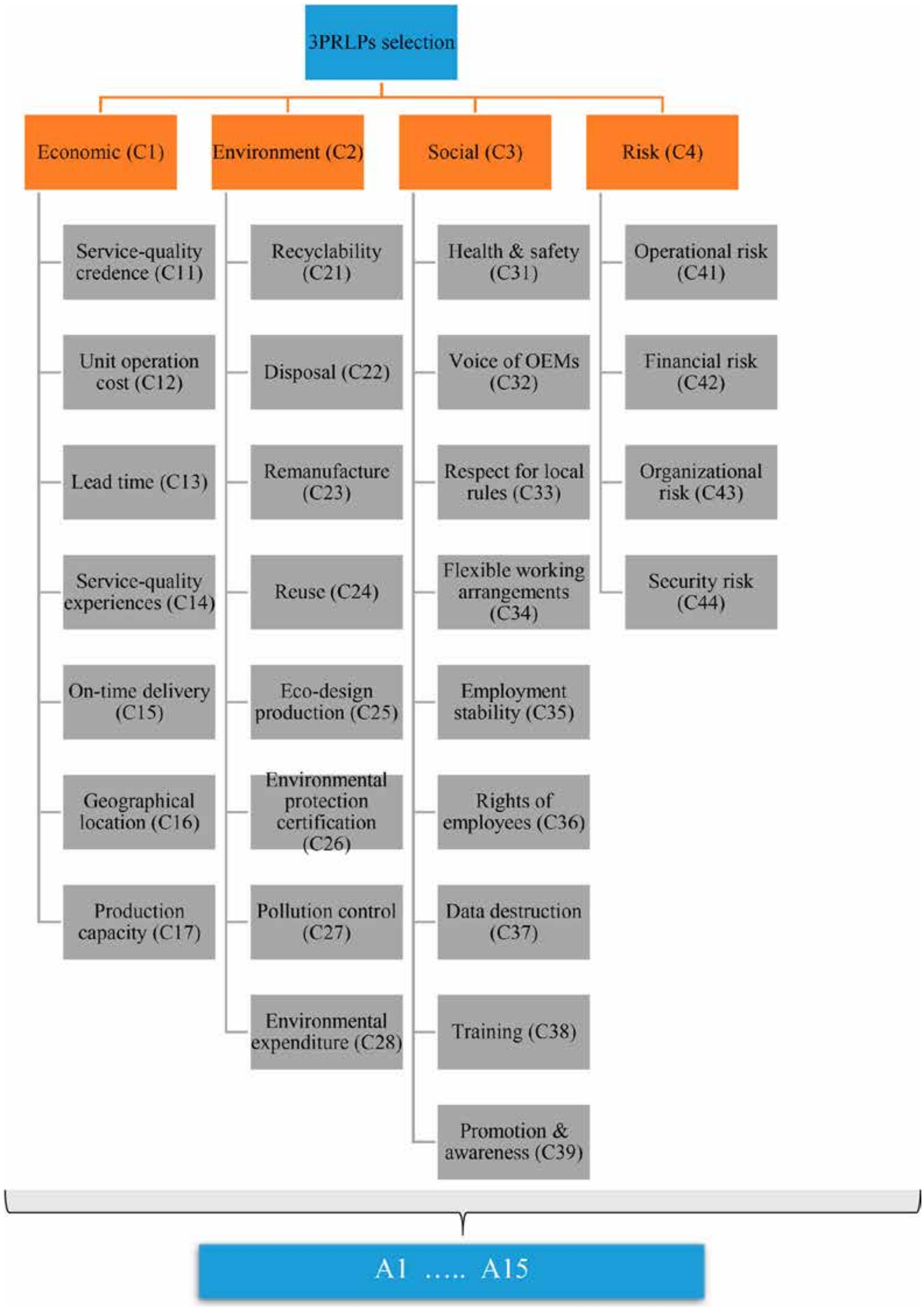


**Figure 4.** Hierarchical structure of the problem.

was created by collecting data from various sources for both quantitative and qualitative criteria, as shown in Appendix A and Table A2. Quantitative criteria, such as environment and economics, are extracted from Talluri and Baker (2002), Saen (2010), and Azadi and Saen (2011). For qualitative criteria, such as social and risk,

**Table 7.** Criteria weights evaluated from three DMs.

| *Decision Makers* | *Weights* | *Main criteria* | *Weights* | *Sub-criteria* | *Weights* | *Ranking* |
|---|---|---|---|---|---|---|
| | | **Economic** | 0.2973 | Service-quality credence | 0.0130 | 23 |
| | | | | Unit operation cost | 0.1077 | 2 |
| | | | | Lead time | 0.0449 | 8 |
| | | | | Service-quality experiences | 0.0299 | 15 |
| ***DM1*** | 0.3 | | | On-time delivery | 0.0359 | 13 |
| | | | | Geographical location | 0.0359 | 13 |
| | | | | Production capacity | 0.0299 | 15 |
| | | **Environment** | 0.3514 | Recyclability | 0.1087 | 1 |
| | | | | Disposal | 0.0085 | 27 |
| | | | | Remanufacture | 0.0499 | 6 |
| | | | | Reuse | 0.0499 | 5 |
| | | | | Eco-design production | 0.0374 | 9 |
| ***DM2*** | 0.5 | | | Environmental protection certification | 0.0374 | 9 |
| | | | | Pollution control | 0.0499 | 6 |
| | | | | Environmental expenditure | 0.0099 | 25 |
| | | **Social** | 0.2342 | Health & safety | 0.0690 | 3 |
| | | | | Voice of OEMs | 0.0362 | 11 |
| | | | | Respect for local rules | 0.0362 | 11 |
| | | | | Flexible working arrangements | 0.0147 | 22 |
| ***DM3*** | 0.2 | | | Employment stability | 0.0203 | 20 |
| | | | | Rights of employees | 0.0244 | 18 |
| | | | | Training | 0.0244 | 18 |
| | | | | Data destruction | 0.0090 | 26 |
| | | **Risk** | 0.1171 | Operational risk | 0.0293 | 17 |
| | | | | Financial risk | 0.0606 | 4 |
| | | | | Organizational risk | 0.0100 | 24 |
| | | | | Security risk | 0.0184 | 21 |

data were collected from the three DMs again using a 1–5 rating scale. The ratings for the Environmental Pollution Certification sub-criteria were assigned to the 3PRLPs based on the number of certifications possessed by each 3PRLP. The state receives five points, the national receives 10 points, and the international receives 15 points.

After generating the initial decision matrix, it is normalised using Eq. (B.10). The weights determined in the previous step were used here by multiplying them with the normalised matrix (Table A3 in Appendix A) using Eq. (B.11). The PIS and NIS were identified from the weighted normalised matrix, as shown in Table A4 in Appendix A, which was determined using Eq. (B.12) and (B.13), respectively. The closeness coefficient of each 3PRLP was calculated using Eq. (B.14) to (B.16); the results are listed in Table 8. The Closeness Coefficient ($CC_i$) in Table 7 represents the final TOPSIS results, which can also be regarded as the sustainable performance score for each 3PRLP. As indicated, suppliers' $CC_i$ rankings were A1 > A9 > A11 > A12 > A6 > A7 > A10 > A14 > A13 > A5 > A3 > A2 > A4 > A8 > A15. In the next phase, the DMs can choose the top ten 3PRLPs for the order allocation model.

**Table 8.** TOPSIS results with ranking.

| 3PRLPs | D+ | D- | $CC_i$ | Rank |
|---|---|---|---|---|
| A1 | 0.025 | 0.083 | 0.770 | 1 |
| A2 | 0.068 | 0.055 | 0.446 | 12 |
| A3 | 0.069 | 0.057 | 0.451 | 11 |
| A4 | 0.071 | 0.056 | 0.440 | 13 |
| A5 | 0.061 | 0.051 | 0.456 | 10 |
| A6 | 0.043 | 0.057 | 0.573 | 5 |
| A7 | 0.048 | 0.057 | 0.545 | 6 |
| A8 | 0.073 | 0.055 | 0.430 | 14 |
| A9 | 0.036 | 0.063 | 0.638 | 2 |
| A10 | 0.058 | 0.054 | 0.482 | 7 |
| A11 | 0.046 | 0.070 | 0.601 | 3 |
| A12 | 0.042 | 0.061 | 0.593 | 4 |
| A13 | 0.064 | 0.056 | 0.466 | 9 |
| A14 | 0.059 | 0.054 | 0.479 | 8 |
| A15 | 0.075 | 0.052 | 0.410 | 15 |

### 4.3. Phase III: Order allocation

The emphasis in traditional supply chain management is on selecting suppliers based on factors such as price, quality, and dependability. However, as concerns regarding sustainability have grown in prominence, the selection of sustainable 3PRLPs has become increasingly important. This study considers not only the selection of 3PRLPs but also the critical decision problem of order allocation.

This study introduces a multi-objective integer linear programming model to optimise order allocation. This model considers various parameters such as sustainability, total cost, and product delivery. Furthermore, the model emphasises the importance of considering the defect rate and the product loss value after delivery, as these factors have a direct impact on the product quality. This method allows for optimal allocation of orders to the selected 3PRLPs for multiple products across multiple periods and scenarios, making it more effective in real-world situations.

Because of the significance of these parameters, the unique feature of the model is its consideration of uncertainty in demand and loss value in real-time scenarios. This is especially important in light of the current global context, in which the COVID-19 pandemic has demonstrated the unpredictability of demand for certain products, such as EOL ventilators. Similarly, uncertainty in the loss value affects both product quality and the manufacturer's overall profit. A scenario-based probabilistic model was selected to model this problem (Babbar and Amin 2018; Tosarkani, Amin, and Zolfagharinia 2020), and these two parameters were defined for each scenario. This model provides a comprehensive solution to the complex decision-making problems of supplier selection and order allocation in the healthcare industry by integrating multi-objective optimisation, integer linear programming, and uncertainty considerations. The model developed in response to the aforementioned problem is described below, along with the definitions of the sets, parameters, and decision variables.

**Indices**

$$I : 3PRLPs, i = 1 \dots I$$
$$J : products, j = 1 \dots J$$
$$S : Scenarios, s = 1 \dots S$$
$$T : Time\ Period, t = 1 \dots T$$

**Parameters**

$SS_i$ : Sustainability performance score of 3PRLP $i$ (the CCi obtained from GBWM - TOPSIS with respect to all the sustainability criteria)
$UC_{ijt}$ : Unit cost of product $j$ from 3PRLP $i$ in peroid $t$
$OC_{ijt}$ : Ordering cost of product $j$ from 3PRLP $i$ in peroid $t$
$T_{ijt}$ : Transportation cost of product $j$ from 3PRLP $i$ in peroid $t$
$I_{jt}$ : Inventory holding cost of product $j$ in peroid $t$
$d_i$ : distance of 3PRLP $i$ from OEM
$D_{ijts}$ : Demand of product $j$ from 3PRLP $i$ in peroid $t$ under scenario $s$
$C_{min}$: Minimum Capacity of 3PRLP $i$ for product $j$ in period $t$
$C_{max}$: Maximum Capacity of 3PRLP $i$ for product $j$ in period $t$
$S_j$ : Storage space of product $j$
$S$ : Maximum storage space
$L$ : Maximum Loss value of products
$P_s$ : Probability of each different scenario $s$
$\alpha_{ijts}$ : Defect rate of product $j$ provided by 3PRLP $i$ in period $t$ under scenario $s$
$\beta_{ijt}$ : On - time delivery rate of product $j$ provided by 3PRLP $i$ in period $t$ (in percentage)
$\gamma_{ijts}$ : Loss value of product $j$ provided by 3PRLP $i$ in period $t$ under scenario $s$ (in percentage)

**Decision variables**

$X_{ijts}$ : Order quantity of product $j$ provided by 3PRLP $i$ in period $t$ under scenario $s$
$H_{jts}$ : On-hand inventory of product $j$ in period $t$ under scenario $s$
$Y_{ijts}$ : 1, if 3PRLP $i$ is selected for providing product $j$ in period $t$, 0 otherwise

**Multi-objective model**

$$Max\ Z_1 = \sum\sum\sum\sum p_s SS_i X_{ijts} \tag{1}$$

$$\begin{aligned} Min\ Z_2 = & \sum\sum\sum\sum p_s UC_{ijt} X_{ijts} \\ & + \sum\sum\sum\sum OC_{ijt} Y_{ijts} \\ & + \sum\sum\sum\sum p_s T_{ijt} X_{ijts} d_i \\ & + \sum\sum\sum\sum p_s I_{jt} H_{jts} \end{aligned} \tag{2}$$

$$Min\ Z_3 = \sum\sum\sum\sum p_s \alpha_{ijts} X_{ijts} \tag{3}$$

$$Max\ Z_4 = \sum\sum\sum\sum p_s \beta_{ijt} X_{ijts} \tag{4}$$

$$Min\ Z_5 = \sum\sum\sum\sum p_s \gamma_{ijts} \tag{5}$$

Subject to,

$$\sum X_{ijts} + H_{j(t-1)s} = D_{jts} + H_{jts} \tag{6}$$

$$\alpha_{ijts} \sum X_{ijts} \le D_{jts} \tag{7}$$

$$\sum \gamma_{ijts} X_{ijts} \le L \tag{8}$$

$$\sum S_i \left( \sum\sum\sum X_{ijts} - \sum\sum\sum D_{ijts} \right) \le S \tag{9}$$

$$X_{ijts}, Y_{ijts} \ge 0 \tag{10}$$

Objective (1) aimed to maximise the sustainability performance score of the 3PRLPs obtained in the previous phase. Objective (2) aims to reduce total costs, including unit purchasing costs, ordering costs, transportation costs, and inventory holding costs. Objective (3) is related to the defect rate of the products, which has a direct impact on the product's quality performance. The delivery of products from 3PRLPs over time is presented in Objective (4). Objective (5) considers a product's loss value while delivering the product.

The inventory flow equilibrium in the model is represented by Constraint (6). Constraint (7) considers demand fulfilment over time. Constraint (8) ensures an acceptable total loss. Constraint (9) defines the capacity of the 3PRLPs and the storage capacity of the OEMs. Constraint (10) implies the boundary condition, which states that the initial inventory must be zero and that all inventories must be used and must be zero at the end of the time period.

There are several methods for resolving multi-objective problems. These techniques are used to generate efficient solutions within the specified constraints. It is clear that a solution method capable of producing more efficient solutions is preferable. As a result, both traditional and modern methods were employed in this study. In the classical, commonly used method, namely $\varepsilon$-constraint, and in the modern, NSGA algorithms have been considered for obtaining efficient solutions, and this research selects the one that produces more efficient and diverse solutions.

#### 4.3.1. $\varepsilon$-constraint method

The $\varepsilon$-constraint method is widely used to solve multi-objective optimisation problems. It is a classical optimisation approach that has proven effective in obtaining efficient solutions. The most prominent objective function was selected as the major objective function in this technique. The other objectives were then mentioned as constraints (Collette and Siarry 2004). For each new constraint of the mathematical model, a new parameter ($\varepsilon$) is assigned using this method. The $\varepsilon$-constraint technique has been used in a variety of fields as it is effective in generating a set of Pareto-optimal solutions that provides trade-offs between objectives (Li and Zabinsky, 2011; Gazijahani et al. 2020). The multi-objective problem is solved using GAMS after being converted into the optimisation model (11).

$$Min\ z_6 = z_2 \tag{11}$$

Subject to,

$$z_1 \geq \varepsilon_1$$

$$z_3 \leq \varepsilon_3$$

$$z_4 \geq \varepsilon_4$$

$$z_5 \leq \varepsilon_5$$

Eqs. (6)-(10)

#### 4.3.2. Non-dominated sorting genetic algorithm II and III

Non-Dominated Sorting Genetic Algorithm II (NSGA II) is one of the most widely used multi-objective Genetic Algorithms (GA) (Deb et al. 2000). It has three distinct features: fast nondominated sorting, fast crowded distance estimation, and a simple crowded comparison operator. It has been tested on several test problems and has been claimed to outperform others in finding a diverse set of solutions; however, it does not work well on many optimisation problems with multiple objective values (Ishibuchi et al. 2016).

Consequently, the Non-Dominated Sorting Genetic Algorithm III (NSGA III) was proposed as an evolutionary multi-objective algorithm (Deb and Jain 2014). NSGA III serves a function similar to NSGA II, but incorporates a reference-point strategy to preserve population diversity. Owing to its ability to converge, it has been used as a benchmark algorithm for multi-objective optimisation problems.

Both NSGA II and NSGA III were used in this study to solve the order-allocation optimisation model. These algorithms are well-suited for solving multi-objective problems by converting optimisation problems with minimal and maximal objectives into multi-objective minimisation or maximisation problems. Thus, a multi-objective GA is used to generate a set of Pareto solutions, where a Pareto solution is one whose objective vector is not dominated by the objective vectors of any other solution. The multi-objective problem was solved using MATLAB after conversion to the multiminimization optimisation model (11).

$$Min\ Z_1 = -\sum\sum\sum\sum p_s SS_i X_{ijts} \tag{12}$$

$$\begin{aligned} Min\ Z_2 = &\sum\sum\sum\sum p_s UC\alpha_{ijt} X_{ijts} \\ &+ \sum\sum\sum\sum OC\alpha_{ijt} Y_{ijts} \\ &+ \sum\sum\sum\sum p_s T_{ijt} X_{ijts} d_i \\ &+ \sum\sum\sum\sum p_s I_{jt} H_{ijts} \end{aligned} \tag{13}$$

$$Min\ Z_3 = \sum\sum\sum\sum p_s \alpha_{ijts} X_{ijts} \tag{14}$$

$$Min\ Z_4 = -\sum\sum\sum\sum p_s \beta_{ijt} X_{ijts} \tag{15}$$

$$Min\ Z_5 = \sum\sum\sum\sum p_s \gamma_{ijts} \tag{16}$$

Subject to, Eqs. (6)–(10)

**Table 9.** Different scenarios were used in the model.

| SCENARIO | LOSS VALUE | DEMAND | PROBABILITY |
|---|---|---|---|
| #1 | 1.15 $\gamma_{ijts}$ | 1.15 $D_{jts}$ | 0.04 |
| #2 | 1.15 $\gamma_{ijts}$ | $D_{jts}$ | 0.16 |
| #3 | 1.15 $\gamma_{ijts}$ | 0.85 $D_{jts}$ | 0.04 |
| #4 | $\gamma_{ijts}$ | 1.15 $D_{jts}$ | 0.16 |
| #5 | $\gamma_{ijts}$ | $D_{jts}$ | 0.2 |
| #6 | $\gamma_{ijts}$ | 0.85 $D_{jts}$ | 0.16 |
| #7 | 0.85 $\gamma_{ijts}$ | 1.15 $D_{jts}$ | 0.04 |
| #8 | 0.85 $\gamma_{ijts}$ | $D_{jts}$ | 0.16 |
| #9 | 0.85 $\gamma_{ijts}$ | 0.85 $D_{jts}$ | 0.04 |

**Table 10.** Parameters and details to be used in the model.

| $O_{ijt} = 500$ | $I_{jt} = 500$ |
|---|---|
| $D_{jts} = 490$ ($s = 3,6,9$), $Djts = 505$ ($s = 2,5,8$), $Djts = 525$ ($s = 1,4,7$) | $UC_{ijt} = 48$ ($i = 3,6,7,8,12$), $UC_{ijt} = 54$ ($i = 4,5,10,14$), $UC_{ijt} = 60$ ($i = 1,2,9,11,13,15$) |
| $\beta_{ijt} = 0.82$ ($i = 1, 5, 11, 14, 15$), $P_{ijt} = 0.87$ ($i = 4, 6, 8, 10, 13$), $P_{ijt} = 0.94$ ($i = 2, 3, 7, 9, 12$) | $S_i = 137$ ($i = 1,2,9$), $Si = 138$ ($_i = 13, 15$), $Si = 139$ ($_i = 4,5,10,14$), $S_i = 140$ ($i = 11$), $S_i = 141$ ($i = 3, 6,7,8,12$) |
| $C_{min} = 80$, $C_{max} = 120$, $S = 7500$, $L = 700$ | $\gamma_{ijts} = 0.115$ ($s = 1, 2, 3$), $\gamma_{ijts} = 0.1$ ($s = 4, 5, 6$), $\gamma_{ijts} = 0.085$ ($s = 7, 8, 9$) |

## 5. Results and discussions

This section illustrates the feasibility of the proposed MOO model for one type of raw material in one period. The basic information required for the decision-making problem and parameters was obtained from industry experts and used to solve the MOO model. As stated in section 4.3, the two parameters in this model are uncertain. Nine scenarios were developed based on discussions with experts and the sensitivity of business information. Each scenario was created by a 15% increase or decrease in each source of uncertainty assumed in the main scenario, Scenario #5, as well as the other scenarios and their associated probabilities, which are listed in Table 9.

Table 10 summarises key information regarding the sets and other model parameters. The ordering cost, inventory holding cost, demand from each supplier, unit cost, on-time delivery rate of each supplier, storage space provided by each supplier, maximum and minimum capacity of each supplier, and loss value of each supplier are also provided below. Taking into account the various important parameters and real-time uncertainty information, the mathematical model is solved to obtain the optimal solutions using both classical and modern methods, as presented in the following sub-sections.

### 5.1. *Results of $\varepsilon$-constraint method*

In a multi-objective optimisation problem, the $\varepsilon$-constraint method allows the prioritisation of certain objectives over others. This method was used in this study to obtain efficient solutions for the optimisation model that considers sustainability, costs, and product delivery, as well as the defect rate and product loss value. Table 11 shows that the method successfully produced a variety of efficient solutions that balanced these objectives. However, obtaining its correct value is difficult; thus, it is useful for a wide range of functions. It is not possible to compare two efficient solutions and determine which is superior because the first efficient solution has better values for some objectives, particularly objectives $Z_1$, $Z_4$, and $Z_5$. However, the second most efficient solution outperforms the first two objectives, $Z_1$ and $Z_2$. Except for the second solution, almost all solutions for objective $Z_5$ have the same value of 1.209. This is the product's lowest possible loss value derived from 3PRLPs.

### 5.2. *Results of NSGA II and NSGA III method*

To obtain a more comprehensive and efficient set of solutions for a multi-objective problem, the model uses two additional methods: NSGA II and NSGA III. The detailed parameter settings used in NSGA II and NSGA III are as follows:

- In both algorithms, the maximum number of generations was set to 500 with a population size of 100 individuals. This value provides a reasonable trade-off between convergence speed and solution quality, and strikes a balance between exploration and exploitation, allowing the algorithm to explore diverse regions of the search space while maintaining a manageable computational load.
- A binary tournament selection was adopted in NSGA II as the selection mechanism. This mechanism balances selection pressure and diversity maintenance, thereby promoting the survival of both elite and diverse individuals in the population.
- NSGA III utilises reference points generated by the reference-point-based nondominated sorting approach. These reference points provide a set of preferred solutions using an epsilon-based selection strategy that guides the optimisation process towards different regions of the Pareto front.
- Both algorithms employ intermediate crossover (NSGA II) and Gaussian mutation (both) operators to maintain diversity and explore the search space. The intermediate crossover with a distribution index of 1.2 balances exploration and exploitation, whereas the Gaussian mutation with a scale of 0.1 and shrink of 0.5, introduces controlled randomness to the search process in NSGA II. In NSGA III, the Gaussian mutation operator with a mutation rate of 0.02 was employed

**Table 11.** Results of $\varepsilon$-constraint method.

| | | | | | MAX | MIN | MIN | MAX | MIN | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Alternatives* | *EEE1* | *EEE3* | *EEE4* | *EEE5* | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ | $Z_5$ | $ZZZ = Z_2$ |
| $\varepsilon$-constraint #1 | 1523 | 300 | 1520 | 1402 | 1523.000 | 195120000.0 | 209.290 | 2541.258 | 1.209 | 1.9512E + 8 |
| $\varepsilon$-constraint #2 | 712 | 1083 | 787 | 630 | 790.491 | 70992.222 | 84.151 | 787.000 | 747.662 | 70992.22 |
| $\varepsilon$-constraint #3 | 1331 | 415 | 1210 | 1232 | 1331.00 | 153350000.0 | 178.369 | 2187.509 | 1.209 | 1.5335E + 8 |
| $\varepsilon$-constraint #4 | 912 | 883 | 907 | 730 | 912.000 | 72934000.0 | 86.892 | 1430.673 | 1.209 | 7.2934E + 7 |
| $\varepsilon$-constraint #5 | 1310 | 490 | 1100 | 1120 | 1310.000 | 148940000.0 | 176.057 | 2151.295 | 1.209 | 1.4894E + 8 |
| $\varepsilon$-constraint #6 | 1011 | 703 | 1110 | 1090 | 1011.000 | 89897000.0 | 97.258 | 1580.987 | 1.209 | 8.9897E + 7 |
| $\varepsilon$-constraint #7 | 1413 | 350 | 1401 | 1322 | 1413.000 | 170560000.0 | 187.395 | 2328.914 | 1.209 | 1.7056E + 7 |

as it introduces diversity while preventing excessive disruption of promising solutions.

- The parameter settings used were influenced by the work of Deb and Jain (2014), ensuring that the chosen values align with the established practices and principles in multi-objective optimisation. These selections were fine-tuned through experimentation to cater to the specific problem at hand, ultimately aiming for efficient convergence, diverse Pareto fronts, and high-quality solutions (Deb and Jain 2014).

By utilising these parameters in our study, NSGA II and NSGA III effectively directed their optimisation efforts towards specific segments of the Pareto front by utilising reference points, objective weighting, and distance considerations. These factors play a pivotal role in producing a comprehensive set of solutions. The progression of solution sets across various generations for all objectives is visually represented in Figure 5, which shows the algorithmic diversification achieved by both NSGA-II and NSGA-III.

The visual representations presented in Figure 5 highlight a consistent pattern in the behaviour of objectives Z3, Z4, and Z5 across the runtime of both NSGA-II and NSGA-III, whereas the value of objective $Z_2$ decreases as the number of generations increases. This demonstrates that the diversification ability of both algorithms is equivalent to zero for objectives $Z_3$, $Z_4$, and $Z_5$, showing no variation.

Figure 6 depicts parallel coordinate graphs, which are useful tools for visualising multidimensional data, such as the objective function values in this study. In these graphs, each axis represents one of the objective functions, and the connections between the values of a given solution form lines that signify the placement of the solution within the multidimensional space. By plotting multiple solutions on a single graph, distinct patterns and interrelationships between objective functions can be easily identified.

Figure 6 also shows the experimental results of both algorithms for the same problem, emphasising similar patterns and ranges of objective function values. Surprisingly, both algorithms in Figures 5 and 6 exhibit the same pattern of diversification, with neither outperforming the other, which is unusual for many multi-objective problems. However, to find the best solutions, the TOPSIS method was used to screen the solution sets generated by NSGA II and NSGA III in their most recent generations.

The top ten best solutions obtained by the TOPSIS method from the NSGA II and NSGA III algorithms are presented in Tables 12 and 13, respectively. The $CC_i$ value in each table indicates an individual solution's performance score, in descending order. The tables highlight the optimal solution for both the NSGA II and NSGA III algorithms. According to Table 11, Solution #10 had the highest performance score ($CC_{10}$) obtained using the TOPSIS method for NSGA-II, whereas Solution #3 had the highest performance score ($CC_3$) obtained using the TOPSIS method for NSGA-III in Table 13.

The average results for both algorithms are shown in the last rows of Tables 12 and 13. Figure 7 shows the objective function values of both the algorithms. When the results are compared, it is clear that NSGA II produces slightly better solutions than NSGA III, as it produces optimal allocated values and Pareto solutions for all five objective functions, whereas NSGA III produces suboptimal solutions for objective functions $Z_1$ and $Z_4$. On the other hand, the correlation between the average results of both algorithms was high, approaching 1.00. This means that any of the average outcomes can be considered the best solution to the problem under consideration. The parallel coordinate graphs in Figures 4 and 5 show that both algorithms produced similar results, confirming our model. Consequently, the final optimal solution can be chosen from any of the solution sets generated by either algorithm.

However, in contrast to many other studies, where the decision to select the appropriate solution is left to the decision maker, we utilised an analytical method in this study to objectively identify the most suitable solution from the set of Pareto optimal solutions. Therefore, we chose to use TOPSIS in this study as a way to objectively select the optimal solution. Using TOPSIS, we were able to effectively compare and evaluate all Pareto optimal solutions and identify the most suitable solution.

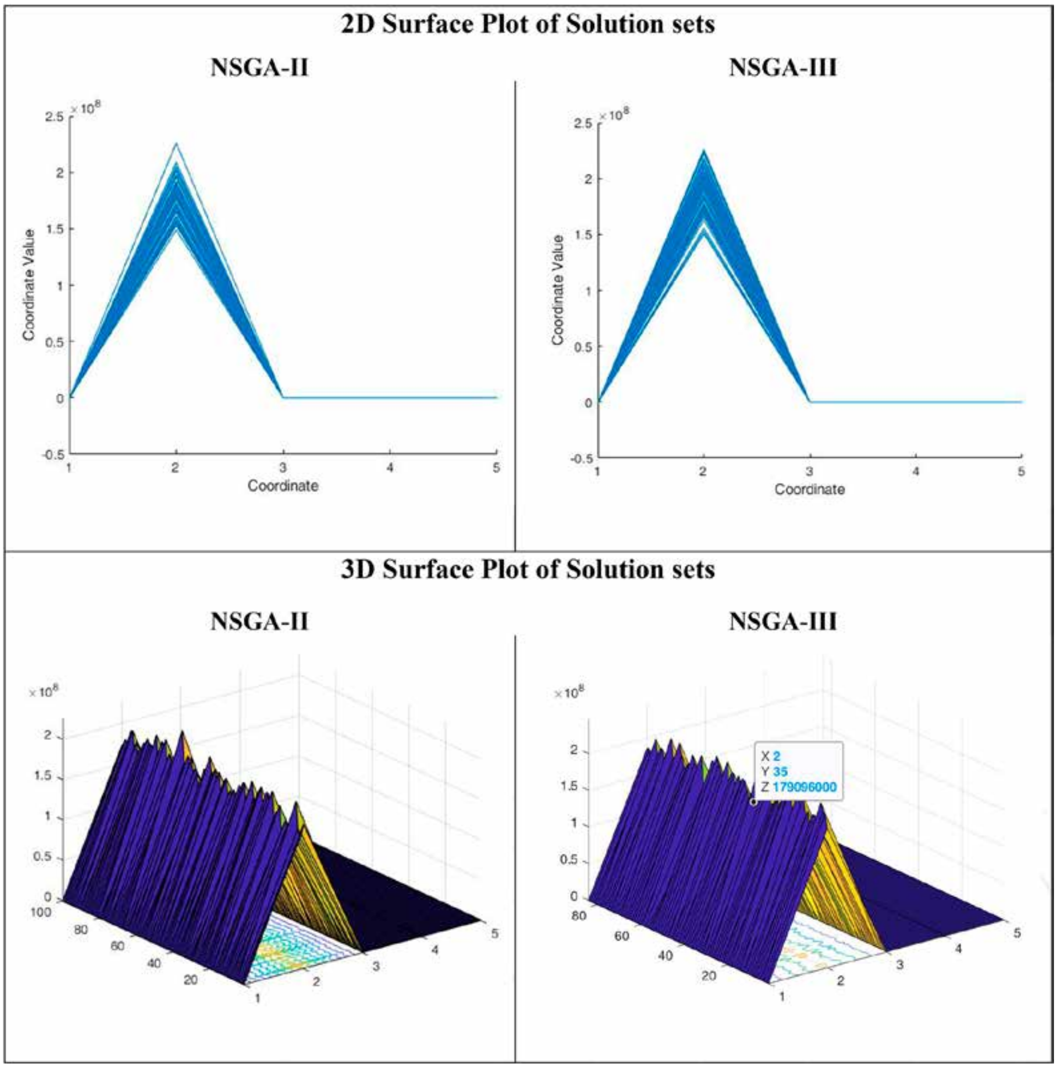


**Figure 5.** 2D and 3D surface visualizations of solution sets of NSGA II and NSGA III.

Overall, the combination of NSGA-TOPSIS enables a thorough exploration of the solution space, resulting in a better understanding of the trade-offs between the different objectives in the model. Furthermore, compared to other techniques such as the $\varepsilon$-constraint method or LP-metrics method, the NSGA-TOPSIS approach offers a more efficient and effective solution as it reduces computational complexity and provides better quality solutions for large-scale problems.

### 5.3. Comparison of results

This study evaluated the results using the value path approach developed by Schilling, Revelle, and Cohon (1983). The value path approach in optimisation problems is a useful tool for presenting trade-offs in optimisation problems because it allows for the simultaneous consideration of both maximisation and minimisation objectives. Figure 8 depicts the results of the classical and modern methods, based on the results presented in Tables 11–13. When calculating the values, both the maximisation and minimisation objectives should be considered. The maximisation objectives are converted to minimisation objectives by multiplying −1 to each objective value.

Figure 8 shows the results of the value path approach for each method, where the intersections between the results indicate that they are non-dominated solutions. It also illustrates a clear and concise visualisation of the trade-off between the objective functions for each nondominated solution, facilitating a visual comparison of these methods in terms of diversity in the solution space. The results reveal that the NSGA is more efficient than the **$\varepsilon$-constraint** method. It should also be noted

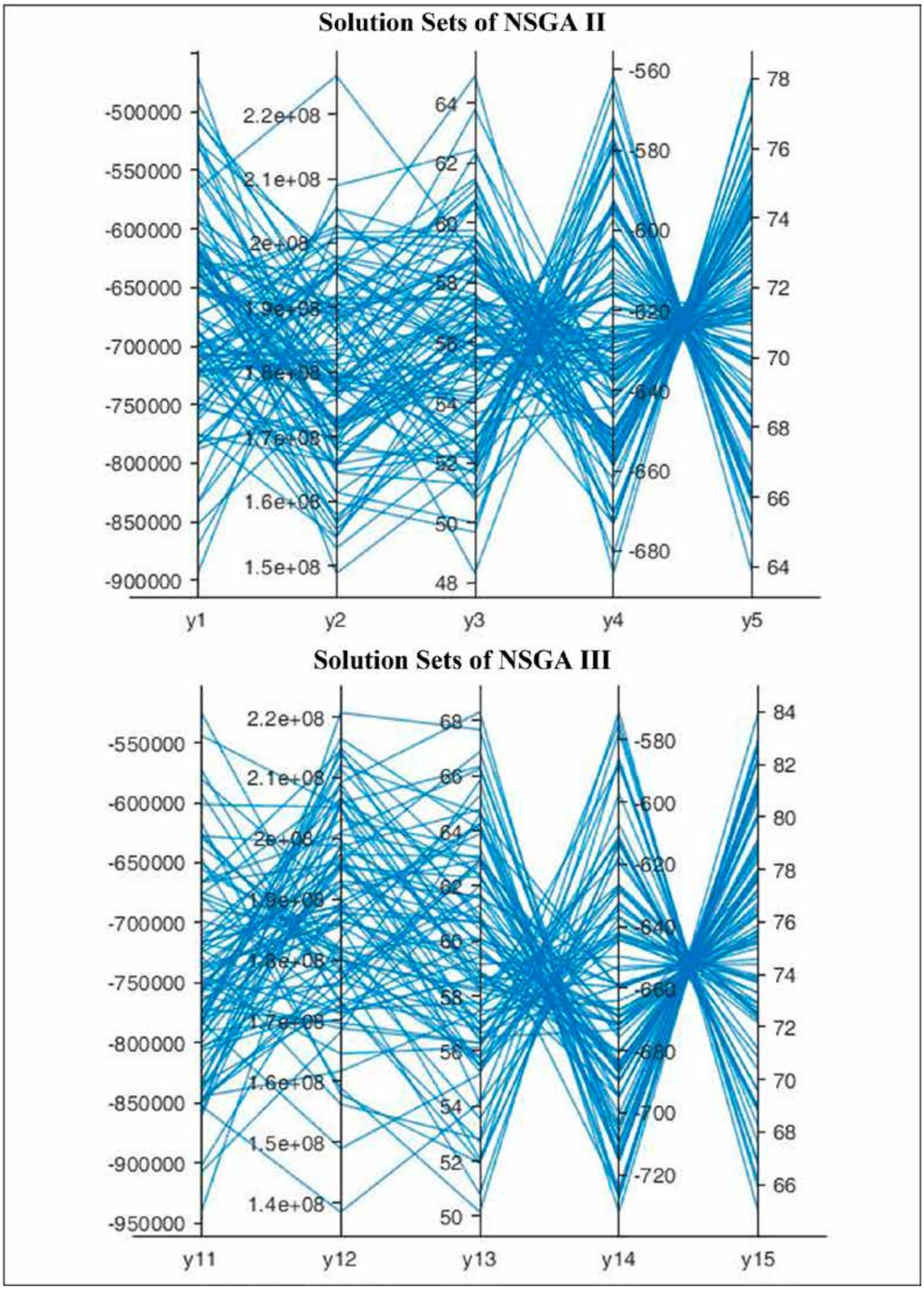


**Figure 6.** Parallel coordinates plots of NSGA II and NSGA III.

that objectives $Z_3$, $Z_4$, and $Z_5$ remain constant and are not significantly affected by any of these methods. The insights gained from this analysis are useful for decision-making purposes, as they allow for the identification of non-dominated solutions and evaluation of the performance of different optimisation methods. The findings of this study demonstrate the effectiveness of modern optimisation methods in generating diverse and efficient

**Table 12.** Results of NSGA II and TOPSIS methods.

| | *MAX* | *MIN* | *MIN* | *MAX* | *MIN* | |
|---|---|---|---|---|---|---|
| *Solution no.* | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ | $Z_5$ | $CC_i$ |
| ***Solution #10*** | **775911.69** | **138000000.00** | **45.71** | **603.76** | **60.16** | **0.8650** |
| *Solution #37* | 704801.01 | 134000000.00 | 46.22 | 642.04 | 61.81 | 0.8324 |
| *Solution #44* | 723192.45 | 137000000.00 | 48.26 | 625.56 | 63.38 | 0.8229 |
| *Solution #52* | 818846.06 | 152000000.00 | 48.40 | 657.71 | 63.83 | 0.7992 |
| *Solution #27* | 689341.83 | 131000000.00 | 52.42 | 615.73 | 64.24 | 0.7927 |
| *Solution #11* | 620549.74 | 128000000.00 | 47.97 | 603.23 | 65.17 | 0.7824 |
| *Solution #3* | 698300.24 | 123000000.00 | 54.67 | 572.63 | 68.84 | 0.7823 |
| *Solution #47* | 704588.24 | 151000000.00 | 46.76 | 673.16 | 60.81 | 0.7731 |
| *Solution #50* | 870162.88 | 159000000.00 | 48.40 | 630.46 | 66.30 | 0.7685 |
| *Solution #63* | 625814.65 | 135000000.00 | 50.77 | 593.89 | 63.68 | 0.7623 |
| ***Avg. result*** | **723150.879** | **138800000** | **48.958** | **621.817** | **63.822** | |

**Table 13.** Results of NSGA III and TOPSIS methods.

| | *MAX* | *MIN* | *MIN* | *MAX* | *MIN* | |
|---|---|---|---|---|---|---|
| *Solution no.* | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ | $Z_5$ | $CC_i$ |
| ***Solution #3*** | **872693.04** | **174743981.20** | **54.40** | **657.70** | **72.92** | **0.8029** |
| *Solution #8* | 893682.78 | 180320067.50 | 56.71 | 692.23 | 71.51 | 0.8000 |
| *Solution #18* | 864302.26 | 171692900.73 | 61.93 | 697.31 | 76.09 | 0.7729 |
| *Solution #41* | 851005.84 | 169709518.30 | 63.40 | 681.38 | 78.13 | 0.7512 |
| *Solution #19* | 848536.20 | 186491952.31 | 51.12 | 711.73 | 71.32 | 0.7432 |
| *Solution #6* | 823403.39 | 177245712.57 | 47.35 | 674.21 | 63.75 | 0.7389 |
| *Solution #11* | 914270.86 | 196922392.66 | 61.82 | 709.10 | 77.20 | 0.7379 |
| *Solution #68* | 819926.35 | 172363493.42 | 56.60 | 684.41 | 76.25 | 0.7221 |
| *Solution #44* | 853029.41 | 188392320.41 | 60.81 | 598.72 | 78.05 | 0.7080 |
| *Solution #62* | 826142.27 | 178090516.17 | 62.20 | 654.86 | 77.41 | 0.6980 |
| ***Avg. result*** | **856699.24** | **179597285.5** | **57.634** | **676.165** | **74.263** | |

solutions for supplier selection and order allocation problems. This study highlights the importance of utilising modern optimisation methods in decision-making processes to achieve better performance and more effective solutions.

## 6. Managerial implications

Many businesses consider outsourcing to the 3PRLP for effective e-waste recycling because of the lack of appropriate infrastructure and RL expertise. This study proposes a benchmarking approach for top management companies and managers to evaluate and select 3PRLPs to increase profit and efficiency in RL and then allocate orders to the chosen 3PRLPs. For example, this model can be used to evaluate and select suppliers based on criteria, such as quality, cost, and environmental impact in the manufacturing industry. For example, the food industry can use this model to select suppliers based on factors, such as food safety, quality, and social responsibility. The application of the study to the healthcare industry produced a detailed quantitative analysis that can provide several managerial insights.

This paper includes a number of sustainability criteria, primarily economic, environmental, and social, for evaluating the 3PRLP's efficiency in the healthcare industry, but it can also be applied to other industries where managers can consider sustainability in their operations processes. In this case, 20% of 3PRLPs received performance scores greater than 0.60. Managers could include other criteria, such as technical and strategic capabilities, in the 3PRLP selection process. The manager can also include DMs with different profiles to increase selection precision. Using this approach, managers can achieve a more comprehensive evaluation of potential suppliers and make informed decisions that align with their organisation's goals and objectives. However, these modifications may affect the evaluation process.

This study also examined the hybrid approach of MCDM and MODM, which could be used as a starting point for similar situations in which managers can modify the problem based on the organisation's objectives and goals, although the authors considered three important objectives in this model: defect rate, delivery time, and loss value. However, their graphical representations in all the methods showed no change. Thus, in practice, managers can eliminate these issues and modify the model to meet their needs.

Managers can also investigate how the parameters behave by substituting another parameter that varies with the market or inflation rate for loss value. On the other hand, managers must have a thorough understanding of firms' demand preferences for various objectives based on different characteristics. As a result, an order allocation system that can meet the real needs of sustainable supply chains must be developed.


**Figure 7.** Comparison of objective function values of NSGA-II and NSGA-III algorithms in different scenarios.

Based on the findings of this study, the modern approach outperformed the classical approach. Multiple diverse and efficient solutions were obtained using modern approaches, and managers could use the TOPSIS method, as used in this study, to select the optimal solution. In multi-objective problems, it is not always certain that NSGA II will outperform NSGA III. Tables 11 and 12 show that the results of NSGA II and NSGA III had nearly identical patterns, with only a minor difference in their average results. This integration approach enables objective and comprehensive supplier evaluation and order allocation based on multiple criteria such as cost, quality, and environmental impact.

According to this study, managers from various industries can benefit from this model because they focus on green supply chain management. Furthermore, the findings of this study could help policymakers develop appropriate pollution regulation standards to create a sustainable business environment for service industries, which could help any country achieve socio-economic success in terms of environmental sustainability in the coming era of global warming, as well as efficiently manage their operational decisions after the post-pandemic scenarios.

Finally, given the global variability in COVID-19 cases, managers must assess the current stage in light of policies and pandemic development. Furthermore, using the recycled raw materials suggested in this study, EOL ventilator production can be adjusted to deal with the impact of virus variants while also promoting environmental sustainability. In addition, the proposed approach can also be applied to industries such as electronics, automotive, pharmaceutical, construction, and retail that prioritise sustainability in their operations or supply chain for e-waste recycling, reducing plastic waste, recycling or refurbishing unwanted parts of any machine, and proper disposal. Overall, the manager of any industry that relies on RL processes can benefit from this proposed approach as it is concerned with developing and implementing sustainable practices throughout the entire supply chain, from sourcing raw materials to end-of-life disposal and recycling.

## 7. Conclusions, and future scopes

In the post-pandemic era, this paper proposes an integrated framework that provides a systematic approach to selecting 3PRLPs and determining order allocation, addressing a critical gap in healthcare supply chain management. As a result, the authors attempted to introduce an innovative approach that holds immense practical significance in navigating complex healthcare logistics within the context of the global pandemic and its aftermath.

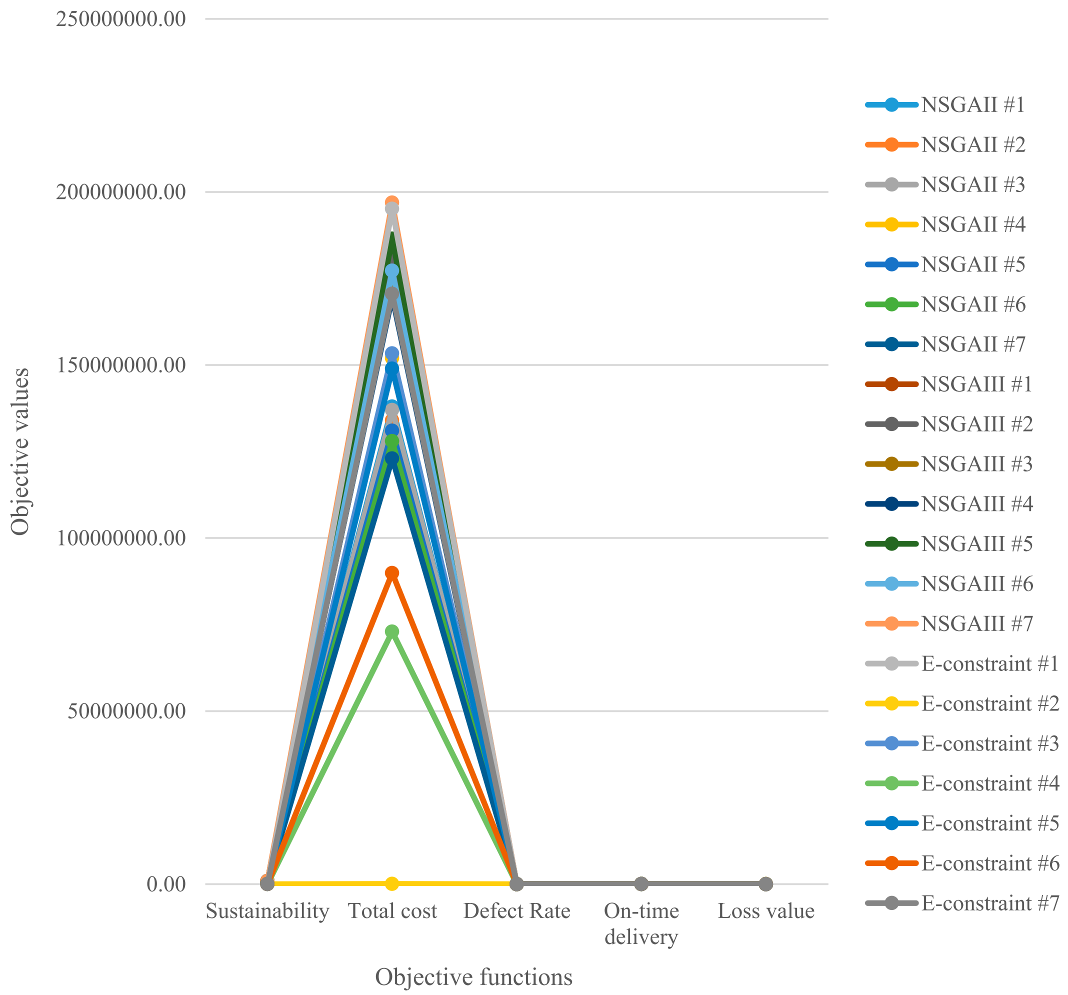


**Figure 8.** Value path approach results of the methods.

The real-world applicability of this study is further underscored by its unique application to healthcare supply chains, a domain in which the proposed model has not been previously explored. By venturing into this uncharted territory, this research contributes valuable insights that can directly impact the efficiency and resilience of healthcare systems. This study introduces a structured framework divided into two essential phases, each addressing distinct facets of the problem.

The initial phase aims to evaluate the efficiencies of the 3PRLPs using a hybrid MADM method of GBWM for weight elicitation and TOPSIS for sustainable performance scores to improve the selection process. This hybrid MADM approach demonstrates the model's adaptability to real-world complexities by incorporating factors, such as risk and social considerations, that enhance the robustness of supplier selection processes, translating to tangible benefits for healthcare organisations.

Furthermore, in the second phase, the study formulates a multi-objective optimisation model for order allocation directly to address practical supply chain challenges. This model captures the intricacies of scenario-based processes by incorporating the uncertainty of parameters, such as the loss value and demand. Notably, the study employed a blend of classical and modern algorithms to optimise solutions, showcasing a well-rounded approach.

Ultimately, this study's practical significance extends to addressing the global e-waste challenge in healthcare. By addressing the growing e-waste challenge on a global scale, the framework emerges as a valuable tool in two key ways:(1) determining the most efficient 3PRLPs for e-waste management, and (2) assisting in the systematic allocation of orders to each supplier. A notable advantage is the provision of a decision support system that offers a concrete solution to reduce errors and management costs, thereby contributing to enhanced operational efficiency.

In conclusion, this study represents notable progress in the field of comprehensive and sustainable e-waste management. It seamlessly aligns with the evolving requirements of the healthcare industry, addressing environmental issues while simultaneously improving the operational effectiveness. The practical significance of this study is substantial as it propels healthcare supply chain management through a carefully designed and innovative framework. This research serves as an enlightening guide, charting a course for prompt operational enhancement and long-lasting sustainability goals within the post-pandemic landscape of healthcare.

In the future, this study can be extended in several ways.

- In the first phase, other criteria related to the sustainability and reliability of the products can be considered. Different methods can be used to evaluate the weights, and quantitative data can be used to select 3PRLPs with a greater number of DMs.
- In addition, fuzziness in the opinions of DMs must also be considered, which can be handled using the fuzzy set theory. Some imputation methods can also be used and considered for handling missing values, if any.
- In addition to the criteria mentioned in the first phase of this research, the healthcare supply chain may be exposed to technical criteria concerning product safety and reliability, strategic criteria concerning sustainability, and risk criteria concerning regulatory compliance, inflation rates, and natural disasters. These qualitative factors were considered in the first phase of the model.
- It would be valuable to investigate 3PRLP selection and order allocation for other e-medical waste products generated during the post-pandemic era. The complexity of the model can be increased by introducing additional constraints related to environmental costs, carbon footprint, and product flow.
- In the last phase, the parameters of both algorithms can be fine-tuned to maintain their effectiveness in the optimisation scenario.

## Notes

1. Source: https://www.statista.com/statistics/1067081/generation-electronic-waste-globally-forecast/
2. Source: https://theroundup.org/global-e-waste-statistics/.
3. Source: https://www.deccanherald.com/business/covid-19-automakers-medical-device-makers-join-hands-to-produce-ventilators-819878.html.
4. Source: https://www.weforum.org/agenda/2020/04/covid-19-ventilator-shortage-manufacturing-solution/
5. Source: https://straitsresearch.com/report/ventilators-market
6. Source:https://www.indiatoday.in/india/story/did-ventilators-from-pm-cares-fund-fail-or-states-failed-to-manage-them-1803473-2021-05-17

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Data availability Statement

The data supporting this study's findings are available on request from the corresponding author.

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## Appendix A

**Table A1.** List of products in different EEE categories.

| Category | Products or Items included |
|---|---|
| Small Equipment | vacuum cleaners, microwaves, ventilation equipment, toasters, electric kettles, electric shavers, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, small monitoring and control instruments |
| Small IT | televisions, monitors, laptops, notebooks, tablets |
| Large Equipment | washing machines, clothes dryers, dish-washing machines, electric stoves, large printing machines, copying equipment, photovoltaic panels |
| Screens | mobile phones, global positioning systems (GPS), pocket calculators, routers, personal computers, printers, telephones |
| Temperature Exchange Equipment | refrigerators, freezers, air conditioners, heat pumps |
| Lamps | fluorescent lamps, high intensity discharge lamps, LED lamps |

## Appendix B

### B.1 GBWM Method

The Best Worst Method (BWM) was recently developed by Jafar Rezaei in 2015. BWM is a comparison-based method that requires very less information comparatively, resulting in a more consistent comparison used to solve the MCDM problems (Rezaei 2015). Being similar to AHP in making pairwise comparison matrix, it differs by formulating a non-linear minmax model used for determining weights. In this study, BWM is considered as a group decision-making method indicating the importance of group decision-making in the decision problems (Safarzadeh, Khansefid, and Rasti-Barzoki 2018). According to the original BWM, the steps for GBWM used to drive the criteria weights are presented below:

***Step 1:*** Identify the set of DMs *(k)* and the set of decision criteria by DMs.

***Step 2:*** Identify the best (most important) and the worst (least important) of each DM.

***Step 3:*** Establish the pairwise comparison matrix of all the criteria with respect to the best. i.e. BO (Best-to-Others) and worst criteria. i.e. OW (Others-to-Worst) by each DMs.

***Step 4:*** Determine the criteria weights by formulating the problem to a non-linear minmax model as follows:

$$\min \sum_{k\in D} w'_k \max\left\{\left|\frac{w_B}{w_j}-a^k_{Bj}\right|,\left|\frac{w_j}{w_W}-a^k_{jW}\right|\right\} \tag{B.1}$$

*s.t.*

$$\sum_j w_j = 1 \tag{B.2}$$

$$w_j \geq 0, \forall j \tag{B.3}$$

where $w'_k$ is the weights of the DMs in percentage value ([0,100]).

***Step 5:*** The above-mentioned model can be modified by defining $\xi_k$ as follows:

$$\xi_k = \max\left\{\left|\frac{w_B}{w_j}-a^k_{Bj}\right|,\left|\frac{w_j}{w_W}-a^k_{jW}\right|\right\} \forall k \in D \tag{B.4}$$

Thus, the model is transferred to the following linear programming model:

$$\min \sum_{k\in D} w'_k \xi_k \tag{B.5}$$

*s.t.*

$$|w_B - a^k_{Bj} w_j| \leq \xi_k, \forall j \tag{B.6}$$

$$|w_j - a^k_{jW} w_W| \leq \xi_k, \forall j \tag{B.7}$$

$$\sum_j w_j = 1 \tag{B.8}$$

$$w_j \geq 0, \forall j \tag{B.9}$$

The model (2) generates a set of optimal weights and has a unique solution. The value of $\xi_k$ is directly considered as an indicator of the consistency in the data and does not require the need to perform the consistency test.

### B.2 TOPSIS method

TOPSIS was proposed by Hwang and Yoon in 1981 (Tzeng and Huang 2011). It is based on the concept of compromise solution that is nearest to the positive ideal solution (PIS) and farthest to the negative ideal solution (NIS). PIS maximizes the maximizing attributes and minimizes the minimizing attributes, while NIS minimizes the maximizing attributes and maximizes the minimizing attributes. It has been applied in many fields, such as e-commerce industry, health, safety and environment management, supplier selection, risk management, energy management, and business and marketing management. The various steps needed to be performed are summarized below.

***Step 1:*** Establish the decision matrix.

***Step 2:*** The decision matrix is normalized using the following equation:

**Table A2.** Initial decision matrix of TOPSIS.

| 3PRLPs | Service-Quality Credence | Unit operation Cost ($) | Lead time (minutes) | Service-Quality Experiences | On-time Delivery | Geographical Location (KM) | Production capacity (T/Annum) | Recyclability (Tonnes) | Disposal | Remanufacture | Reuse | Eco-design production | Environmental Protection Certification | Pollution control | **Environmental Expenditure(1000 $)** | Health & Safety | Voice of OEMs | Respect for local rules | **Flexible workingarrangements** | Employment Stability | Rights of employees | Training | Data destruction | Operational risk | Financial risk | Organizational risk | Security risk |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 90 | 253 | 1355 | 240 | 187 | 39.2 | 30000 | 20 | 3 | 2 | 2 | 3 | 5 | 4 | 197 | 2 | 5 | 2 | 3 | 3 | 2 | 2 | 1 | 3 | 2 | 3 | 2 |
| A2 | 80 | 268 | 790 | 210 | 194 | 32.0 | 1500 | 130 | 1 | 1 | 2 | 2 | 20 | 2 | 198 | 2 | 3 | 3 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 1 |
| A3 | 70 | 259 | 421 | 270 | 220 | 18.1 | 1250 | 30 | 4 | 1 | 4 | 3 | 60 | 3 | 229 | 4 | 4 | 2 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 3 |
| A4 | 70 | 180 | 545 | 200 | 160 | 17.6 | 16.5 | 30 | 3 | 2 | 3 | 4 | 120 | 5 | 169 | 4 | 5 | 5 | 3 | 3 | 3 | 2 | 5 | 4 | 3 | 3 | 3 |
| A5 | 70 | 257 | 570 | 160 | 204 | 35.4 | 9000 | 240 | 2 | 1 | 3 | 2 | 5 | 2 | 212 | 2 | 3 | 3 | 2 | 2 | 1 | 1 | 3 | 3 | 2 | 3 | 1 |
| A6 | 80 | 248 | 545 | 230 | 192 | 16.9 | 15000 | 280 | 3 | 1 | 3 | 3 | 15 | 4 | 197 | 3 | 5 | 4 | 3 | 3 | 2 | 2 | 4 | 3 | 2 | 2 | 2 |
| A7 | 90 | 272 | 787 | 200 | 194 | 19.7 | 12000 | 10 | 3 | 2 | 4 | 4 | 25 | 3 | 209 | 3 | 4 | 4 | 3 | 3 | 3 | 2 | 4 | 3 | 3 | 2 | 2 |
| A8 | 60 | 330 | 820 | 170 | 195 | 14.3 | 300 | 240 | 4 | 2 | 3 | 4 | 75 | 5 | 203 | 4 | 4 | 5 | 3 | 4 | 3 | 3 | 5 | 4 | 4 | 4 | 4 |
| A9 | 70 | 327 | 855 | 180 | 200 | 2.6 | 19500 | 110 | 3 | 3 | 4 | 5 | 50 | 4 | 208 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 3 | 3 | 3 |
| A10 | 60 | 330 | 745 | 170 | 171 | 22.3 | 9000 | 530 | 5 | 3 | 5 | 4 | 5 | 4 | 203 | 3 | 4 | 3 | 3 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 3 |
| A12 | 80 | 321 | 1420 | 200 | 174 | 181.0 | 20520 | 100 | 5 | 2 | 4 | 5 | 65 | 5 | 207 | 4 | 5 | 5 | 3 | 3 | 3 | 3 | 5 | 4 | 3 | 3 | 3 |
| A12 | 100 | 329 | 405 | 210 | 209 | 7.5 | 12000 | 70 | 3 | 2 | 3 | 3 | 75 | 5 | 234 | 4 | 3 | 4 | 3 | 3 | 3 | 3 | 4 | 2 | 3 | 3 | 4 |
| A13 | 90 | 281 | 465 | 300 | 165 | 67.5 | 2400 | 190 | 4 | 2 | 4 | 4 | 5 | 4 | 173 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | 2 | 2 |
| A14 | 80 | 309 | 870 | 250 | 199 | 6.8 | 6000 | 120 | 4 | 4 | 4 | 4 | 60 | 5 | 203 | 4 | 4 | 5 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 2 |
| A15 | 90 | 291 | 870 | 250 | 188 | 63.5 | 750 | 330 | 3 | 2 | 3 | 4 | 25 | 4 | 193 | 4 | 3 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 3 |

**Table A3.** Normalized decision matrix.

| 3PRLPs | Service-Quality Credence | Unit operation Cost ($) | Lead time (minutes) | Service-Quality Experiences | On-time Delivery | Geographical Location (KM) | Production capacity (T/Annum) | Recyclability (Tonnes) | Disposal | Remanufacture | Reuse | Eco-design production | Environmental Protection Certification | Pollution control | Environmental Expenditure (1000 $) | Health & Safety | Voice of OEMs | Respect for local rules | Flexible working arrangements | Employment Stability | Rights of employees | Training | *Data destruction* | Operational risk | Financial risk | Organizational risk | Security risk |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 0.292 | 0.291 | 0.275 | 0.282 | 0.253 | 0.180 | 0.610 | 0.643 | 0.224 | 0.234 | 0.152 | 0.212 | 0.025 | 0.251 | 0.298 | 0.149 | 0.303 | 0.132 | 0.265 | 0.268 | 0.196 | 0.183 | 0.070 | 0.242 | 0.195 | 0.200 | 0.199 |
| A2 | 0.260 | 0.274 | 0.172 | 0.247 | 0.263 | 0.147 | 0.030 | 0.085 | 0.075 | 0.117 | 0.152 | 0.141 | 0.098 | 0.125 | 0.251 | 0.149 | 0.202 | 0.199 | 0.176 | 0.178 | 0.196 | 0.183 | 0.140 | 0.161 | 0.195 | 0.200 | 0.100 |
| A3 | 0.227 | 0.235 | 0.172 | 0.318 | 0.298 | 0.083 | 0.025 | 0.036 | 0.298 | 0.234 | 0.303 | 0.282 | 0.294 | 0.251 | 0.251 | 0.373 | 0.245 | 0.265 | 0.282 | 0.241 | 0.314 | 0.302 | 0.350 | 0.209 | 0.293 | 0.319 | 0.299 |
| A4 | 0.227 | 0.244 | 0.180 | 0.235 | 0.217 | 0.081 | 0.000 | 0.024 | 0.224 | 0.234 | 0.227 | 0.282 | 0.589 | 0.314 | 0.215 | 0.298 | 0.269 | 0.331 | 0.265 | 0.268 | 0.295 | 0.183 | 0.350 | 0.322 | 0.293 | 0.299 | 0.299 |
| A5 | 0.227 | 0.253 | 0.270 | 0.188 | 0.276 | 0.163 | 0.183 | 0.146 | 0.149 | 0.117 | 0.227 | 0.141 | 0.025 | 0.125 | 0.258 | 0.149 | 0.202 | 0.199 | 0.176 | 0.178 | 0.098 | 0.092 | 0.210 | 0.242 | 0.195 | 0.200 | 0.100 |
| A6 | 0.260 | 0.242 | 0.235 | 0.271 | 0.260 | 0.078 | 0.305 | 0.291 | 0.224 | 0.117 | 0.227 | 0.212 | 0.074 | 0.251 | 0.266 | 0.224 | 0.330 | 0.265 | 0.265 | 0.268 | 0.196 | 0.183 | 0.280 | 0.242 | 0.195 | 0.200 | 0.199 |
| A7 | 0.292 | 0.170 | 0.128 | 0.235 | 0.263 | 0.091 | 0.244 | 0.230 | 0.298 | 0.234 | 0.303 | 0.282 | 0.123 | 0.251 | 0.265 | 0.298 | 0.296 | 0.331 | 0.265 | 0.268 | 0.295 | 0.366 | 0.280 | 0.322 | 0.293 | 0.200 | 0.299 |
| A8 | 0.195 | 0.238 | 0.259 | 0.200 | 0.264 | 0.066 | 0.006 | 0.012 | 0.298 | 0.234 | 0.227 | 0.282 | 0.368 | 0.314 | 0.220 | 0.298 | 0.236 | 0.331 | 0.265 | 0.357 | 0.295 | 0.275 | 0.350 | 0.322 | 0.293 | 0.299 | 0.299 |
| A9 | 0.227 | 0.204 | 0.133 | 0.212 | 0.271 | 0.012 | 0.396 | 0.340 | 0.224 | 0.351 | 0.303 | 0.353 | 0.245 | 0.251 | 0.270 | 0.298 | 0.269 | 0.265 | 0.353 | 0.357 | 0.393 | 0.366 | 0.210 | 0.322 | 0.293 | 0.299 | 0.299 |
| A10 | 0.195 | 0.265 | 0.249 | 0.200 | 0.231 | 0.103 | 0.183 | 0.158 | 0.298 | 0.351 | 0.303 | 0.282 | 0.025 | 0.251 | 0.258 | 0.224 | 0.249 | 0.199 | 0.265 | 0.268 | 0.196 | 0.275 | 0.140 | 0.242 | 0.195 | 0.299 | 0.299 |
| A11 | 0.260 | 0.308 | 0.428 | 0.235 | 0.235 | 0.832 | 0.417 | 0.400 | 0.373 | 0.234 | 0.303 | 0.353 | 0.319 | 0.314 | 0.291 | 0.298 | 0.317 | 0.331 | 0.265 | 0.268 | 0.295 | 0.275 | 0.350 | 0.322 | 0.293 | 0.299 | 0.299 |
| A12 | 0.325 | 0.234 | 0.147 | 0.247 | 0.283 | 0.034 | 0.244 | 0.291 | 0.224 | 0.234 | 0.227 | 0.212 | 0.368 | 0.314 | 0.263 | 0.298 | 0.212 | 0.265 | 0.268 | 0.241 | 0.268 | 0.293 | 0.280 | 0.185 | 0.293 | 0.286 | 0.398 |
| A13 | 0.292 | 0.302 | 0.248 | 0.353 | 0.223 | 0.310 | 0.049 | 0.121 | 0.298 | 0.234 | 0.303 | 0.282 | 0.025 | 0.251 | 0.252 | 0.224 | 0.202 | 0.132 | 0.176 | 0.178 | 0.196 | 0.183 | 0.140 | 0.161 | 0.293 | 0.200 | 0.199 |
| A14 | 0.260 | 0.256 | 0.275 | 0.294 | 0.269 | 0.031 | 0.122 | 0.133 | 0.298 | 0.468 | 0.303 | 0.282 | 0.294 | 0.314 | 0.258 | 0.298 | 0.283 | 0.331 | 0.265 | 0.268 | 0.295 | 0.275 | 0.280 | 0.242 | 0.293 | 0.299 | 0.199 |
| A15 | 0.292 | 0.315 | 0.448 | 0.294 | 0.254 | 0.292 | 0.015 | 0.036 | 0.224 | 0.234 | 0.227 | 0.141 | 0.123 | 0.188 | 0.245 | 0.149 | 0.202 | 0.132 | 0.265 | 0.178 | 0.196 | 0.275 | 0.210 | 0.242 | 0.195 | 0.200 | 0.199 |
| Weights | **0.013** | **0.108** | **0.045** | **0.030** | **0.036** | **0.036** | **0.030** | **0.109** | **0.008** | **0.050** | **0.050** | **0.037** | **0.037** | **0.050** | **0.010** | **0.069** | **0.036** | **0.036** | **0.015** | **0.020** | **0.024** | **0.024** | **0.009** | **0.029** | **0.061** | **0.010** | **0.018** |

**Table A4.** Weighted normalized decision matrix

| 3PRLPs | Service-Quality Credence | Unit operation Cost ($) | Lead time (minutes) | Service-Quality Experiences | On-time Delivery | Geographical Location (KM) | Production capacity (T/Annum) | Recyclability (Tonnes) | Disposal | Remanufacture | Reuse | Eco-design production | Environmental Protection Certification | Pollution control | Environmental Expenditure(1000 $) | Health & Safety | Voice of OEMs | Respect for local rules | Flexible working arrangements | Employment Stability | Rights of employees | Training | *Data destruction* | Operational risk | Financial risk | Organizational risk | Security risk |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 0.004 | 0.031 | 0.012 | 0.008 | 0.009 | 0.006 | 0.018 | 0.070 | 0.002 | 0.012 | 0.008 | 0.008 | 0.001 | 0.013 | 0.003 | 0.010 | 0.011 | 0.005 | 0.004 | 0.005 | 0.005 | 0.004 | 0.001 | 0.007 | 0.012 | 0.002 | 0.004 |
| A2 | 0.003 | 0.030 | 0.008 | 0.007 | 0.009 | 0.005 | 0.001 | 0.009 | 0.001 | 0.006 | 0.008 | 0.005 | 0.004 | 0.006 | 0.002 | 0.010 | 0.007 | 0.007 | 0.003 | 0.004 | 0.005 | 0.004 | 0.001 | 0.005 | 0.012 | 0.002 | 0.002 |
| A3 | 0.003 | 0.025 | 0.008 | 0.010 | 0.011 | 0.003 | 0.001 | 0.004 | 0.003 | 0.012 | 0.015 | 0.011 | 0.011 | 0.013 | 0.002 | 0.026 | 0.009 | 0.010 | 0.004 | 0.005 | 0.008 | 0.007 | 0.003 | 0.006 | 0.018 | 0.003 | 0.006 |
| A4 | 0.003 | 0.026 | 0.008 | 0.007 | 0.008 | 0.003 | 0.000 | 0.003 | 0.002 | 0.012 | 0.011 | 0.011 | 0.022 | 0.016 | 0.002 | 0.021 | 0.010 | 0.012 | 0.004 | 0.005 | 0.007 | 0.004 | 0.003 | 0.009 | 0.018 | 0.003 | 0.006 |
| A5 | 0.003 | 0.027 | 0.012 | 0.006 | 0.010 | 0.006 | 0.005 | 0.016 | 0.001 | 0.006 | 0.011 | 0.005 | 0.001 | 0.006 | 0.003 | 0.010 | 0.007 | 0.007 | 0.003 | 0.004 | 0.002 | 0.002 | 0.002 | 0.007 | 0.012 | 0.002 | 0.002 |
| A6 | 0.003 | 0.026 | 0.011 | 0.008 | 0.009 | 0.003 | 0.009 | 0.032 | 0.002 | 0.006 | 0.011 | 0.008 | 0.003 | 0.013 | 0.003 | 0.015 | 0.012 | 0.010 | 0.004 | 0.005 | 0.005 | 0.004 | 0.003 | 0.007 | 0.012 | 0.002 | 0.004 |
| A7 | 0.004 | 0.018 | 0.006 | 0.007 | 0.009 | 0.003 | 0.007 | 0.025 | 0.003 | 0.012 | 0.015 | 0.011 | 0.005 | 0.013 | 0.003 | 0.021 | 0.011 | 0.012 | 0.004 | 0.005 | 0.007 | 0.009 | 0.003 | 0.009 | 0.018 | 0.002 | 0.006 |
| A8 | 0.003 | 0.026 | 0.012 | 0.006 | 0.009 | 0.002 | 0.000 | 0.001 | 0.003 | 0.012 | 0.011 | 0.011 | 0.014 | 0.016 | 0.002 | 0.021 | 0.009 | 0.012 | 0.004 | 0.007 | 0.007 | 0.007 | 0.003 | 0.009 | 0.018 | 0.003 | 0.006 |
| A9 | 0.003 | 0.022 | 0.006 | 0.006 | 0.010 | 0.000 | 0.012 | 0.037 | 0.002 | 0.018 | 0.015 | 0.013 | 0.009 | 0.013 | 0.003 | 0.021 | 0.010 | 0.010 | 0.005 | 0.007 | 0.010 | 0.009 | 0.002 | 0.009 | 0.018 | 0.003 | 0.006 |
| A10 | 0.003 | 0.029 | 0.011 | 0.006 | 0.008 | 0.004 | 0.005 | 0.017 | 0.003 | 0.018 | 0.015 | 0.011 | 0.001 | 0.013 | 0.003 | 0.015 | 0.009 | 0.007 | 0.004 | 0.005 | 0.005 | 0.007 | 0.001 | 0.007 | 0.012 | 0.003 | 0.006 |
| A11 | 0.003 | 0.033 | 0.019 | 0.007 | 0.008 | 0.030 | 0.012 | 0.043 | 0.003 | 0.012 | 0.015 | 0.013 | 0.012 | 0.016 | 0.003 | 0.021 | 0.011 | 0.012 | 0.004 | 0.005 | 0.007 | 0.007 | 0.003 | 0.009 | 0.018 | 0.003 | 0.006 |
| A12 | 0.004 | 0.025 | 0.007 | 0.007 | 0.010 | 0.001 | 0.007 | 0.032 | 0.002 | 0.012 | 0.011 | 0.008 | 0.014 | 0.016 | 0.003 | 0.021 | 0.008 | 0.010 | 0.004 | 0.005 | 0.007 | 0.007 | 0.003 | 0.005 | 0.018 | 0.003 | 0.007 |
| A13 | 0.004 | 0.033 | 0.011 | 0.011 | 0.008 | 0.011 | 0.001 | 0.013 | 0.003 | 0.012 | 0.015 | 0.011 | 0.001 | 0.013 | 0.002 | 0.015 | 0.007 | 0.005 | 0.003 | 0.004 | 0.005 | 0.004 | 0.001 | 0.005 | 0.018 | 0.002 | 0.004 |
| A14 | 0.003 | 0.028 | 0.012 | 0.009 | 0.010 | 0.001 | 0.004 | 0.014 | 0.003 | 0.023 | 0.015 | 0.011 | 0.011 | 0.016 | 0.003 | 0.021 | 0.010 | 0.012 | 0.004 | 0.005 | 0.007 | 0.007 | 0.003 | 0.007 | 0.018 | 0.003 | 0.004 |
| A15 | 0.004 | 0.034 | 0.020 | 0.009 | 0.009 | 0.010 | 0.000 | 0.004 | 0.002 | 0.012 | 0.011 | 0.005 | 0.005 | 0.009 | 0.002 | 0.010 | 0.007 | 0.005 | 0.004 | 0.004 | 0.005 | 0.007 | 0.002 | 0.007 | 0.012 | 0.002 | 0.004 |
| | + | - | - | + | + | - | + | + | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + | - | - | - | - |
| PIS | 0.004 | 0.018 | 0.006 | 0.011 | 0.011 | 0.000 | 0.018 | 0.070 | 0.003 | 0.023 | 0.015 | 0.013 | 0.022 | 0.016 | 0.003 | 0.026 | 0.012 | 0.012 | 0.005 | 0.007 | 0.010 | 0.009 | 0.003 | 0.005 | 0.012 | 0.002 | 0.002 |
| NIS | 0.003 | 0.034 | 0.020 | 0.006 | 0.008 | 0.030 | 0.000 | 0.001 | 0.001 | 0.006 | 0.008 | 0.005 | 0.001 | 0.006 | 0.002 | 0.010 | 0.012 | 0.005 | 0.003 | 0.004 | 0.002 | 0.002 | 0.001 | 0.009 | 0.018 | 0.003 | 0.007 |

$$r_{ij} = \frac{xij}{\sqrt{\sum_{j=1}^{n} x_{ij}}}, \forall i = 1, 2 \ldots\ldots m; j = 1, 2 \ldots\ldots n \quad \text{(B.10)}$$

where $x_{ij}$ is the value of the $i$th alternative for the $j$th criteria.

***Step 3:*** Weighted normalized decision matrix is calculated by multiplying the above normalized decision matrix with its associated calculated weights.

$$v_{ij} = w_j \times r_{ij}, \forall i = 1, 2 \ldots\ldots m; j = 1, 2, \ldots\ldots n \quad \text{(B.11)}$$

***Step 4:*** Positive Ideal Solution (A+) and Negative Ideal Solution (A-) is identified using the following equations:

$$A^{+} = \{v_1^{+}, v_2^{+}, \ldots\ldots, v_n^{+}\} = \{(max_j v_{ij} | i \in I'),$$
$$(min_j v_{ij} | i \in I')\},$$
$$\forall i = 1, 2 \ldots\ldots m; j = 1, 2 \ldots\ldots n \quad \text{(B.12)}$$

$$A^{-} = \{v_1^{-}, v_2^{-}, \ldots\ldots, v_n^{-}\} = \{(min_j v_{ij} | i \in I'),$$
$$(max_j v_{ij} | i \in I')\},$$
$$\forall i = 1, 2 \ldots\ldots m; j = 1, 2 \ldots\ldots n \quad \text{(B.13)}$$

***Step 5:*** Euclidean distance of each alternative from the PIS and NIS is determined.

$$D^{*} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{+})^2, \forall i = 1, 2 \ldots\ldots m} \quad \text{(B.14)}$$

$$D^{-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{-})^2, \forall i = 1, 2 \ldots\ldots m} \quad \text{(B.15)}$$

***Step 6:*** Relative coefficient of $i$th alternative to ideal solution is calculated.

$$C_i^{*} = \frac{D_i^{-}}{D_i^{*} + D_i^{-}}, \quad \forall\, i = 1, 2 \ldots\ldots m \,\&\, with\ 0 \leq C_i^{*} \leq 1 \quad \text{(B.16)}$$

***Step 7:*** Rank all the alternatives based on $C_i^{*}$ and choose the optimal one.

### *B.3 ε-constraint Method*

The $\varepsilon$-constraint method is a technique commonly used in multi-objective optimization to convert a multi-objective problem into a series of single-objective subproblems. This method allows for the optimization of a single objective function while imposing constraints on the other objectives. The detailed steps are summarized in Algorithm 1.

### *B.4 Non-dominated sorting genetic algorithm II*

The NSGA II (Non-dominated Sorting Genetic Algorithm II) is a multi-objective optimization algorithm designed to find solutions that provide a trade-off between multiple conflicting objectives. It aims to approximate the Pareto front, which represents a set of optimal solutions where improving one objective comes at the cost of degrading another. The algorithm operates through a series of steps described in Algorithm 2.

### *B.5 Non-dominated sorting genetic algorithm III*

The NSGA III (Non-dominated Sorting Genetic Algorithm III) is an advanced multi-objective optimization algorithm designed to handle problems with more than three objectives. It builds upon the principles of NSGA II while introducing reference points and innovative selection mechanisms to improve convergence and diversity on the Pareto front.

**Table B1.** The pseudocode of $\varepsilon$-constraint Method.

```
Algorithm 1: ε-constraint Method
Input: Objective functions: f1(x), f2(x), ..., fn(x)
Constraints: g1(x), g2(x), ..., gm(x)
Epsilon values: ε1, ε2, ..., εn;(initially small)
Output: Approximated Pareto front solutions
Initialize an empty set of solutions ParetoFront
    for each ε in εn:
    Initialize an empty set of solutions Subproblem Solutions
    for each objective fi(x) (except the primary objective):
  Set the objective constraint: fi(x) < = εi:
    Solve the single-objective optimization problem:
    Optimize: primary objective f1(x)
Minf1(x)
      Subject to: g1(x), g2(x), ..., gm(x) and fi(x) < = εn:
    Add the solutions obtained to Subproblem Solutions
    Add Subproblem Solutions to ParetoFront
  return ParetoFront
end Procedure
```

**Table B2.** The pseudocode of NSGA II algorithm.

```
Algorithm 2: NSGA II
Input: Population S
Output: Child Population
Initialize the number of population
Generate random population S
Evaluate objective values
Assign Rank
Generate Child Population for size S
  for each i = 1: Max do
    for each parent and child∈S do
      Assign Rank
      Generate sets of nondominated solutions
      Crossover and mutation
      Loop based on existing solution to next generation
    end for
    Select points on the lower front with high distance
    Generate next
  end for
return Child Population
```

**Table B3.** The pseudocode of NSGA III algorithm.

```
Algorithm 3: NSGA III
Input: Population S, Reference Points Zr
Output:Child Population
Initialize the number of population
Generate random population S
Evaluate objective values
Assign Rank
Generate Child Population for size S
  for each i = 1: Max do
      for each parent and child∈S do
        Assign Rank
        Generate sets of nondominated solutions
        Crossover and mutation
        If child is nondominated w.r.t reference points Zr then
          Add child to child population
      end if
    end for
  Select points on the lower front with high distance to reference points Zr
  Generate next population by selecting the best individuals
  Update population S with next population
  end for
return Child Population
```

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# Household Plastic Waste Mis-Management Effect On Environmental Plastic Pollution.

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**ABSTRACT**

The world today is facing the challenge of rational resource management and recovery for the huge amount of plastic waste. The lack of technical skills for hazardous waste management, inadequately developed recycling and recovery infrastructure, and, above all, a lack of knowledge about rules and regulations are key factors. Behind this huge accumulation of plastic waste. The severity of plastic pollution has detrimental effects on the environment and the entire ecosystem. In this study, domestic waste is one of the main sources of municipal solid waste including food waste, paper, plastic, rags, metal, and glass from residential areas. The main bottleneck lies in its removal. This study could provide the Jaipur government with background information to determine the future implementation of household waste segregation activities. This study also proposes to focus on community involvement in segregation at source, waste minimization, and recycling as a habit and way of life. Local governments can facilitate this by providing bins for sorting waste and by setting up waste banks and recycling facilities on a larger scale than those currently available. The indiscriminate disposal of plastic waste at an astonishing rate has led to the search for comprehensive, effective, and sustainable remediation studies in search of a practical alternative to the management, disposal, and destroy plastic debris. While there are a number of processes such as incineration, landfilling, and recycling already in place, they are unsustainable, expensive, and have serious impacts on the environment, wildlife, marine, and human health.

**KEYWORDS:**

Plastic waste, household waste, waste separation, disposal of plastic, Environment

**Introduction:**

Plastic is the most useful manmade synthetic product, composed of ingredients taken from fossil fuel resources. It enabled the majority of the 21st-century economic and technical revolutions. Polyethylene (LDPE, MDPE, HDPE, LLDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PUR), polybutylene terephthalate (PBT), and nylons are all utilized extensively within the food, pharmaceutical, clothing, shelter, transportation, construction, medical, and recreational time industries over a period of 30 years considering these substances are lightweight, cheap to manufacture, highly resistant to damage, and relatively unbreakable **(Kumar *et al.,* 2007)**.

The use of plastic has increased intensively in daily life due to its durability, lightweight, easy availability, and inexpensiveness. The problem that occurs is that they are not highly stable and not easily degraded, thus accumulating in our environment and causing pollution **(Vijaya & Reddy, 2008)**. Most of the plastic used is inert, which due to improper waste management and uncontrolled littering accumulates in our environment, leading to ecological and health-related problems **(Comăniță *et al.,* 2016)**.

Considering stability and flexibility, the plastics are impeccably adequate for use with numerous accomplishments **(Hossain *et al.,* 2021; Klemeš *et al.,* 2021; Joseph *et al.,* 2021)**. Plastics are now the world's third-largest production material, second only to concrete and steel **(Watts, 2019)**. Similarly, due to its widespread applications across the globe, plastic manufacturing may continue in the future **(Mihai *et al.,* 2021; Kumar *et al.,* 2021)**. The manufacturing and use of plastic products on a global level have been on the rise since 1950. Approximately 8300 million tons of plastic were made, and 6300 million tons of plastic waste were thrown in landfills or dispersed into the environment **(Boucher *et al.,* 2017; Watkins *et al.,* 2019)**. In addition, about 415 million tons of plastic are produced annually worldwide **(Azoulay *et al.,* 2019)**. The contribution of plastic waste to municipal solid waste (MSW) is significant and cannot be ignored **(Barchiesi *et al.,* 2021; Xu *et al.,* 2020)**. The recycling of plastic waste is nearly 14–18% **(Haward, 2018)**. Likewise, part of recycling, 24% of plastic waste is managed through energy recovery, and the remaining 58–62% has directly been disposed of in landfills or open environments **(Geyer *et al.,* 2017)**. Due to the poor global waste management policies, around 10–12 tons of non-degradable harmful plastic waste have been dumped in water bodies **(Hu *et al.,* 2021; Bulannga *et al.,* 2022)**. It is also estimated that 1.2–2.4 tons of plastic waste enter the ocean from rivers annually **(Maghsodian *et al.,* 2022; James *et al.,* 2022)**.

The use of plastics is deeply embedded in our daily lives, in everything from grocery bags and cutlery to water bottles and sandwich wraps. But the quest for convenience has gone too far and we are failing to use plastics efficiently, wasting valuable resources and harming the environment. Plastic overconsumption and mismanagement of plastic waste is a growing menace, causing landfills to overflow, choking rivers, and threatening marine ecosystems **(Plastics Europe. 2015)**. Asia has emerged as a hot spot for plastic pollution because of rapid urbanization and a rising middle class, whose consumption of plastic products and packaging is growing due to their convenience and versatility. But local waste management infrastructure has not kept pace, resulting in large quantities of mismanaged waste.

Household waste is one of the primary sources of Municipal Solid Waste comprising food waste, paper, plastic, rags, metal, and glasses from residential areas **(Abdullah *et al.,* 2017)**. After a single use, these plastic products are either properly disposed of or littered and dumped in open places, roadsides, market places, among others. Properly disposed ones are collected by municipal waste collectors and disposed of in dumpsites and landfills. The illegally disposed and littered ones are blown by the wind or stormwater into road gutters and drainage channels through which they end up in canals, lagoons, other water bodies, and the ocean. Limiting illegal waste, especially plastic waste disposal would limit their entry into the oceans, hence to need to find a way to limit illegal disposal. Also, given poor management, some of the plastic wastes at the dumpsites are dispersed by wind and found in drainage channels and waterways, ending up in the ocean. However, cleaning up road gutters and drainage channels before the onset of rains, as indicated in **Figure.1**, will reduce the flow of plastics into waterways and oceans. Hence this study estimates the factors that influence the willingness of households to participate in the clean-up of road gutters and drainage channels to reduce the flow of plastics into the ocean **(Jambeck *et al.,* 2015)**.

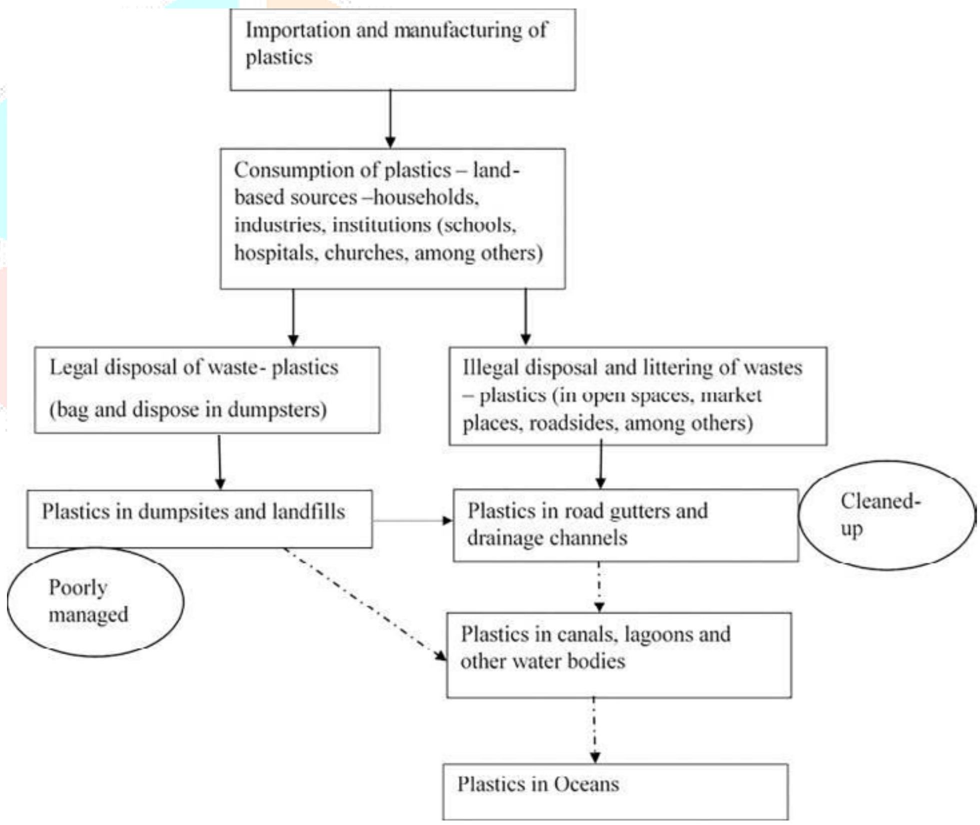



**Figure.1:** Conceptual framework showing the pathway of generation of plastic waste in the environment and their flow into the oceans.

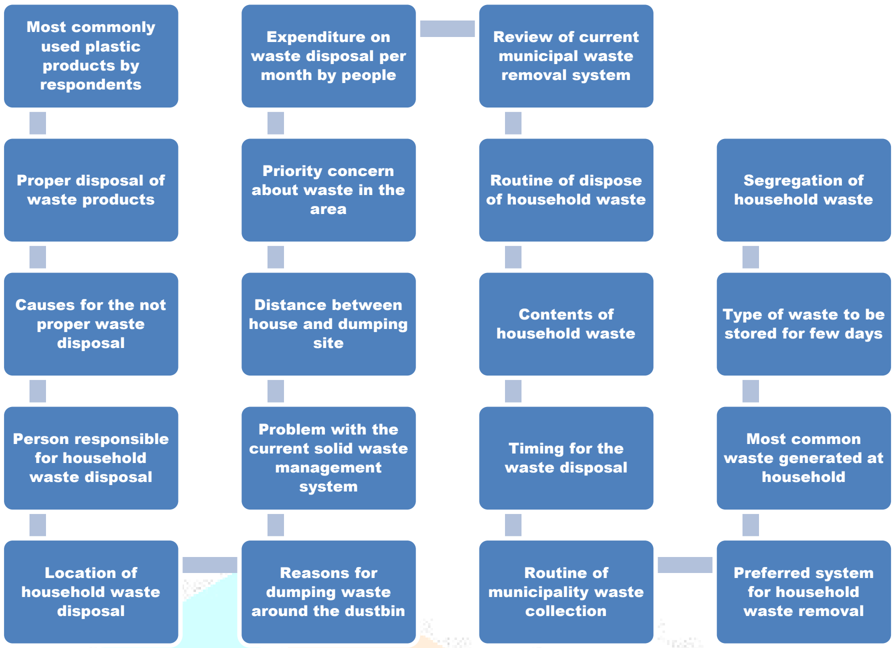
**Material and Methods:**

**Data collection:**

Data were collected from 160 respondents. The study subjects were selected using a random sampling technique. A deductive approach was selected to gather the data. The target population was comprised of all the households in Jaipur city (a population of 3.1 million) but it was impossible to do an investigation with such a large number population therefore, a multi-stage random sampling technique was employed to select an appropriate sample to evaluate the objectives of this study. Therefore, in the initial stage, 4 major areas with respect to each direction (Jaipur East, Jaipur West, Jaipur North, and Jaipur South) were randomly selected in Jaipur City. In the second stage, 4 minor areas from each direction (Jaipur East, Jaipur West, Jaipur North, and Jaipur South) were randomly selected out of all the major areas. The localities in east Jaipur were Adarsh Nagar, Malviya Nagar, Sikar Road, and Subhash Nagar. In the north were Bani Park, Shivaji Nagar, Jhotwara, and Shastri Nagar. In the south were Bapu Nagar, Sanganer, Jawahar Nagar, and Jagatpura; and in the west were Nirman Nagar, Mansarovar, Vaishali Nagar, and Vivek Vihar. In the third stage, 10 households from each minor area were eventually selected as the sample size from neighboring households which were in the distance of 100 to 200 m far from each other. Among the visited households, at least one member of the family was picked randomly for the study regardless of his/her age, educational status, sex, and occupation as long as he/she was willing.

**Methods:**

The data for the study of the nature, pattern, quantum, and variability of plastic intake in each household was obtained from the sampling technique. The most commonly used plastic products were categorized on the nature of plastics such as plastic bags, plastic bottles, storage containers (buckets, bins, barrels, etc.), plastic disposables, and packaging materials (sachets, food packets, food containers, and others). The data of the survey was represented in the form of a bar graph diagram. For the study of plastic use, disposal, and management by each household, an online survey was also conducted which consisted of 30 questions in it regarding the use of plastic at different levels at home and their disposal of, people's behavior regarding plastic use, disposal, its effects on nature, their dependency on it, and various things which were covered in the questionnaire. Data from the survey was represented in the form of a pie diagram. During the online survey, numerous questions were asked in various formats:




## RESULT & DISCUSSION:

### A) Use of plastic products survey

Of the 160 respondents, the largest proportion of them **(45%)** used plastic bottles at high frequency as compared to other plastic products. Despite being aware of the severe impacts of plastics on human health and the environment, the reasons for preferring plastic products are their cheap cost, light weight, durability, easy availability, and lack of alternative materials. The most commonly used plastic products are bottles, storage containers, carry bags, and packaging materials **(Figure.2)**. This was followed by the usage of plastic storage containers (buckets, barrels, and baskets) **(42.5%)**, plastic bags **(35%),** plastic packaging products **(31.88%)** and plastic disposables **(16.25%).** These results revealed that the majority of the respondents in each category use plastic bottles in their daily life. The results also indicated that the usage of plastic bottles is high among residents of Jaipur City, and the residents noticed the increasing trend of usage of plastic bottles from time to time.

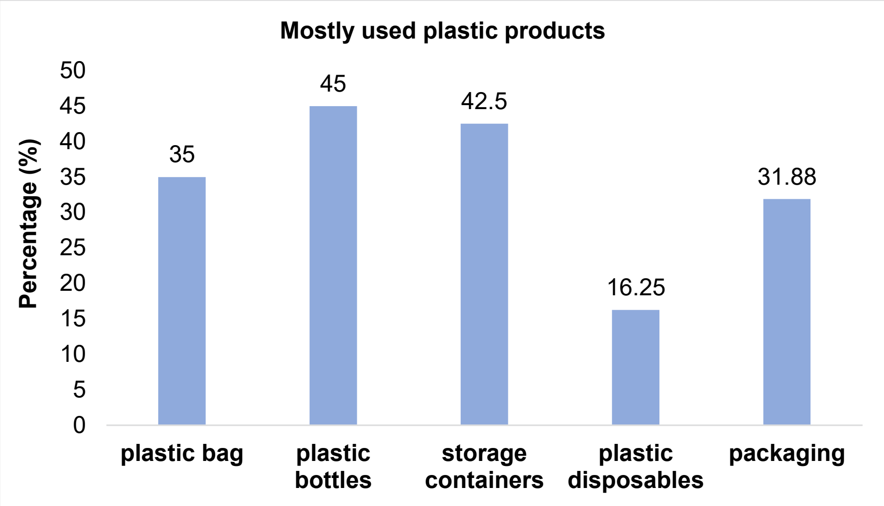



**Figure.2:** Most commonly used plastic products by respondents

**B) Plastic waste management at household level survey**

For the study of plastic use, disposal, and management by each household, an online survey was also conducted and 317 responses were collected. During the survey, it was found that solid waste management was done by the Jaipur Nagar Nigam municipality in all the areas. The majority of the head of the household respondents were literate **(94%)** and were well aware of the solid waste management system. The survey's findings showed that the majority of city residents utilized plastic items extensively in their daily lives, irrespective of gender, education level, age group, or occupation. It is understood that plastic products quickly turn into waste after being used. As a result, the respondents were also questioned regarding the methods they utilized to get rid of waste plastic products.

The respondents were asked if the waste is not disposed of properly, it can pollute the environment **(Figure.3)**, and **97.2%** of the respondents agreed and answered the question yes, that plastic is harmful to the environment and human health if not disposed of properly. The main cause for this problem was investigated and responses were collected **(Figure.4)**. The majority of **63.9%** population is not able to discard the waste as there is no availability of dustbins nearby. **37.4%** population finds it hard to dispose of plastic waste as it is not collected on a regular basis. **28.4%** of respondents have observed that the waste is left on the road.

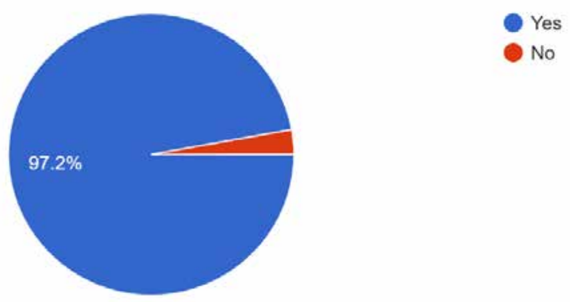



**Figure.3:** Proper disposal of waste products

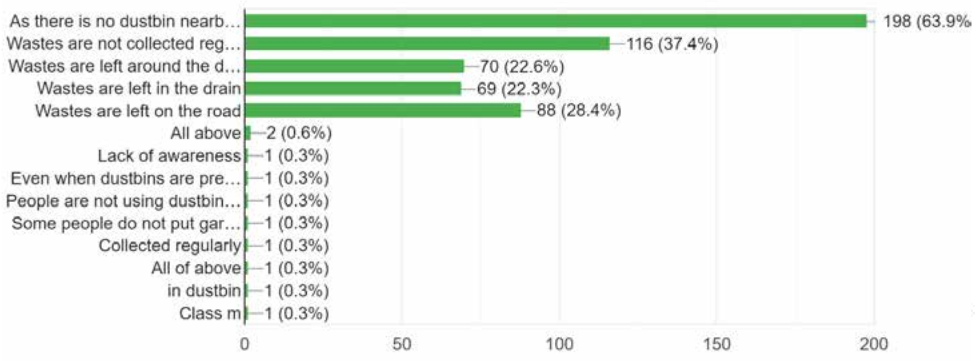



**Figure. 4:** Causes for the not proper waste disposal

Most of the household waste is disposed of by the family member (**83%**) in Jaipur city and in many houses by the servants (**10.7%**). **(Figure.5)**

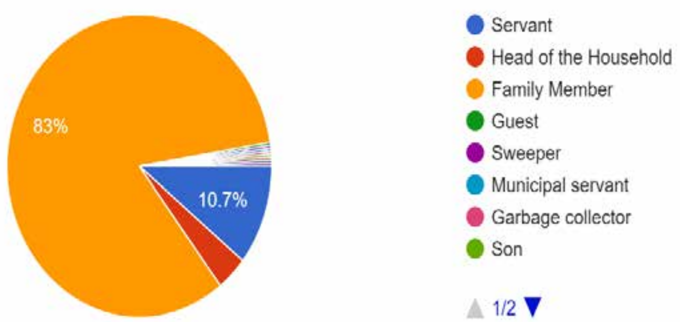



**Figure.5:** Person responsible for household waste disposal

In the survey **(Figure.6)**, **56.2%** of waste is collected from door to door by the Jaipur Nagar Nigam Municipality. **33.1%** of the waste is dumped and collected from public dustbins.

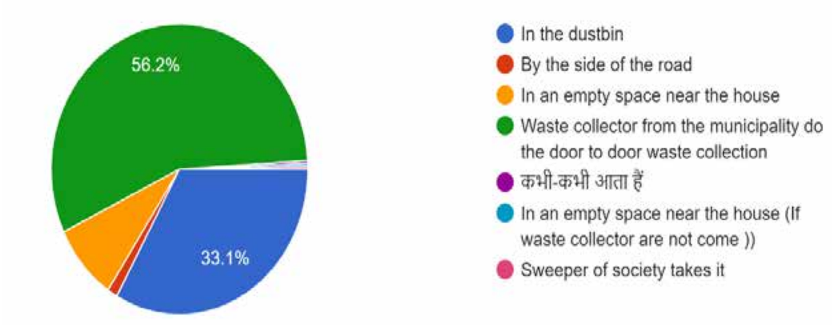



**Figure.6:** Location of household waste disposal

It is commonly noticed that most of the waste is dumped around the dustbin rather than put inside it. The cause was analyzed **(Figure.7)** and **53.9%** responded that it is difficult to put the waste inside the dustbin due to the garbage and litter spread around the bin. **22.7%** of respondents identified the reason to be due to the stray animals (dogs, rats, cats, etc.) waste. **15.8%** mentioned the reason to be the height of the dustbin which can't hold the waste enough and lead to the waste around the dustbin.

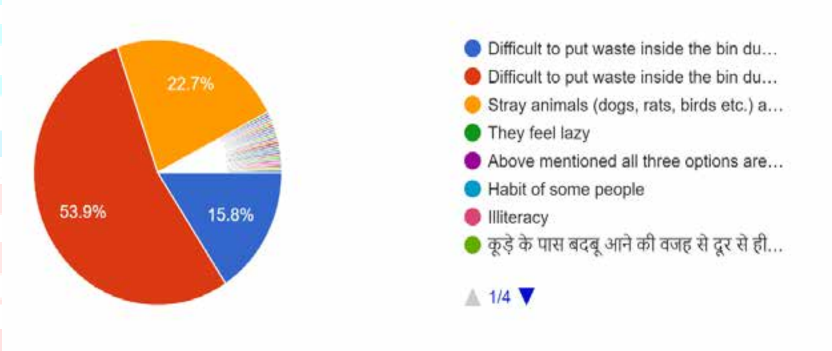



**Figure.7:** Reasons for dumping waste around the dustbin

A worldwide environmental problem is determining how to manage the growing amounts of solid garbage pollution. In addition to the rising amounts, an insufficient management system is largely to blame for the generated waste. Due to inadequate knowledge of guidelines, waste management generally lacks organization and planning. To identify the main problem respondents were asked about their view on the issue with the current solid waste management system **(Figure.8)**. Due to the ignorance of the solid waste management system, several problems to the environment and human health occur, such as the waste is lying around **(82%),** bad odor **(12.3%),** the emergence of rats, unhygienic environment leading to many communicable diseases, etc.

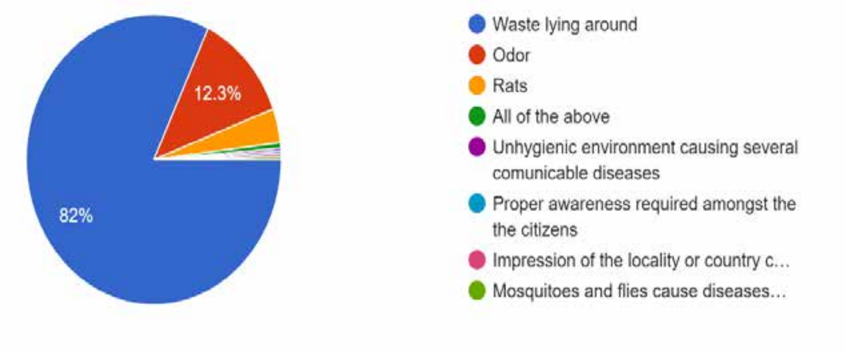



**Figure.8:** Problem with the current solid waste management system

For every household waste management, there is a dumping site for every area. For most of the respondents **(Figure.9)**, the dumping site was within 100 m **(32.8%)**. And the average dumping site distance was found to be 100 m **(25.2%)**, 50 m **(23%),** and 25 m **(18.95).**

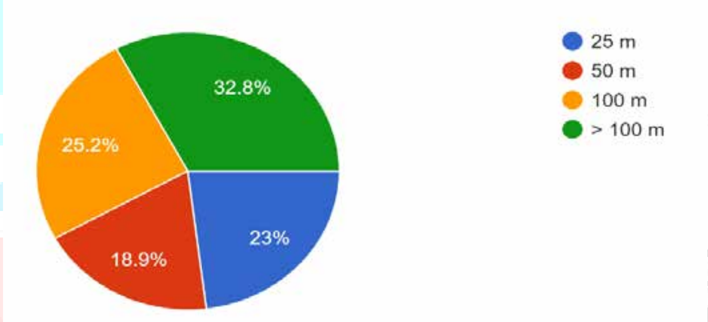



**Figure.9:** Distance between house and dumping site

The waste building up in the neighborhood still is a concern for people. People are now more aware of the effects of waste developed in the surroundings and their effect on the environment **(58%),** human health **(31.9%),** and the piling up of waste and bad odor **(Figure.10)**.

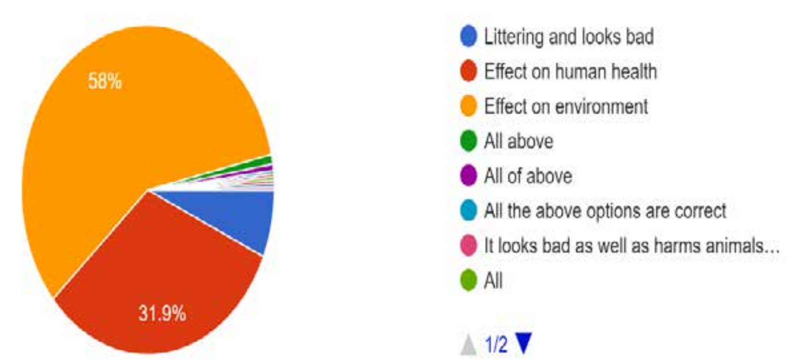



**Figure.10:** Priority concern about waste in the area

Respondents were asked about their current spending for waste disposal per month **(Figure.11)**. Majority of people **43.5%** don't get involved whereas **19.9%** spend Rs. 50, **20.8%** spend Rs. 100, and **15.8%** spend more than Rs. 100 waste disposable per month.

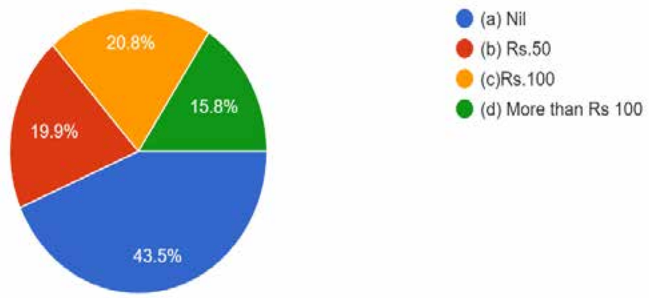



**Figure.11:** Expenditure on waste disposal per month by people

The municipal system is responsible for removing the waste from the city. However, each waste management system is not able to fulfill every task. On asking about the satisfaction level of the concerned municipal system **(Figure.12)**, **39.7%** were commonly satisfied whereas, **28.1%** rated the system to be good enough and **12%** of respondents were very satisfied and happy with the municipal system service. **20.2%** were not satisfied with the municipal system service.

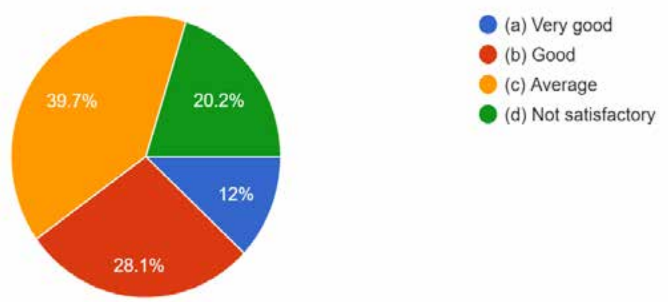



**Figure.12:** Review of the current municipal waste removal system

Every household disposes of its waste on a regular periodic basis. The majority of the people dispose of waste every day **(64.4%)** whereas **26.5%** of people dispose the waste on a period of every two days **(Figure.13)**. This can be considered a positive outcome of initiatives like Swachh Bharat Mission and also because of media highlighting environmental issues like plastic pollution and proper waste management.

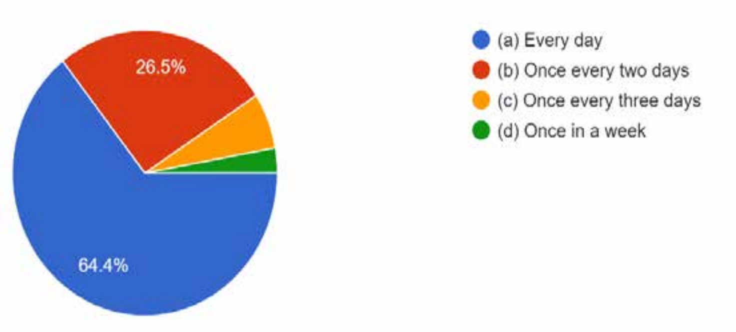



**Figure.13:** Routine of disposing of household waste

The method of disposing of the waste is different for each household **(Figure.14)**. Some people practice waste disposal in polythene or plastic bag **(21.8%),** some utilize disposable bags **(28.4%)** and some uses any type of container **(9.8%).** The majority of people practice waste disposal in a small buckets **(40.1%).** This suggests that people are becoming more aware of the side effects of plastic and the practice of proper waste disposal.

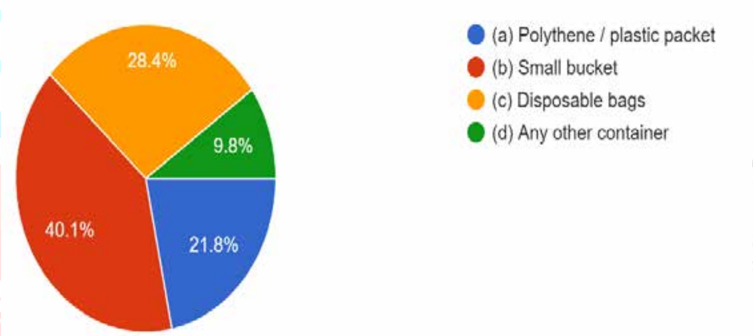



**Figure.14:** Contents of household waste

For disposing of the waste **50.5%** of respondents prefer the time between 6 am to 6 pm whereas for **36.9%** there is no definite time for the waste disposal **(Figure.15)**.

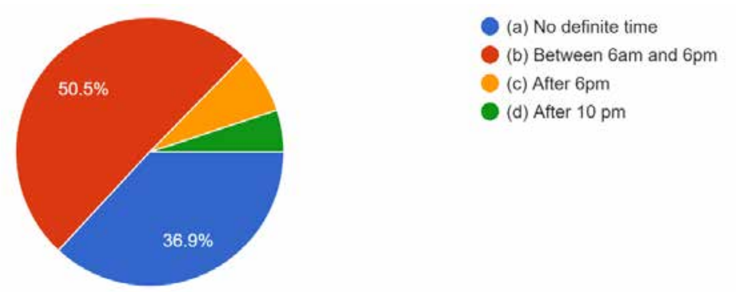



**Figure.15:** Timing for the waste disposal

The municipal waste management system works on a daily basis for the collection of waste and disposal of them. **47.9%** of people every day dispose of waste in the municipal system. **22.1%** of people dispose of waste in a period of two days whereas, **22.7%** of municipal system collects waste irregularly **(Figure.16)**.

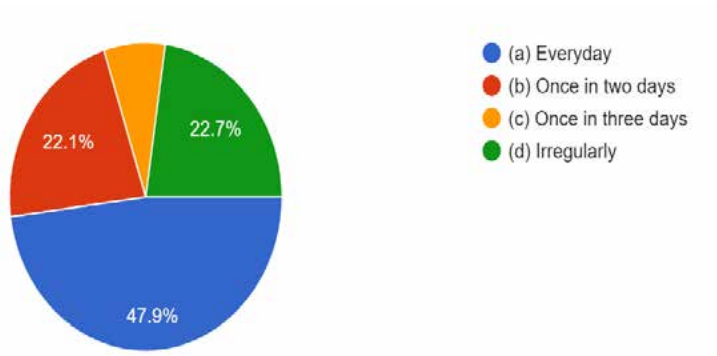



**Figure.16:** Routine of municipality waste collection

Many people prefer different methods for the removal of household waste **(Figure.17)**. **32.8%** of respondents prefer to hand over waste to municipal collectors from the house door while **27.1%** prefer to dispose of waste in the dustbin by themselves. **22.4%** prefer to keep the waste container at a certain time by the roadside and the collectors will collect it from there while **17.7%** prefer that the collector will come to a certain place at a certain time and they will hand over the waste.

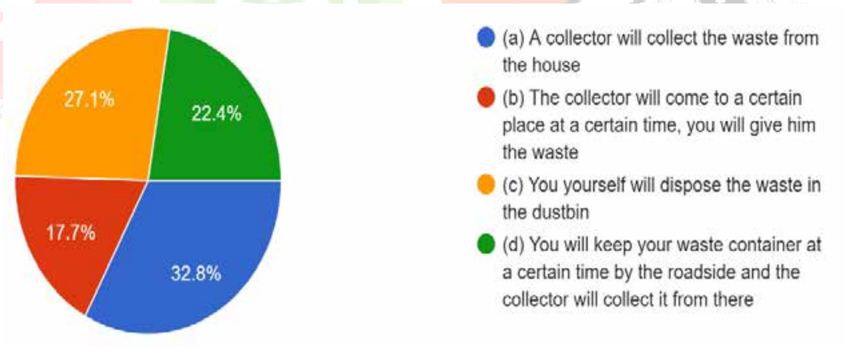



**Figure.17:** Preferred system for household waste removal

The respondents were asked about the most common type of waste generated at home **(Figure.18)**. **54.6%** of people responded it was plastic waste like polythene, bags, and bottles while **25.9%** was paper waste to be generated in households.

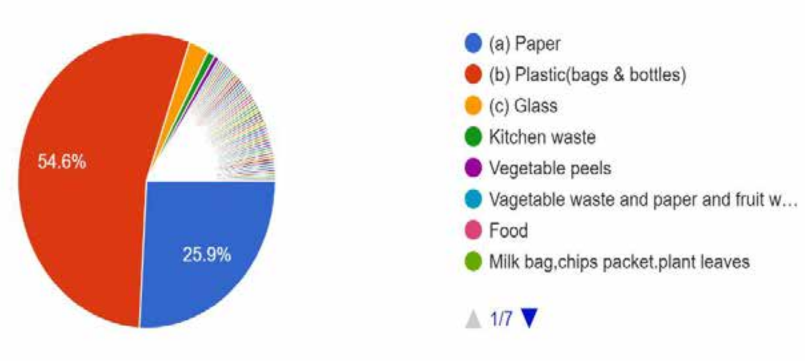



**Figure.18:** Most common waste generated at the household

However, recycling at the societal level needs to be promoted. On asking about the type of waste suitable to be stored for a few days **(Figure.19)**, **41.6%** of respondents reported it to be an electronic waste, **37.2%** reported it to be packaging material including milk covers and other food packaging, **15.1%** mentioned it to the household sanitary waste and **14.8%** reported it to be the batteries.

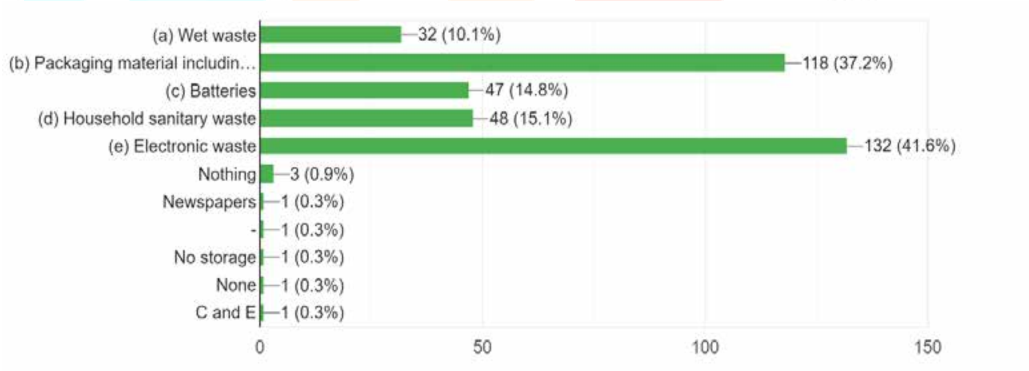



**Figure.19:** Type of waste to be stored for a few days

The respondents were asked if they practice segregating their household waste **(Figure.20)** in which **63.7%** of respondents agreed that it's their responsibility to segregate the biodegradable and non-biodegradable waste at the household level, **16.4%** are aware of segregation and practice it to be mandatory to do it, while **14.5%** thinks that it is an easy way to dispose of waste accordingly.

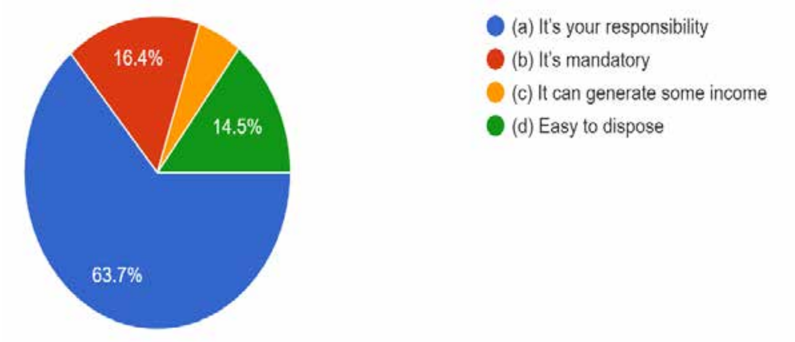



**Figure.20:** Segregation of household waste

The respondents were asked about how they can reuse household waste at home to which the majority of people believed that plastic waste can be recycled and suggested recycling plastic bags, and containers for storage and packaging while others responded to using the kitchen biodegradable waste for making bio compost from them. However, recycling needs to be encouraged at a societal level. Most of the respondents reported that the people in their society tie up with waste recyclers to recycle waste like plastic, paper, books and newspaper, glass items like bottles, iron, and tin waste, electronic waste, etc. By selling the recyclable waste to recyclers, many of the products are being made in reuse and the respondents are also benefited from it as they get money in return which is a good way of promoting the selling of recyclable products and saving the environment from the solid waste pollution.

## CONCLUSION AND RECOMMENDATIONS

This study explores a behavioural perspective in which the way people dispose of waste is related to their attitudes and perceptions. An individual's perception is governed by one's history and current situation, shaped by the individual's values, moods, social circumstances, and expectations. The results of this study are discussed under three aspects: (1) characteristics of household solid waste management practices and respondents' perceptions (2) correlation between socioeconomic background and respondents' background with waste segregation practices and (3) correlation between socioeconomic background and respondents. Knowledge of waste management awareness. One of the main purposes of collecting respondents' characteristics is to understand the correlation between the household's level of participation in SWM activities and the characteristics of the respondents.

The study found that respondents' practice of garbage sorting can be considered low, with respondents sorting their garbage comparable to those who don't, implying that there is still room for 'improvement'. '. The main components of solid waste generated at home are largely compostable leftovers and recyclable plastics, most of which are disposed of without segregation. The local solid waste management agency should focus on using this organic waste on a larger scale and involve more people in the composting program. The development of small-scale community composting could be a potential starting point to accelerate this program without significant investment from local governments. The authorities of the study area provided suitable waste disposal sites, but some were disposed of at inappropriate sites. The majority of respondents are also aware that poor waste management can lead to disease. Age, marital status, and home type were found to be the most discriminatory of their births, suggesting that respondents belonging to this group may be targeted for further interventions. This study suggests that local authorities should design garbage separation programs tailored to the needs of the target population, to ensure high participation rates in the community. Marketing and campaigns should focus on positive perceptions and attitudes towards home waste sorting as well as negative perceptions among non-participants. This study could provide the Jaipur government with background information to determine the future implementation of household waste segregation activities. This study also proposes to focus on community involvement in segregation at source, waste minimization, and recycling as a habit and way of life. Local governments can facilitate this by providing bins for sorting waste and by setting up waste banks and recycling facilities on a larger scale than those currently available. Have. Top-down and bottom-up approaches should go hand in hand for successful sustainable solid waste management.

However, recognizing the limitations of the current study, a more detailed and in-depth study should incorporate a broader area and profound linkages between waste segregation programs and health implications. The combination of survey questionnaires with statistical analysis serves as a springboard to expand the research by involving the community in actual garbage sorting activities. This can be done by initiating a partnership between local authorities, community leaders, and the people themselves within the framework of a pilot study. In addition, the findings of this study will serve as baseline data and pave the way for other researchers and policymakers to conduct more rigorous studies in this area.

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Research article

# Sustainable solid waste management system using technology-enabled end-of-pipe strategies

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A R T I C L E I N F O

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A B S T R A C T

Ever Increasing accumulation of solid waste, attributed to population growth and rapid urbanization, is a serious issue for all nations. This creates hindrance in implementing sustainable solid waste management systems (SWMS), which contribute to socio-economic-environmental-operational (SEEO) benefits for the nations and their citizens. Limited understanding of various solid waste management (SWM) practices, their operational sequence, and other system constraints pose numerous challenges for the concerned authorities and policy-makers. This paper provides a framework depicting three broad categories of strategies for managing solid waste: preventive, end-of-pipe (EOP), and environmental restoration. Among these, the research emphasizes on EOP strategies, being suitable alternative as per current requirements, to deal with massive amounts of generated waste. It further adopts Grey-DEMATEL approach to models the causal relationship among EOP strategies to identify the most influential strategy, which influences other ones. The model suggests waste segregation to be the major enabler for other EOP strategies, as it has maximum overall significance value (R + C) between 1.18 and 1.41 and it is the only one with positive value in "net-effect" computation (R–C), compared to other strategies with negative (R–C) values. This would enable concerned authorities to understand and follow the sequence of actions. Finally, a comprehensive framework is proposed for effective, efficient, and sustainable methods of handling different types of solid waste using technology-enabled EOP strategies. A case study is performed to demonstrate the significance of waste segregation towards SEEO benefits. It indicates that technology-based solutions at decentralized depots and establishment of biogas plant in the vicinity of garbage collection point leads to reduction in transportation cost and energy saving in efficient manner. The ground level implementation of our research in an Indian city resulted in the reduction of daily vehicle requirement from 25 to 20 vehicles, leading to approx. 25% savings in overall transportation costs thereby cutting exchequer's bill by up to $ 2820/month. It also reveals that mechanized and decentralized solutions were not effective for inert waste, its disposal to landfill was more suited alternative.

## 1. Introduction

Rapid growth in population, urbanization, and changing lifestyle of people has recently led to increased rate of resource consumption and solid waste generation. This incessant increase in solid waste is the cause of global concern towards its management in sustainable way (Pujara et al., 2019). The worldwide solid waste generation is anticipated to be more than 2.2 billion tons/year by 2030 (Al-Dailami et al., 2022; Tyagi et al., 2018). This poses significant threats to socio-economic-environmental-operational (SEEO) factors, necessitating a solid waste management system (SWMS) that strikes a balance between SEEO and administrative factors (Palomar et al., 2019). Each year, the world generates 2.01 billion tons of municipal solid refuse, of which one-third is left untreated, thereby aggravating the problem (Wang et al., 2022). A lot of researchers have focused on different countries to highlight the issues in managing solid waste. Sala-Garrido et al. (2023) performed a study to estimate the shadow price of unsorted waste in Chilean municipalities, in order to quantify its negative impact on environment. It was found that the average environmental cost of unsorted rubbish is 297.66 euros per ton and factors that influence the shadow price include population density, tourism intensity and generation of waste per capita. It also highlights the eco-efficiency score of

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0.272 indicating the inefficient operations of concern municipalities, prompting for adopting new and efficient policies in place. Al-Dailami et al. (2022) focused on the issue of solid waste in Yemen, where it is getting generated at a rate of 0.6 kg/day in urban areas and 0.35 kg/day in rural areas. They have also highlighted that the main landfill is in Sana's city, where the amount of waste received is 500,000 tons per year, that compels authorities to look for sustainable ways to manage this increasing amount of solid waste. Considering Indian scenario, Pujara et al. (2023) conducted research highlighting the risk of dumping solid waste in the open on environment and public health. They suggested that integrated solid waste management (ISWM) need to be accomplished and treated systematically. Untreated solid waste disposal also results in water contamination as water picks up a variety of substances when it percolates through such waste, including metals, minerals, organic chemicals, bacteria, viruses, explosives, flammables, and other toxic materials (Naveen et al., 2018). These substances pollute water and also results in leachate formation, which occurs when waste becomes saturated with water (Yeilagi et al., 2021). This unscientific waste disposal further results in steep and unstable slopes that contaminate surface and ground water when leachate runoff into nearby water bodies. This causes high TDS concentrations in nearby water bodies and degrades surface water quality, rendering it unfit for drinking (Hossain et al., 2014; Maiti et al., 2016). Households, markets, institutions, commercial establishments, and roadside sweeping are some of the common sources of solid waste generation. This waste severely affects SEEO aspects that impede the sustainability goals for any nation.

The need of the hour for concerned authorities and decision makers of any nation is therefore to adopt appropriate technologies and strategies, with capabilities to implement an effective, efficient and sustainable solid waste management system (SWMS). Ng and Yang (2023) presented a comprehensive system model for evaluating waste management performance based on a stock-and-flow diagram, emphasizing the importance of deploying more advanced waste valorization technologies in waste management policy and planning. The strategies or practices to be adopted for achieving such solid waste management system can be classified in three categories: waste prevention practices, end-of-pipe strategies, and environmental restoration practices. Fig. 1 depicts the three ways of handling solid waste along with their evaluation measures, required during its adoption. These measures include efficiency, effectiveness, and adaptation rate of practices to be adopted.

The first classification corresponds to preventive practices for solid waste elimination or reduction at both the producer and consumer end. At the production stage, the emphasis is on designing and developing products that produce no or little waste (Zhang et al., 2023). On the contrary, preventive practices at the consumer level necessitate their awareness and responsible behavior towards managing solid waste through the use of sustainable items and changing their daily habits to generate less waste. Government regulations also play a significant role in implementing preventive practices by compelling and convincing citizens and government officials to reduce solid waste. The second classification includes various end-of-pipe (EOP) strategies that process solid waste before its final discharge or disposal to the landfill or environment (Dutt and King, 2014). This mainly include the processes of waste segregation, waste reuse and recycle, waste conversion to energy, and scientific waste treatment such as use of bio-refineries, microbial fuel cells (MFC) etc. (Mukherjee et al., 2021). The third categorization of adopting practices for managing solid waste comprises of environmental restoration practices, which is the last stage when none of the preventive or EOP strategies have been taken or found ineffective. This deals with the unscientifically and untreated solid waste disposal and mainly emphasizes on controlling and managing the expected sever impact to SEEO aspects.

Fig. 1 highlights the adoption of these different practices based on tradeoff between the key measures of efficiency, effectiveness, and adaptability rates. Prevention of solid waste is the most preferred and least expensive alternative among all. Restoration, on the other hand, is the least preferred and most expensive option due to the delay in managing the waste and involvement of processes handling untreated or unscientifically treated waste disposed to landfills. EOP strategies falls in-between the preventive and restoration practices with respect to the considered measures. Although adoption of preventive practices weighs more preference than other two classifications, but ever-increasing solid waste generation and its inappropriate treatment before disposal strongly challenges SEEO benefits, which compels firms and authorities to first deal with the generated waste. The concerned authorities therefore look forward to adoption of EOP strategies. The use of technology-based solutions with advance capability of predicting and forecasting the rate of solid waste generation, and process monitoring further compliments the adoption of strategies to achieve an effective and efficient SWMS (Elshaboury et al., 2021; Vu et al., 2019). Blockchain is an effective technology that helps in real-time monitoring of operations and ensure traceability with the system (Gupta and Shankar, 2023). Another major issue faced by authorities is lack of a framework, highlighting the influence of strategies on one-another, which would enable them to take informed decision knowing the sequence of actions to implement.

There is ample research in the area of solid waste management. However, there is still a gap in literature, to the best of our knowledge, where the research provides an influence-based decision model and use it to develop a comprehensive framework that would enable the authorities understand what sequence to follow while adopting EOP strategies, and further to use the framework to deal with different types of solid waste in sustainable manner. Moreover, there is a research gap with respect to ground level implementation of proposed framework to depict its positive impact on SEEO aspects. There is dearth of studies detailing the technology-enabled EOP implementation in solid waste management. This research attempts to perform the same. To fill the mentioned research gaps in literature, this study first focuses on EOP strategies to find their causal relationships in terms of their influence on one another. Highly influential strategy(s) are also termed as causal strategy(s), as their implementation results in adoption of rest of the strategies (referred to as effect strategies). Once identified the most influential EOP strategy, the paper then proposes a framework depicting various technology-enabled sustainable ways of disposing different types of solid waste. Finally, a case study is presented to demonstrate how implementing the proposed waste management practices results in SEEO benefits. The novelty of this research is therefore based on.

(i) suggestion to adopt EOP strategies as a suitable alternative to handle solid waste (Section 1 and Section 2.3),
(ii) identification of the most influential EOP strategy based on mathematical modeling using Grey-DEMATEL (Section 4.1),
(iii) proposal of a comprehensive framework depicting the strength of technology towards mechanization of processing different types of waste (Section 4.2), and
(iv) case study to support the significance of resulted influential EOP strategy towards handling solid waste through its positive impact on SEEO aspects (Section 6).

The flow of research is as follows. Section 2 provides literature review on solid waste management issues, business cases used as benchmarks, and the importance of EOP strategies for solid waste management. Section 3 emphasizes on research need analysis. Session 4 discusses adopted methodology for establishing causal relationships between EOP practices using Grey-DEMATEL approach. Section 5 proposes conceptual framework depicting (a) role of organizational and operations management aspects and (b) sustainable ways of disposing different types of solid waste. Section 6 presents a case study showing the ground level implementation of proposed framework and its results depicting its benefits towards SEEO aspects. Section 7 focuses on the uniqueness of our research by providing a comparative analysis with existing literature on qualitative and quantitative basis. Finally, conclusions are covered in section 8.

## 2. Literature review

### 2.1. Solid waste management issues

The rate of resource consumption and waste generation is getting increased to multiple folds due to rapid growth in population, urbanization, economic status, and changing lifestyle of people for both developed and developing economies (Simoes and Marques, 2012; Fan et al., 2020). More than 54% of global population live in urban cities and the urban growth of approximately 2% per year (UN Habitat, 2016) further results in rapid production of household waste, which has adverse effects on society as a whole. Unawareness and low level of participation of citizens towards SWM practices, further increases the difficulty level. Kubanza (2020) performed qualitative research to examine the role of community participation in managing solid waste in Johannesburg, South Africa. It revealed that lack of awareness and low community participation exacerbates the concerned problem despite availability of technology-based solutions. The problem is therefore more prevalent in developing economies such as India, where the population is large and people are unaware of ways to deal with the generated solid waste. The other involved stakeholders also find it difficult to handle disposed solid waste, due to limited clarity on appropriate actions to be taken and unavailability of adequate resources and waste treatment methods. Despite being aware of the significance of managing solid waste, it becomes a highly challenging task for the authorities, when the waste is disposed to dumpsites without any prior scientific treatment. This unscientifically treated and unorganized solid waste disposal, along with shortage of municipality's waste management system and lack of knowledge towards waste management practices adversely affect overall ecosystem, mainly through water and air pollution (Rahman and Bohara, 2023). This further results in severe long-term problems such as leachate formation, landfill gas (LFG) emissions, odor problems, and various health concerns. In India, due to limited waste treatment plants and insufficient sanitary landfills, less than 70% of waste is currently collected, resulting in overflowing waste bins, foul-smelling litter on streets, ground-level pollution, and clogged drainage systems. Moreover, emission of landfill gases such as methane (40%–50%), carbon dioxide, ammonia, sulphides, hydrogen, carbon monoxide, and others poses serious environmental, ecological, and health consequences for human society (Al-Dailami et al., 2022; Kashyap et al., 2016; Siddiqui et al., 2013; Shaw et al., 2012). Also, water flowing through these landfills result in the formation of toxic leachate, which contaminates underground water. To reduce the effect of leachate, one of the solutions is to construct the liners around landfills. However, if the waste is not segregated or treated before its disposal, the liners may also get punctured. The environmental risks of LFG emissions can be reduced by prior extraction and collection of emitted gases using a series of wells and a blower vacuum system. Kashyap et al. (2016) demonstrated the method of recovering LFG from an unscientifically managed landfill site in Ghazipur, Delhi, India, and also highlighted the challenges encountered. Rahman and Bohara (2023) performed a study to investigate the public's preference and propensity to pay for a superior solid waste management system and concluded that the waste management policy should be localized. They also revealed that sustainable solid waste management practices may enhance the opportunity to increase income level by promoting tourism and other attractive places in a country. Despite different ways to treat solid waste, most of the local bodies administering a city/town in India find it difficult to manage and convert the dumpsites into sanitary landfills, which could have enabled the collection of LFG and treat leachate. The reasons being limited finances, unsegregated and unsustainable waste collection practices, lack of appropriate technology and skilled manpower, low participation of people, and huge capital expenditure associated with waste and leachate treatments. This study therefore presents the three major alternatives of sustainable SWMS, available to authorities and emphasizes on adoption of EOP practices at first. It further proposes an influence-based mathematical model to identify the causal relationships among EOP strategies. The next section highlights the three business cases, which successfully modelled the required waste management practices and received the recognition of being "zero-waste" cities in India.

### 2.2. Business cases

It is evident that untreated or unscientifically treated solid waste disposal has adverse effect on environmental, ecological, and health related aspects. This requires all stakeholders, including citizens, workers and concern authorities, to make collaborative efforts to make their cities as "zero-waste" city. Due to the increasing concerns of managing solid waste, involved authorities are compelled to take appropriate actions. The performance of entire system is assessed on the basis of overall output in terms of reducing cost and improving operations. This research thus attempts to assist concern stakeholders in the long run by providing them with a complete basis of resource planning to achieve zero waste target using the three successful Indian cases.

The three selected cities include Indore, Surat, and Vijaywada, based on their rankings (1st, 2nd, and 3rd, respectively) in MoHUA's Swachh Survekshan (2021). Singh (2021) study the case of Indore and highlighted that here, waste segregation has been made a mandatory practice at the source. Every day, approximately 1115 metric ton (MT) of solid waste is generated, with approximately 90% of it being collected. The collected waste is transported to ten stations located throughout the city, where waste workers ensure that the waste is properly segregated. The waste is then transported to a waste processing facility, where approximately 550 MT of organic waste generated daily is converted to compost and sold to farmers as manure. Different companies use recyclable waste, while non-recyclable and inert waste is used as concrete in the construction industry, road construction, and in crushed form to make bricks and paver tiles. The required segregation of waste, conversion to compost, monitoring of transportation, dealing with recyclable and non-recyclable waste only happens due to incorporation of technology-enabled mechanized solutions.

The second cleanest city, Surat generates approximately 2200 MT of solid waste per day (PIB, 2021). Here, the waste is collected and separated in a centralised waste processing treatment plant at Khajod. 30%–35% of total waste consisting of wet organic material that is been composted; 35%–40% consists of dry organic material that is used in producing Refuse-Derived Fuel (RDF) that works on a 'waste to energy (WtE)' approach; and remaining plastic and rubber items are send for recycling. Construction waste is recycled into various building materials such as sand, block, Paver block, and so on (Rezaei, 2018).

The third cleanest city, Vijaywada, is divided into 64 sanitary divisions and 64 municipal wards for managing the solid waste. The total waste generated per day is approximately 550MT, of which approximately 265MT is wet waste and 285MT is dry waste. The city processes 240MT of wet waste and 229MT of dry waste for composting and other commercial purposes, while the remaining 81MT is disposed to landfills, where technology-enabled solutions are further used for its processing in a sustainable way (IUC, 2021).

These implemented SWM system in mentioned cases provide valuable insights to concern decision makers, as to how technology-enabled solutions contribute in required waste management practices. This involves waste segregation, waste recovery, conversion of waste to useful product/energy, minimization of dumping to landfills/incinerators, close monitoring of processing waste, creating awareness among people for better habits and their increased participation in the processes. Though regular attempts are made in all the mentioned cases for adopting waste preventive practices and also making people aware of its benefits to SEEO aspects, still it is evident that more efforts are taken towards managing already generated solid waste using EOP practices, before its final disposal to landfills. This research therefore proposes a model highlighting the most influential EOP strategy to initiate with and a comprehensive framework showing the sustainable ways to handle different types of waste.

### 2.3. Perception towards significance of EOP strategies

Among the SWM strategies highlighted in Section 1, waste prevention practices are preferred alternative over EOP and restoration practices, as this is a preventive measure that reduces generation of solid waste. However, as evident from the previous sections, considering current context where tremendous amount of waste is getting generated on a regular basis with severe impact on SEEO aspects, the need of the hour is its management through adoption of EOP strategies (Dutt and King, 2014). Prior to roughly two decades ago, it was believed that EOP strategies to treat waste inhibits prevention of waste generation and the organizations that rely on these practices, would lose out on their operational efficiency benefits with respect to waste minimization (Clelland et al., 2000; Porter and van der Linde, 1995). A few researchers stated that EOP practices result in lower waste reductions because it separates waste observation from waste generation, thereby reducing employees' capability to eliminate waste. It also diminishes awareness level of workers and their ability to identify the root causes (Rothenberg et al., 2001; King and Lenox, 2001). A few researchers indeed emphasize on the requirement of stringent government regulations to avoid adoption of EOP (Kemp, 2000; Cebon, 1992). However, this leads to a natural question as to why then organizations still look for adopting EOP practices. There are a few studies that highlighted a straightforward fact about EOP adoption by organizations, which states that its implementation provides a way to manage the waste without disturbing ongoing production processes (King, 1995). A few used organizational theory to predict that managers have a tendency, in most of the cases, to pick least disruptive response to new requirements (Galbraith, 1974; Thompson, 1967). This conventional perception about EOP strategies inhibiting waste prevention has been challenged later by a few researchers. Dutt and King (2014) conducted case studies on EOP systems and highlights that EOP treatment provides relevant data related to waste, which can further be used and analyzed to reduce the waste. Considering the research in the area of quality management and other management principles and integrating those with EOP strategies, contributes in exploring the strengths of EOP towards sustainable SWMS. These contribute to the collection of data on solid waste treatment, measurement, and analysis, which enables the application of various analytic tools to suggest future waste reduction strategies (Pil and Rothenberg, 2003). Thus, EOP strategies provide information regarding the causal linkages between the production process and the point of waste generation (Pil and Rothenberg, 2003); like how quality management practices facilitate continuous process improvement by providing the necessary data.

Various predictive analytics tools and forecasting methods can be used for an accurate prediction rate of waste generation, be it municipal solid waste or other types of waste such as e-waste of solar photovoltaic disposal (Elshaboury et al., 2021; Vu et al., 2019; Gautam et al., 2021). Concerning municipal solid waste, accurate forecasting of its generation enables an effective design of SWMS with efficient operations in place (Soni et al., 2019). There are various factors that impact the amount of solid waste generation such as geographic locations, seasonal changes, population, urbanization, changing lifestyle, regulations, waste management infrastructure etc. (Singh and Satija, 2018; Kolekar et al., 2016). The availability of data on all these variables not only help in anticipating generation of waste in future for better optimization in waste management but also towards implementation of circular economy to reuse the waste material (Kolekar et al., 2016). Circular economy is a sustainable alternative to traditional linear model and helps in reducing waste by reuse, repair, refurbish, and recycle existing material. It helps in waste disposal methods while performing material and energy recovery (Ministry of Housing and Urban Affairs, 2021). Thus, there is an abundance of research leveraging potential of technology for managing solid waste through circular economy principles towards optimizing underlying operations such as waste collection, transportation, monitoring. These mainly include analytics, forecasting methods such as artificial intelligence methods, statistical analysis, time-series analysis, material flow analysis (Soni et al., 2019; Abbasi and Hanandeh, 2016), and multi-objective optimization (Hirani, 2005) techniques. The study conducted by Soni et al. (2019) compared various artificial intelligence models to evaluate their capability in forecasting the rate of solid waste generation. This helps in advance planning of required operations.

As EOP practices facilitate the required data for quantification and accurate measurement of waste, its integration with technological advances result in a system with proper planning of operations to manage solid waste in a sustainable manner. This will further prevent its adverse effects on SEEO aspects and also helps in the reduction of waste generation. Thus, technology-enabled EOP strategies enable local administrative authorities and other concerned managers to analyze waste, facilitate information for future preventive practices, and manage generated solid waste before its final disposal to the landfills. Although, technology-enabled EOP poses challenges to sustainable system as it increases the complexity and cost of implementation, but a well-structured framework would enable managers and concern authorities understand the sequence of taking adequate actions to reap maximum benefits while minimizing cost and complexity. This study attempts to provide such framework.

### 2.4. Research gaps

Many solid waste management studies focus on developing nations and supports the fact that existence of sustainable SWMS is vital for the country's development and economy as a whole. This requires collaborative efforts of private NGOs, government towns, and environmental engineers to put in place a framework of improvement measures and progressive ways to attain the objective of sustainable SWM (Al-Dailami et al., 2022). The proposed research is centered on the creation of such a framework. As evident from the previous sections, despite an abundance of research in the field of SWMS, there is a dearth of studies with the focus on (i) operations management aspect of adopting EOP strategies for different types of solid waste, (ii) establishment of causal relationship among EOP strategies, (iii) a comprehensive framework based on identified influential EOP strategy, and (iv) ground level implementation to validate the proposed framework. This study attempts to bridge these gaps in literature by, (i) developing a framework depicting the operational aspects of preventive, EOP, and restoration practices and focusing on the EOP strategies towards sustainable system, (ii) establishing the cause-effect relationship among various EOP strategies using mathematical model, Grey-DEMATEL approach, (iii) proposing a comprehensive framework on managing solid waste using most influential EOP strategy (dominating cause-strategy), and (iv) ground level implementation in case-based approach to depict the actual SEEO benefits of implementing proposed framework. The comparative analysis of our research with previous research work on some of the factors such as, used methodology, ground level implementation of research and managerial implications has also been shown post case study analysis.

## 3. Research need

The major issue with solid waste management is its disposal without any prior scientific treatment to the landfills. This poses significant risks to SEEO aspects. As a result, this study seeks to comprehend the consequences of untreated waste disposal and to identify sustainable solutions.

represented below from Eqs. (1)–(4) for reference.

$$\otimes z_1 + \otimes z_2 = \left[\underline{z}_1 + \underline{z}_2, \overline{z}_1 + \overline{z}_2\right] \quad \text{Eq. (1)}$$

$$\otimes z_1 - \otimes z_2 = \left[\underline{z}_1 - \overline{z}_2, \overline{z}_1 - \underline{z}_2\right] \quad \text{Eq. (2)}$$

$$\otimes z_1 \times \otimes z_2 = \left[\min\left(\underline{z}_1\underline{z}_2, \underline{z}_1\overline{z}_2, \overline{z}_1\underline{z}_2, \overline{z}_1\overline{z}_2\right), \max\left(\underline{z}_1\underline{z}_2, \underline{z}_1\overline{z}_2, \overline{z}_1\underline{z}_2, \overline{z}_1\overline{z}_2\right)\right] \quad \text{Eq. (3)}$$

$$\otimes z_1 \div \otimes z_2 = \left[\underline{z}_1, \overline{z}_1\right] \times \left[\frac{1}{\underline{z}2}, \frac{1}{\overline{z}2}\right] \quad \text{Eq. (4)}$$

The traditional approach of grey-DEMATEL first converts grey number into a real number followed by DEMATEL analysis. This conversion results in the loss of information leading to inaccurate results, as implementation of both steps are done independently. This study therefore follows the steps defined by Bai and Sarkis. (2013), which does not convert grey numbers until calculation of degree of prominence and net cause/effect is performed. Following section provides details about used approach in current context.

### 4.1.3. Application of Grey-DEMATEL

The approach consists of following steps.

**Step 1.** Formulate a fuzzy direct-relation matrix for each decision maker. This step has following sub-steps.

*Sub-step 1:* Defining grey linguistic scale.

For the required analysis, a five-level scale has been used indicating the influence of one factor on the other using the extremes between no influence to very high influence. The five-level scale along with their associated grey numbers are shown as below.

(a). No Influence: [0,0]
(b). Very Low Influence: [0,1]
(c). Low Influence: [1,2]
(d). High Influence: [2,3]
(e). Very High Influence: [3,4]

*Sub-step 2:* Formulating Direct-relation matrix.

To establish relationship between EOP strategies, three decision makers were requested to develop pair-wise comparison of EOP strategies using linguistic terms. These decision makers are high-ranked government officials in the concerned department, dealing with solid waste management. Thus, in total 3 grey matrices, corresponding to 3 decision makers, were obtained with each matrix having grey numbers as its elements. Let $c = \{c_i | \ i = 1,2,..,n\}$ corresponds to the criteria. Here there are five criteria i.e. five EOP strategies including, waste segregation, waste reuse, waste recycle, incineration, and proper landfilling. Also, let $k$ corresponds to decision makers and the corresponding grey decision matrix would therefore be $M^1, M^2,..,M^k$. This study includes direct-relation grey matrix for each of the three considered decision makers and each element of the matrices corresponds to the influence of one criterion over other. The input values by decision makers for pair-wise influence matrices are provided in supplementary file as Table 1(a, b,c).

*Sub-step 3:* Combine the judgements of all three decision makers using averaging their inputs using Eq. (5), to result into an aggregated decision matrix $M$. The aggregated grey direct-relation matrix is provided in the supplementary file as Table 2.

$$M = \left(\sum_{i=1}^{K} M^k\right) / K \quad \text{Eq. (5)}$$

**Step 2.** Once the aggregated grey direct-relation matrix is obtained, the next step is to obtain normalized grey direct-relation matrix, $N$, using Eqs. (6)–(8). The generated normalized matrix is further used for computing total relation matrix in the next step. Normalized matrix can be referred to in the supplementary file as Table 3.

$$\otimes z = \left[\underline{z}, \overline{z}\right] = \frac{1}{\underset{1 \le i \le n}{max} \sum_{j=1}^{n} \otimes m_{ij}}, i,j = 1,2,..,n \quad \text{Eq. (6)}$$

$$N = \otimes z \,.\, M \quad \text{Eq. (7)}$$

$$\otimes n_{ij} = \left[\underline{z} \,.\, \underline{m}_{ij}, \overline{z} \,.\overline{m}_{ij}\right] \quad \text{Eq. (8)}$$

**Step 3.** This step involves formulation of total relation matrix (T) using Eq. (9), where $I$ denote identity matrix. Finally computed total relation matrix is shown in Table 1.

$$T = N(I - N)^{-1} \quad \text{Eq. (9)}$$

**Step 4.** This step involves developing causal relationship and digraph diagram, which can be completed in below mentioned sub-steps.

*Sub-step1:* Determine row ($\otimes R_i$) and column ($\otimes C_j$), as sum of each row $i$ and column $j$ using total-relation matrix, shown in Table 1. Use Eqs. 10 and 11 for determining row and column sums.

$$\otimes R_i = \sum_{j=1}^{n} \otimes t_{ij}; for\ all\ i \quad \text{Eq. (10)}$$

$$\otimes C_j = \sum_{i=1}^{n} \otimes t_{ij}; for\ all\ j \quad \text{Eq. (11)}$$

The $\otimes R_i$ values represent the sum of both direct and indirect influence of a EOP strategy, $i$, on other EOP strategies for SWMS. In the same way, the $\otimes C_j$ values represent the sum of both direct and indirect influence that a EOP strategy, $j$, is receiving from other EOP strategies.

*Sub-step 2:* This step comprises of determining the overall significance ($\otimes OS_i$) or importance and net effect ($\otimes NE_i$) of EOP strategy $i$, using Eq. 12 and 13. The value of $\otimes OS_i$ represents total cause and effect i.e. larger the value means higher overall prominence/significance or influence of EOP strategy $i$ on other strategies. On the other side, the value of $\otimes NE_i$ shows net effect or cause of strategy $i$. To classify cause factors and effect factors, it is important to look for the value of $\otimes NE_i$; If $\otimes NE_i > 0$, then strategy $i$ is a net cause; and if $\otimes NE_i < 0$, then strategy $i$ is net effect of other strategies. The results are shown in Table 2.

$$\otimes OS_i = \left\{\otimes R_i + \otimes C_j \middle| \ i = j\right\} \quad \text{Eq. (12)}$$

$$\otimes NE_i = \left\{\otimes R_i - \otimes C_j \middle| \ i = j\right\} \quad \text{Eq. (13)}$$

*Sub-step 3:* This step helps in developing overall DEMATEL causal

**Table 1**
Total-relation matrix (T).

| EOP Strategy | Waste Segregation | Waste Reuse | Waste Recycle | Incineration | Proper Landfill |
|---|---|---|---|---|---|
| **Waste Segregation** | [0.000,0.010] | **[0.281,0.314]** | **[0.316,0.353]** | **[0.194,0.238]** | **[0.414,0.450]** |
| **Waste Reuse** | [0.000,0.005] | [0.000,0.019] | [0.043,0.098] | [0.006,0.024] | **[0.196,0.238]** |
| **Waste Recycle** | [0.000,0.005] | [0.000,0.041] | [0.012,0.033] | [0.006,0.087] | [0.190,0.235] |
| **Incineration** | [0.000,0.004] | [0.000,0.014] | [0.008,0.045] | [0.004,0.016] | [0.127,0.175] |
| **Proper Landfill** | [0.000,0.024] | [0.000,0.082] | [0.063,0.135] | [0.032,0.086] | [0.016,0.065] |

**Table 2**
Degree of influence and net cause/effect of EOP strategies.

| EOP Strategy | R | C | Overall Significance (R + C) | Net Effect (R–C) |
|---|---|---|---|---|
| Waste Segregation | [1.181,1.366] | [0.000,0.049] | [1.181,1.415] | [1.181, 1.317] |
| Waste Reuse | [0.246,0.380] | [0.281,0.471] | [0.527,0.851] | [-0.035, −0.091] |
| Waste Recycle | [0.208,0.402] | [0.443,0.665] | [0.651,1.066] | [-0.234, −0.263] |
| Incineration | [0.139,0.253] | [0.217,0.451] | [0.356,0.705] | [-0.078, −0.198] |
| Proper Landfill | [0.111,0.393] | [0.944,1.158] | [1.055,1.551] | [-0.833, −0.766] |

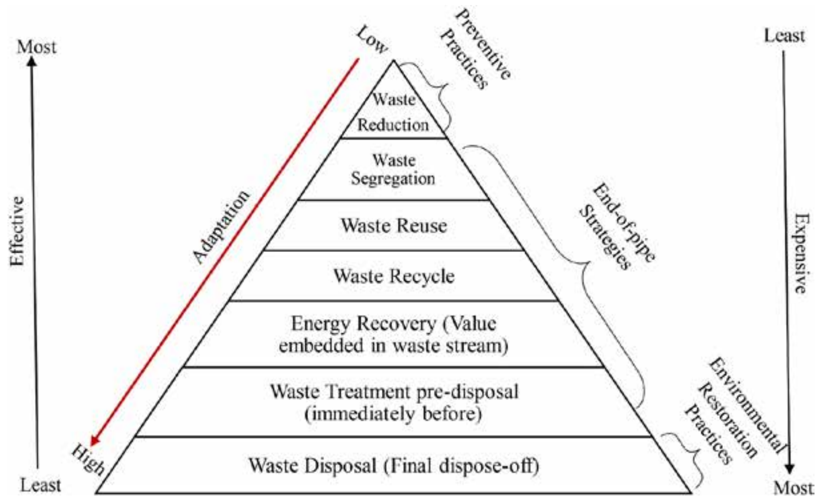


**Fig. 1.** Solid waste management practices.

relationships graph using Table 2. The values of last two columns of Table 2 (R + C and R–C) are plotted on a two-dimensional axis for each of the EOP strategy. The final causal digraph, depicting overall aggregated strategic significance and net effect is shown in Fig. 3.

The arrows shown in the diagraph, Fig. 3, represents the interrelation among EOP strategies. As there is a possibility that with some value, each of the EOP strategy has some influence on the others, it is necessary to only depict the significant causal relationships. This can be done using a threshold value (θ), which is calculated using the method considered by many researchers, by taking the mean and standard deviation of the elements of total relation matrix (T), and adding one standard deviation to the mean. Thus, in this case, the value of $\theta = [0.194, 0.236]$. All the values above θ are highlighted in bold in Table 1 only and those influence relationships are only shown in Fig. 3. As per the analysis, it is evident that among the five EOP strategies selected, waste segregation is the one which is having maximum influence on rest of the strategies. Thus, the result provides a clear indication and enable decision makers to take informed decisions to focus on segregation of waste to achieve the goal of establishing an effective and efficient SWMS.

### 4.2. Stage II: sustainable ways of solid waste disposal

The analysis in Stage 1 demonstrates that waste segregation is the most influential EOP strategy for sustainable SWM. The ever-increasing generation and disposal of solid waste necessitates its segregation and the subsequent sustainable treatment methods. To bolster the conducted analysis, a cost-effective and more sustainable waste disposal system has been proposed. The study first provides a detailed description of a mechanized method of waste segregation through an actual visit to a facility in Durgapur city, India and then suggests sustainable methods


**Fig. 2.** Plasma gasification plant.

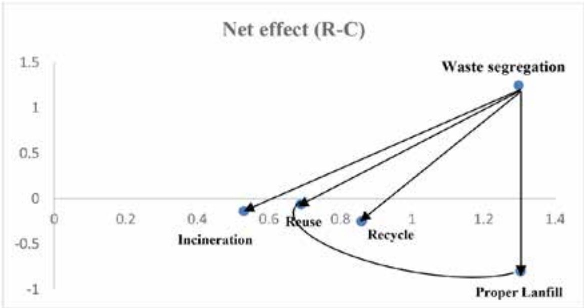


**Fig. 3.** Overall DEMATEL causal diagram.

for removing the separated wastes.

*4.2.1. Mechanized segregation of waste*

Landfill waste typically consists of metals, fines, polymers, and inert materials, which can be separated using a vibrating feeder conveyor with a top-opening (PIB, 2020). A visit to the CSIR-CMERI facility was done to comprehend the entire procedure. There was a mechanized segregation unit under operation with 100 kg/h capacity and involves three phases of legacy waste separation. CSIR-CMERI is an excellent case to highlight the significance of public-private partnership towards sustainable SWMS. There are various models accessible in the open literature linked to public-private partnerships in the solid waste management industry. During this case study analysis, it was observed that the general public (private-entity) participated by delivering waste to the garbage collector and paying a monthly fee of INR 50/- (less than a dollar) to the plant operator. After collecting garbage, the garbage collector used to operate the facility and sell resalable waste. The total revenue collected was sufficient to cover working expenses. The government covered the initial cost of the facility as well as major repairs. This collaborative efforts by various entities contributes to a successful SWMS in place. First stage removes dust or biodegradable residue from waste by feeding waste through a chute to a rotary trommel having perforated (8 mm dia holes) screen. The waste > 8 mm is collected in a rotatory magnetic drum to separate iron components (Fe), and the remaining waste is transmitted through an Eddy Current Separator to separate non-ferrous metallic components (Al, Cu). Remaining waste, including plastics, polymer, and papers, etc., from the second stage are conveyed into an air separation unit by means of an inclined bucket conveyor. This separates the lightweight fractions (plastic and polymer refuse) from the heavier fractions (inert materials). Lighter particles are collected by the chamber's two air movers, while heavier particles are collected by gravity. In the third stage, the material is passed through an inclined vibratory screen with 80 mm × 80 mm perforations, where heavier particles will descend through the perforated screen and light and flat products will be collected over the screen. Regarding polymer residue, it can be fed directly into a shredder and then sent for pyrolysis. The comprehensive process flow diagram is depicted in Fig. 4.

*4.2.2. Cost effective integrated municipal solid waste disposal system (CE-iMSWDS)*

This system begins with the separation of municipal solid waste, followed by the processing of each category of waste to produce value-added end products. This approach is cost-effective and sustainable because it utilizes roof-mounted solar panels to provide the required energy and reduces operational costs by supplying excess energy to mini-grids. It also utilizes decentralized waste collection plants (equipped with disinfestation devices to break any possible serious disease chain) of 0.5–5.0 ton/day capacity at various localities to eliminate unnecessary long-distance transportation of waste from one location to another, thereby reducing transportation costs and environmental impacts. Decentralized waste processing at local depots is therefore a sustainable option (Sarkilahti et al., 2017) and opens-up future opportunities to realize the "zero waste and zero landfill" idea, a step towards a clean and green nation (PIB, 2020). It is also noteworthy that there are several rag-pickers who scour landfills for materials with resale value as a profession. A strategy that engages rag pickers in training and incorporates them into a team that utilizes mechanized segregation of legacy refuse, as well as providing them with the opportunity to sell their collected recyclables, is an effective ecological model. These parsimonious and sustainable methods contribute to the advancement of society. For a greater understanding of solid waste disposal and value extraction, the following subsections illustrate various types of waste disposal.

*4.2.2.1. Disposal of biodegradable waste.* If biodegradable waste is not treated scientifically, it impacts the environment by emitting greenhouse gases. In contrast, if the proper technology is applied, waste can serve as a source of prosperity. Biogas extracted from waste can be collected and stored for heating and electricity production. Moreover, the residual sediment can be converted into compost (Rani, 2021). Therefore, it is recommended that biodegradable waste be processed at adjacent localized depots and all vegetable vendors, restaurant chains, food courts, and other sources separate their waste in a small-scale bio-methanation facility. In addition, dry leaves, fallen branches, and dry grass can be shred and combined with biogas slurry to create briquette (fuel for cooking/heating). When briquettes are burned, they produce ash, which, when combined with cement and water in the proper proportion, is used to make bricks (PIB, 2020). Briquettes are also used in gasifiers to produce syngas for electricity generation. The picture of actual small-scale bio-methanation plant at CSIR-CMERI can be referred in the supplementary file as Fig. 1.

*4.2.2.2. Disposal of polymeric waste.* Polymer waste, such as polybags, plastic bottles or receptacles, HDPE, PVC, sanitary waste, etc., can be safely disposed of using two main processes, namely pyrolysis and plasma gasification. Plasma gasification is not an economically viable option for dealing with polymeric waste, so the pyrolysis process is preferred. In the pyrolysis process, polymer residue is converted to syngas, oil, and char by heating at 400–800 °C in an anaerobic atmosphere. The volatile substances can be condensed to form pyrolysis oil. Non-condensed syngas can be reused for heating. The solid residue, known as char, can be combined with the biogas slurry to create briquette, which is then used to heat the reactor of the pyrolysis process, thereby making the process fuel self-sufficient.

*4.2.2.3. Disposal of inert waste.* Construction and demolition (C&D) waste is increasing in parallel with the growth of the construction industry. Soni et al. (2022) evaluated the characteristics, advantages, disadvantages, and worldwide economics of building materials derived from solid waste recycling, considering the materials' sustainability, social, and environmental implications. According to their results, there is a misalignment between the perceptions and behaviors of various populations due to a lack of information, awareness, economic hurdles, operational errors, and a lack of practices for reducing waste at the source. As a sustainable solid waste management strategy, they advocated recycling solid waste for building construction. The proposed framework recommends the use of ash, aggregates, and other recycled solids.

If untreated C&D waste is disposed in water bodies and wetlands, the natural permeation of precipitation from the surface is impeded, resulting in a falling ground water table. One method to dispose it is to crush it in a jaw crusher and then separate it into different pore sizes (1–5 mm) in a trommel. When combined with cement and water in the proper proportions, the finer particulates produce bricks with the desired strength. This method also conserves the natural sand that is excavated and transported daily from riverbeds to urban areas, and helps to reduce the likelihood of riverbank instability, soil erosion, and flooding. Due to their similar physical properties, such as aggregate density, gravity, particle size, and texture, inert waste is a viable alternative to natural sand. For a variety of construction purposes, inert waste composed of heavy particulates can be used to produce concrete. The generated concrete can also be used to enclose landfills, thereby decreasing the likelihood of heavy materials leaching into the groundwater. In other words, the proposed method not only aids in the elimination of legacy wastes and landfill space, but it also reduces the consumption of natural resources.

The comprehensive analysis of various waste disposal systems provides a clear indication of which activities and in what order should be carried out by responsible authorities and policymakers to develop an effective and efficient SWMS.

## 5. Proposed conceptual framework

### *5.1. Role of organizational and operations management for solid waste management*

The issues of untreated solid waste disposal and the high recurring costs of the plasma arc gasification process necessitate the incorporation of organizational and operations management aspects for an effective, efficient, and long-term SWMS. As a result, this study attempts to propose a comprehensive framework with three broad categories of strategies to manage solid waste, as well as practices and tasks associated with each. The same is depicted in Fig. 5. The framework enables concerned authorities to take informed decisions by leveraging the significance of inculcating organizational and operations management aspects in waste prevention, EOP and restoration strategies for solid waste management. The use of internal organizational processes and operations management aspects help in implementing technology-enabled solutions, which further results not only in prevention of solid waste

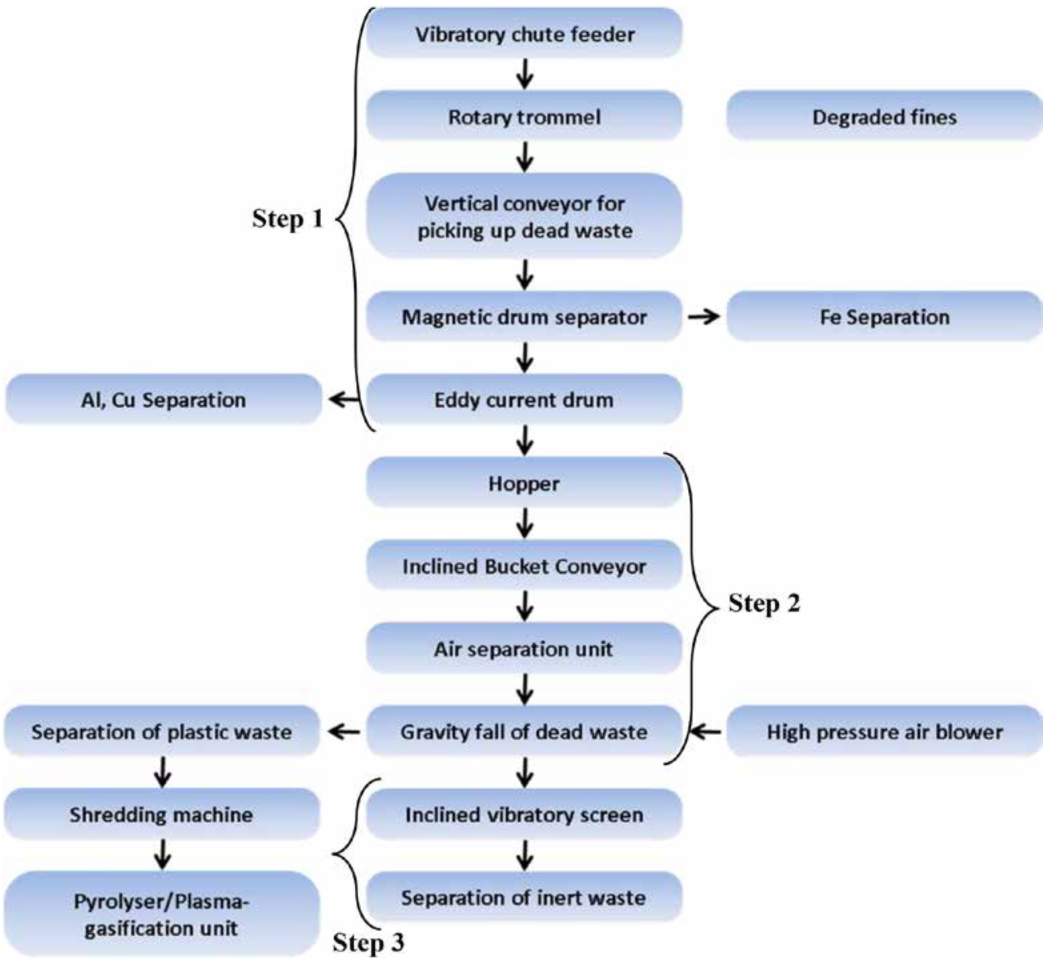


**Fig. 4.** The process flow diagram of the mechanized segregation unit (Legacy Waste).

is a misalignment between the perceptions and behaviors of various populations due to a lack of information, awareness, economic hurdles, operational errors, and a lack of practices for reducing waste at the source. As a sustainable solid waste management strategy, they advocated recycling solid waste for building construction. The proposed framework recommends the use of ash, aggregates, and other recycled solids.

If untreated C&D waste is disposed in water bodies and wetlands, the natural permeation of precipitation from the surface is impeded, resulting in a falling ground water table. One method to dispose it is to crush it in a jaw crusher and then separate it into different pore sizes (1–5 mm) in a trommel. When combined with cement and water in the proper proportions, the finer particulates produce bricks with the desired strength. This method also conserves the natural sand that is excavated and transported daily from riverbeds to urban areas, and helps to reduce the likelihood of riverbank instability, soil erosion, and flooding. Due to their similar physical properties, such as aggregate density, gravity, particle size, and texture, inert waste is a viable alternative to natural sand. For a variety of construction purposes, inert waste composed of heavy particulates can be used to produce concrete. The generated concrete can also be used to enclose landfills, thereby decreasing the likelihood of heavy materials leaching into the groundwater. In other words, the proposed method not only aids in the elimination of legacy wastes and landfill space, but it also reduces the consumption of natural resources.

The comprehensive analysis of various waste disposal systems provides a clear indication of which activities and in what order should be carried out by responsible authorities and policymakers to develop an effective and efficient SWMS.

## 5. Proposed conceptual framework

### 5.1. Role of organizational and operations management for solid waste management

The issues of untreated solid waste disposal and the high recurring costs of the plasma arc gasification process necessitate the incorporation of organizational and operations management aspects for an effective, efficient, and long-term SWMS. As a result, this study attempts to propose a comprehensive framework with three broad categories of strategies to manage solid waste, as well as practices and tasks associated with each. The same is depicted in Fig. 5. The framework enables concerned authorities to take informed decisions by leveraging the significance of inculcating organizational and operations management aspects in waste prevention, EOP and restoration strategies for solid waste management. The use of internal organizational processes and operations management aspects help in implementing technology-enabled solutions, which further results not only in prevention of solid waste

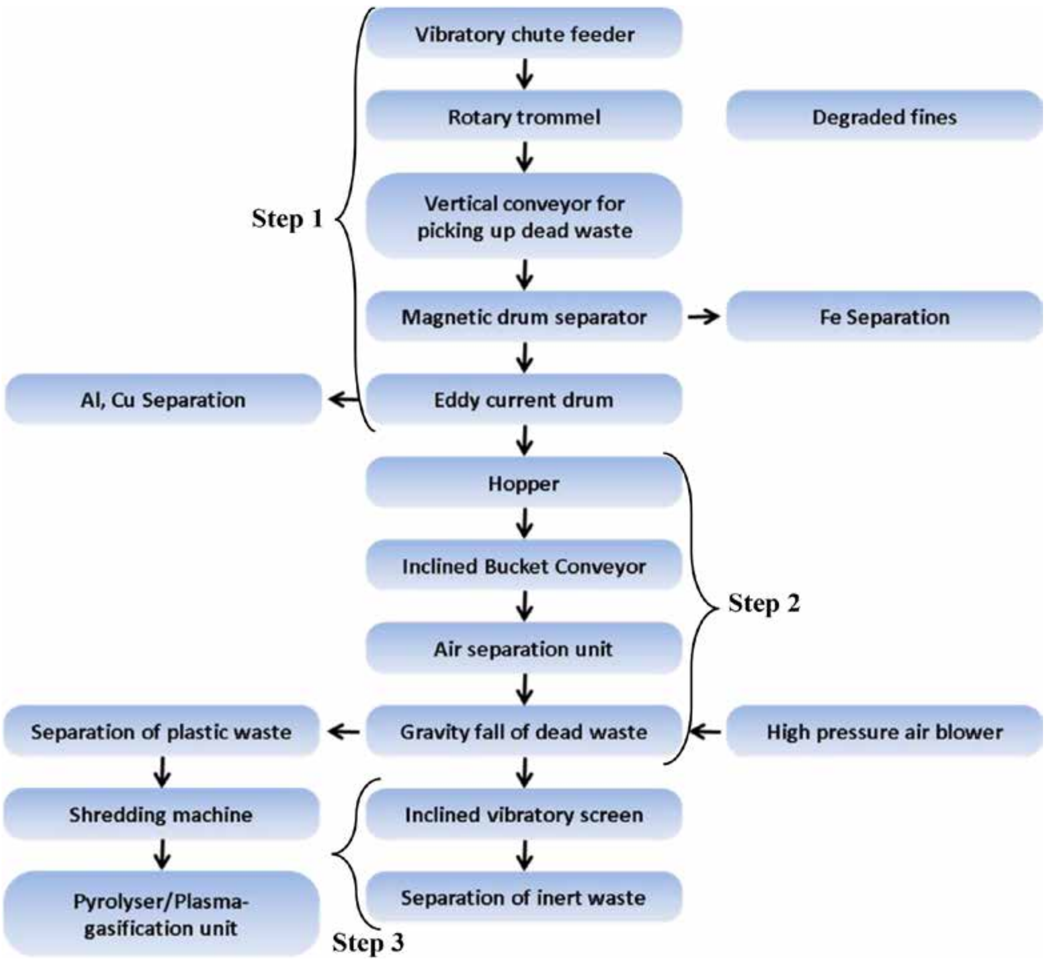


**Fig. 4.** The process flow diagram of the mechanized segregation unit (Legacy Waste).

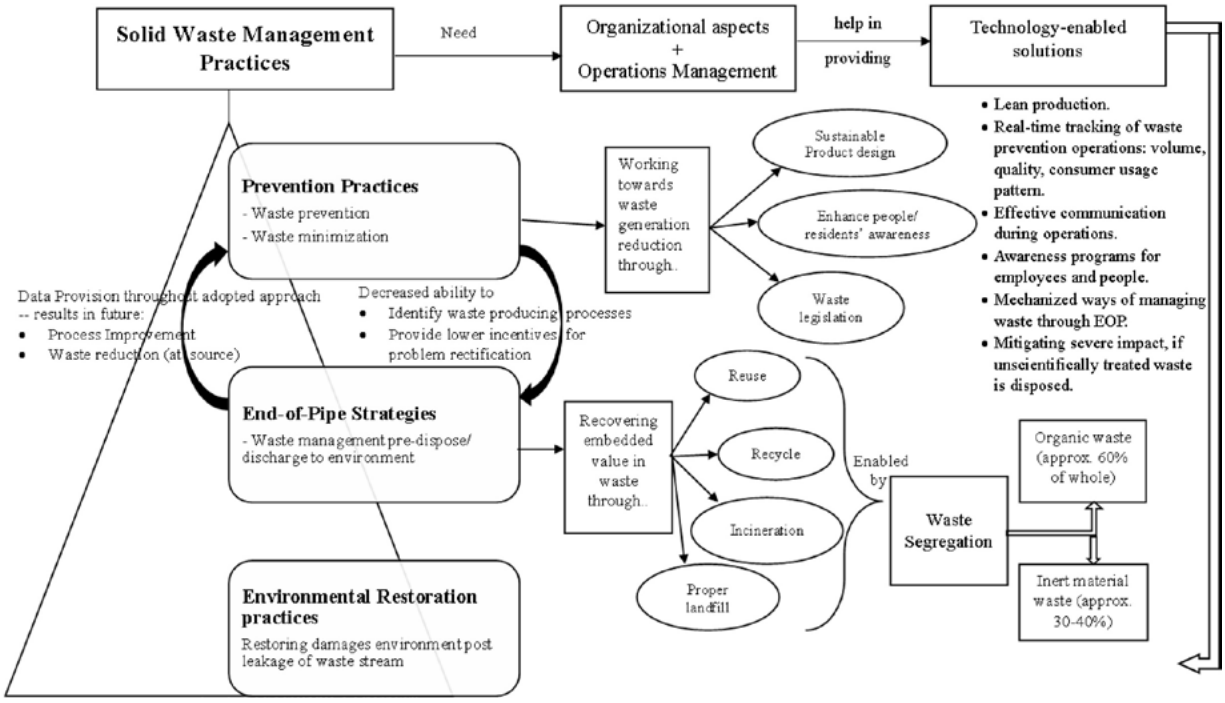


**Fig. 5.** Framework depicting organizational and operations management aspects towards SWM practices.

generation but in handling already generated waste. Waste legislation plays a significant role in preventing the solid waste generation and therefore it is necessary to be in place for an effective system to keep running. Similarly, organizational aspects not only focus on operational effectiveness through collaborative efforts among workers but also cover organizing awareness programs for general public and internal workforce to communicate the importance of solid waste management in sustainable manner.

### 5.2. Ways to deal with solid waste post collection

This research attempts to propose a conceptual framework, depicting what actions to be taken post collection of solid waste, which can either be segregated or unsegregated. This depends upon a number of factors such as availability of resources, willingness of authorities to participate in establishing an effective and efficient SWMS, and their awareness of the consequences of handling segregated or unsegregated waste. The framework is shown in Fig. 6. This framework not only provides a plan for handling both separated and mixed wastes but also demonstrates that waste segregation is a viable option for an end-to-end solid waste management solution. It is also evident from the framework that performing waste segregation at an initial step helps to reap SEEO benefits. To validate this, a case study has been presented in the next section where ground level implementation has been done in an Indian city, Durgapur in West Bengal.

## 6. Case study

In the city of Durgapur (West Bengal, India), a case study analysis was performed to illustrate the impact of proposed sustainable SWM practices on SEEO aspects. Consideration has been given to the landfills in the Shankarpur region, where approximately 150 tons of mixed waste are deposited daily using 25 waste-dumping vehicles, including 14 dumpers, 4 tractors, and 7 other vehicles. The collection and transportation of garbage from various locations to landfills involves an average distance of 15 km per trip, resulting in the consumption of between 1588.50 and 2113.50 gallons of diesel per year. Table 3 lists the costs associated with the transportation of refuse.

Table 3 shows that there is a significant cost associated with transportation of solid waste, posing economic challenges. Moreover, the unscientific disposal of untreated and unsorted waste to dumpsites poses serious social and environmental challenges as well. When waste is collected and transported, a large amount of carbon dioxide and methane is released, negatively impacting the environment. Furthermore, modes of transportation contribute to pollution. To address the issue of managing solid waste in a sustainable manner, the local authorities in the region performed technology-enabled waste segregation at decentralized local depots. Waste segregation separates biodegradable waste, which accounts for approximately 70% of total waste, from non-biodegradable insert waste, which accounts for approximately 30% of total waste. It was observed that waste segregation at decentralized local depots significantly lowered the transportation costs and amount of spillage/contamination also gets reduced during transportation. This was made possible through a sustainable approach by using a biogas plant, to process biodegradable waste at local depots, which resulted in the production of biogas. Another method was used to compact biomass waste into biomass-briquettes that help reduces the volume of waste by tenfold and makes it easier to manage. The obtained biogas and biomass-briquettes can be used for a variety of household purposes such as heating and cooking. As biodegradable waste (the majority of total solid waste) gets managed in decentralized manner, it eliminated the need of transporting the same to the landfill sites and thereby helped in saving the operational costs associated with transportation. During case study analysis, it was observed that the daily transportation cost of solid waste disposal, including transportation and maintenance, is approximately \$564/month/vehicle (approximately \$188 monthly transport plus \$376 monthly maintenance cost). As a result of decentralized bio-waste processing, the number of required dumping vehicles got reduced from 25

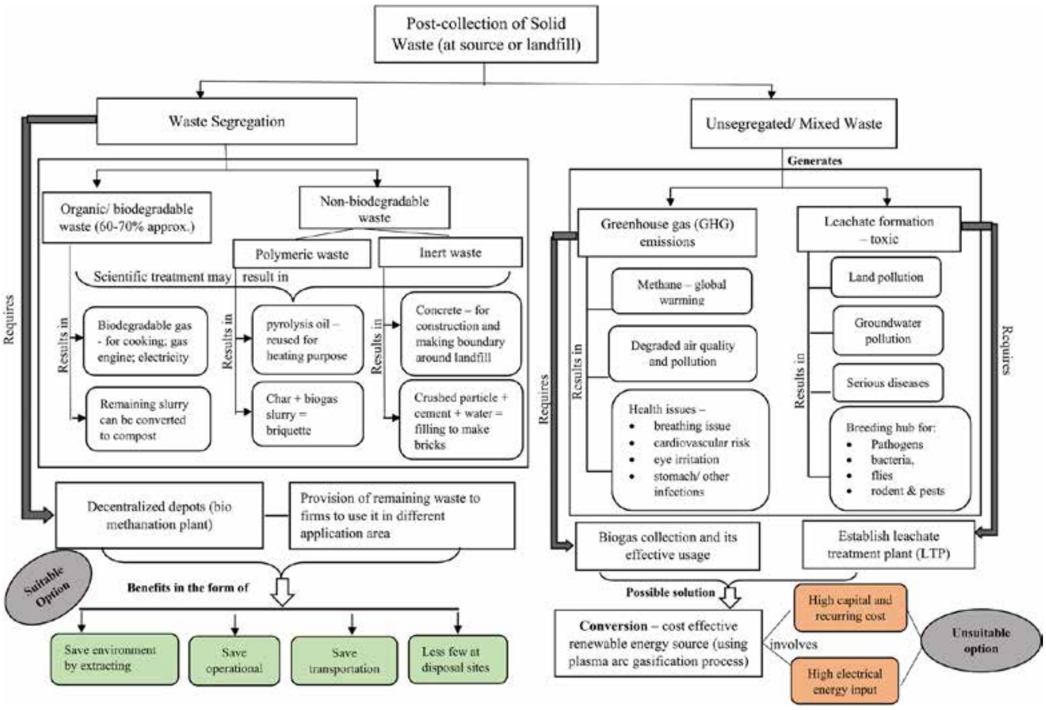


**Fig. 6.** Framework depicting possible ways to deal with Solid waste post collection.

**Table 3**
Approximate cost associated with transportation of waste.

| S.No. | Description | Annual Expenditure[a] ($) | Remarks |
|---|---|---|---|
| 1 | Cost of Consumables | 87,690 | Diesel consumption (Monthly consumption: ~1585 gallon)* |
| 2 | Cost of Maintenance | 18,791 | No. Of Vehicles under operation (Maintenance, Registration, Insurance etc.) |
| 3 | Cost of Manpower | 125,271 | Manpower engaged in transportation (Driver, Helper, Loader)- 60 Nos |
| Total Expenditure | | 231,750 | |

[a] Conversion Rate: INR 1 = $0.013; 1 L = 0.26US liquid gallon.

**Table 4**
Profit generation by decentralized processing of biodegradable waste.

| Component | Process | Qty (ton) | Output | Price ($) | Expenditure | Costing ($) |
|---|---|---|---|---|---|---|
| Bio-Waste | Biogas Plant | 6.6 | Biogas (300 cum) | 94 | Manpower (10 No) | 75 |
| Briquette | Dry biomass | 1.1 | Briquette (1.1 ton) | 37 | Electricity (200 kW) | 19 |
| | | | Total Cost | 131 | Total Expenditure | 94 |

to 20, resulting in a total profit generation of more than $10 million per year. The generated biogas and biomass-briquette provided economic benefit because their prices are higher than the involved expenditure, as shown in Table 4.

The adopted approaches also helped in reduction of greenhouse gas (GHG) emissions to the environment, alleviating both social and environmental concerns. The ground level implementation of proposed framework helped the city of Durgapur to achieve SEEO benefits. The process is still ongoing in the established plant. The decentralized processing of non-biodegradable and inert waste, on the other hand, revealed that it does not contribute significantly to SEEO benefits. As a result, it is directly transported for disposal to landfill sites, where it is primarily used by various companies for construction and other related purposes.

The case is consistent with our suggested system of SWM. It clearly demonstrates that an effective and efficient system first requires segregation of waste. This when further combined with process mechanization and scientific treatment of biodegradable waste at decentralized local depots, results in significant reduction of overall transportation cost along with socio-environmental benefits. Additionally, if a biogas plant is established near vicinity of waste collection point, it further reduces the operational cost and saves energy by producing biogas and briquette. During case analysis, the decentralized processing was also performed for inert waste but it was observed that it did not add much value to SEEO benefits. The case recommends that in case of inert waste, it is better to either hand it over to other firms or dispose it to the landfills, from where the firms can further process it for construction and/or similar purposes.

## 7. EXISTING LITERATURE *vis-à-vis* OUR RESEARCH

We present our comparison in following two sub-sections -

**Table 5**
Research contribution of current and previous research in similar research domain.

| | Current work and Previous Research in Similar Research Domain | Practical (Ground level) Implementation of Research | Methodology Used | Major Issue Addressed | Managerial Implications |
|---|---|---|---|---|---|
| 1. | Our Research | Yes (Ground level implementation performed at Durgapur city, West Bengal, India) | • Grey-DEMATEL using expert's view<br>• Case study analysis | • Social, economic, environmental and operational (SEEO) aspects.<br>• Minimization of transportation cost (involved during solid waste transportation).<br>• Preference among adoption of preventive, EOP, or restoration practices, based on their significance in current scenario of solid waste generation and management.<br>• Base framework to be used as an action plan for authorities.<br>• Validation of framework through ground level implementation. | • Adoption of End-of-Pipe (EOP) practices, suitable to deal with already generated untreated solid waste.<br>• Waste segregation, being the most influencing enabler to other EOPs, is recommended to initiate with.<br>• Decentralized treatment reduces<br>✓ number of vehicles<br>✓ transportation cost<br>✓ carbon footprint<br>• Bigas and bio-briquettes treatment<br>✓ eliminate need of transportation<br>✓ SEEO benefits<br>• Practical implementation of research clearly demonstrated.<br>• Required steps and its efficacy is well established as reference for concern authorities to take informed decisions towards achieving sustainable solid waste management system. |
| 2. | Dutt and King (2014) | No (focus on mediation effect of selected variable) | • Hypothesis Testing<br>Pre-treatment/Post-treatment analysis<br>Statistical testing;<br>Testing of mediation effect | • Countering argument that End-of-Pipe (EOP) treatment impede waste prevention and reduction.<br>• Testing EOP and waste reduction using data of U.S. manufacturing establishments from 1991 to 2005.<br>• Challenges to effective management of environmental practices. | • The research challenged the argument and existing literature, supporting EOP as hindrance to waste prevention and reduction.<br>• EOP helps managers collect, measure and analyze data about processes.<br>• Strongly justify that the argument, despite revealing important aspect, lacks adequate empirical testing.<br>• Recommends that EOP treatment increases information about problem and help in finding root causes.<br>• EOP treatment acts as prediction of waste reduction.<br>• Policies to be make that encourages careful monitoring of process waste |
| 3. | Pujara et al. (2019) | No | • Review on utilization of LCA.<br>• Case scenarios analysis using hypothetical model: three waste management cases studied for the period 2001–2051, considering sustainable development goals (SDG) 2030 of India.<br>✓ 1st: current scenario of waste management.<br>✓ 2nd: when 60% waste can be treated: reducing 40% land requirement<br>✓ 3rd: when 80% waste reduction | • Environmental and economic sustainability.<br>• Minimization of landfills to reduce land requirement. | • Strong recommendations on integrated solid waste management (ISWM) practices to reduce landfilling.<br>• Life cycle assessment (LCA) and Waste to Energy (WtE) are key factors of ISWM.<br>• supportive analysis towards efficacy of LCA in Indian waste management, including composting, anaerobic digestions, incineration, landfilling.<br>• WtE practices: help in avoiding material loss from municipal solid waste (MSW) and thereby reducing environmental and economic impacts.<br>• Incentives and training required in all concerned sectors to minimize losses and energy. |
| 4. | Sala-Garrido et al. (2023) | No | • Mix of parametric and linear programming approach<br>✓ Directional distance function using general algebraic modeling system and CPLEX solver.<br>✓ Regression tree model | • Efficiency from economic and environmental perspective.<br>• Shadow price of unsorted waste in Chilean municipalities. | • Average shadow price i.e. environmental cost is 297.66€/ton.<br>• Population density, tourism intensity, and waste generation per capita influence shadow price of unsorted waste.<br>• Poor eco-efficiency scores of 0.272 indicates inefficiency of Chilean municipalities, therefore policies need to be developed to improve it.<br>• Increase in percentage of recyclable waste collected also helps. |
| 5. | Al-Dailami et al. (2022) | No | • Bibliometric analysis.<br>• SWOT analysis | • Incessant increase in solid waste generation and its management challenges in Sana's city, Yemen. | • Corrective measures for policymakers and environmental engineers. |

(continued on next page)

**Table 5** (*continued*)

| | Current work and Previous Research in Similar Research Domain | Practical (Ground level) Implementation of Research | Methodology Used | Major Issue Addressed | Managerial Implications |
|---|---|---|---|---|---|
| 6. | Rahman and Bohara (2023) | No | • Choice experiment method.<br>• Spatial analysis using survey of 611 household in Siddharthanagar municipality in Nepal.<br>• Generalized Multinomial Logit Model (GMNL) | • Comparison of solid waste management condition with neighbouring countries.<br>• Analysis of preference and willingness of people to pay for better solid waste management system.<br>• Analysis and impact of spatial heterogeneity on marginal willingness to pay (MWTP) | • Supports that public prefers for better waste management service.<br>• Preference to pay highest amount (Nepalese Rupee, NPR 158/month ~ USD 1.43) for constructing and maintaining sanitary landfill.<br>• Both choice model and spatial model asks for policy to be targeted at localized level for further increase in awareness. |
| 7. | Soni et al. (2022) | No | • Review of recycling potential of solid for building material<br>• factors responsible for waste generation | • Alternative materials for building construction.<br>• Environmental efficacy of solid waste management (SWM) w.r.t. Economic structure, regulatory structure, science, and time.<br>• Sustainable building dealing with environmental concerns; economic and technical aspects.<br>• Different intricacies and specialities of different methods | • Sustainable building material: suitable solution.<br>• Recycling of solid waste as a viable option for building construction.<br>• This would generate employment, reduces the cost of construction, improving health benefits.<br>• The gap due to attitude and behavior of people towards management of solid waste is to be filled with effective policy in place. |
| 8. | Zhang et al. (2021) | No | • Life Cycle Assessment (LCA).<br>• Literature Review on LCA studies focusing on municipal waste management (MSWM) in 45 cases from developed and developing regions. | • Environmental impact of municipal waste management (MSWM).<br>• Explored distribution and evolution of LCA studies.<br>• Focus on critical factors for conducting LCA | • Modification of waste management strategies.<br>• Integrated solid waste management, observed to be the dominant alternative among various efforts towards waste management.<br>• Rather than focusing only on technical factors, other factors should be considered such as underlying management chain, local limitation, environmental concerns. |
| 9. | Zhang et al. (2023) | No | • Structural decomposition analysis (SDA) and structural path analysis (SPA)<br>✓ for decomposing the economic structure and tracing key transmission paths. | • Analysis of intensity change of NOx emissions in China, considering end-of-pipe treatment (last two decades 1997–2018)<br>• Study of related development strategies<br>• Key areas of NOx reduction<br>• Issue of where and how to decouple economic growth from NOx emissions | • Provide China's declining curve of NOx emission as reference for governance and development strategy for other countries.<br>• Construction contributes to maximum NOx emissions followed by transportation.<br>• Emission intensity effect drives NOx emissions/intensity reduction. It gets benefitted from end-of-pipe treatment and energy efficiency improvement<br>• Demand effect is primary deterrent, which is due to investment and consumption effects.<br>• Need to focus on construction & building material, transportation and other service industries for reduction of NOx emissions. |
| 10. | Mukherjee et al. (2021) | No | • Review of innovative technologies adopted in various countries for waste disposal and management | • Handling and dispose of waste in economic and eco-friendly ways.<br>• Understanding strategies adopted by various countries.<br>• Focus on solid, liquid, gaseous, and radioactive waste management processes. | • Provide insights of using various waste management techniques and concepts including plasma gasification, transmutation, incineration, bio-refineries, microbial fuel-cells (MFC).<br>• Potential of Mr. Trash Wheel and Smart bin explained. |

qualitative comparison and quantitative comparison.

### *7.1. Comparison on qualitative basis*

Unlike most of the existing research work dealing with the three pillars of sustainability, this research attempts to deal additionally with operational aspects for an effective and efficient SWMS in place. It bridges the gap in literature by, (i) developing a framework depicting the significance of preventive, EOP, and restoration practices and highlighting the one to focus upon, based on underlying effectiveness, efficiency and adaptation rates; (ii) modeling the cause-effect relationship among various EOP strategies (the focused one) using Grey-DEMATEL mathematical approach, (iii) proposing a comprehensive framework on managing solid waste using most influential EOP strategy (dominating cause-strategy) i.e. waste segregation, and (iv) ground level implementation of proposed framework in Indian city, Durgapur, to assess its impact on cost efficiency, operational effectiveness, energy savings, and social-environmental benefits. To better understand the focus, strength, and uniqueness of this research work, Table 5 attempts to highlight the major aspects covered in highly significant peer-reviewed journals from existing literature *vis-à-vis* our research. The basis for selecting the papers presented in Table 5 is its relevance and contribution in the area of managing solid waste.

### 7.2. Comparison on quantitative basis

A majority of the past research in this area have not provided quantitative monetized value of

Their implementation and other performance indicators for solid waste management system (SWMS). We have compared our work with existing literature as follows.

Sharma and Chandel (2021) have presented cost comparison of municipal solid waste (MSW) management under different scenarios using life cycle cost (LCC) approach for Mumbai city in India. Their research revealed that among different scenarios (recycling, composting, anaerobic digestion, incineration, and landfilling), incineration was cost-intensive with a net LCC of USD38/ton, while combination of recycling and sanitary landfill was most economical option with net LCC of USD19/ton of MSW. As compared to this, in our study we have emphasized on the role of decentralized depots to segregate and process solid waste, eliminating the need for all the six scenarios. Our research focuses on biogas plant and biomass-briquettes, which further eliminate the need of transporting waste and results in an annual profit of around USD 10 million. Islam et al. (2019) focused on municipal solid waste (MSW) management practices in Khulna city, Bangladesh with respect to quantity of waste and daily driven distance with fuel consumption of collection and transportation trucks. The study detailed about the total MSW generated and total distance travelled to manage the same considering the case of four location sites including, secondary disposal site (SDS), large hauled container points (LHCP), small hauled container points (SHCP), and distinct collection routes (DCR). It revealed that total quantity of SWM collected and transported from the four considered sites is 374,000 kg $d^{-1}$ out of which 18,000 of MSW is used for composting and 356,000 is managed through landfilling. Total distance: 2632.10 km and diesel consumption is 623.26 L $d^{-1}$. The monetized value of gains for their implementation has not been provided. For our case, the monetized value is presented in Section 6. Rahman and Bohara (2023) have performed experiments to estimate the public's preference and willingness to pay for better solid waste management system. They reported that the preference to pay highest amount is for construction and maintenance of a sanitary landfill is Nepalese Rupee (NPR) 158/month. (~ USD 1.2). As compared with this, in our study of CSIR-CMERI plant, it is INR 50 (~ USD 0.61). This is about 50% lesser than a near similar implementation in Nepal. Zhang et al. (2023) have revealed that emission intensity effect is the primary driver of NOx emissions/intensity reduction, which got benefitted from end-of-pipe treatment and energy efficiency improvement. The study showed that during 2012–18, they decreased 11,916 Kt-$NO_x$ and 8103 Kt-$NO_x$ emissions and aggregate intensity by 43.2% and 29.8%, respectively. In our study, no emission and its associated societal cost is involved as one of our proposed models eliminates the need of transportation of waste to landfill sites and therefore avoid emission of $NO_x$.

## 8. Conclusions

This study examines the grave global issue of solid waste management, which is worsening day-by-day due to ever-increasing population and urbanization. Limited understanding of waste management practices, operational inefficiencies, unstructured action plans, technological constraints, limited participation of people, and lack of coordination in efforts from all involved stakeholders, further makes the task of managing solid waste more complex and challenging. This directly affects the socio-economic-environmental-operational (SEEO) aspects. Despite existing work in the field with major focus on sustainability pillars, this research focuses additionally on operational aspect. It first proposes that EOP strategies are better suited for solid waste management in comparison to preventive and restoration practices in the current context, due to the urgency of handling massive amount of already generated waste, for a sustainable solid waste management system (SWMS) in place. The study further provides a sequence of performing EOP strategies by highlighting most influential EOP strategy, which has the capability to lead to other strategies. Mathematical approach, Grey-DEMATEL, has been used to model this causal relationship, which can be used by authorities to plan their course of actions. Waste segregation, being the major enabler to other strategies, needs the technological support for a cost efficient, operationally effective and resource-friendly SWMS. The strength of this research lies in the ground level implementation of proposed framework and analysis of its results. A case study has been performed in Indian city, Durgapur, where technology-based waste segregation at decentralized depots and establishment of biogas plant in the vicinity of garbage collection point, results in reduction of transportation cost and energy saving. The reduction of number of vehicles on a day-to-day basis led to 25% savings in overall transportation costs thereby cutting exchequer's bill by up to $ 2820/month. It also reveals that while mechanized and decentralized solutions were not effective for inert waste, its disposal to landfill was more suited alternative. It is important to understand if there are no incentives for the involved stakeholders, they won't be motivated to perform the task. Therefore, policy makers should consider incentivization as a key element while formulating waste management policies. The results of ground level implementation of the proposed framework could have further enriched if some forecasting technique would have applied to predict the rate of waste generation at different periods and then to check the effectiveness of technology-enabled solutions to manage the same. As a future scope, the same can be performed.

## CRediT author statement

Rachita Gupta: Methodology, Writing- Original draft preparation, Formal Analysis, Data Curation, Visualization. **Harish Hirani**: Conceptualization, Validation, Project Administration, Investigation. **Ravi Shankar**: Resources, Supervision, Writing- Reviewing and Editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119122.

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# A data-driven digital transformation approach for reverse logistics optimization in a medical waste management system

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ABSTRACT

COVID-19's aftereffects have had a significant impact on our daily lives. The recent pandemic caused by the new coronavirus epidemic has increased the production of infectious medical waste (IMW) and demand for medical care and protective equipment. Although national and local initiatives are primarily concerned with saving lives and bolstering local economies, hazardous waste management is essential for reducing long-term human and environmental health threats. In this situation, establishing a dependable and efficient reverse logistics network of IMW can prevent the spread of viruses. Few studies have been conducted on this topic and those that have rarely considered how to operate a network of multiple medical waste generation centres (MWGCs) cost-effectively and risk-averse. This study proposes a framework for reducing the accumulation of IMW products using reverse logistics in the context of medical waste management. The optimal values of the multiple objective functions were determined using a multi-objective optimization model. Our proposed framework considers four objective functions and their respective constraints while using data-driven digital transformation in reverse logistics energy optimization for managing single-use medical waste.

## 1. Introduction

The COVID-19 pandemic, also known as the coronavirus pandemic, is a global outbreak of coronavirus disease (COVID-19) illness in 2019 caused by coronavirus 2. The novel virus was discovered during an epidemic in the Wuhan district of China in December 2019. Attempts to contain disease spread have failed, allowing the virus to spread throughout China and, eventually, the world (UN, 2022). On January 30, 2020, the World declared the epidemic an international public health emergency; on March 11, 2020, it declared it a pandemic (WHO, 2022). The epidemic outbreak had resulted in more than 59.7 crore illnesses and 64.5 lakh deaths as of August 23, 2022, making it one of the worst in history (Rejeb et al., 2022).

Based on a global assessment of waste generated in the healthcare sector in the context of COVID-19 conducted by the World Health Organization, this is based on nearly 87,000,000 kg of personal protective equipment (PPE) purchased between March 2020 and November 2021 and dispatched to assist nations' immediate COVID-19 pandemic response requirements via a combined United Nations Emergency Initiative. Most of this equipment is most likely to be discarded. This is a rough estimate of the COVID-19 pandemic's waste and health issues (Cao et al., 2023).

It excluded any COVID-19 products purchased outside the project and trash generated by the general public, such as single-use medical masks. They emphasized that over 140 million test kits have been distributed, with the ability to generate 2,600,000 kg of non-infectious, non-hazardous waste (largely plastic) and around 700 thousand liters of chemical waste (equivalent to 1/3 of an Olympic pool), and that over 800 crore vaccine doses have been delivered globally, generating an additional 144,000,000 kg of waste as needles, syringes, and safety boxes (WHO, 2022).

The COVID-19 pandemic response, according to a new WHO report, has resulted in tens of thousands of additional tons of medical waste, putting waste-management systems for healthcare around the world under extreme stress, endangering both human health and the environment, and emphasizing the urgent need for better waste management

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methodologies (WHO, 2022). Owing to the use and expiration of medical supplies, these statistics indicate that waste control is critical in the supply chain (Jauhar et al., 2023; Datta et al., 2023). Poor and ineffective medical waste disposal can harm the environment and public health while significantly impacting human and global health (Ghosh et al., 2023).

As a result, it is critical to implement a sustainable waste management method, excluding any COVID-19 products purchased outside the project, as well as garbage generated by the public, such as single-use medical masks (Wan et al., 2023). They emphasized that over 140 million test kits have been distributed, with the potential to generate 2, 600,000 kg of non-infectious, non-hazardous waste (largely plastic) and 700 thousand liters of chemical waste (equivalent to 1/3 of an Olympic pool) and that over 800 crore vaccine doses have been delivered globally, resulting in an additional 144,000,000 kg of waste in the form of needles, syringes, and safety boxes (WHO, 2022). In the face of epidemics such as COVID-19, the healthcare sector must protect communities, healthcare professionals, and the environment while preventing pollution (Schilling et al., 2023).

Along with the need for healthcare equipment, another critical concern is managing infectious medical waste (IMW) generated during patient diagnosis and treatment. The amount of IMW generated increases significantly as the number of patients requiring care increases, necessitating additional equipment (Hallioui et al., 2022). As improper IMW segregation, collection, and processing can hasten disease transmission and place additional strain on the medical profession and patients, effective IMW management is a critical component of disease prevention. For example, researchers have described the serious consequences of hospital workers handling improperly treated HIV-infected garbage (Marchi and Zanoni, 2017).

The health industry accounts for 4.6 percent of global greenhouse gas emissions, with the US healthcare system accounting for more than a quarter (Jauhar and Pant, 2016; Sengazani Murugesan et al., 2020). The linear (take-make-dispose) consumption model is more prevalent in the healthcare industry than in American culture. Environmental materials are used to build gadgets in the traditional healthcare economy used in hospitals before being discarded. The top four explanations are: (1) The single-use mentality in healthcare dictates that medical equipment should be discarded after use. Proper disposal of used equipment is believed to reduce the risk of infection; the less we reuse it, the safer we are. (2) Reusing these devices is difficult. Before they can be used again, they must be collected, transported, cleaned, tested, and occasionally sterilized. After one use, placing the device down and picking up another is far easier. (3) Because the cost of many devices is low and the required investment is high, reuse is not a financially sound practice. (4) By designing products for single use, the gadget manufacturing industry increases its earnings because single use means that the hospital purchases more (Sharma et al., 2023).

In this sense, waste management is a reverse logistics network problem. The system and procedure for managing COVID-19 infectious medical waste should be well-designed to reduce potential risks, including virus spread (Pratap et al., 2022; Prajapati et al., 2022). After considering the actual difficulties encountered by the administrations of infected cities, towns, and so on who followed the World Health Organization's rules for the safe segregation, collection, and treatment of infectious medical waste in the event of an epidemic outbreak, a research proposal on medical waste management using reverse logistics techniques was presented (Dev et al., 2021; Rasool et al., 2023).

Reverse logistics is supply chain management that returns items from buyers to sellers or producers. Following a customer's receipt of a product, reverse logistics procedures, such as returns or recycling, are required (Gobbi, 2011; Hall et al., 2013; Hazen et al., 2014). Organizations use reverse logistics when items return from their destination to the seller and possibly back to the suppliers via the supply chain. The goal is to sell or recover some of the product's value. Global payback is around one lakh crore dollars per year, which is becoming more common with the rise of e-commerce (Larsen et al., 2018; Russo et al., 2019).

Data-driven digital transformation uses data analytics and digital technologies to improve business processes and decision-making. This approach has become more common in healthcare settings in recent years, including managing infectious medical waste (Jauhar et al., 2022; Murugesan et al., 2021). Data-driven digital transformation has the potential to revolutionize infectious medical waste management by enabling real-time data analysis and decision-making. According to Li et al. (2021), the use of digital technologies, such as the Internet of Things (IoT) and cloud computing, can aid in the optimization of the entire waste management process, from generation to disposal. The authors proposed a digital infectious medical waste management system that can track waste generation and disposal in real time, provide predictive analytics to optimize waste collection and disposal, and ensure regulatory compliance (Khan et al., 2023).

In addition to increasing efficiency and lowering costs, data-driven digital transformation in infectious medical waste management can improve safety and reduce infection risks. According to Xie et al. (2020), a digital platform can monitor and manage medical waste in hospital settings. The platform tracks waste collection and disposal in real-time and monitors personnel. According to the authors, using such digital technologies can help reduce infection transmission risk and improve waste management personnel's and patients' safety (Jauha and Pant, 2013; Jauhar et al., 2012).

Suppliers come first in a traditional product flow, followed by manufacturers and distributors. Subsequently, products are distributed to stores and customers. Reverse logistics management works backward from customers to return goods to any location in the supply chain. Supply chains that are well-planned and adaptable can handle some reverse logistics requirements. This reverse procedure can return products to their original source or one level up the supply chain. They can even return items to regular sales stores or discount stores. The major research questions of this study are as follows:

**RQ1:** How can implementing reverse logistics help minimize the disposal of single-use medical waste?
**RQ2:** How can the reverse logistics model be optimized using a multi-objective model?
**RQ3:** How to identify potential research areas to further improve the energy-efficient performance of reverse logistics optimization in a medical waste management system.

This paper is divided into six sections. Section 2 builds on the introduction in Section 1 by thoroughly reviewing the relevant literature. Section 3 defines the problem, and Section 4 discusses implementing this research's two-phase decision-making framework. The analysis of the results is presented in Section 5. Section 6 discusses managerial implications, and Section 7 concludes with recommendations for future research.

## 2. Literature review

To identify the study and address the current health-related challenges, this section briefly reviews the literature, emphasizing research papers related to the COVID-19 pandemic and medical waste management. According to scientific databases, most new coronavirus research is in medicine. Understanding the virus and developing a treatment or cure are critical; however, when an epidemic or pandemic occurs, it is also critical to predict its trajectory and take control of the various aspects of the problem that the virus directly or indirectly affects. Table 1 summarizes a recent literature review on medical waste management. Appendix Table A1. Complete explanation of the abbreviations used in this article.

**Table 1**
Summary of recent literature reviews on managing medical waste.

| Researcher(s) (Year) | Technique | Type of Product | Real Locations |
|---|---|---|---|
| Taghipour and Mosaferi (2009) | Comparative study | Medical wastes | ✓ |
| Mantzaras and Voudrias (2017) | Optimization Model | Infectious Medical Wastes | ✓ |
| Mantzaras and Voudrias (2017) | Comparative study | Single-use medical devices | |
| Marchi and Zanoni (2017) | Comparative study | No specific product | |
| Shirouyehzad et al., (2020) | Data envelopment analysis | No specific product | ✓ |
| Zareie et al. (2020) | GAM model, Prediction | No specific product | ✓ |
| Tirkolaee et al., (2021) | Optimization Model | Medical waste | ✓ |
| Ivanov (2020) | Discrete event simulation methodology | No specific product | ✓ |
| Elavarasan and Pugazhendhi (2020) | Qualitative study | No specific product | ✓ |
| Kargar et al. (2020) | Revised Multi-choice goal programming, sensitivity analysis | Infectious Medical Wastes | ✓ |
| Emenike and Falcone (2020) | Comparative study | Natural Gas | ✓ |
| Abid and Mhada (2021) | Simulation-based optimization | No specific product | ✓ |
| Lickert et al. (2021) | Comparative study of different ML algorithms | No specific product | ✓ |
| Kandasamy et al., (2022) | Exploratory factor analysis, Fuzzy theory-decision making | Medical Wastes | ✓ |
| Mallick et al. (2022) | Empirical study | Single-use medical devices | ✓ |
| Akkad et al. (2022) | Metaheuristic Optimization | No specific products | |

### 2.1. COVID-19 and reverse-logistics

Elavarasan and Pugazhendhi (2020) attempted to decipher the covert function of technological advancements that may aid in pandemic containment in the future. Ivanov (2020) predicted the potential effects of an ongoing epidemic on the global supply chain by using a simulation-based study. They proposed a method for monitoring and forecasting the effects of a pandemic as a supply chain risk.

Klemeš et al., (2020) investigated the short- and long-term effects of plastic trash, energy use, environmental and ecological effects, and growing waste management issues before and after disease outbreaks.

Shirouyehzad et al., (2020) assessed how well the countries with the most recorded cases performed regarding medical treatment and efforts to contain the illness to forecast the virus's spread pattern. Zareie et al. (2020) proposed a predictive model for COVID-19 trends in Iran based on attributes such as transfer, recovery, and mortality rate. Govindan et al., (2020) presented a decision-based support system that considers doctors' expertise and a fuzzy inference system to help manage demand in the healthcare sector, reduce community stress, and postpone the development of COVID-19.

The "circular economy" is a production and consumption paradigm emphasizing sharing, renting, reusing, repairing, refurbishing, and recycling old goods for as long as possible. This method extends the life cycle of the items (Schilling et al., 2023). This refers to the reduction in waste. When a product reaches the end of its useful life, its components are reused whenever possible. These can be used productively and again by adding additional value. This approach ignores the standard linear economic paradigm based on a take-make-consume-throw-away cycle (Hallioui et al., 2022). This concept is based on a large amount of low-cost, readily available energy and materials (Circular economy, 2015).

Various challenges encountered in various stages of a product's circular economy are listed below: Six stages in the medical waste management process must be followed to ensure effective recycling and waste disposal (Sharma et al., 2023). First, proper recycling techniques should be used to recycle the collected medical waste. Second, coordination with clients and vendors is required to collect recyclables found in medical waste. The third stage entails increasing consumption through increased awareness of recycling and medicinal items. The fourth stage focuses on improving medical product design and developing a framework for its use, processing, and disposal. The fifth stage entails recycling and utilizing recycled raw materials. Finally, logistics should be improved to ensure that medical supplies are delivered over time (Akanbi et al., 2018). Medical waste can be effectively managed, and the environment can be protected by following these stages (Cao et al., 2023).

In the healthcare industry, reprocessing single-use medical devices is a source of contention. Concerns have been raised by the World Health Organization (WHO) and Pan American Health Organization (PAHO) regarding the safety and efficacy of this practice. They pointed out that single-use equipment may not be designed to allow for complete disinfection and that reprocessing can change the properties of a device, potentially affecting its performance (Rejeb et al., 2022). Furthermore, single-use devices are not subjected to extensive validation and reuse testing, and their design may result in cross-infection, particularly in the case of fine tube bores. Certain chemicals may also slowly leak out of some materials over time, causing the device materials to corrode or change. Furthermore, the device's material may become stressed during reuse, failure, strain, or shatter. Finally, unclean equipment may contain bacterial endotoxins that can survive bacterial eradication (Sharma et al., 2023).

Given these concerns, healthcare facilities must consider alternative practices to ensure patient safety. This could include prioritizing using single-use devices when appropriate and ensuring that when reprocessing is required, they are only reprocessed by reputable companies that adhere to safety and quality standards (Wan et al., 2023). By adhering to these guidelines, healthcare facilities can provide the best possible care for their patients while ensuring a safe and sustainable healthcare environment (Cao et al., 2023).

### 2.2. Medical waste management and optimization

In addition to the larger studies described above, a few scholars have investigated the infectious Medical Waste COVID-19 problems. Abu-Qdais et al., (2020) used a statistical model to calculate the overall IMW creation rate in treating a novel Coronavirus procedure at a major Jordanian hospital. Tirkolaee et al., (2021) investigated the location-routing problem for COVID-19 related medical waste. .

Some studies have examined waste management optimization issues. Taghipour and Mosaferi (2009) investigated the quality, quantity, rate of production, and chemical composition of wastes generated in an important northwestern city in Iran. Budak and Ustundag, (2017) proposed a mixed-integer model for gathering and managing the trash generated by Turkish healthcare facilities to reduce costs. Mantzaras and Voudrias (2017) developed an optimization model to reduce the high costs of maintaining and operating an infectious waste management network. Wei et al., (2021) discussed the challenges because of the increase in medical waste since SARS outbreak.

Kargar, Pourmehdi, and Paydar (2020) propose a triple-objective mathematical model that reduces the monetary value and risk of infectious medical waste extraction, procurement, and processing during COVID-19, as well as the significant effects caused by uncollected trash at each medical waste generation facility (MWGF). This analysis included current and temporary hospitals (EH and TH), labs, clinics, residential areas (RA), and cemeteries as potential MWGC. There are also several objectives for determining the amount of waste produced by each MWGC.

Integrating advanced technologies and data analytics into business operations to drive efficiency, productivity, and competitiveness is a data-driven digital transformation. This approach has been shown to improve decision-making and reduce costs in reverse logistics optimization by leveraging data analytics to identify inefficiencies and optimize operations (Ghosh et al., 2023). According to Zhang et al. (2021), data-driven digital transformation can cut reverse logistics costs by up to 30% by improving visibility, analysis, and decision-making. Zhu et al. (2020) highlighted the potential benefits of data-driven digital transformation, such as improved efficiency, lower costs, and increased safety. The authors proposed a framework for tracking and monitoring the generation, collection, transportation, and disposal of infectious medical waste using digital technologies, allowing for real-time data analysis and decision-making.

Using data-driven digital transformation in infectious medical waste management can also help address environmental concerns regarding waste disposal (Rejeb et al., 2022). According to Fan et al. (2020), implementing a digital waste management system in a hospital setting reduces waste generation while improving waste segregation and recycling practices. The authors pointed out that this approach can be further improved by employing artificial intelligence and machine learning algorithms to predict waste generation patterns and optimize waste collection and disposal processes. Data-driven digital transformation can improve operational and environmental outcomes in infectious medical waste management.

Mantzaras and Voudrias (2017) proposed a report outlining the dangers of reusing single-use medical devices to ensure patient safety. The research focused on a specific target group of healthcare leaders, clinicians, healthcare purchasing agents, etc. Kandasamy et al., (2022) discussed the potential challenges of implementing a Circular Economy in the medical waste industry. Prioritizing and connecting key problems required applying a fuzzy theory-based decision-making trial and evaluation laboratory approach. Mallick et al. (2022) describe the remedial measures used by the medical waste industry to implement a circular economy for disposable medical waste.

### 2.3. Research gaps and contributions

According to a literature review, there is a critical lack of a comprehensive and functional network of reverse logistics systems for infectious medical waste in areas affected by pandemics. This deficiency is particularly relevant in light of the ongoing COVID-19 epidemic, as it poses a significant risk of disease propagation. Although extensive research has been conducted on waste management in reverse logistics, there has been limited investigation into energy-efficient optimization in this field.

Research gaps exist in accurately estimating the amount of waste generated in various types of medical waste generation centres (MWGCs) owing to various complex factors. One area that requires attention is the effect of different working shift lengths on the model. The research objective of this study is to address the issue of energy efficiency in reverse logistics systems by accounting for uncertainties in various factors that affect waste generation in different MWGCs. The study also examines the impact of other parameters, such as $CO_2$ emissions and cost reduction, on the model to better understand and address this issue.

In our research, we employed machine learning techniques to predict supply. Specifically, we analyzed time-series data collected over a series of time units, as this type of data was readily available, and other parameters and features were not considered. Time series data refer to observations indexed by time, including trends, seasonality, or a combination of the two. Based on the results, the model with the lowest root mean squared error (RMSE) value was selected for demand forecasting, and machine-learning methods were deemed the most appropriate for supply forecasting.

We employed Naive Bayes, a probabilistic algorithm, for time-series forecasting. This method calculates the conditional probability of a future event based on the previous values of the variable (Chen and Liu, 2019). The model assumes that the probability of a future value is independent of past values, given the current value. The simplicity of its implementation and its potential usefulness in complex scenarios make it a viable option for machine learning. In addition, it has been utilized as a machine-learning method.

The findings of this study provide valuable insights and recommendations for improving reverse logistics systems and promoting sustainability. The major contributions of this study are as follows.

- We propose a framework for utilizing reverse logistics to decrease the volume of single-use medical waste that is disposed of.
- Our framework optimizes the reverse logistics model using a multi-objective function.
- Our framework considers energy efficiency as the primary objective function and aims to identify and point out a future research scope.

## 3. Problem statement

The process of moving goods from their point of use to their point of origin for proper disposal, recycling, or reuse is reverse logistics. In the case of medical waste, reverse logistics operations can be complex and challenging because of the potential hazards associated with proper handling and disposal of medical waste. Reverse logistics operations for medical waste involve collecting, transporting, and disposing of the waste generated by healthcare facilities. However, this process is fraught with difficulties that must be overcome to be effective.

Regulatory compliance is a major challenge in reverse logistics operations for medical waste. To prevent environmental pollution and public health risks, stringent regulations are in place to ensure safe and effective disposal of medical waste. Compliance with these regulations is critical for avoiding legal ramifications. Another challenge is risk management. Handling and transporting medical waste pose several hazards to employees, the public, and the environment. Effective management of these risks requires a robust risk-management plan that incorporates proper training, equipment, and procedures.

Furthermore, reverse logistics operations for medical waste can be costly because of the specialized equipment and expertise required. Consequently, cost-cutting strategies must be implemented to ensure the operations are financially viable. Medical waste reverse logistics operations must consider these challenges to ensure compliance, minimize risks, and control costs.

Data-driven digital transformation can help solve the problems associated with medical waste reverse logistics operations. Organizations can optimize their processes, reduce costs, and improve compliance and risk management by leveraging technology and data. For example, real-time tracking and monitoring systems can provide visibility of medical waste's location, condition, and disposal, allowing for better tracking and regulatory compliance. Furthermore, digital transformation can enable process automation, reduce the need for manual intervention, and increase efficiency.

Using data-driven digital transformation in reverse logistics optimization can potentially transform infectious medical waste management. Healthcare organizations can gain insight into waste management practices, identify inefficiencies, and optimize their reverse logistics operations by leveraging data and analytics. Data can be used to track the amount and type of waste generated at each stage of a medical facility, monitor the performance of waste management vendors, and identify areas for improvement in the supply chain. Healthcare organizations can forecast the amount of waste generated and optimize the collection and disposal processes using predictive analytics and machine learning algorithms. Healthcare organizations can improve the efficiency and effectiveness of their waste management practices while also lowering their environmental impact by implementing data-driven digital transformation.

However, using data-driven digital transformation in reverse logistics optimization for infectious medical waste management has several limitations. First, data quality is critical to the success of data-driven digital transformation initiatives. The data must be accurate, timely, and comprehensive to enable effective decision-making. Furthermore, data complexity and diversity can pose significant challenges to implementing data-driven digital transformation. Data from various sources, such as electronic health records, supply chain data, and waste management systems, must be integrated and analyzed to provide meaningful insights. Finally, the cost of implementing data-driven digital transformation can be prohibitively high, especially for small healthcare organizations that may lack the resources to invest in advanced analytics tools and technology. Therefore, healthcare organizations must carefully weigh the benefits and costs of data-driven digital transformation and devise a comprehensive implementation strategy.

Addressing the challenges associated with reverse logistics operations for medical waste is critical to protect public health and the environment. Improper medical waste disposal can spread infectious diseases, environmental contamination, and wildlife. Furthermore, noncompliance with regulations can result in fines, legal liabilities, and reputational harm to the organization. Consequently, data-driven digital transformation in reverse logistics operations for medical waste is critical for ensuring safe and effective disposal.

Fig. 1 depicts a flow diagram that explains the flow of medical tools, equipment, protective gear, etc., throughout their life cycle until they reach their end of life (EOL) and hurt the environment. Due to the COVID-19 epidemic, a large amount of single-use infectious medical waste (IMW) has been generated from various sources, and authorities have found it difficult to manage these wastes effectively while minimizing the environmental impact. The flowchart above depicts each area of medical waste generation, transfer, and disposal, which is explained below.

### 3.1. Primary medical waste generating sources

Waste contaminated with blood and other body fluids includes waste from corpses and diseased animals in laboratories, infectious agent cultures and stocks from laboratory work, and diseased individuals (e.g., swabs, bandages, and disposable medical devices). These are referred to as infectious medical waste. Waste management has become increasingly important in recent years, particularly with the increasing demand for personal protective equipment (PPE) due to the COVID-19 pandemic. Healthcare facilities, households, and littered waste are potential sources of PPE waste.

The PPE waste generated by healthcare facilities includes items such as masks, gloves, and other medical instruments. Because COVID-19 is highly contagious, healthcare workers must wear PPE for extended periods, resulting in more waste. People use masks, gloves, and other protective equipment to prevent the spread of COVID-19 in their homes, contributing to PPE waste generation. The amount of PPE waste generated by households has increased because of the widespread use of these items.

Littering is another source of personal protective equipment (PPE) waste. Masks, gloves, and other safety equipment become dirty after use and are discarded or left in public places. This not only adds to the accumulation of PPE waste but also endangers public health. To summarize, managing PPE waste is critical in the fight against COVID-19, and it requires everyone's help from healthcare facilities, households, and individuals. Appropriate waste management practices can help reduce PPE waste's negative environmental and public health impacts.

### 3.2. Medical waste transfer station

These stations store and transfer IMWs generated by the primary sources. Such stations in this scenario include hospitals, clinics, and community waste centres. Waste is separated and routed to various waste disposal facilities based on feasibility, efficiency, and public safety.

### 3.3. Medical waste disposal centres

Medical waste is a significant issue that must be addressed. There are several methods for disposing of medical waste, including incineration, landfill dumping, and ocean dumping. Medical waste incineration involves burning medical waste in a safe environment for workers and nearby residents. Although this method mitigates the harmful effects of medical waste, it still contributes to air pollution, greenhouse gas emissions, and public health concerns. Another medical waste disposal method is landfill dumping, in which medical waste is treated, and the remaining matter is disposed of in a designated landfill. Unfortunately, some medical waste is littered or mixed with other waste before being dumped in a landfill without treatment, contaminating the soil and groundwater. Some medical waste is washed into the ocean by rainwater, while others are deliberately dumped in the ocean, ignoring environmental consequences. Proper medical waste disposal is critical for avoiding negative consequences for human health and the environment.

### 3.4. Reverse logistics framework

This study aimed to address this issue during an epidemic by utilizing an efficient and feasible reverse logistics application in medical waste management. For our model scenario, we chose a COVID-19 epidemic outbreak so that the medical wastes considered were related to COVID-19 precautionary products and protection equipment. The above flow diagram depicts the proposed model for dealing with medical waste during a pandemic. When waste is generated, it is initially stored in the area in which it is generated. These wastes are classified based on their properties, toxicity levels, and disposal methods. These wastes are then separated and packaged in containers designed to prevent the spread of infectious pathogens. These containers are then labeled, color-coded, etc., so that they can be correctly identified and no errors occur. The reverse logistics flow of the infectious medical waste is shown in Fig. 2.

This waste is handled by trained professionals who use appropriate precautionary measures and protective equipment. The packaged waste is then transported to disposal centres and stored before treatment. Following the treatment and elimination of the infectious pathogen, the final waste is disposed of by incineration or landfill deposition.

## 4. Solution framework

This research is intended to follow the solution framework mentioned above, with the next step being data collection, data cleansing and pre-processing, and a basic statistical analysis to

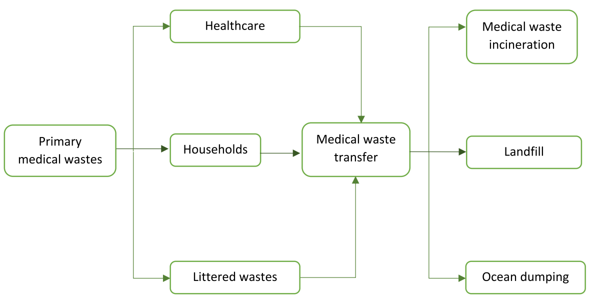


**Fig. 1.** Flow of medical wastes.

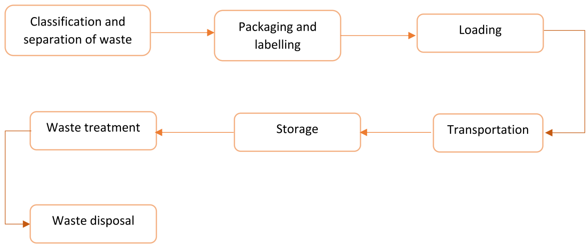


**Fig. 2.** Reverse logistics flow of IMW.

determine the general characteristics of the data. Subsequently, multiple objective functions and a multi-objective decision framework were defined. The framework was modeled after selecting appropriate methodologies, tools, and techniques. The results will be analyzed and interpreted to gain useful insights. Fig. 3 depicts the research framework.

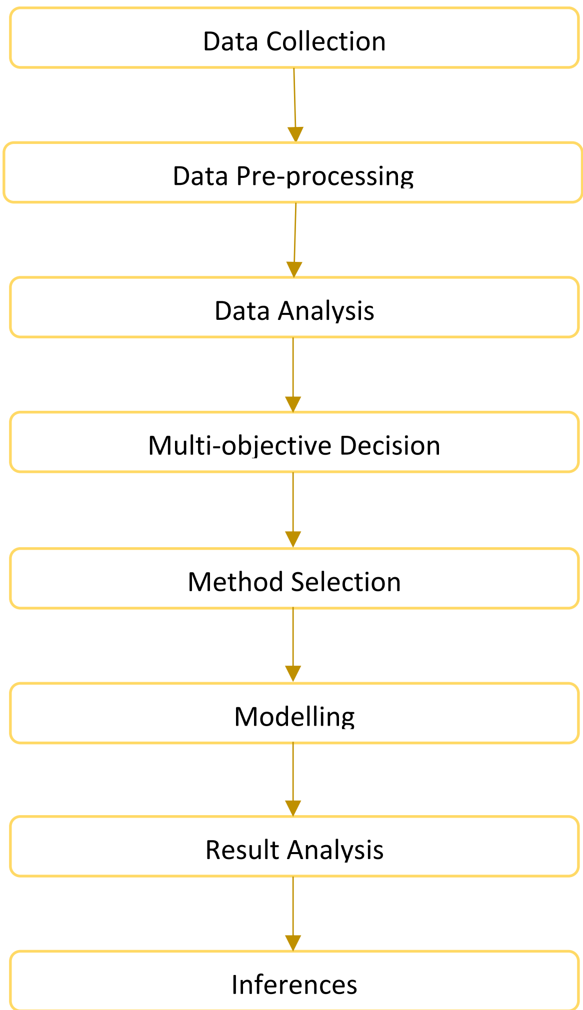


**Fig. 3.** Proposed solution framework.

### 4.1. Data for the problem under investigation

Owing to the difficulty in finding useful datasets, the initial data required were generated randomly based on the approximate values taken for each parameter (realistic data consideration). We used a time-series dataset with four years of daily data on medical waste supply to collection centres for Phase 1 supply forecasting. Appropriate machine learning techniques are used to forecast the supply better. The following are the approximate values of the parameters used for solving the Phase-2 mathematical model:

a. Plant installation cost = 20000000Rs–25000000Rs
b. $CO_2$ emission per truck = 0.2 kg/Km
c. Average amount of medical waste transported per truck = 1000 Kg
d. Power consumption by machineries = 0.2KWh/Kg
e. Machinery considered per each plant/center = 4–6 machines

### 4.2. Phase-1: supply forecasting

Forecasting future values of a variable based on its past behavior is time series forecasting. Several methods are used for time-series forecasting, including Naive Bayes, simple average, moving average, and ARIMA. Naive Bayes is a simple probabilistic algorithm for time-series forecasting that involves calculating the conditional probability of an event occurring given the variable's previous values (Chen and Liu, 2019). Given the current value, the model assumes that the probability of the future value is independent of past values. The Naive Bayes method is simple to implement and useful in some situations; however, it may be inaccurate for complex time series.

The simple averaging method is a fundamental forecasting technique that uses the average of the variable's past values to predict future values, assuming that the future value will be like past values. The simple average method is useful for stable time series with little variation but may not be accurate for time series with trends, seasonality, or other complex patterns. The moving average is an extension of the simple average method that takes the average of previous values over a fixed-size moving window and can help smooth fluctuations in time series, making it useful for detecting trends and seasonality (Feng and Lu, 2019). The moving average method can be useful for stable time series with little variation; however, it may not be accurate for time series with abrupt changes or irregular patterns.

ARIMA is a more advanced forecasting method that considers the autocorrelation and stationarity of the time series (Hyndman and Athanasopoulos, 2018). The ARIMA model comprises three parts: an autoregressive (AR) component, a moving average (MA) component, and an inverse component (I). The AR component captures the current value's dependence on past values, the MA component captures the dependence on past errors, and the I component captures the time-series differencing to make it stationary. ARIMA can be applied to time series with trends, seasonality, or other complex patterns.

Using ARIMA models to forecast stock prices is an example of machine-learning forecasting. In a study by Zhang et al., ARIMA models were used to forecast the stock prices of Chinese-listed companies. (2020). Regarding forecasting accuracy, the study discovered that ARIMA models outperformed other models, such as neural networks and support vector regression. The researchers also compared different ARIMA models and discovered that the (1,1,1) model performed best. The findings of this study indicate that the ARIMA model is a useful tool for predicting stock prices.

Another application of machine learning forecasting is predicting energy consumption using simple average and moving average (MA) models. Zhang et al. (2019) used simple average and moving average models to forecast daily energy consumption in China. Both models effectively predicted energy consumption, with the moving average model outperforming the simple average model. The researchers also compared the models' performances using an evaluation metric known as the mean absolute percentage error (MAPE). According to the results, the moving average model had a lower MAPE than the simple average model. The potential of simple and moving average models for forecasting energy consumption was demonstrated in this study.

In conclusion, the appropriate time-series forecasting method is determined by the time series' nature and the desired accuracy level (Wei and Wei, 2020). The moving average can help smooth out fluctuations in the time series but may not be accurate for sudden changes or irregular patterns. Naive Bayes and simple average methods are simple to implement but may not be accurate for complex time series. ARIMA is a more advanced method that considers the autocorrelation and stationarity of time series, and it can be useful for time series with trends, seasonality, and other complex patterns.

### 4.3. Phase 2: mathematical modelling

Fig. 4 depicts the forward and reverse flows of the single-use medical devices. Raw materials are delivered from supplier centres to the Manufacturing Center, where the device is assembled and transported to the Distribution/Collection Center. It is then delivered to various customer service centres. The used medical devices are then transported to a distribution/collection center, where this paper's reverse logistics and mathematical model are initiated. These medical wastes are then appropriately segregated and sent to various facilities as needed. These infectious medical wastes are sent to three facilities: a remanufacturing/revival center, a recycling center, and a disposal/incineration center. The remanufactured product is returned to the manufacturing center, whereas the product from the recycle center is sent to the supplier center. This process is repeated to reduce the amount of medical waste that must be completely disposed of.

| Indices and Sets | |
|---|---|
| $(a \epsilon A)$ | Index and set for distribution/collection centres of single-use IMW |
| $(b \epsilon B)$ | Index and set for remanufacturing and revival centres |
| $(c \epsilon C)$ | Index and set for recycling centres |
| $(d \epsilon D)$ | Index and set for disposal/incineration centres |
| $(p \epsilon P)$ | Index and set for different products under the category single-use |
| $(l \epsilon L)$ | Index and set for manufacturing centres |
| $(k \epsilon K)$ | Index and set for supplier centres |
| $(j \epsilon J)$ | Index and set for customer centres (MWGC's) |
| **Parameters** | |
| $y_{ja}$ | Cost of processing and transporting each unit of single-use IMW from MWGC's to distribution/collection centres |
| $y_{ab}$ | Cost of processing and transporting each unit of single-use IMW from distribution/collection centres to remanufacturing and revival centres |
| $y_{ac}$ | Cost of processing & transporting each unit of single-use IMW from distribution/collection centres to recycling centres |
| $y_{ad}$ | Cost of processing & transporting each unit of single-use IMW from distribution/collection centres to disposal/incineration centres |
| $y_{bl}$ | Cost of processing & transporting each unit of single-use IMW from remanufacturing and revival centres to manufacturing centres |
| $y_{ck}$ | Cost of processing and transporting each unit of single use IMW from recycling centres to supplier centres |
| $q_a$ | Fixed cost of setting up distribution/collection centre |

(continued on next column)

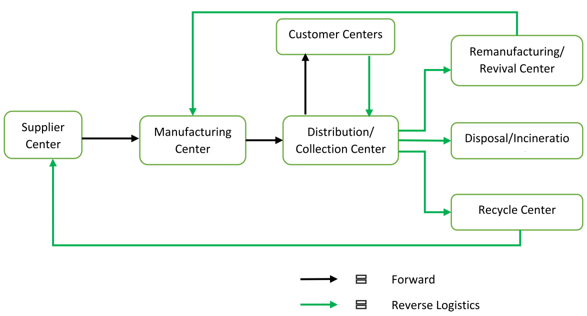


**Fig. 4.** Forward and Reverse flow of activity.

(continued)

| Indices and Sets | |
|---|---|
| $q_b$ | Fixed cost of setting up remanufacturing and revival centre |
| $q_c$ | Fixed cost of setting up recycling centres |
| $q_d$ | Fixed cost of setting up disposal/incineration centre |
| $m_a$ | Number of machines distribution/collection centre |
| $m_b$ | Number of machines in remanufacturing and revival centre |
| $m_c$ | Number of machines in recycling centres |
| $m_d$ | Number of machines in the disposal/incineration centre |
| $o_{ja}$ | Amount of $CO_2$ emission for each unit of single-use IMW from MWGCs to distribution/collection centres |
| $o_{ab}$ | Amount of $CO_2$ emission for each unit of single-use IMW from distribution/collection centres to remanufacturing and revival centres |
| $o_{ac}$ | Amount of $CO_2$ emission for each unit of single-use IMW from distribution/collection centres to recycling centres |
| $o_{ad}$ | Amount of $CO_2$ emission for each unit of single-use IMW from distribution/collection centres to disposal/incineration centres |
| $o_{bl}$ | Amount of $CO_2$ emission for each unit of single-use IMW from remanufacturing and revival centres to manufacturing centres |
| $o_{ck}$ | Amount of $CO_2$ emission for each unit of single use IMW from recycling centres to supplier centres |
| $w_a$ | Energy usage of machines per unit Kg of IMW processed at distribution/collection centres to disposal/incineration centres |
| $w_b$ | Energy usage of machines per unit Kg of IMW processed at remanufacturing and revival centres |
| $w_c$ | Energy usage of machines per unit Kg of IMW processed at recycling centres |
| $w_d$ | Energy usage of machines per unit Kg of IMW processed at disposal/incineration centres |
| **Variables** | |
| $x_{ja}$ | Quantity of single-use IMW transported from MWGC's to distribution/collection centres |
| $x_{ab}$ | Quantity of single-use IMW transported from distribution/collection centres to remanufacturing and revival centres |
| $x_{ac}$ | Quantity of single-use IMW transported from distribution/collection centres to recycling centres |
| $x_{ad}$ | Quantity of single-use IMW transported from distribution/collection centres to disposal/incineration centres |
| $x_{bl}$ | Quantity of single-use IMW transported from remanufacturing and revival centres to manufacturing centres |
| $x_{ck}$ | Quantity of single-use IMW transported from recycling centres to supplier centres |
| $e_a$ | $\begin{cases} 1, \text{if thedistribution/collection centre of single} - \text{use IMWis established} \\ 0, \text{if the centre is not established} \end{cases}$ |
| $e_b$ | $\begin{cases} 1, \text{ifremanufacturing and revival centreis established} \\ 0, \text{if the centre is not established} \end{cases}$ |
| $e_c$ | $\begin{cases} 1, \text{ifarecycling centreis established} \\ 0, \text{if the centre is not established} \end{cases}$ |
| $e_d$ | $\begin{cases} 1, \text{if adisposal/incineration centreis established} \\ 0, \text{if the centre is not established} \end{cases}$ |

#### 4.3.1. Objective function 1: energy-efficiency

$$Min\ Z_1 = \sum_{o}^{j} \sum_{0}^{a} x_{ja}.w_a + \sum_{o}^{a} \sum_{0}^{b} x_{ab}.w_b + \sum_{o}^{a} \sum_{0}^{c} x_{ac}.w_c + \sum_{o}^{a} \sum_{0}^{d} x_{ad}.w_d \tag{1}$$

#### 4.3.2. Objective function 2: cost reduction

$$Min\ Z_2 = \sum_{0}^{a} q_a.e_a + \sum_{0}^{b} q_b.e_b + \sum_{0}^{c} q_c.e_c + \sum_{0}^{d} q_d.e_d + \sum_{o}^{j} \sum_{0}^{a} x_{ja}.y_{ja} + \sum_{o}^{a} \sum_{0}^{b} x_{ab}.y_{ab} + \sum_{o}^{a} \sum_{0}^{c} x_{ac}.y_{ac} + \sum_{o}^{a} \sum_{0}^{d} x_{ad}.y_{ad} + \sum_{o}^{b} \sum_{0}^{l} x_{bl}.y_{bl} + \sum_{o}^{c} \sum_{0}^{k} x_{cl}.y_{ck} \tag{2}$$

Here,

$$\text{Fixed Cost} => \sum_{0}^{a} q_a.e_a + \sum_{0}^{b} q_b.e_b + \sum_{0}^{c} q_c.e_c + \sum_{0}^{d} q_d.e_d$$

$$\text{Processing} + \text{Transportation Cost}=>\sum_{o}^{j}\sum_{0}^{a}x_{ja}.y_{ja}+\sum_{o}^{a}\sum_{0}^{b}x_{ab}.y_{ab}+\sum_{o}^{a}\times\sum_{0}^{c}x_{ac}.y_{ac}+\sum_{o}^{a}\sum_{0}^{d}x_{ad}.y_{ad}+\sum_{o}^{b}\sum_{0}^{l}x_{bl}.y_{bl}+\sum_{o}^{c}\sum_{0}^{k}x_{cl}.y_{ck}$$

#### 4.3.3. Objective function 3: machine reduction

$$Min\ Z_3=\sum_{0}^{a}m_a.e_a+\sum_{0}^{b}m_b.e_b+\sum_{0}^{c}m_c.e_c+\sum_{0}^{d}m_d.e_d \tag{3}$$

#### 4.3.4. Objective function 4: $CO_2$ emission reduction

$$Min\ Z_4=\sum_{o}^{j}\sum_{0}^{a}x_{ja}.o_{ja}+\sum_{o}^{a}\sum_{0}^{b}x_{ab}.o_{ab}+\sum_{o}^{a}\sum_{0}^{c}x_{ac}.o_{ac}+\sum_{o}^{a}\sum_{0}^{d}x_{ad}.o_{ad}+\sum_{o}^{b}\sum_{0}^{l}x_{bl}.o_{bl}+\sum_{o}^{c}\sum_{0}^{k}x_{cl}.o_{ck} \tag{4}$$

Equations (1)–(3) depict the three objective functions considered in this study. The primary or first objective function considered in this study is energy efficiency, which is critical for optimizing the best possible solution for the reverse logistics of infectious medical waste. The overall cost reduction is the second objective function. The fixed cost of establishing various centres, as well as the cost of processing and transportation of IMW, are all considered, and the total overall cost is reduced. The third objective function considers the goal of machine reduction and optimization in each center. The fourth objective function considers the amount of $CO_2$ emitted during the transport of IMW from one location to another.

These objective functions consider energy efficiency, sustainability through $CO_2$ emissions reduction, cost efficiency, and machine reduction. Using these four constraints, we optimize the reverse logistics flow and reduce any potential losses or negative impacts that may occur. The following are considered and associated with mathematical modelling:

Subject to:

$$\sum_{0}^{a}e_a\geq 1 \tag{5}$$

$$\sum_{0}^{b}e_b\geq 1 \tag{6}$$

$$\sum_{0}^{c}e_c\geq 1 \tag{7}$$

$$\sum_{0}^{d}e_d\geq 1 \tag{8}$$

Constraints 5–8 indicate that at least one center of each type has been established. Each distribution and collection center, remanufacturing and revival center, recycle center, and disposal/incineration center has at least one.

$$x_{ja},x_{ab},x_{ac},x_{ad},x_{bl},x_{ck}\geq 0 \tag{9}$$

Constraint 9 depicts all non-negative restrictions on the variables.

$$e_a,e_b,e_c,e_d=\{0,1\}\text{for all}a,b,c,d \tag{10}$$

Constraint 10 depicts the binary variable in constraint.

## 5. Results and discussion

This section presents the phase-1 and phase-2 results and a discussion.

### 5.1. Phase-1: results for supply forecasting

Several stages of the reverse logistics optimization process were utilized. In Phase 1, machine learning techniques were employed to forecast the total supply of single-use medical device waste from multiple centres. The root mean square error (RMSE) was used to evaluate the performance of these models, as it penalizes significant errors.

The scheduling of production, transportation, personnel, finances, and other resources is crucial for their efficient use. A critical component of this scheduling is forecasting the demand for a specific product, material, labor force, funding, or service. The time required to source raw materials, hire employees, or purchase machinery and equipment can vary from a few days to several years, making forecasting necessary. Accurate forecasts enable stores to minimize excess inventory and improve their services.

The time-series data collected over a series of time units were used. Time series data were chosen as they were available, and other parameters and features were not considered. A time series comprises a set of time-indexed data points and typically includes trends, seasonality, or a combination of both. The model with the lowest RMSE value was used to forecast demand.

Fig. 5 shows the actual and predicted data obtained using the naive method. It depicts the actual and predicted values of medical waste supply, with the blue line representing the actual data and the red line representing the predicted data. The given date values are the number of months in which the first month was considered 0. Table 2 presents the RMSE values for each method.

Because the RMSE value for the Nave method is the lowest, it is considered the best method in this scenario and is used to forecast the supply of infectious medical waste. The supply forecasted by the Nave method on time-series data was used as the initial supply of IMW for subsequent modeling.

### 5.2. Phase-2: results of solving the mathematical model

An optimization technique must be applied to a multi-objective function to simultaneously optimize the objective functions. Multiple criteria decision-making refers to mathematical optimization problems with multiple concurrently optimized objective functions. Numerous scientific disciplines, including engineering, economics, and logistics, have used multi-objective optimization to make the best choices when trade-offs exist between two or more competing goals. In this case, the Pareto solution was obtained using a heuristic method. The solution methodology employed an epsilon-constraint approach (Yang et al., 2014). GAMS version 1.12.2 utlised to solve the mathematical models.

#### 5.2.1. Epsilon-constraint method

The epsilon-constraint approach is a widely used method for multi-objective optimization. This approach involves defining a primary objective and expressing secondary objectives as inequality constraints while incorporating the epsilon constraint model. The ε constraint

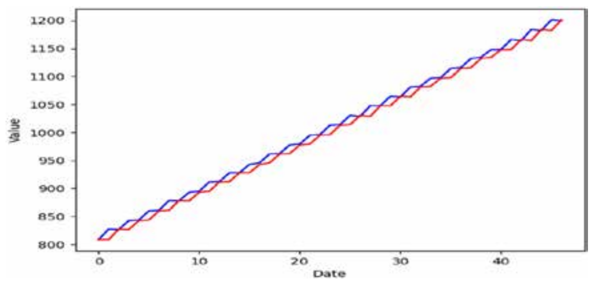


**Fig. 5.** Graph of predicted and actual value using the Naïve method.

**Table 2**
Comparison of RMSE values for different forecasting methods.

| Metrics | Naïve method | Simple Average | Moving Average | ARIMA |
|---|---|---|---|---|
| RMSE | 11.768 | 220.727 | 219.475 | 12.125 |

technique has been employed in various domains (Gazijahani et al., 2020; Li and Zabinsky, 2011). The epsilon constraint model is structured as follows.

Min $Z_1$

Subject to:

$Z_2 \le \varepsilon_2$

$Z_3 \le \varepsilon_3$

$Z_4 \le \varepsilon_4$

and constraints from (4) to (9)

When $Z_2$ is used as the objective function, $Z_1$, $Z_3$, and $Z_4$ are eliminated to determine the best value for $Z_2$, denoted in this context. When $Z_3$ is the goal function, $Z_1$, $Z_2$, and $Z_4$ are removed to obtain the best value for $Z_3$, which is represented as. $Z_4$ was used as the objective function, and $Z_1$, $Z_2$, and $\underline{Z_3}$ were eliminated to determine the optimal value of $Z_4$. To find the Pareto optimum solutions, the epsilon assigned to $Z_2$, $Z_3$, and $Z_4$ was based on 229213800 Rs, 46 machines, and 17.25 g of $CO_2$, respectively. Table 3 lists some values associated with epsilon.

*5.2.2. Weighted sum method*

In the weighted-sum method, combining multiple objectives into a single objective is achieved by multiplying each objective by a user-specified weight. However, assigning the appropriate weights to each objective is challenging. Typically, the weight of an objective is proportional to its importance in solving the problem. Nevertheless, caution should be exercised when considering the magnitude of the objective functions because the problem can be solved by normalizing all objective functions to the same scale, as shown in Table 4. The weighted sum method has been utilized across multiple domains, as demonstrated by Liu et al. (2016) and Babbar and Amin (2018). The table lists the weights and objective function values obtained using the weighted-sum method.

Min $Z_5 = w_1 * Z_1 + w_2 * Z_2 + w_3 * Z_3 + w_4 * Z_4$

Where, $\boldsymbol{w_1 + w_2 + w_3 + w_4 = 1}$ **……** (sum of weights should be equal to 1).

*5.2.3. Value path approach*

The Value Path Technique, a method developed by Schilling et al., in 1983, was employed in this study to analyze the results. This approach allows for an efficient graphical demonstration of the interrelationships between the criteria and the trade-offs associated with them. Several researchers have employed the utilization of this method of communication to present their findings in the form of trade-offs, and it is particularly suitable for the visualization of the results of our analysis of multi-objective methods (Jauhar et al., 2012). Table 5 shows the value path approach results obtained using the -constraint method and Table 6 shows the results obtained using the weighted sum method.

In addition to the value estimates, maximization and minimization objectives should be considered. By multiplying each objective value by −1, the minimization objectives are converted into maximization objectives. The minimum value of the non-dominated solution is then divided by each objective value in the case of the maximizing objective function. The maximum value of the non-dominated solution is divided by each objective value in the case of the minimization objective function.

The graphs (Fig. 6) below are plotted in Tables 5 and 6 and show the results of the value path approach. Because the resulting graph contains intersections, it can be deduced that the solutions are nondominant. It also shows how objective functions with non-dominant solutions trade off against one another. This graph also shows variations in non-dominated solutions obtained using the -constraint and weighted sum method.

The graph below (Fig. 7) shows Pareto solutions for the objective functions. The points depict the variations performed using the ε constraint and the weighted sum method.

## 6. Managerial implications

This research presents a study that showcases reverse logistics optimization for single-use medical device waste, considering energy efficiency. Utilizing a multi-objective optimization model enables the identification of the optimal solution's desired values for four objective functions. By improving reverse logistics, operational efficiency and growth can be enhanced. Significant savings can be achieved by considering the energy efficiency. The findings of this research provide managers and decision-makers with the ability to reduce overall costs and $CO_2$ emissions, ultimately protecting the environment while maintaining a competitive edge in the current market. These efforts will also prepare them for the future.

The present study employed machine learning techniques to forecast the supply of single-use medical waste. The Nave, simple average, moving average, and Autoregressive Integrated Moving Average (ARIMA) methods are utilized to make predictions. The results of this study indicate that managers can benefit from these methods in scenarios where demand forecasting is necessary. This study examined the Root Mean Squared Error (RMSE) values obtained through various methodologies to provide a comprehensive analysis. Managers can also employ additional performance measures to achieve optimal results.

Machine learning in demand forecasting has significant managerial implications for businesses. One of the most noteworthy advantages is enhanced forecasting accuracy, leading to better inventory, production, and staffing decision-making. By utilizing machine-learning algorithms to analyze vast amounts of historical data, businesses can uncover

**Table 3**
$\varepsilon$ values and objective function values obtained using $\epsilon$-constraint method.

| $\varepsilon_2$ | $\varepsilon_3$ | $\varepsilon_4$ | $\varepsilon_2$ | $\varepsilon_3$ | $\varepsilon_4$ | $Z_1$ (Wh) | $Z_2$ (Rs) | $Z_3$ (No. of machines) | $Z_4$ (g) |
|---|---|---|---|---|---|---|---|---|---|
| $0.0002 * \alpha + \alpha$ | $\beta$ | $\Gamma$ | 229266050 | 46 | 17.25 | 1063.75 | 229266050 | 46 | 17.25 |
| $0.95 * \alpha + \alpha$ | $0.90 * \beta + \beta$ | $0.75 * \gamma + \gamma$ | 446966910 | 87 | 30.19 | 1041.25 | 229282200 | 46 | 22.15 |
| $0.85 * \alpha + \alpha$ | $0.80 * \beta + \beta$ | $0.70 * \gamma + \gamma$ | 424045530 | 83 | 29.32 | 1041.25 | 229208800 | 46 | 20.1 |
| $0.15 * \alpha + \alpha$ | $0.20 * \beta + \beta$ | $0.10 * \gamma + \gamma$ | 263595870 | 56 | 18.97 | 1045.79 | 229273570 | 46 | 18.97 |
| $0.05 * \alpha + \alpha$ | $0.07 * \beta + \beta$ | $0.06 * \gamma + \gamma$ | 240674490 | 50 | 18.28 | 1050.875 | 229270940 | 46 | 18.28 |
| $0.20 * \alpha + \alpha$ | $0.20 * \beta + \beta$ | $0.20 * \gamma + \gamma$ | 275056560 | 56 | 20.7 | 1043.32 | 229278260 | 46 | 20.7 |
| $0.01 * \alpha + \alpha$ | $0.05 * \beta + \beta$ | $0.05 * \gamma + \gamma$ | 231505938 | 49 | 18.11 | 1053 | 229270140 | 46 | 18.11 |
| $0.008 * \alpha + \alpha$ | $0.01 * \beta + \beta$ | $0.04 * \gamma + \gamma$ | 231047510.4 | 47 | 17.94 | 1055.125 | 229269330 | 46 | 17.94 |
| $0.005 * \alpha + \alpha$ | $0.03 * \beta + \beta$ | $0.45 * \gamma + \gamma$ | 230359869 | 48 | 25.01 | 1041.25 | 229282200 | 46 | 22.15 |
| $0.002 * \alpha + \alpha$ | $0.25 * \beta + \beta$ | $0.03 * \gamma + \gamma$ | 229672227.6 | 58 | 17.77 | 1057.25 | 229268520 | 46 | 17.77 |
| $0.001 * \alpha + \alpha$ | $0.20 * \beta + \beta$ | $0.40 * \gamma + \gamma$ | 229443013.8 | 56 | 24.15 | 1041.25 | 229282200 | 46 | 22.15 |

**Table 4**
Different weights and objective function values obtained using the weighted sum method.

| Parameters | | | | Values of the objective functions | | | |
|---|---|---|---|---|---|---|---|
| | | | | Min | Min | Min | Min |
| $w_1$ | $w_2$ | $w_3$ | $w_4$ | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ |
| 0.5 | 0.3 | 0.05 | 0.15 | 1094 | 229213800 | 46 | 31.05 |
| 0.6 | 0.25 | 0.005 | 0.145 | 1094 | 229213800 | 46 | 31.05 |
| 0.0001 | 0.0001 | 0.0001 | 0.9997 | 1074.25 | 229260650 | 46 | 17.55 |
| 0.001 | 0.001 | 0.035 | 0.963 | 1095.5 | 229214100 | 46 | 29.85 |
| 0.9 | 0.05 | 0.02 | 0.03 | 1094 | 229213800 | 46 | 31.05 |

**Table 5**
Value path approach-based results using the ϵ-constraint method.

| $\varepsilon_2$ | $\varepsilon_3$ | $\varepsilon_4$ | $Z_1$ (Wh) | $Z_2$ (Rs) | $Z_3$ (No. of machines) | $Z_4$ (g) |
|---|---|---|---|---|---|---|
| 229266050 | 46 | 17.25 | 1063.75 | 0.99993 | 1 | 0.778781 |
| 446966910 | 87 | 30.19 | 1041.25 | 1 | 1 | 1 |
| 424045530 | 83 | 29.32 | 1041.25 | 0.99968 | 1 | 0.907449 |
| 263595870 | 56 | 18.97 | 1045.79 | 0.999962 | 1 | 0.856433 |
| 240674490 | 50 | 18.28 | 1050.875 | 0.999951 | 1 | 0.825282 |
| 275056560 | 56 | 20.7 | 1043.32 | 0.999983 | 1 | 0.934537 |
| 231505938 | 49 | 18.11 | 1053 | 0.999947 | 1 | 0.817607 |
| 231047510.4 | 47 | 17.94 | 1055.125 | 0.999944 | 1 | 0.809932 |
| 230359869 | 48 | 25.01 | 1041.25 | 1 | 1 | 1 |
| 229672227.6 | 58 | 17.77 | 1057.25 | 0.99994 | 1 | 0.802257 |
| 229443013.8 | 56 | 24.15 | 1041.25 | 1 | 1 | 1 |

**Table 6**
Value-path approach-based results using the weighted sum method.

| Parameters | | | | Values of the objective functions | | | |
|---|---|---|---|---|---|---|---|
| | | | | Min | Min | Min | Min |
| $w_1$ | $w_2$ | $w_3$ | $w_4$ | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ |
| 0.5 | 0.3 | 0.05 | 0.15 | 0.998630 | 0.999796 | 1 | 1 |
| 0.6 | 0.25 | 0.005 | 0.145 | 0.998630 | 0.999796 | 1 | 1 |
| 0.0001 | 0.0001 | 0.0001 | 0.9997 | 0.980602 | 1 | 1 | 0.565217 |
| 0.001 | 0.001 | 0.035 | 0.963 | 1 | 0.999797 | 1 | 0.961353 |
| 0.9 | 0.05 | 0.02 | 0.03 | 0.998630 | 0.999796 | 1 | 1 |

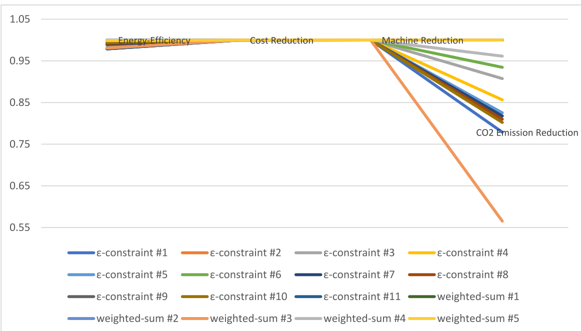


**Fig. 6.** Graph of the value path approach.

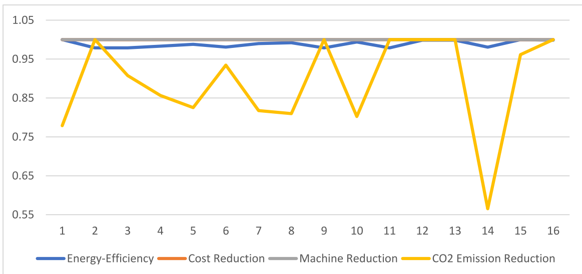


**Fig. 7.** Graph of the value path approach.

patterns and trends that human analysts may miss. This enables managers to allocate resources more effectively, lower costs, and optimize production schedules. Furthermore, machine learning enables faster decision-making and responsiveness to changes in demand, which is particularly critical in fast-moving industries. Businesses can enhance customer satisfaction by accurately forecasting demand and ensuring that products are available when customers need them. Ultimately, implementing machine learning for demand forecasting can provide a competitive advantage over businesses that rely on traditional forecasting methods. In conclusion, utilizing machine learning for demand forecasting can assist businesses in making informed decisions, lowering costs, increasing customer satisfaction, and gaining a competitive advantage.

The modelling process involved the consideration of four objective functions. Managers have the discretion to modify their objectives and uncertainty factors based on the requirements of their organization. Models with multi-objective criteria are commonly utilized in logistics, e-commerce, smartphone manufacturing, and other similar contexts. The optimization of reverse logistics is crucial for the smartphone and large e-commerce industries, making this study relevant to those settings as managers can adjust the model to suit their specific needs.

Using multi-objective criteria in reverse logistics optimization has several important implications for managers. First, it requires a more comprehensive decision-making approach that considers cost reduction and the environmental impact of operations, material recovery, and customer satisfaction. This broader perspective has the potential to generate sustainable and socially responsible outcomes. Second, the use of multi-objective criteria requires a greater degree of data collection and analysis. Managers must gather information on transportation costs, environmental impacts, material recovery rates, and customer feedback and then analyze these data to identify trade-offs and potential solutions. This process can be time-consuming and resource-intensive but can significantly improve reverse logistics operations.

In conclusion, utilizing multi-objective criteria necessitates cooperation between various functional departments, including transportation, environmental, and customer services. By working together, these teams can identify and implement solutions that balance numerous objectives, improving communication, coordination, and overall organizational performance. The optimization of reverse logistics for single-use medical devices presented in this paper provides decision-makers with tools to employ as necessary and choose the most suitable location for various facilities.

## 7. Conclusions and future research directions

Our study focuses on reverse logistics optimization for managing single-use medical waste while considering energy efficiency. Energy efficiency uses less energy to complete a task or reach a goal, and commodities manufactured in energy-efficient manufacturing facilities use less energy. Energy efficiency is one of the simplest and most cost-effective ways to slow climate change, reduce consumer energy bills, and boost business competitiveness. Energy efficiency is also important for achieving net-zero carbon dioxide emissions through decarbonization. This study combines a multi-objective model with machine learning (for supply forecasting), which is then processed using an algorithm to determine the best solution. This paper provides healthcare industries with an efficient way to plan of time and easily manage the reverse logistics of medical devices.

This research focuses on processing energy efficiency and minimizing setup, transportation, and processing costs while considering reducing the number of machines in production lines and lowering $CO_2$ emissions. To fill this research gap, this study proposes a multi-objective model for planning, building, and optimizing a reverse logistics network. The objective function values were determined using the weighted sum approach and epsilon-constraint method.

The multi-objective optimization model was then solved using the abovementioned methods, and Pareto solutions were obtained. Thus, the user can select the optimal solution depending on the situation. This study can optimize existing reverse logistics by considering multiple objective functions and efficiently planning locations for the installation of plants and other constructions. For example, because it considers multi-objective optimization problems, this model can be used by manufacturers to select suppliers, and they can provide the required objective functions and constraints to obtain the solution.

In this study, the availability of data was a significant constraint. The data about the supply of single-use medical waste was limited to four years. A larger and more diverse dataset would enable more accurate prediction and forecasting. This study focused on only four objective functions; however, additional objective functions and constraints can be added in future studies to account for other influencing factors. The literature analysis revealed a lack of well-functioning reverse logistics systems for infectious medical waste in specific locations and that research on optimizing these systems with energy efficiency in mind has been limited because of the specialized nature of the field.

The current model for analysing product returns adopts a deterministic approach that assumes perfect knowledge and accuracy in forecasting future events. However, as uncertainties and variability are inherent in the behavior of customers, products, and markets, this methodology may not fully capture the system's intricacies under examination. Future investigations could incorporate uncertainty in various aspects, such as the quality of customer returns, quality of recovered products, demand fluctuations, and variations in the number of customer returns of used products, to improve the model's accuracy. By accounting for these uncertainties, the model could provide a more precise and robust evaluation of the effectiveness of product-return strategies, enabling businesses to make more informed decisions regarding their reverse logistics processes.

Research gaps can be perceived as a conglomeration of factors that impede determining the amount of waste produced by various MWGC systems. Therefore, it is advisable to consider the impact of diverse working shift durations on the model. Another potential area of research is incorporating the traffic aspect in the location where reverse logistics optimization is carried out. This paper presents new research avenues and potential research topics. In Phase 1, other novel and complex digital transformation methods, such as artificial intelligence, Bloch chain, and data analytics, can be employed to estimate the supply of medical waste.

## CRediT authorship contribution statement

**B. Yaspal:** Investigation, Formal analysis, Writing – original draft, Revision. **Sunil Kumar Jauhar:** Conceptualization, Supervision, Investigation, Formal analysis, Writing – original draft, Revision. **Sachin Kamble:** Supervision, Discussion, Writing – review & editing. **Amine Belhadi:** Conceptualization, Discussion. **Sunil Tiwari:** Supervision, Discussion, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Appendix A. Abbreviations

**Table A1**
Complete explanation of the abbreviations used in this article.

| Abbreviation | Guidance |
|---|---|
| ARIMA | simple average, moving average, and Autoregressive Integrated Moving Average |
| $CO_2$ | Carbon emission |
| IMW | infectious medical waste |
| PPE | personal protective equipment |
| MWGCs | multiple medical waste generation centres |

(*continued on next page*)

**Table A1** (*continued*)

| Abbreviation | Guidance |
|---|---|
| RSME | Root Mean Squared Error |
| WHO | World Health Organization |
| UN | United Nation |

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# Solid Waste Management in Indian Metropolitan Cities: A Case Study of Raipur City

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## Abstract
Raipur is among the fastest-growing metropolitan cities in India. Due to population growth and changing lifestyle, the waste generated in the city has increased rapidly. The amount of waste generated in the city has increased from 184 tonnes/day (TPD) in 2004-05 to 684 TPD/day in 2021. The annual growth rate (AGR) of waste generated in the city remained faster than the population growth rate during the reference period. Due to the increasing amount of waste, solid waste management (SWM) becomes a complex and challenging task. In 2015, the Govt. of India launched Swachh Bharat Mission (SBM) to prioritise the issue of sanitation, and in 2016, new SWM Rules were introduced. Subsequently, the Raipur Municipal Corporation (RMC) has initiated multiple reforms in the SWM system of the city. In 2016, a door-to-door collection was introduced, which has achieved 100% collection efficiency. Secondary segregation and scientific landfilling have also started through the public-private participation (PPP) mode. Modern technology and new equipment have been added to the infrastructure required for effective SWM. These reforms have gradually increased the city's score and ranking in Swachh Survekshan (The Govt. of India's urban cleanliness and sanitation survey, set up in 2016)..

**Keywords:** Raipur City, Municipal Solid Waste, Solid Waste Management, SWM Rules- 2016, Swachh Survekshan

## Introduction
Municipal solid waste (MSW) refers to a heterogeneous collection of waste material produced in urban areas (Amasuomo & Baird, 2016). Under the Solid Waste Management Rules, 2016 (SWM), solid waste includes solid or semi-solid domestic waste, sanitary waste, commercial waste, institutional waste, catering and market waste and other non-residential wastes, street sweepings, silt removed or collected from the surface drains, horticulture waste, agriculture and dairy waste, treated bio-medical waste. This definition excludes industrial waste, bio-medical,

e-waste, battery, and radioactive waste. These are covered under separate rules framed under the Environment (Protection) Act 1986 (Jacob, 2022).

The Union Ministry of Environment, Forests, and Climate Change notified the new SWM rules in 2016, replacing the MSW (Management & Handling) Rules, 2000 (MoEFCC,, 2016). The new rules are applicable in all urban local bodies (ULBs), urban agglomerations, census towns, notified industrial townships, areas under the control of Indian Railways, airports, special economic zones, places of pilgrimage, religious and historical importance, and state and central government organisations (Ghosh, 2017). In recent years the government of India has prioritised the issue of sanitation, and SWM launched the flagship programmes such as Smart City Mission (SCM) and Swachh Bharat Mission (SBM). The union government launched the second phase of the mission as SBM Urban 2.0 in October 2021, emphasising the management of plastic waste ULBs. The government emphasises the effective implementation of SWM Rules 2016 through these flagship programmes.

In 2020, the world was estimated to generate 2.24 billion tonnes of solid waste, amounting to a footprint of 0.79 kilograms per person per day. With rapid population growth and urbanisation, annual waste generation is expected to increase by 73 per cent from 2020 to 3.88 billion tonnes in 2050 (World Bank, 2020).

Urban local bodies in India collectively generate about 160,000 tonnes (MT) of waste daily. This waste collectively becomes roughly 58 million MT per year; at current rates (CPCB, 2021). It is expected to jump to some 125 million MT a year by 2031. What is also of concern is that not only is the quantity increasing, but the composition of waste is changing—from a high percentage of biodegradable waste to non-biodegradable waste. The waste characterisation determines the strategy for its management (NITI Aayog, 2021). The amount of per capita waste generated in Indian cities ranges from 0.2 to 0.6 kg per day (Gupta & Gupta, 2015; Prakasam & Das, 2016). According to an estimate, if the current practice of dumping untreated MSW continues, the country would require about 88 square kilometres i.e. almost the size of its capital city, New Delhi, as a dumping ground by 2050 (ASSOCHAM and PwC, 2017).

In the Chhattisgarh state, 168 ULBs are responsible for implementing the SWM Rules, 2016. These ULBs collectively generate solid waste of about 1650 tonnes per day (TPD); out of that, 1386 TPD (84%) is collected, and 1271 TPD (77%) is treated. A total of 115 landfill sites are operating in the 168 ULBs of the state (CECB, 2019).

Accurate data on waste generation and other aspects of waste management is required to formulate effective solid waste management strategies. Regulatory, financial and institutional decision-making is deeply associated with the availability of desired data. This study is mainly based on published and unpublished data from the Raipur Municipal Corporation (RMC), the nodal authority for SWM in the city and the only source of comprehensive data. Data from other sources, such as Central Pollution Control Board (CPCB), was also utilised as needed for the study. Despite some minor errors in the compilation of SWM data or non-comparable datasets for long-term assessment, sizable information was available to execute this study.

Raipur is the capital city of Chhattisgarh, and with a population of more than one million, it is the state's largest urban centre. Raipur is among the fastest-growing metropolitan cities in India. It is a multi-functional city possessing a mixed land-use pattern. Population size, functional characteristics, and land-use patterns determine the amount of waste generated in the city.

This is a descriptive study formulated to identify the trends, patterns, sources and composition of waste generated in the city. The study attempts to analyse the various steps involved in the SWM of the city. It also intends to evaluate physical infrastructure and human resources engaged in SWM. Finally, the study attempts to investigate the performance of Raipur city through the Swachch Survekshan.

## Generation of Solid Waste in the City

This section describes the trends of solid waste generation, source-wise generation of solid waste, the composition of solid waste, and per household waste generated in the city.

### *Quantity of Solid Waste Generated in the City*

Estimating the amount of waste generated in any city is most important to plan SWM strategies. Table 1 describes the amount of waste generated in Raipur city.

**Table 1: Quantity of Solid Waste Generated in Raipur City**

| Sl. | Duration | Amount (Tonnes Per Day) | Source Agency |
|---|---|---|---|
| 1 | 2004-05 | 184 | CPCB[1] |
| 2 | 2010-11 | 224 | CPCB[2] |
| 3 | 2015-16 | 230 | CPCB[2] |
| 4 | 2006-07 | 448 | CDP[3] |
| 5 | 2013-14 | 408 | CDP-2014[4] |
| 6 | 2015-16 | 413 | Municipal Corporation Website[5] |
| 7 | 2016-17 | 437 | Municipal Corporation Website[5] |
| 8 | 2017-18 | 462 | Municipal Corporation Website[5] |
| 9 | 2019 | 542 | RMC[6] |
| 10 | 2020 | 641 | RMC[6] |
| 11 | 2021 | 684 | RMC[6] |

*Sources: 1. CPCB, (2005) 2. CPCB (2016) 3. CDP, Raipur (2006) 4. City Development Plan, 2014*
*5. https://nagarnigamraipur.nic.in//RaipurDataSet.aspx 6. Unpublished data from Raipur Municipal Corporation*

The 2006-07 waste generation data of RMC seems unreliable as their subsequent estimates were much lower. Despite this, Table 1 precisely reveals that 684 TPD of waste were generated in Raipur city in 2021, which was 3.7 times higher than the amount generated in the city in 2004-05. The annual growth rate (AGR) of waste generated during the reference period (2005-2021) was 8.55 per cent. Over the last five years, the AGR of waste generation has reached a to 10.6% .

waste (6%) is that generated from construction and demolition activities. Small industries like rice mills, pulse mills, food manufacturing, food packaging, small- scale iron and steel industries located in the city generated about 3 per cent of the total waste.

### *Composition of Solid Waste*

Waste composition refers to the characteristics of solid waste. Knowing the composition is the first and foremost step in formulating a plan for SWM. Source segregation of waste, doorstep collection, options for recycling and reuse, and selection of technologies for treatment and disposal depend on the waste composition. According to the City Development Plan prepared for Jawaharlal Nehru National Urban Renewal Mission (JNNURM) in 2006, about 42 per cent of the solid waste of Raipur city was organic or biodegradable waste. Households and hotels are the primary sources of organic waste generated in the city. About 10 per cent of waste was recyclable which consists of metals and plastic items, while another 48 per cent of the waste was inert. The inert waste was mainly derived from the construction industry (CDP, 2006). According to the CPCB report, the share of compostable, biodegradable waste (51.4%) and recyclable waste (16.3%) was slightly higher (CPCB, 2016).

Carbon to nitrogen ratio (C/N ratio) and moisture content in solid waste are two controlling factors that determine the decomposition process of solid waste. As per the SWM Rule, 2016, the limit of the C/N ratio for ULBs is <20, while the C/N ratio of municipal waste in Raipur city was 23.5 per cent (CPCB, 2016).

The moisture content of MSW is usually expressed as the weight of moisture per unit weight of wet material. The prescribed moisture content limit under SWM, Rules, 2016 should range from 15-25 per cent. However, the moisture content in the solid waste generated in the city was about 29 per cent (CPCB, 2016) which is higher than the prescribed limit (15-25%) to decompose waste.

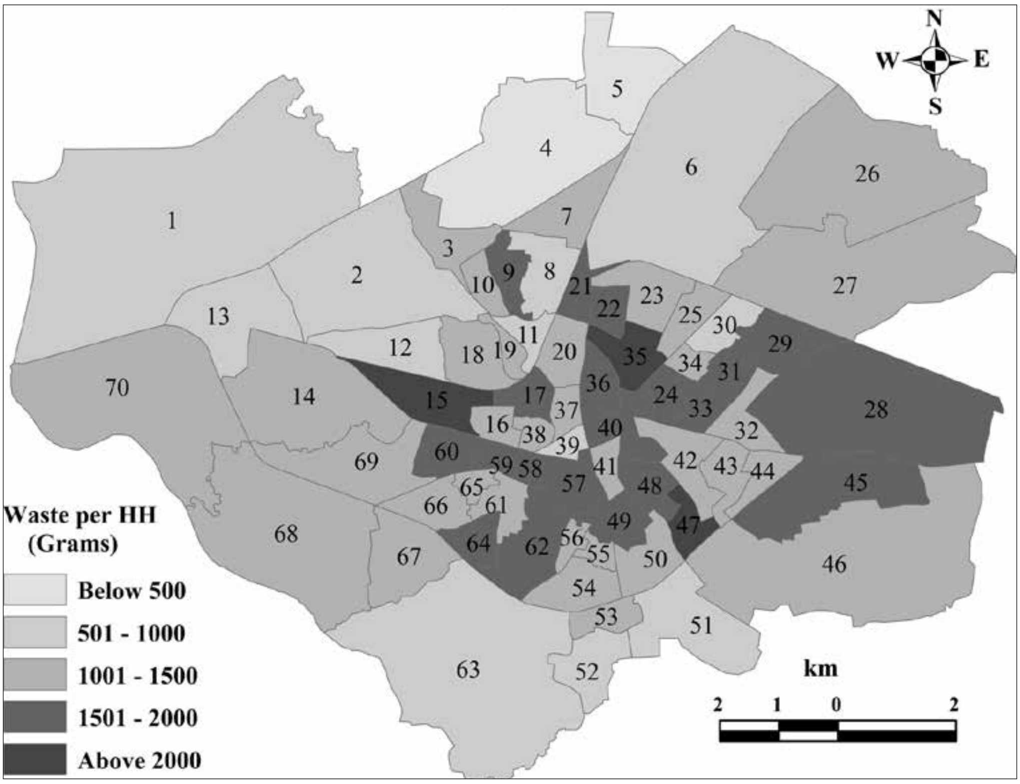
A higher amount of plastic characterises the solid waste generated in the city as more than 7 per cent of the city's waste is plastic (ASSOCHAM and PwC, 2017), making the decomposition process difficult and polluting the environment. As per the SWM, Rules, 2016, incineration was to be phased out until 2018.

### *Per Household Waste Generation*

Ward-wise wise generation of per capita waste is analysed through 2019 data. According to RMC data, Raipur city households generated 1.2 kg of waste every day in 2019. As per Census 2011 the average household size in the city was 4.7 people per household. It can be inferred from the two facts that about 255 grams of per capita solid waste was generated in the city.

Figure 1 indicates that households in the city's inner wards have generated more waste than the outer wards. The high average per household waste is mainly related to the consumption pattern. As indicated in Figure 1, Ward-15, Swami Atmanand Ward (2640 gram/HHS), Ward-47, Lt. Arvind Dixit Ward (2481 gram/HHs), and Ward-35, Swami Hemu Kalani Ward (2278 gram/HHs) generated the highest waste in the city. The core commercial areas of the city, such as Pandri, Malviya Road, Sadar Bazar, and Pachpedi, fall under the limits of these wards.

**Figure 1: Per Capita Generation of Household Waste in Raipur**




*Source: Based on unpublished data of RMC, 2019*

Apart from commercial areas, the households of the posh and prosperous residential areas, such as Jawahar Nagar, Tatyapara, Aminapara, Shankar Nagar, Chaubey Colony, Samata Nagar, Tagore Nagar, VIP State, and Shanti Nagar, generate a higher amount of waste. It is also observed that online delivery services, particularly online food delivery services, were not confined but primarily concentrated in the areas which generate a higher amount of waste.

## Management of Solid Waste in Raipur City

Raipur Municipal Corporation (RMC) is the nodal agency for managing solid waste in the city. It takes care of all the infrastructure and human resources required to complete the task. Various issues regarding solid waste management have been discussed in subsequent paragraphs.

### *Steps Engaged in Solid Waste Management*

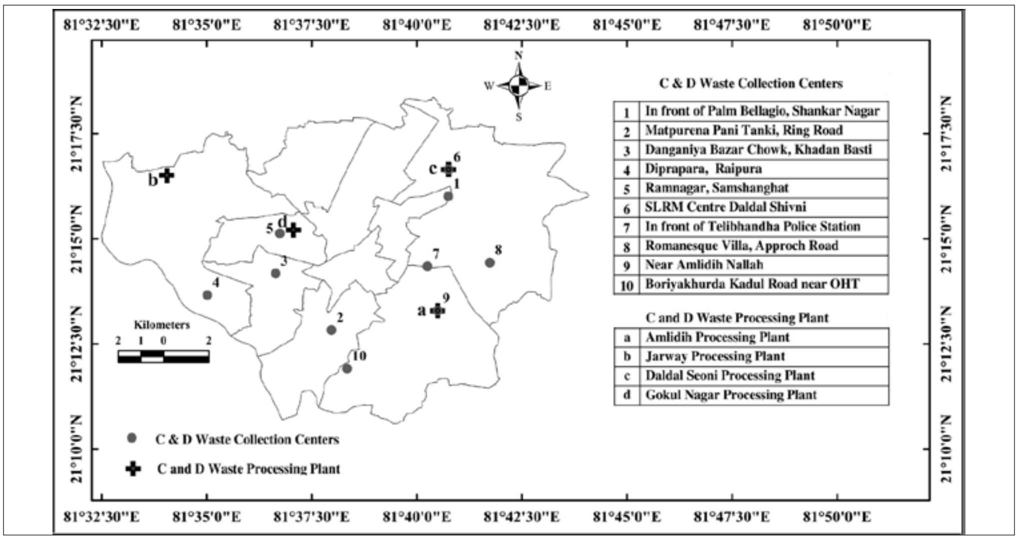
The system of SWM in the city has changed drastically in the second decade of the 21st century. The Swachh Bharat Mission (SBM) was introduced in 2014, and Smart City Mission (SCM) was introduced in 2015. Before the commencement of SCM, the ULBs were solely responsible for every aspect of SWM in the city. However, the scenario has changed drastically as a public-private partnership model is adopted under SCM. SWM Rules, 2016, was introduced to determine the standard practices that need to be followed by ULBs. The RMC has introduced many reforms for the compliance of SWM Rules, 2016, in the city. The RMC has handed over the task of SWM to Delhi Municipal Solid Waste Solution Ltd. (DMSWSL) through the public-private partnership (PPP) model. The current practices for SWM in Raipur city are briefly described here.

*Collection*

In compliance with the SWM Rules, 2016, the door-to-door solid waste collection was initiated in August 2016. Initially, the door-to-door collection was started in 38 wards. Later in 2018, all 70 wards were included. RMC claims that all households in the city are covered under the door-to-door collection. Delhi Municipal Solid Waste Solution Limited (DMSWSL), or Ramky Enviro, is involved in the door-to-door waste collection and transportation from all 70 wards. RMC collects the waste with the help of hollow-body container-mounted mini trippers (Tata Ace). These vehicles are also known as the Chhota Hathi. The vehicle has two different chambers. One is for dry waste, and the second is for wet waste. A model of public-private partnership (PPP) is adopted for the management of SWM.

The construction and demolition waste (C & D waste) is collected from the generation site and transported to the C & D waste plants for further processing. A total of 10 such plants are installed in the city (Figure 2). The RMC charges the generator to collect their waste.

**Figure 2: Collection and Demolition Waste Collection Centre, Raipur City, 2021**




*Source: RMC, unpublished data (2021) digitised by authors.*

*Segregation*

A two-step segregation is conducted by RMC. Primary segregation is performed at the collection points where the dry and wet waste is separated from each other. For waste segregation in households, the municipal corporation has distributed twin bins. Similarly, twin bins are installed in public places for primary segregation (Figure 3).

**Figure 3: Primary Segregation Mechanism of Raipur in Public Places**


*Source: Photo taken during the field survey, 2022.*

Secondary segregation facilities are installed in conjunction with waste transfer stations. There are a total of 9 such stations in the city.

The final waste segregation is conducted at the integrated waste management plant installed at Sakri village through PPP mode. Chhattisgarh Environmental Conservation Board (CECB) gave the green signal to DMSWSL to set up a waste processing unit at Sakri in 2018, and the plant started functioning in June 2020. A 15-year contract between the RMC and DMSWSL was signed to operate the plant. The same group was to install a 12 MW power plant to generate power from the waste (India Education Diary, 2020).

*Storage*

Earlier, solid waste storage was conducted in reinforced cement concrete (RCC) bins, dustbins, and metal bins of different sizes. A total of 726 such containers were installed in many locations in the city. However, under the Smart City Mission (SCM), the waste storage system of the city has reformed significantly. Older bins are replaced with twin bins (Figure 3). RMC installed 1024 twin bins at 315 locations. Apart from this, 38 smart bins were installed at 30 places in the city under the PPP model with the assistance of the Bangalore-based Jonta company (henceforth popularly known as Jonta bins). These smart bins have ensured the effective disposal of waste with minimum human interference.

*Transportation*

Transportation of waste is a multi-stage task performed through many types of vehicles. DMSWSL is responsible for door-to-door waste collection and transportation from all 70 wards. Tricycles, wheelbarrows, and autotrippers are engaged in the double task of door-to-door collection and transportation. Apart from this, Tata ace vehicles, portable compactors, tractors, hook lifters, refuse compactors, tippers, and JCBs have been used to collect waste from public places and transport them to secondary segregation facilities. All door-to-door waste arrives at the nine transfer stations and the vehicle then empties it in a portable compactor, which is then transported to the processing plant at Sakri with the help of large hook-lifters.

*Disposal*

Schedule-I of SWM Rules, 2016 is concerned with the specification for the construction of sanitary landfill sites, which give the criteria for site selection for the development of facilities at the sanitary landfills and criteria for specification for landfilling operations. The construction of landfilling sites becomes a daunting task for RMC due to multiple disputes with local people, DGCA and environmental clearance authorities for the construction of the land site. A fine of seven crore rupees was proposed by the Chhattisgarh Environment Conservation Board (CECB) on RMC for non-compliance with norms in the construction of landfill sites. However, RMC authorities ensured the high court they would complete tasks as per norms and within the extended time limit. Finally, in June 2020, the RMC inaugurated the SWM plant at Sakri after a delay of over three years.

After the commencement of SWM Rules, 2016, the ULBs were bound to modify their existing system of SWM management. Schedule-II of SWM Rules, 2016, concerns the standard of processing and treatment of solid waste management (MoEFCC, 2016). The RMC has developed compost sheds and a garbage clinic centre at the Sakri landfill site for composting and recycling the waste generated in the city. Now the Sakri plant is functioning through PPP mode, where modern technology is applied for segregation, decomposition and disposal (landfilling).

### *Workforce Engaged in Solid Waste Management*

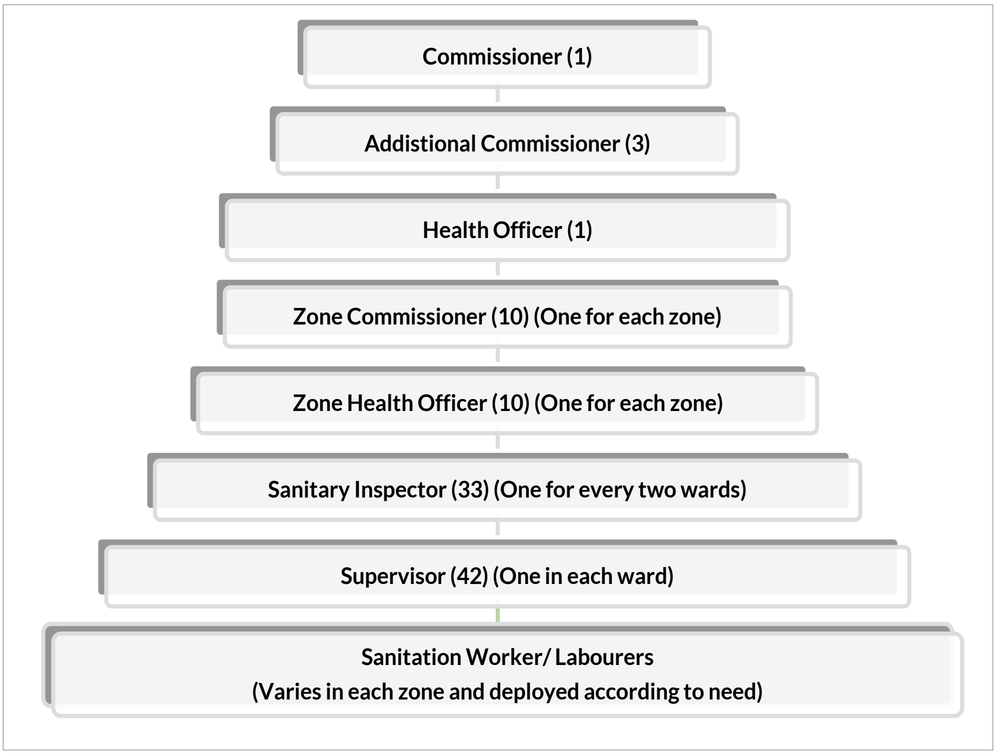
This section describes the hierarchy of workers and officials engaged in the SWM programme of the city. The numerical strength of workers required for the complex task of sanitation and SWM in the city is also elaborated subsequently.

*Administrative and Workforce Hierarchy in SWM*

Figure 4 demonstrates the hierarchy of workers and officers involved in the implementation of the SWM programme in the city. Labourers, popularly known as safai Kamgar, are engaged in sanitation, door-to-door collection, and transportation and are at the lowest rung in the hierarchy.

The rest of the officers and higher-order workers are involved in monitoring and implementing work at the ground level. The number in the bracket (Figure 4) indicates the number of posts filled in September 2022. Many positions of supervisors were vacant at the time of this study, which would have hampered the effective monitoring of the SWM programme of the city.

**Figure 4: Workforce Hierarchy in SWM of Raipur**




*Source: Based on unpublished data of RMC, 2022.*

*Safai Kamgar (Sanitation Workers) Engaged in Sanitation and SWM*

Strength and engagement level of safai Kamgar and other manual workers deployed in SWM is compiled in Table 3 which indicates that more than 4100 labourers are engaged in the sanitation and SWM department of Raipur city. These workers include the safai kamgar (sanitation workers) and special purpose workers of RMC, and SWM workers of DMSWSL. The latter workers are engaged in door-to-door collection and transportation of waste. RMC workers are employed at the ward level for street cleaning and garbage collection from different bins.

Special purpose workers are engaged in sanitation and SWM at the zone and city levels. At the zone level, these special-purpose workers are known as Zone Gang (120 workers) and Swachchta Commando (18 workers), while at the city level, they are called Central Gang (50 workers). Special purpose workers are primarily engaged in emergency and arrangement duties. Workers deployed in the slum areas are known as Basic Service for Urban Poor (BSUP) Colony Workers.

**Table 3: Task-wise Distribution of Labourers for SWM in Raipur, 2011**

| Sl. | Type of Workers | Engagement Level | No. of workers | Remark |
|---|---|---|---|---|
| 1 | Safai Kamgar | Ward | 2762 | Street cleaning and collection of solid waste from streets and bins |
| 2 | Door-to-door Collection and Transportation Workers (DMSWSL) | Household | 650 | Collection and transportation of household waste |
| 3 | Zone Gang | Zone | 120 | Emergency workers at zone level |
| 4 | Swachchta Commando | Zone | 18 | Emergency workers at zone level |
| 5 | Basic Service to Urban Poor (BSUP) Colony Workers | Slums | 59 | Deployed in slum areas |
| 6 | Special Purpose Workers for Commercial Areas and Public Places | City | 144 | Deployed in core commercial areas |
| 7 | VIP Gang | City | 100 | For social, cultural, and religious gatherings of state government |
| 8 | Mahapour Swachchta Cell | City | 100 | For social, cultural, and religious gatherings of RMC |
| 9 | Central Gang | City | 50 | Emergency workers at the city level |
| 10 | Health Camp | City | 100 | Health-related activities |
| | Total workers | | 4103 | |

*Source: Compiled from unpublished data of RMC, 2021.*

Apart from the above, 250 special purpose workers are deployed in the Head Office for floating needs associated with sanitation and SWM. They are called VIP Gang (100 workers), Mahapaur Swachhta Cell (100 workers), and Central Gang (50 workers). These workers have to ensure cleanliness and SWM during cultural and religious gatherings. Another 100 workers are deployed to collect waste generated from the activities of the health department of RMC; they are called health camp workers.

### *Existing Infrastructure for Solid Waste Management*

Diversified infrastructure facilities are required at different stages of solid waste management. A considerable investment is made in the infrastructure to ensure effective waste management. The city's waste management system has gradually shifted from a traditional labour-intensive system towards a machinery-based modern system. Table 4 provides details of the available infrastructure for SWM in Raipur city. Many of these infrastructure facilities are old and obsolete but still functioning.

**Table 4: Available Infrastructure for SWM in Raipur**

| Sl. | Name of The Facility | No. | Capacity/Size | Purpose |
|---|---|---|---|---|
| 1 | Tricycles | 100 | 80-100 kg | collection & transportation |
| 2 | Wheelbarrows | 300 | 2 cubic feet | collection & transportation |
| 3 | Autotrippers | 61 | 1.5 cubic meters | collection & transportation |
| 4 | Mini-trippers | 198 | 0.7 cubic meter | collection & transportation |
| 5 | Dustbins | 176 | 1.1 cubic meter | Storage |
| 6 | Metal bins | 250 | 120-600 Litres | Storage |
| 7 | Smart bins | 38 | 2.5 cubic meter | Storage |
| 8 | Dholas | 7 | - | Storage |
| 9 | Tata ace vehicles | 220 | - | Transportation |
| 10 | Portable compactors | 29 | - | Transportation |
| 11 | Hook lifters | 6 | - | Transportation |
| 12 | Refuse compactors | 4 | - | Transportation |
| 13 | Trippers | 6 | - | Transportation |
| 14 | JCB | 2 | - | Transportation |
| 15 | Sakri landfill site | 1 | - | Integrated Segregation & Landfill Site (New) |

*Source: Compiled from CDP, 2006 & 2014 and websites of RMC and Smart City Raipur.*

The door-to-door collection is the primary measure of waste collection in the city, conducted through 100 tricycles, 300 wheelbarrows, 61 autotrippers, and 198 mini-trippers. Apart from it, the waste generated in public places such as parks, markets and streets is stored in twin bins. One thousand twenty-four twin bins are installed at 341 locations. Earlier, 176 dustbins, 300 RCC bins, and 250 metal bins were installed in almost every part of the city. Now, they have been replaced by twin bins and smart bins. In 2018, 38 smart bins were installed in 30 places to store waste more hygienically.

RMC uses three different types of vehicles for SWM. Tricycles and wheelbarrows are engaged in door-to-door collection and collection from the streets. Autotrippers and mini-trippers are used in the door-to-door collection and transportation of waste to the transfer station. Tata ace vehicles also perform the same task. All waste from the city is collected at nine transfer stations and transported to Sakri in portable compactors. Hook lifters, refuse compactors, Trippers and JCB are used as assistance vehicles as per requirement.

Sakri Integrated Segregation and Landfill Site is functioning since 2020. Before, the waste collected from households or bins was transported to the landfill site unhygienically via 17 loaders and seven tractors. However, relatively modern technology has replaced these loaders and tractors as 220 Tata ace vehicles, 29 portable compactors, six hook lifters, two refuse compactors, six trippers, and two JCBs are used to transport solid waste for secondary segregation and landfill.

## Post-2014 Scenario of the SWM in the City

In 2014 newly elected NDA government prioritised the issue of urban sanitation and SWM in the country through the flagship programmes such as Smart City Mission (SCM) and Swachch Bharat Mission (SBM) (NITI Aayog, 2021).

The SCM was launched on 25 June, 2015 to encourage cities to develop core infrastructure facilities and provide a decent quality of life to their citizens, a clean and sustainable environment, and the application of 'Smart' Solutions[1]. The SWM is among the core infrastructure elements that need to be developed under SCM. Some of the changes that have taken place in the city after 2014 are described below:

i. An integrated approach to SWM is adopted, and all steps involved in the SWM are streamlined.
ii. Public-private partnership was introduced in the SWM that has revolutionised the SWM.
iii. Door-to-door collection was introduced in 2016, and 100 per cent collection efficiency was achieved in 2018.
iv. Secondary segregation was started in the city in 2019.
v. 38 Smart bins were installed in 30 public places.
vi. The practice of garbage burning was banned after 2016, and scientific landfilling of waste was initiated.
vii. A considerable investment has been made in establishing an integrated SWM facility/plant at Sakri, which started functioning in 2020. The Sakri landfill site was established according to the norms stated in SWM Rules, 2016.
viii. The MoHUA, GoI, initiated a competition among the cities through Swachh Survekshan in 2016. In the initial years of Swachh Survekshan, the city secured a relatively low ranking which has motivated the RMC to reform the system of sanitation and SWM of the city. Changes such as door-to-door collection, primary and secondary segregation, the introduction of citizen feedback and the construction of an integrated waste management plant on a priority basis are the few reforms initiated by RMC to ensure better ranking in the Swachh Survekshan.

## Performance of the City in Swachh Survekshan (2016-22)

It needs to be emphasised that the city has made significant progress in the SWM after 2014. However, it is difficult to objectively comment on the city's progress without factual information. Despite a few limitations, the data of Swachh Survekshan can be used to objectively measure the city's progress. Swachh Survekshan introduced in 2016 may provide objective information regarding sanitation and SWM, as the essential component of SWM is included in this survey.

In 2009-10, Raipur city was ranked 274th among the 423 cities surveyed regarding sanitation. With a score of a mere 30.7 per cent marks, the city was categorised as a red-listed city in the survey (MoHUA, 2010). No other objective information on the past performance of the city's

[1]https://smartcities.gov.in/about-the-mission#:~:text=Smart%20Cities%20Mission%20was%20launched,application%20of%20'smart%20solutions'.

condition in terms of sanitation and SWM is available. Data of Swachh Survekshan compiled in Table 5 summarises the city's progress in sanitation and solid waste management.

**Table 5: Performance of Raipur City in Swachh Survekshan (2016-2020)**

| Year | Marks Scored | Total Marks | % of Marks | Rank | No. of Cities in Survey |
|---|---|---|---|---|---|
| 2016 | 818 | 2000 | 40.90 | 68 | 73 |
| 2017 | 1175 | 2000 | 58.75 | 129 | 434 |
| 2018 | 2437 | 4000 | 60.93 | 139 | 434 |
| 2019 | 3393 | 5000 | 67.86 | 41 | 100 |
| 2020 | 4099 | 6000 | 68.32 | 62 | 100 |
| 2021 | 4811 | 6000 | 80.11 | 6 | 100 |
| 2022 | 5395 | 7500 | 71.93 | 36 | 100 |

*Source: Compiled from Final Reports of Swachch Survekashan, 2016-22.*

In 2016, Raipur was the only city in Chhattisgarh that participated in Swachh Survekshan. The city has scored a mere 41 per cent marks and secured 68th position among the 73 cities that participated in the survey. Probably the lack of methodological awareness (essential for data compilation) among the officials is the main reason for the city's below expectation performance in 2016. In 2017 the city's score increased by 18 per cent, ranking it 129th among the 434 cities. In 2018, the city's performance was almost similar to the previous year, and the ranking was even lower. The local and national media criticised the city's performance in 2018, as the city's rank was the lowest among the ULBs of Chhattisgarh (Gupta, 2018). However, the city had already initiated the door-to-door collection programme in 2016 and secondary segregation in 2018. It had also initiated the collection of the citizen's feedback. These are the three key areas responsible for the lower score and a decline in the city's previous ranking. In 2019, the city was awarded the 'fastest mover big city at the national level' in sanitation and SWM. The word of appreciation made in Swachh Survekshan-2019 justifies the efforts made by RMC. In 2019, the city scored 67 per cent marks and secured 41st position among the 100 most populous cities. In 2020, the city secured the 62nd rank among the 100 cities with a 68 per cent score.

In Swachh Survekshan-2021, Raipur city achieved its highest ranking (6th position) with an 81 per cent score. However, the city's data quality for the year 2021 seems ambiguous, as the data for Swachh Survekshan-2021 was only collected online. Furthermore, only 28 days were given to collect the data. In Swachh Survekshan-2022, the city scored only 71 per cent of the total points, and its score declined by 9 per cent compared to the previous year. The city has ranked 36th among the top 100 cities in India.

Swachh Survekshan 2022 reports further indicate that the city scored satisfactorily in many critical areas. However, waste segregation at source (at households) needs much improvement. Similarly, citizen grievance redressal needs immediate attention to improve ranking in the upcoming Swachh Survekshan. Overall, the city has shown significant improvement in the many critical areas of SWM, which is reflected in the city's score and has improved its ranking in Swachh

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# Stakeholder Assessment on Closing Nutrient Cycles through Co-Recycling of Biodegradable Household Kitchen Waste and Black Water between Rural and Urban Areas in South India

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**Abstract:** Agricultural land degradation, urban migration, increasing food demand and waste, and inadequate sanitation systems all affect farmers, local society, and the environment in South India. Joint recycling of biodegradable secondary household resources to close nutrient cycles between urban and rural regions can address all these challenges and thus several SDGs at the same time. Efforts are being made to this end, but many attempts fail. The central research question is, therefore: how can co-recycling concepts be evaluated in this context? For this purpose, composting plants, biogas fermenters, and a high-tech concept to produce plant charcoal, design fertilizer, and biopolymers are considered. The aim of this study is to evaluate the recycling concepts from the stakeholders' perspective to avoid gaps between theory and practice. Six expert and one focus group interviews on two successful on-site case studies and 15 online expert interviews with thematic actors were qualitatively evaluated and presented in a social network analysis to identify preferences and indicators for the further evaluation of co-recycling concepts. The results show that the focus is on mature technologies such as compost and biogas. High-tech solutions are currently still in rudimentary demand but will play a more important role in the future. To evaluate such concepts, seven key indicators and their measured values were identified and clustered into the categories ecological, social, technical, economic, and connective. The results show that this methodology of close interaction with stakeholders and the evaluation of successful regional case studies minimize the gap between practice and theory, contribute to several goals of the SDGs, and thus enable such concepts to be implemented sustainably.

**Keywords:** India; circular economy; kitchen waste; black water; resource efficiency; sustainable development goals; natural fertilizer

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## 1. Introduction

### 1.1. Problem Status

India faces a number of challenges such as population growth, rapid urbanization, food security, water scarcity, environmental pollution, and climate change [1]. This is illustrated by the second largest population in the world, the generation of 62 million tons of municipal solid waste in urban areas in 2011, and the increase in population-based $CO_2$ emissions per capita from 0.98 in 2000 to 1.73 tons in 2014 [2,3]. In addition, factors such as rapid economic growth and a growing middle class influence production and consumption behavior, which has socio-economic and ecological effects [4]. These effects are also evident in waste management with regard to waste generation, collection, transport, treatment, and disposal [5].

Due to the large population, the high proportion of organic waste (defined as wet waste in India, which in this paper includes kitchen, green, and market waste) with 61% by weight in urban household waste and inadequate sanitary facilities, the biodegradable secondary household resources kitchen waste, green waste, and black water are considered to have great potential for agricultural use as natural fertilizer [6–8]. This is also an important point because the high energy requirements in the production of mineral fertilizers can cause the greatest environmental pollution in agriculture [9]. Furthermore, agriculture is the main source of livelihood in India as 70% of rural households largely depend on it, with 82% of farmers being smallholders [10]. Smallholder farmers must be guaranteed safe and affordable procurement of fertilizers [11]. The use of natural fertilizers, which can be produced from secondary household resources, can contribute to this and counteract long-term and widespread soils degradation by improving soil fertility [12].

The misconnection between rural and urban regions in terms of carbon and nutrient fluxes exacerbates all of these challenges, while the connection offers significant potential to address them [13].

### *1.2. Relevance*

Alternative co-recycling systems (systems that consider different waste streams simultaneously) for black water and organic waste to those in developed cities that are resource-intensive and non-circular have the potential to reduce pollution and improve public health [14,15]. In addition, a regional circular economy can increase the resilience to environmental influences in communities [1]. This indicates a need for action worldwide, which is particularly advantageous in India when implementing new concepts by skipping traditional concepts.

The Indian government is taking steps to adapt the circular economy, for example through the Swachh Bharat Mission, in which stakeholders have shown that they can benefit from global best practices in public heath, sanitation, energy, water and land conservation [1].

This underlines the fact that several Sustainable Development Goals (SDGs) can be addressed with appropriate circular economy concepts. Examples of the many possible contributions of circular concepts are SDG 7 “Affordable and Clean Energy” that can be obtained from secondary biological household resources and SDG 2 “Zero Hunger” in the context of sustainable agriculture [16,17].

### *1.3. Research Gap*

Due to the increasing urgency of implementing circular concepts, the need for stakeholder perspectives and evaluated successful case studies is also increasing to ensure sustainable implementation using evaluation indicators. Since these perspectives are missing for South India and are important for the transferability and scaling of future concept implementation, these aspects are examined in more detail in this study.

### *1.4. Objectives*

The aim of this study is to evaluate co-recycling concepts with biodegradable kitchen waste and black water from households for agricultural use and thus the closing of cycles between urban and rural regions in South India. We consider a high-tech concept (RUN—“Rural Urban Nutrient Partnership” [18]) with integrated vacuum toilets for the collection of black water for the joint recycling with separately collected kitchen waste to produce fertilizer (magnesium-ammonium phosphate), plant charcoal, and biopolymers (Figure 1) and compare this with the conventional technologies of anaerobic digestion and composting (Figure 2). To reach this goal, the following research questions are defined:

- Which is currently the most suitable co-recycling concept?
- What are currently the most suitable key indicators for the implementation of such concepts?
- How can these key indicators be assessed?


**Figure 1.** High-tech concept (1) of a rural urban nutrient partnership (RUN), as an example for short circular economy [18]. The image shows the closure between urban (**right side**) and rural areas (**left side**). The RUN plant produces fertilizer, plant charcoal, and biopolymers.

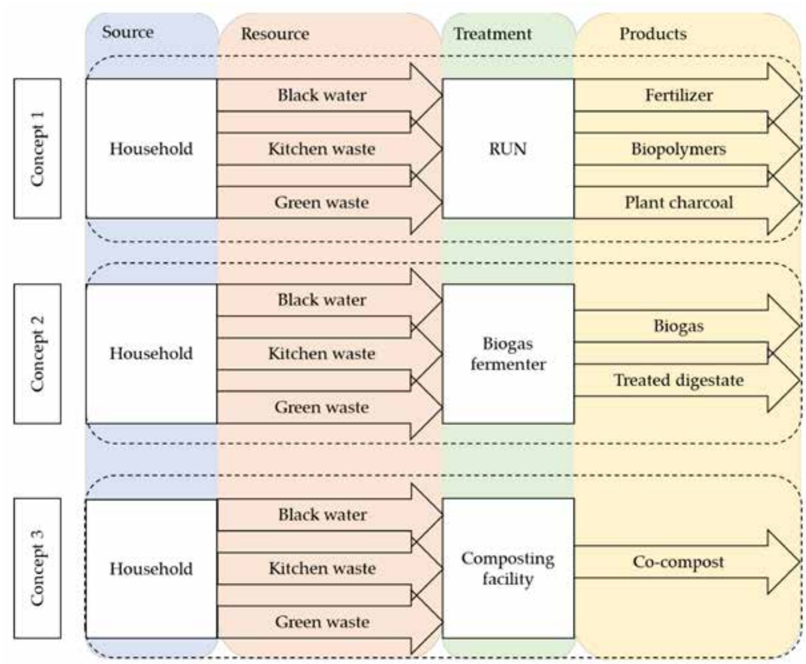


**Figure 2.** The three co-recycling concepts considered for the thematic online expert interviews. Comparing the high-tech RUN (rural urban nutrient partnership) concept with the wildly used technologies biogas fermenter and compost facility.

The evaluation is based on case studies and stakeholder perspectives to avoid gaps between theory and practice, which is essential for the sustainable implementation of alternative concepts.

## 2. Materials and Methods

A multi-tool approach was used: a combination of digital thematic expert interviews, a social network analysis (phase 1), and an on-site evaluation of two case studies with further expert interviews and a focus group interview (phase 2). This was done in the sequence described in successive phases. Digital data collection took place from June to October 2021 and on-site data collection—from October to December 2021 in the peri-urban regions of Bangalore and Ooty in South India. Interviews lasted between 30 and 90 min.

### *2.1. Interviews with Thematic Stakeholders*

In summary, it was asked how co-recycling with the use of urban and semi-urban household kitchen waste and black water for use in surrounding agriculture could be suitable for closing loops in South India. In this context, the focus was on practicability, implementation options, challenges, opportunities, suitability, experience, prerequisites, and framework conditions. These questions aimed to answer the research questions considering the RUN system, biogas digestion, and composting plants. The concepts were explained using a presentation and the RUN graphic (Figure 1).

The results were obtained by conducting semi-structured interviews with 15 thematic stakeholders involved in the circular economy in South India. The circular economy experts are active in organic waste and black water treatment and are local scientists, private investors and executive directors, managers and employees of non-governmental organizations, non-profit organizations, and corporations. In order to have a well-covered spectrum and excellent technical expertise, stakeholders were selected in equal parts who are either experts in biogas, compost, or plant charcoal and then the snowball principle was applied [19–21]. The interviews with additional stakeholders ended after the indicators, identified in the literature were discussed and no new indicators were added.

These interviews were conducted digitally face to face, recorded, and transcribed. The resulting data were qualitatively analyzed and coded, clustered and categorized according to the research questions, resulting in categories, key indicators, and evaluation criteria [19].

### *2.2. Social Network Analysis*

The qualitative data from the interviews were used for a cognitive mapping method. This method was chosen due to a large amount of data and perceptions of different stakeholders and to authentically integrate the local knowledge. The method visualizes perceptions of social realities with networks of nodes and lines. This is based on a binary matrix that sets numbers for a relation (0) and no relation (1) and is visualized with software (as fc mapper: available at http://www.fcmappers.net/joomla/, accessed on 10 January 2022). In this study, the correlations are not weighted as usual [21], in order to avoid bias [22]. Each asset is defined by its centrality, which is the sum of the ingoing and outgoing lines. It is assumed that the greater the centrality, the more important the indicator is for the implementation of a new alternative circular concept. The indicators from the social network analysis with high centrality were used as selection criteria for 7 key indicators, which were divided into 5 categories. These were identified for a successful implementation of a co-recycling concept of secondary household resources between urban and rural areas.

### *2.3. Case Studies*

Two successful case studies of co-composting plants in South India were evaluated by relevant actors including administrative directors and employees, plant managers, and workers. In this context, 6 expert interviews and 1 focus group (with the plant workers) discussion were conducted out on site. The interviews included questions about mass flows, framework conditions, and the identified key indicators and evaluation criteria. Stakeholders' statements on the key indicators were ranked on a scale from 1 to 4 (Table 1).

**Table 1.** Scale of evaluation criteria assigned according to stakeholders' responses.

| Scale | Value | Answers of Stakeholders |
|---|---|---|
| 1 | Insufficient | The criterion does not exist or is the reason for the failure of the concept. |
| 2 | Improvable | The criterion is seen as a major challenge and a change is necessary for a successful continuation of the concept. |
| 3 | Good | The criterion is satisfactorily met, but improvement is aimed. |
| 4 | Very good | The criterion is met and is not perceived as a challenge. |

A composting plant is located in Devanahalli, in the peri-urban area of Bangalore in the state of Karnataka, which is operated by the municipality and receives technical support from the CDD Society [23]. The other two composting facilities (defined as a single case study) are located in Ketti and Athigaratty in the peri-urban areas of Udhagamandalam (Ooty) in Nilgiris in the state of Tamil Nadu and are managed by RDO Trust [24,25]. Both organizations are non-profit institutions.

The technical details (obtained from the interviews) about the process of producing the co-compost entails at first the manual separation of organic waste of possible contaminants. In addition to household kitchen waste, black water from households, public green waste and restaurant and market waste are used as resources. The black water first flows through several tanks. In Devanahalli these are closed for the additional production of biogas (which is currently not used) and in Nilgiris these tanks are open. Both have the concept of separating the solid from the liquid part by sedimentation. The solid part is dried under polycarbonate sheets between 20 and 25 days. Composting is done in layers with treated black water and organic waste in a weight ratio of 1 to 2 in Devanahalli and 1 to 4 in Nilgiris. It is composted for 42 days in Nilgiris, where it is turned once a week, and 60–75 days in Devanahalli, where it is turned every two weeks.

## 3. Results

The social network analysis shows indicators for and against the preferences for the co-recycling concepts compost, biogas, and the high-tech concept RUN. The results are visible in 5 main categories: "ecological", "social", "technical", "economical", and "connective" (Figure 3).

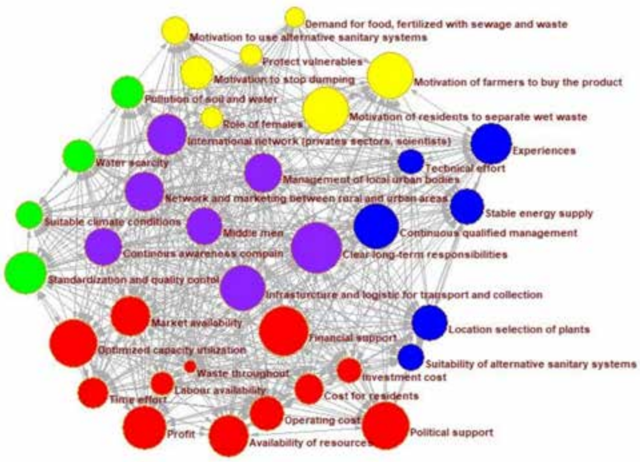


**Figure 3.** Social network analysis of indicators of co-recycling concepts between rural and urban areas from the view of thematic stakeholders. This is generated by using the cognitive mapping method (described in the material and method section). The indicators are represented by colored circles and the relation by lines. The larger the circle the higher its centrality and relevance for the concept. The color code is: green = ecological, yellow = social, blue = technical, red = economical, purple = connective.

The seven key indicators and their assessment criterion for the successful implementation of co-recycling concepts with secondary household resources were grouped into these five categories of social network analysis (Table 2).

**Table 2.** Key indictors from stakeholder perspectives and their evaluation options, clustered in categories. The key indicators were derived from the social network analysis and summarized.

| Category | Key Indicator | Assessment Criterion |
|---|---|---|
| Ecological | Standardization and quality control | Measured values of the sales products and the wastewater after treatment in relation to limit values and definitions of specific measures if exceeded |
| Social | Motivation of residents to separate wet waste | Rate of segregation of wet (organic) waste |
| | Motivation of farmers to buy the product | Share of informed farmers and farmers who buy the product regularly |
| Technical | Continuous qualified management | Employee satisfaction and dealing with operating and management problems |
| Economical | Financial support | Assessment of the government support of the entire supply chain |
| | Optimized capacity utilization | Efficiency of capacity utilization |
| Connective | Logistics network and clear long-term responsibilities | Clear responsibilities at state, municipal and operational level, and the possibilities to resolve stagnations in the supply chain |

The specific assessment based on the identified key indicators on the two case studies is shown graphically in the following figure (Figure 4).

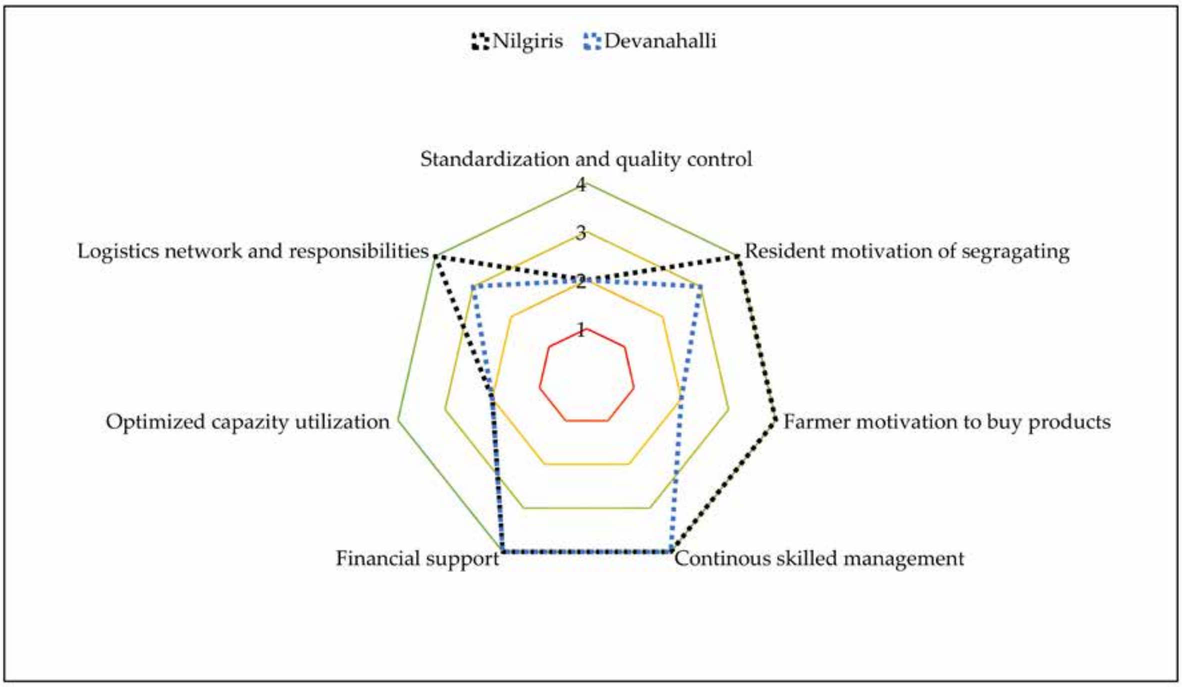


**Figure 4.** Evaluation of two case studies, based on the identified criteria and the assessment of the stakeholders (1 = insufficient; 2 = satisfactory; 3 = good; 4 = very good).

The preferences of the respective categories from the perspective of the thematic stakeholders are presented in detail below. The key indicators are explained in more detail based on the case studies and the opinion of the experts on site.

### 3.1. Ecological

Mixing black water with wet waste for recycling is critical from an ecological point of view since many different chemicals are used in the cleaning of sanitary facilities and it is not known whether these can be found in recycled products. On the other hand, the nutritional value that could be brought into local agriculture through co-recycling is viewed positively.

All co-recycling concepts can reduce the impact on the environment. On the one hand, it can be reduced through use because, for example, long transport routes and the production of fertilizers could be saved. On the other hand, it can be reduced by avoiding waste dumping. Improper disposal of black water and wet waste has significant negative impacts on the environment such as soil and water pollution and creates additional problems during the dry season. Water scarcity during periods of drought and degradation of agricultural soils are widespread in southern India. Here the necessity of using natural compost (compost from waste streams) is pointed out to improve water retention capacity and soil fertility in the long term. As the environmental impact is acute, it has often been stressed that quick and effective solutions should be implemented to improve the situation.

A fertilizer with a low probability of contamination in combination with the use of plant charcoal, as provided for the RUN system, was rated positively. Nevertheless, the prevailing opinion is that co-compost offers a solution to a large number of current problems in South India. Co-fermentation was particularly advocated for very densely populated urban areas where there is less space for co-compost. It has been argued that in this way dumping and negative environmental impacts on regions near cities can be avoided.

Key Indicator: Standardization and Quality Control

Regular checks and tests are required to avoid the contamination of the soil and water. In both case studies (which are described in the materials and methods section), regular checks of compost and treated wastewater for micropollutants and pathogens as well as temporary checks for raw input (black water and organic waste), heavy metals, and nutrients are carried out at university laboratories. If the specified limit values were exceeded, action plans were defined and implemented.

The lack of sufficient basic data for the characterization of wet waste, black water, compost, and wastewater, as well as uniformly structured standards in a guide, which is necessary for the upscaling and transfer of concepts to other regions, is problematic. Furthermore, clearer time rules for measuring and testing could be improved. Both case studies showed a large discrepancy in the answers between the respondents.

### 3.2. Social

Much attention was paid to the social aspects. The management of black water and wet waste is essential for health reasons, for people, animals, and the environment, but also to support the local population.

It has often been emphasized that the smallholders who make up most Indian farmers need more support, which also serves to ensure food security. Farmers should have affordable, safe, and natural fertilizers such as co-compost available.

In addition, sanitation is needed for all, with a special emphasis on the urgency for women. A high-tech vacuum toilet will only be available to a minority in certain regions. No problem is seen with the motivation to use such a toilet if a toilet has already been used. Therefore, the focus is currently on the nationwide expansion of the sanitary facilities. With technologies that have been known and tested for many years, it is possible to reach many regions and people.

For people to be able to buy food that has been fertilized with organic waste and black water, there needs to be awareness and a market for all co-recycling concepts. Residents are expected to be less reluctant to design fertilizers (such as magnesium-ammonium phosphate), although this aspect is not considered significant.

From the stakeholders' point of view, the main thing is not to create any disadvantages and to enable as many actors as possible (including the socially disadvantaged) to add regional value, which is why they are more committed to tried-and-tested technologies such as biogas fermenters and compost facilities.

#### 3.2.1. Key Indicator: Motivation of Residents to Separate Wet Waste

In both case studies, a lot has been and will be invested in ongoing awareness raising. Measures include street motivation via microphones, information brochures, and garbage cans that are freely available to households. To improve segregation, waste in Devanahalli will be segregated manually when collected on the means of transport.

Part of this motivation is also an acceptance of the technology, where the not-in-my-backyard syndrome occurs. In Devanahalli and Nilgiris, the co-composting facility was built on a former dumping place, which initially met with resistance from residents in Devanahalli. Positive experiences, absence of odor, and visual preferences promoted acceptance.

Even if these aspects are considered, continuous campaigns have to be brought even more into focus.

#### 3.2.2. Key Indicator: Motivation of Farmers to Buy the Product

This indicator is strongly influenced by external circumstances. Cost and accessibility of co-compost and alternative products (with greater competition in Nilgiris), as well as water scarcity and soil fertility, play a role here as long-term factors. The prerequisite is that the farmers are informed, advised, and supported in the conversion from conventional fertilizer to natural fertilizer and the practical implementation. Both case studies show that most farmers trust local organizations and are willing to try new opportunities after the benefits become apparent. Free samples, participation in information and awareness-raising events, and positive personal or shared experiences provide additional encouragement. Then the willingness to invest a little more at the beginning increases to benefit in the long term if the additional investment is within the scope of the possibilities. The cost of 5 to 7 rupees (~0.06–0.08 €) per kilogram of co-compost is lower than that of chemical fertilizers in both case studies. In Devanahalli, conventional fertilizer costs about four times more per kilogram (using ammonia-based chemical fertilizer No. 5 as an example) and in Nilgiris (using muriate of potash MoP as an example)—about three times more. Fertilizer No. 5 has a nutrient content of 6:12:6% NPK, which is much higher compared to the co-compost in Nilgiris (0.9:0.5:0.5% NPK) and Devanahalli (0.7:0.2:1% NPK). The advantages of co-compost, such as the high content of organic carbon and the improvement of soil properties, mean that the recommended quantities for co-compost are equal to or at most double those for mineral fertilizers, which is why combinations are usually applied—with positive results. Therefore, chemical fertilizer is only substituted to a certain extent. For comparison: farmyard manure costs about 3 to 5 rupees/kg (~0.04–0.06 €) in Nilgiris and is thus closer to the cheaper price range than co-compost.

Points that could be improved: more focus on advertising would be crucial in Devanahalli, as well as more pick-up stations (within a radius of 20 km). Both case studies could offer farmers more transport support and information dissemination on the availability of co-compost.

### *3.3. Technical*

From a technical point of view, co-composting was particularly emphasized as it has proven itself in practice over the long term. These are mainly small and decentralized systems in which technical challenges can be solved independently, without downtime or external maintenance. Given the recent pandemic, it has been suggested that independence is a major issue.

Experience has shown that this concept works more long-term and more sustainably in South India than biogas plants and high-tech concepts such as waste incineration plants.

Most stakeholders clearly preferred compost instead of biogas to high-tech solutions, while hardly anyone saw much potential in high-tech solutions, also because of the more complex structures in responsibility and supply chains. Problems with technical knowledge or knowledge transfer are not seen.

Another point that reinforces this assessment is the unstable energy supply in large parts of southern India, which would be a basic requirement for a high-tech concept like RUN. Such a system is also hard to imagine in rural regions, which is why the choice of location is crucial and severely restricted.

The potential for biogas plants was seen in densely populated areas due to the lack of space, the direct use of energy, and the closed construction. However, if fermentation residues from biogas plants are not processed and marketed, disposal can be difficult because the liquid part could get into the wastewater.

Key Indicator: Continuous Qualified Management

Detailed instruction, regular training, and clear responsibilities are the key words for continuous and qualified maintenance of a system. Both case studies show a high functionality of this area due to adequate local management support. Management in combination with highly motivated employees make after-sales services unnecessary, as problems or stagnations can be effectively resolved. The high level of motivation is generated and maintained through better salaries and more structured working hours compared to the previous activities of employees. Higher job security also plays a role here, due to the continuous need for compost and waste and black water disposal. This sense of security has been reinforced by the recent impact of the pandemic.

In Devanahalli, unused biogas escapes into the atmosphere because biogas is produced but is no longer used after the demolition of the plant house where it was directly used. In Nilgiris, the compost heaps give off unusually strong odors, which could indicate that these can be improved with building material.

All this underlines the importance of a functioning and good management system.

### *3.4. Economical*

The investment costs are lower for composting plants than for biogas digesters, which in turn are lower than for high-tech plants (like RUN). Experience has shown that investment-intensive concepts are often not profitable, and examples where it works are easy-to-use, low-cost technologies that make products locally marketable at low prices.

The competition for biogas is difficult because liquid gas (LPG) is subsidized, and the state relies on other renewable energies such as sun and wind. It is clearly perceived that the decision about a concept depends heavily on the orientation of the government level. Political support is an important indicator for this sector.

The government support chemical fertilizers in South India. The design fertilizer would therefore fit in well with the already established structures. Conventional fertilizers are very popular and in high demand, with natural fertilizers increasingly coming into focus again. Compost is marketable, but still needs financial support and nationwide offers for broader use.

For residents, the overall schemes should also entail costs to support the waste and black water management, which is partly the case.

High-tech concepts harbor many uncertainties and biogas is not the focus of energy in South India. This shows that co-compost is the most popular option here too.

#### 3.4.1. Key Indicator: Financial Support

In Nilgiris, 20% of production costs can be covered by the sale of compost, while in Devanahalli it is 21% (both values refer to the year 2020). These values show the high dependency on financial support. Without government support, it is very difficult to make such a concept profitable if the framework conditions are not adapted. These adjustments would have to be decided at the government level, such as reduced subsidies for chemical fertilizers and greater support for the entire production chain of natural and local fertilizers. In addition, strict rules and controls, while preventing corruption, ensure that improperly disposed waste and black water are avoided. This supports planning, capacity optimization and reduces the impact on the environment and climate. The costs for residents should also be adjusted via waste fees to promote such systems. All these points can help reduce or even eliminate the need for direct financial support.

#### 3.4.2. Key Indicator: Optimized Capacity Utilization

Optimum utilization of the system capacities is necessary to increase profitability, which is already possible in the planning phase with suitable scaling. The insufficient database for the available resources turned out to be problematic in both case studies (also due to changes in the data basis in long-lasting planning phases), which is why the utilization shows potential for improvement. Therefore, despite correct theoretical calculations, there were deviations from reality in practice. The achieved capacity, measured on black water, is 38% in Devanahalli and 22% in Nilgiris, while the plant capacity is 6 $m^3$/day in Devanahalli and 6.7 $m^3$/day in Nilgiris. Table 3 shows the mass flows achieved for both case studies.

**Table 3.** Mass balances from the two case studies in Devanahalli and Nilgiris in 2020.

| Category | Unit | Devanahalli | Nilgiris |
|---|---|---|---|
| Kitchen waste | $t{\cdot}a^{-1}$ | 540 | 2120 |
| Green waste | $t{\cdot}a^{-1}$ | 108 | - |
| Black water | $m^3{\cdot}a^{-1}$ | 840 | 534 |
| Compost | $t{\cdot}a^{-1}$ | 33 | 522 |

The scaling is improved with each plant, as in Nilgiris, where the subsequent plant can be better assessed based on previous experience in the region.

There are also natural resource fluctuations that occur due to certain situations such as the Corona Pandemic or market conditions (in Devanahalli). This problem requires plans to deal with the fluctuations in the raw material. In Devanahalli there is often a surplus of wet waste that is composted separately in a designated place. In Nilgiris, tea residues are used in other compost compositions to compensate for the lack of wet waste. This problem exists in Nilgiris in contrast to Devanahalli as the population density is lower and more farmers are recycling wet waste themselves, suggesting the need to identify unused resources. Capacity utilization could improve due to increased focus on restaurant and market waste and improved management of kitchen waste from households.

Another aspect is the additional utilization of dry waste streams, such as plastic. In Devanahalli, a local distribution center increases total return, while in Nilgiris, dry waste is transported to Coimbatore, shifting the value.

Optimum plant utilization is an important point among all concepts considered to increase local added value and use local resources optimally, instead of long transports with negative effects on the climate and independence. Small and decentralized systems in semi-urban and semi-rural areas are often preferred in South India, as in the case of the two case studies.

### *3.5. Connective*

The connecting aspect has often been highlighted by stakeholders as an important sustainability factor for the circular economy.

From the point of view of network management, which includes the connection of logistical aspects and clear responsibilities in all areas, high-tech concepts such as RUN are viewed particularly critically. Since such concepts are very complex, it is primarily about the central control of all areas, the connection of the different stakeholders, and a responsible umbrella unit of different levels. This applies to all co-recycling concepts in the exchange between rural and urban areas but becomes more difficult as the concept becomes more complex.

Experience has shown that other high-tech projects have had problems with unclear responsibilities in production and along the supply chain. Problems that arose here remained partially unsolved.

Future potential for high-tech concepts such as RUN is seen in urban and semi-urban regions for newly emerging, prosperous, and established settlements of a minority. However, many boundary conditions must be covered for this, with well-functioning infrastructure, clear responsibilities, and the network to all parties involved being important aspects.

Key Indicator: Logistics Network with Clear and Long-Term Responsibilities

Co-recycling concepts are complex and involve many actors, which poses challenges for network management.

For clear responsibilities, an umbrella organization at the government level, but also central and long-term responsibilities at the regional, local, and operational levels are necessary. As in the case studies, the actors must be motivated to pursue common goals. As a result, fluctuations, or other challenges in the supply chain between the collection, transport, and distribution can be better managed.

Site planning is another important aspect here to meet the needs of farmers, residents, and infrastructure, which is why the case study selection fell on semi-urban and semi-rural regions. Needs are, for example, the availability of resources, products, and markets as well as the elimination of middleman problems. In addition, it is the task of the central levels to look at the socially disadvantaged, such as waste pickers and smallholders so that they are not neglected in these concepts. In Nilgiris, women from socially disadvantaged backgrounds were offered a secure and better-paid job (compared to previous jobs) as a part of a self-help group in the co-composting facility.

For further training and promotion of the overall concept, exchange in an international network that integrates various thematic actors such as business and research is desirable. Both case studies are in international exchange with non-governmental organizations, universities, and civil society organizations.

A challenge in both case studies was that black water was occasionally discharged into the environment to save fuel for transport to the co-composting facility, which was addressed with strict controls and awareness programs. Honey suckers are often privately owned, while waste disposal is contracted by the municipality and has fewer problems in this regard. Safe and good working conditions are further aspects that help to reduce and stop dumping.

## 4. Discussion

### *4.1. Potential of Alternative Circular Co-Recycling Concepts*

Looking at the different SDGs that can be directly addressed through the implementation of suitable cycle concepts [4,7,12] the potentials for compost, biogas, and the RUN concept differ within the considered framework. In India, due to the cost-benefit ratio, the greatest potential is seen in small and decentralized compost technologies [1,12,26]. Additionally, India has struggled with waste-to-energy methods such as incineration and pyrolysis, and mature technologies such as biogas fermenters and compost facilities are showing better success [26]. Large-scale biogas plants with subsequent composting were also seen as problematic [27]. Nevertheless, there is also a need for large cities to integrate incinerators with optimal separation for success [27], showing differences in approaches between urban and rural regions. Moreover, in the broader emerging market context, it is proposed to focus biodegradable waste on mature technologies (like biogas and compost) rather than expensive high-tech solutions (like RUN) [26,28,29].

Farmers who use co-recycling products to manage their land sustainably can also benefit, although there is no standard solution and the technology should be adapted to the circumstances [28]. Using black water after appropriate treatment improves sustainable agricultural soils while providing a wastewater disposal solution [29]. Smallholders are sometimes exposed to a high price dependence of chemical fertilizers, which is why composted digestate and compost can be the best alternatives for them [11]. This shows that the best options to implement SDG 2, which relates to food security and sustainable agriculture, are mainly seen in the context of co-compost or vermicomposting [7,11]. In urban areas, in-vessel composting is a good solution to quickly produce hygienic and high-quality compost [30], again pointing to the need to differentiate between urban and rural areas.

Co-fermentation can improve biogas yield through synergy effects, which can contribute to SDG 7 in terms of affordable and clean energy [31–33]. A high-quality fertilizer is added to the energetic advantages [34]. Heavy metals can be within tolerable heavy metal limits here while composting and drying can completely remove pathogens [11]. Even if anthropogenic trace substances, such as harmful medicines, can be inactivated [15], more attention must be paid to this area for more clarity [14]. Decentralized installed biogas fermenters can create additional livelihoods in India and have a positive effect on health and the environment [35]. Biogas digesters are established and are therefore seen as an accessible and possible solution to energy, waste, and greenhouse gas problems, while being able to handle varying waste streams and can have modern emission control measures and high efficiency [36]. In both the Indian and global context, there is a dependency on political decisions as to which renewable energy sources are favored [37]. Biogas technologies are therefore in competition with other renewable energy technologies such as solar and wind in India [38].

Plant charcoal has the potential to reduce climate-relevant emissions, sustain soil health and enhance crop yields, especially in tropical soils [39]. There is also a big potential for recycling phosphorus, especially when using struvite fertilizer (which is also produced in the RUN concept) as it is considered a safe fertilizer [40]. Although high-tech solutions are promoted in India, they are problematic because the informal recycling sector is often not involved and these concepts frequently fail because they are not adapted to the waste composition [41]. The informal sector is an important part of waste management, so participation is necessary, also to improve working conditions and promote integration [27,38]. There already are successful integration approaches [42,43]. In addition, it has also been shown that transport and containers are more important for successful implementation than high investments [27].

### 4.2. Importance of the Methodology

Due to the high complexity and breadth of stakeholders, cooperation and interaction are considered important in this context in order to follow consistent paths in research and new implementation in practice [12]. The integration of different views and advice underlines the importance of the unifying aspect [12,35]. This is important to understand the interplay between the circular economy and the local context of the local and thematic experts and stakeholders [1,44]. Threats and opportunities are made visible by stakeholders, which is necessary for sustainable concept implementation [37]. These can be used to support specific calls for political support [37].

### 4.3. Potential of the Indicators

The categories technology, economy, ecology, social affairs and politics are mainly used for the circular economy [28,39,40,45,46]. It is assumed that political, economic, and legal aspects are the key indicators, and that ecological and social aspects are derived from them [37]. The inclusion of the stakeholder perspective shows a stronger focus on social aspects [47]. Here, our own categories and indicators as defined in the results section can be embedded.

In our study, great importance is attached to the category "connective" in the context of the circular economy. International cooperation is one of the main drivers for the optimization of circular economy concepts [36]. It benefits both Indian industry and communities in the transfer of technologies that have proven beneficial in the promotion of health, energy, water and land conservation, and cost savings [1]. For the implementation, the leadership and commitment of top management coupled with clear and strong responsibility are the most important factors in the circular economy [45]. Added to this are the long-term and clear responsibilities of the municipalities in waste management [5,26,48].

A successful circular economy depends above all on the political will to create the necessary framework conditions, which underlines the role of the state. [1,38,39,48,49]. Otherwise, the hurdles are high and in many cases not profitable [46]. The high financial dependency in emerging countries is also due to the high investment costs, which makes clear the need for successful business principles [12,50]. The lack of a suitable market and good marketing of recycled products is also noted [50]. The potential of composting plants can be economical for several Asian countries if the framework conditions are right and, for example, good quality is guaranteed and the market value is given [49]. In this study, financial support is considered essential, since the framework conditions are currently designed in such a way that profitable implementation is not yet possible.

Similar economic and logistical factors can also be found in the context of the industrialized countries [37]. The fact that availability and logistics management is an essential factors in optimizing capacity utilization is consequently a global factor [35]. The database on the amount and composition of waste streams in India is often insufficient, which is necessary for optimally adapted technologies and scaling, which is why it is considered necessary to implement pilot plants first [27].

Technical aspects are contradictory. On the one hand, the lack of qualified specialists is seen as a key barrier [5], on the other hand, technical aspects for implementing a concept are seen as unproblematic [37]. The latter is confirmed in this study, based on the two case studies and the thematic expert interviews.

A key factor in social issues is the separation rate [27]. Communication innovation, consumer behavior, acceptance, and continuous awareness campaigns play an important role here [1,40,49]. Both in India and worldwide there is a need for improvement in civil society awareness of waste management and separate disposal [48].

Another persistent problem is the illegal dumping of waste and black water into the environment to save on fuel costs [47]. This study shows that awareness programs and rigorous reviews can reduce this.

If the composting facility is operated improperly, there is a risk of pathogens in the compost as well as nitrogen and carbon, which can escape into the environment as gases that are harmful to the climate [7,15]. Samples show that Indian and international standards for heavy metal levels in major Indian cities are not always undercut [8]. To counteract this, tests are carried out regularly.

### *4.4. Data Quality and Limitations*

By integrating different stakeholders with different backgrounds, the results could be influenced by how familiar the interviewees are with each circular economy technology [37]. There are limitations due to the number of actors and case studies as well as the regional perspective.

### *4.5. Further Research*

The transferability of these indicators to other regions in India as well as to other countries could be further explored as overlaps have been identified. Additional case studies should be included to support the findings. Additionally, this study shows that alternative solutions for miscalled facilities and better planning tools are needed to appropriately scale new facilities, which also points to improved and adapted management systems and network management. To ensure sustainability, broader interest groups should also be considered and involved.

## 5. Conclusions

Overall, biogas received partial support from stakeholders' perspectives, with co-composting of black water and wet waste being the most popular, underlined by numerous positive arguments packaged as indicators. The current situation in South India shows a focus on these mature technologies and the majority sees great potential in co-compost in particular. The most difficult perceived scenario in comparison was that of RUN's high-tech solution, with co-recycling generally raising more concerns than mono-recycling. Nevertheless, combinations with alternative and even more environmentally friendly concepts are seen, especially for the future once the pressing problems have been solved. Thus, RUN can be a good, decentralized option for prosperous new developments if the focus is on high compatible sustainability and recycling rates of valuable materials, closed loops, and reduced wastewater. It is agreed that there is no ultimate technology or concept. The choice depends on the circumstances and location but currently shows a clear preference as described.

This study also shows that the inclusion of the stakeholder's perspective and the focus on successful case studies lead to a realistic picture of the current situation and can contribute to the sustainable implementation of new circular economy concepts. This could be transformable not only for southern India but also for emerging countries, as there are global overlaps, as the discussion shows.

In conclusion, co-composting to close urban-rural cycles can address several SDGs and pressing issues in India, underscoring the urgent need to focus on implementation.

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# The Impact of Using Co-Compost on Resource Management and Resilience of Smallholder Agriculture in South India

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**Abstract:** Agriculture is the main source of income in India, with most farmers being smallholders and facing multiple challenges, such as climate change and land degradation. For the sustainable implementation of alternative circular approaches, it is important that agriculture benefits. To assess this, the impact of using co-compost (organic waste and black water consisting of feces and urine) was evaluated through surveys of 120 smallholder farmers in two case studies in South India. All 149 questions related to the overarching research question: what is the impact of using co-compost on closing loops in smallholder agriculture in terms of resource management and resilience. Secondary smallholder resources were found to be well managed and local networks and economies proved to be particularly effective in pandemics, reinforcing the potential for nutrient sources from urban areas. For most farmers, using co-compost improved yields (90%), soil (80%), plant health (93%) and, consequently, profits (67%), as well as water management (53%). Water management was significantly less of a problem for co-compost users (15%) than non-users (42%). In addition, the users of co-compost were able to save resources. Chemical fertilizer use was significantly reduced from 1.42 ± 2.1 to 0.9 ± 1.35 t (acre·year)$^{-1}$, with total savings ranging from 37 to 44%. Overall, 67% were able to reduce chemical fertilizer use and 25% were able to reduce chemical spray use. Additionally, 53% reduced water consumption by 30.3% ± 19.92%. The visible benefits could motivate others to try co-composting. The reservations of non-users were due to personal or societal aspects (25%). In addition, the desire of farmers to convert to organic farming and try alternative farming methods, such as using smart technologies, vermicomposting or co-compost, was high (43%) and was positively influenced by the profitable use of alternative circular concepts. Information dissemination was mainly promoted by advertising (60%) and demonstrations (27%), which influenced openness to alternative circular concepts and products. In conclusion, co-composting and co-recycling approaches have a positive impact on the resource management and resilience of smallholder agriculture and thus, contribute to achieving sustainability goals.

**Keywords:** co-compost; co-recycling concepts; farmer perspectives; resilience; resource management; smallholder agriculture; South India; sustainable development goals

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## 1. Introduction

### 1.1. Problem Status

India faces a number of challenges, such as rapid urbanization, population growth, food security, water scarcity, pollution and climate change, which significantly affect farmers [1]. Agriculture is the main livelihood in India, accounting for 70% of rural households, with the majority (82%) of farmers being smallholders [2]. Smallholders are also of great global importance, growing at least half of the world's food crops [3]. They face many problems; for example, soil degradation is progressing worldwide and the predicted average soil erosion rate in Asia is 3.47 Mg ha$^{-1}$ yr$^{-1}$ [4]. Smallholders often face low productivity, lack access to productive resources and finance, are highly dependent on cultivation and harvesting, and are at the mercy of climate and crises, while potential opportunities for improvement lie in high soil fertility and increasing the overall rural economy [5–7].

Sustainability and resilience are closely related, with the former having a long-term perspective and the latter having more of a current perspective for dealing with unexpected disruptions [1]. Both are important aspects of smallholder agriculture and climate change and must be strengthened. Climate change is causing problems in agriculture as conditions, such as water availability, are changing and smallholders are highly vulnerable and dependent on these inputs, making the sustainable use of resources essential [8,9].

Due to the high energy demand, the production of chemical fertilizers causes the greatest environmental pollution in agriculture [10] and creates dependencies, which is why smallholders must be guaranteed secure and affordable access to fertilizers [11]. The overuse of chemical fertilizers can affect soil health, water resources [12,13] and human health [14,15]. Despite the increasing use of chemical fertilizers, India is experiencing soil quality degradation and agricultural productivity is stagnating [16].

In addition, the waste and wastewater situations pose many challenges, such as solid waste management. In Asia, due to the high population and the currently insufficient supply of improved sanitation facilities, there is great potential for covering P requirements through the use of alternative recycling technologies [17]. Plant nutrients, such as nitrogen and phosphorus, are excreted in human feces and urine, which, together with organic waste from urban areas, form nutrient sinks that are associated with the removal of nutrients from agricultural soils [18]. In addition, production and consumption behavior is changing, which has an impact on waste management [19,20]. The high proportion of organic waste (61% by weight) from urban households, together with black water and green waste, has great potential for agricultural use as a natural fertilizer [17,21,22]. "Natural fertilizer" in this study refers to organic fertilizer and also co-compost, which has not been declared as an organic fertilizer in India. Recycling secondary household resources into natural fertilizers could improve the situation for smallholder agriculture by improving soil fertility and thus, counteracting the widespread soil degradation [23].

### *1.2. Relevance*

Links between rural and urban regions and between the waste and agricultural sectors through co-recycling offer the potential to close carbon and nutrient flows and counteract many of the current challenges that are acute in India, as well as other countries in the Global South [21,23,24]. Looking at India, co-compost has excellent potential to address multiple sustainability issues while benefiting the waste and agriculture sectors [23,25].

This underscores the fact that multiple Sustainable Development Goals (SDGs) could be addressed with appropriate circular economy concepts, such as co-compost [21,23,26–28]. This study focused on contributing to SDG 2 "Zero Hunger", with the target of doubling the productivity and income of smallholders by 2030 (target 2.3) and ensuring and implementing sustainable food production systems and resilient agricultural practices that strengthen the ability to adapt to climate change (target 2.4) [27]. In addition, there are further opportunities for circular economy approaches to have positive impacts on the SDGs, including direct impacts on SDG 12 "Responsible Consumption and Production" and SDG 13 "Climate Action" [23,27]. A closer look could also address other goals, such as SDG 6 "Water and Sanitation" by increasing water use efficiency (target 6.4) and SDG 11 "Sustainable Cities and Communities" by minimizing environmental impacts through waste management (target 11.6) [23,27]. These examples, which represent just some of the positive impacts of circular economy concepts, underscore their far-reaching importance. To achieve these goals, it is crucial to meet the needs of farmers, who are at the core of these circular economy approaches, to enable sustainable development [23].

### 1.3. Research Gap

More holistic approaches are needed to implement new recycling concepts, such as an integrated systems approach is needed to understand the interactions of the circular economy [29,30], including the farmers' perspectives. Social acceptance is one of the most important aspects when introducing new circular economy concepts [1]. In addition, further research is needed on how resource management is changing through composting practices, and what challenges smallholders face [23].

The literature contains some experimental studies on the co-composting of household organic kitchen waste and black water [31,32], but few cases of practical application [33], with most co-composting concepts involving the recycling of animal manure, agricultural residues, and sewage sludge published more than 10 years ago. Although there is literature on the perception of the use of co-compost [34] or of human excreta in agriculture [35], the literature is notably lacking on the impact of co-composting on smallholder farmers from their perspective, providing a broader perspective on the opportunities and challenges related to resource use and resilience in India, and in general.

### 1.4. Objective

The aim of this study was to answer the research question of how the use of co-compost from secondary household resources (black water consisting of feces and urine, kitchen waste, and green waste) to close cycles between urban and rural areas affects smallholder agriculture in terms of resource management and resilience. This is divided into the following sub-objectives, all of which are related to smallholder farmers: identify current challenges, the impacts of co-compost use, the status of resource management, and opportunities for improvement.

## 2. Materials and Methods

A total of 120 on-site interviews were conducted in India between 15 October and 15 December 2021. The study areas were the Nilgiris Mountains around the Ketti co-composting facility (near Ooty) and a peri-urban region of Bangalore around the Devanahalli co-composting facility. A total of 100 farmers were interviewed in Nilgiris and 20 in Devanahalli, half of whom were users of co-compost.

### 2.1. Co-Compost

The technical details of the production process for the co-compost include the composting of secondary household resources black water and kitchen waste, as well as public green waste, restaurant, and market waste. Black water (fecal sludge) from household septic tanks is desludged by septic tank operators and then taken to the fecal sludge treatment plant. The treatment process includes solid–liquid separation via sedimentation, stabilization, and dewatering. The sludge is further processed through drying under polycarbonate sheets in sludge drying beds. Composting then takes place with treated fecal sludge and organic waste in a weight ratio of 1 to 2 in Devanahalli, and 1 to 4 in Nilgiris, and composted for 42 days (with one turn per week) in Nilgiris and for 60–75 days (with one turn every two weeks) in Devanahalli. The capacity of the plants is 6 $m^3$/day in Devanahalli and 6.7 $m^3$/day in Nilgiris. The information in this section comes from on-site interviews with the operators of the plants [25].

The co-compost produced using this method has a content of 0.9:0.5:0.5% NPK (nitrogen–phosphorus–potassium) in Nilgiris and 0.7:0.2:1% NPK in Devanahalli [25]. In comparison, fertilizer No. 5 (an ammonia-based fertilizer), one of the fertilizers commonly used by farmers in Devanahalli, has a content of 6:12:6% [25]. Nevertheless, the recommended rates for co-compost are equal to, or at most, double those for mineral fertilizers, as the application of co-compost brings other beneficial effects [25]. Usually, combinations are used, and chemical fertilizers are replaced only to a certain extent [25]. In terms of cost, co-compost costs 5–7 rupees (~ 0.07–0.09 $) per kilogram, while fertilizer No. 5 in Devanahalli and fertilizer in Nilgiris (using muriate of potash MOP) cost about three times more [25]. For further comparison, farmyard fertilizer costs about 3–5 rupees/kg (~0.04–0.07 $) [25]. All USD values follow the conversion factor from Table 1 and are noted for the 2021 survey period.

**Table 1.** Background information of the interviewed farmers.

| Indicator | N | Unit | User [1] | Non-User [1] |
|---|---|---|---|---|
| Place | | | | |
| • Nilgiris | 100 | % | 83 | 83 |
| • Devanahalli | 20 | % | 17 | 17 |
| Age | 120 | Years (average) [2] | 47 ± 12 | 46 ± 13 |
| Gender | | | | |
| • Female | 19 | % | 15 | 17 |
| • Male | 101 | % | 85 | 83 |
| Land size | 120 | Acres (average) [2] | 2.13 ± 2.04 | 2.18 ± 2.74 |
| Property | | | | |
| • Own | 74 | Valid % | 63 | 62 |
| • Rented | 36 | Valid % | 27 | 33 |
| • Both | 9 | Valid % | 10 | 5 |
| • No indication | 1 | Frequency | 1 | 0 |
| Irrigation system | | | | |
| • Sprinkler/butterfly | 85 | Valid % | 78 | 75 |
| • Manual | 14 | Valid % | 15 | 11 |
| • Drip irrigation | 12 | Valid % | 7 | 14 |
| • No indication | 1 | Frequency | 5 | 4 |
| Water source | | | | |
| • Own well/pond | 52 | Valid % | 52 | 50 |
| • River/stream | 29 | Valid % | 26 | 31 |
| • Shared/public well/pond | 17 | Valid % | 18 | 15 |
| • Other | 4 | Valid % | 4 | 4 |
| • No indication | 1 | Frequency | 10 | 8 |
| Annual income [3] | | | | |
| • <910 $ | 42 | Valid % | 39 | 32 |
| • 910–1560$ | 31 | Valid % | 29 | 24 |
| • >1560 $ | 45 | Valid % | 32 | 44 |
| • No indication | 2 | Frequency | 1 | 1 |
| Distance to the closest market | 120 | km (average) [2] | 41.88 ± 15.98 | 42.34 ± 14.9 |
| Usage of middlemen | | | | |
| • Yes | 41 | Valid % | 39 | 34 |
| • No | 54 | Valid % | 43 | 54 |
| • Both | 17 | Valid % | 18 | 13 |
| • No indication | 8 | Frequency | 4 | 4 |
| Co-compost (average numbers)[2] | | | | |
| • Years of usage | 120 | Years (average) [2] | 1.94 ± 1.09 | 0.00 |
| • Price [3] | 120 | $/kg (average) [2] | 0.07 ± 0.007 | 0.07 ± 0.008 |
| • Distance for pick up | 120 | km (average) [2] | 5.84 ± 5.91 | 4.94 ± 5.05 |

N = Number of respondents. [1] The number of respondents of users and non-users is 60 each. [2] Average numbers are given with standard deviation. [3] ₹ = Rupees. Exchange rate of 1 ₹~0.013 US Dollar $ in October/November 2021.

### *2.2. Background of The Investigation Area*

Much of the information is presented as a percentage, which always refers to the sample size divided into 60 users and 60 non-users, or to the total number of survey participants from 120 smallholder farmers. More detailed information about the respondents is given in Table 1. Most of the participants are male (84%), the owned farmland area averaging about 2 acres, and sprinklers are used for irrigation from their own water source. In total, 35% of the respondents are under 40, 49% are between 40 and 60, and 16% are over 60 years old. The income categories are distributed around the average income of farming in southern India [1]. In total, 67% have no additional source of income besides farming, while 93% indicated that farming is their main occupation. The distance to the market is about 40 km, with about half of the farmers using middlemen for transport. Co-compost users have been using the co-compost for an average of 2 years. About half of the respondents (45%) cited problems with the co-compost, while almost all (97%) are interested in continuing to use it.

The participants' main crops are carrots (grown by 83% of farmers), potatoes (58%), beetroot (44%), and garlic (37%). Another 30 different plants, such as beans and flowers, are cultivated, with a greater diversity being seen in Devanahalli. This diversity also occurs in livestock farming. Overall, 17 farmers have 3.47 ± 2.10 cows, 8 farmers have 12.25 ± 10.01 chickens, 6 farmers have 9.00 ± 4.65 sheep, and 5 farmers have 8.80 ± 7.19 goats.

### 2.3. Methodology

The users of co-compost were randomly selected via the village cluster using the contact data pool of the supporting organizations Consortium for the DEWATS Dissemination (CDD) Society in Bengaluru and the Rural Development Organization (RDO) Trust in Ooty [36,37]. The non-users were selected equally in the village clusters according to the snowball principle [38].

A combination of different survey approaches was used to reduce errors and to verify values. Open and closed questions were integrated, and on-site observations were also included [39,40]. The questionnaire contained 149 questions on background data, and the research questions. Control, filter, and icebreaker questions were integrated, and metric, ordinal, and nominal data were collected [39]. Five test surveys were carried out in advance. A translator was always available for the direct translation of the interviews. Translations were made from Tamil, Kannada, and further local languages, into English. All questionnaires were filled out directly from the author and signed by the respondents [39,41].

To obtain even more precise quantitative data, in addition to the exact amounts, categorizations (limitation of value ranges) and personal impressions of the amounts (as good, acceptable, or problematic) were requested. In the cases of changes caused using co-compost, the participants were also asked to classify these in percentages and percentage classes.

The quantitative evaluation was carried out with IBM SPSS Statistics. Mean values, and maximum and minimum values, as well as standard deviations, were determined for the metric data. Frequencies were counted for the ordinal and nominal data. All data were checked for significant differences for the user, non-user, Nilgiris, and Devanahalli groups. For this purpose, cross tables were tested with Chi-squared, phi, and Cramer-V, etc., and contingency coefficient [39]. Significance levels of $p \leq 0.05$ were used for all means and enumerations. Thus, the null hypothesis that values do not differ significantly between users and non-users is rejected when $p \leq 0.05$ with a 5% probability of error [39]. The Eta coefficient describes the extent to which metric variables can be explained using normalized variables (users and non-users), and shows whether a relationship exists, whereby a value of greater than 0.3 can already be regarded as a rather strong relationship [39].

## 3. Results

### 3.1. Challenges

Looking at Figure 1a, it becomes clear that the most frequently perceived problems for smallholder farmers are high input costs and unstable sale prices. This is followed by topics related to climate change and water resources, which also receive a lot of attention. Significant differences can be seen for water resource problems, with $p = 0.002$ (Figure 1b—including all ratings), with 15% of users and 42% of non-users perceiving water resources in agriculture as being unproblematic. For the other problems from Figure 1, no significant differences between users and non-users could be determined. This also includes the problematic aspects that are directly related to the cultivation of the crops (health, yield, and germination rate).

However, in the detailed questions on harvest yields (by means of qualitative assessment by the smallholders), there are clear differences for beetroot with $p = 0.05$, and for all crops combined, with $p = 0.011$. More non-users reported poor to very poor crop yields (N = 30 for beetroot with 20%, and N = 60 for all crops with 14.6%). This compares to users who rarely or never gave this rating (N = 24 for beetroot with 0%, and N = 60 for all crops with 2.3%).

Yields differed between users and non-users, but not to a significant extent, considering information on actual plant yields using quantitative estimates (Table 2).

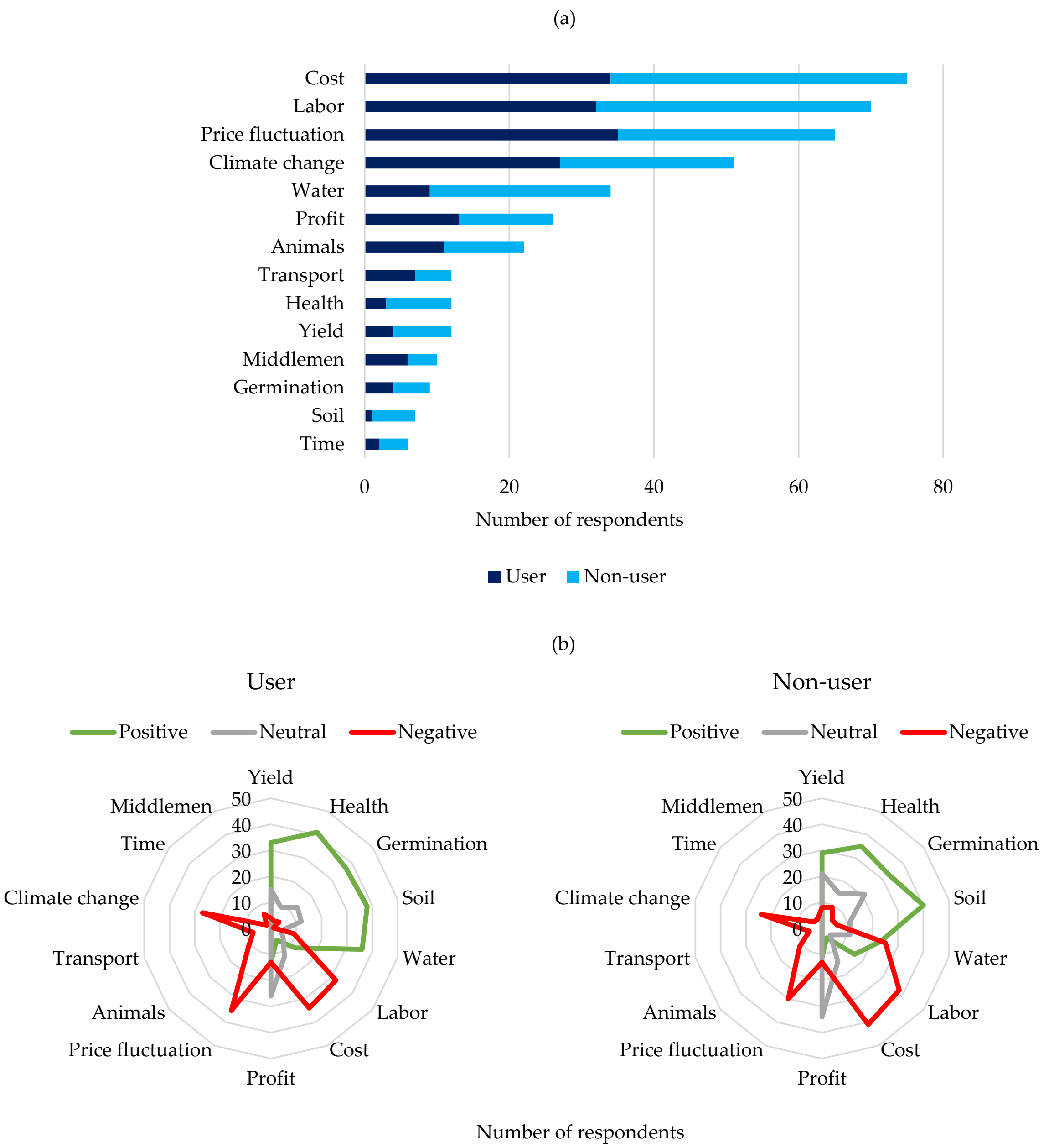


**Figure 1.** Main challenges of smallholder farmers, including users and non-users of co-compost, with multiple responses possible. (**a**) shows the challenging (negative) factors (**b**) includes the neutral, positive, and challenging (negative) ratings. All given in N = Number of respondents.

**Table 2.** Yield of the main harvested crops. N = number of respondents.

| Indicator | N (User) | N (Non-User) | Unit [1] | User | Non-User | Eta-Coefficient |
|---|---|---|---|---|---|---|
| Carrots | 48 | 52 | t/acre | 13.52 ± 7.76 | 11.41 ± 6.27 | 0.150 |
| Potato | 31 | 39 | t/acre | 9.15 ± 6.10 | 7.17 ± 4.10 | 0.193 |
| Beetroot | 27 | 30 | t/acre | 11.76 ± 8.14 | 9.64 ± 7.48 | 0.137 |
| Garlic | 22 | 22 | t/acre | 6.15 ± 3.68 | 6.42 ± 3.88 | 0.037 |

[1] Given in average values tons per acre and standard deviation. Referring to the year 2021.

Farmers have changed their farming practices due to climate change, with significant differences, with $p = 0.017$ between users (33%) and non-users (55%). The crops or varieties grown changed (15% user, 22% non-user), chemical use is increasing (7% user, 23% non-user), and water management changes (13% user, 17% non-user). With a significance of $p = 0.04$ between users (63%) and non-users (45%), smallholder farmers have noticed changes in soil fertility since the beginning of their agricultural practice. The majority have reported that soil fertility improved with organic fertilizer (43% of users and 39% of non-users) and co-compost (63% of users), and only a minority considered the use of chemicals to be the main contributor (10% of users and 8% of non-users), with significant differences of $p = 0.001$.

The problematic points are almost all felt to be improved using co-compost (seen in Figure 2), whereby the costs and the availability of labor remain unaffected by the changed resource management. In particular, plant and soil health, and crop yield improved. At the same time, the costs for the substrate used and water consumption fell. These aspects together explain the improved profit. All responses show significant improvements when directly compared to non-user responses for the same issues. Significance is shown for plant health ($p = 0.027$), yield ($p = 0.014$), soil ($p = 0.001$), germination ($p = 0.012$), and water ($p = 0.017$). Few respondents attributed the fact that the water requirement worsened and thus increased to the heat radiation of the co-compost. Although there are significantly fewer water issues for users of co-compost than for non-users (Figure 1), this is not the main criterion that is seen as a benefit of co-compost. The focus is on returns and profits (Figure 2).

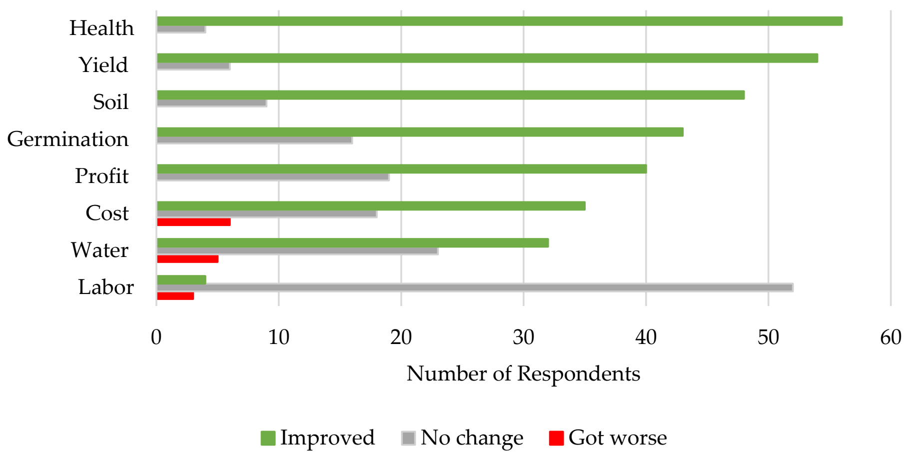


**Figure 2.** Changes in agriculture after using co-compost. Responses from co-compost users.

The problems for most farmers in 2020–2021 during the COVID-19 pandemic was that prices for their crops were very low (50% user, 37% non-user), and that they could only sell in local markets (17% user, 25% non-user) or not at all (25% user, 27% non-user). Therefore, transport (32% user, 15% non-user), labor (13% user, 12% non-user), and the market and the associated lack of income were very problematic. In particular, market problems were seen due to difficulties with transport (30% user, 44% non-user), labor (12% user, 15% non-user), profit (15% user, 10% non-user), and middlemen (5% user, 13% non-user). Another difficulty was the lack of availability of inputs (fertilizers, corn production products, and seeds) for agricultural practice (7% user, 8% non-user). Access to co-compost was rated as unproblematic more often (25%) than the access to and the pricing of chemical fertilizers (3%). However, most farmers who engaged in farming during this period had their own stocks or were supported by supplies in the community. Farmers managed on the one hand, with savings (37% user, 28% non-user), and on the other hand, with the help and credit of relatives, neighbors, and friends (22% user, 13% non-user). Other solutions were external work (5% user, 20% non-user), loans from banks (15% user, 7% non-user), state support (7% user, 8% non-user) and other internal earning opportunities (7% user, 12% non-user).

### *3.2. Resource Management*

A total of 91% of smallholders composted their plant residues (visible in Figure 3). These were often either mulched or composted in windrows directly in the field. A total of 94% of respondents had their kitchen waste collected, and 43% composted some or all of it. A minority of farmers used the black water directly (6%) or after composting (4%). Since only the use of black water was the subject of the survey, it was not recorded here that most farmers had their black water collected with suction vehicles (called honey suckers). While 28% of smallholder farmers blended charcoal from stoves into compost, 18% used it directly in agriculture or in kitchen gardens. Dumping, slash-and-burn practices, and selling to middlemen played a minor role. No significant differences between users and non-users could be determined in resource management.

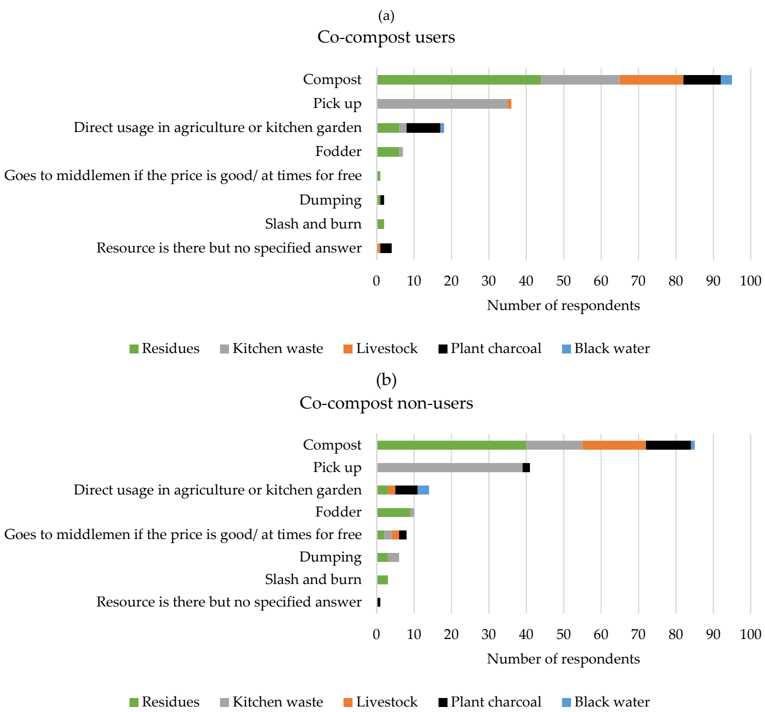


**Figure 3.** Practices in the internal resource management of (**a**) co-compost users and (**b**) co-compost non-users with N (number of respondents) = 120 (60 users and 60 non-users). Multiple answers were possible. Only data for internal use were collected for black water, which is why the collection via suction vehicles was not recorded here. "Pick up" includes collection from households and municipal collection points.

From Figure 4, it can be seen that farmers using co-compost did not renounce traditional organic and chemical fertilizers. The most popular fertilizer among users was co-compost, at 42%, followed by farmyard manure (23%) and chemical fertilizers (12%). Non-users preferred farmyard manure (50%), followed by 10%, who preferred chicken waste, and 10%, who preferred chemical fertilizer. However, the most commonly used inputs were still chemical fertilizers (used by 90% of users and 97% of non-users) and sprays (used by 97% of users and 87% of non-users). Chemical sprays in these interviews included herbicides, pesticides, and insecticides.

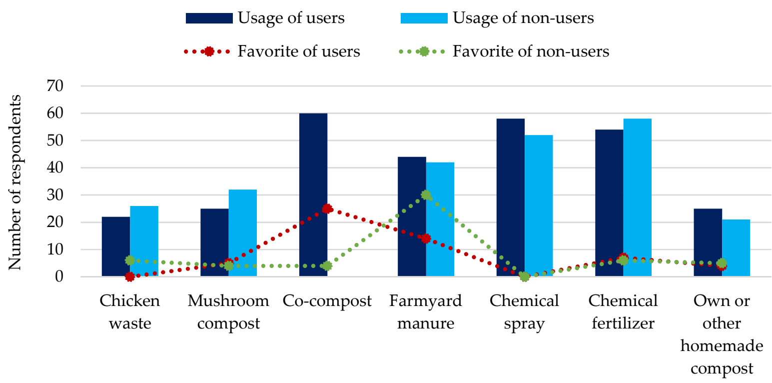


**Figure 4.** External input of smallholders. Showing the actual usage and the preferred one.

Table 3 shows that co-compost is used in smaller quantities compared to other natural fertilizers, with an average of 3.3 t (acre·season)$^{-1}$ ± 6.7, which is recommended. Looking at the farmers who used farmyard manure (users: 73% and non-users: 70%, visible in Figure 4) and the quantity in Table 3, it becomes clear that this plays an important role for farmers, alongside the use of chemicals (referring to chemical fertilizers and sprays). This applies for both users and non-users. In Table 3, the Eta coefficient is well below 3, indicating that there are no significant differences between users and non-users. Nevertheless, it can be stated that the use of chemicals and water consumption for users decreased after co-composting.

A quarter of the co-compost users indicated that using co-compost did not change the amount of chemical fertilizer. Here, 23.3% noticed a reduction of under 25%, and 43.3% saw a reduction of over 25 %. This result confirms the results from Table 3, which show a reduction potential of between 37 and 44%. In total, 70% of smallholders did not change the amount of sprays (herbicides, pesticides, and insecticides) when using co-compost. Here, 11.7% recorded a decrease of up to 25%, and 13.3% of over 25%. In total, 1.7% reported an increase of less than 25%. The result that only a few farmers see a potential for saving pesticides by using co-compost is supported by the results in Table 3, which shows a low response rate. If farmers manage to reduce, then the reduction is between 19 and 35%.

A total of 38.3% (Figure 2) of farmers could see no change in water management. A total of 36.7% of users saw a reduction in the amount of water used, by up to 25%, and 13.3% by more than 25%. Overall, 53.3% (Figure 2) of users saw a reduction. The results from Table 3 show an average reduction (with 36.7% of users) of 30.3% ± 19.92, also with a wide range. A minority of 8.3% saw an increase of less than 25%, and thus, a negative impact on water demand (Figure 2).

**Table 3.** Quantitative data on smallholder resource management. N = number of respondents.

| | Unit | User N | User Mean | User SD | Non-User N | Non-User Mean | Non-User SD | Eta-Coefficient |
|---|---|---|---|---|---|---|---|---|
| Own compost | t (acre ·season)$^{-1}$ | 11 | 2.24 | 3.86 | 8 | 2.28 | 4.17 | 0.016 |
| Co-compost | t (acre ·season)$^{-1}$ | 43 | 3.3 | 6.7 | | | | |
| Mushroom waste | t (acre ·season)$^{-1}$ | 22 | 9.22 | 10.36 | 30 | 13.08 | 16.63 | 0.134 |
| Farmyard manure | t (acre ·season)$^{-1}$ | 34 | 13.82 | 16.8 | 36 | 12.51 | 11.61 | 0.046 |
| Chicken waste | t (acre ·season)$^{-1}$ | 18 | 8.66 | 11.19 | 20 | 12.66 | 13.37 | 0.163 |
| Plant charcoal | kg (month)$^{-1}$ | 17 | 26.53 | 24.76 | 18 | 18.54 | 24.28 | 0.165 |
| Chemical fertilizer | | | | | | | | |
| • Before co-compost usage | t (acre ·year)$^{-1}$ | 46 | 1.42 | 2.1 | 53 | 1.57 | 5.42 | 0.019 |
| • After co-compost usage | t (acre ·year)$^{-1}$ | 35 | 0.9 | 1.35 | | | | |
| • % reduction [1] | % | 33 | 44.21 | 15.91 | | | | |
| Chemical spray | | | | | | | | |
| • Before co-compost usage | L (acre ·year)$^{-1}$ | 26 | 8.16 | 12.88 | 29 | 8.35 | 13.62 | 0.007 |
| • After co-compost usage | t (acre ·year)$^{-1}$ | 4 | 6.63 | 9.03 | | | | |
| • % reduction [1] | % | 11 | 35.45 | 21.27 | | | | |
| Water usage reduction in dry season [1] | % | 22 | 30.3 | 19.92 | | | | |

[1] The percentage reduction in chemical consumption has been queried separately from the amounts reported, as some farmers have preferred to report the change as a percentage.

*3.3. Motivation*

The motivation to start co-composting comes when the benefits are seen and communicated (Figure 5). In total, 60% of users cited advice and promotion from NGOs and local actors as the main reason, with trust playing an important role. A total of 27% saw benefits from recommendations or demonstrations from neighbors, friends, and family. Additionally, the main reasons for continuing to use co-compost were to improve crop yield (58%), and plant and soil health (30%), as well as monetary reasons, such as price and profit (15%). Most non-users have not yet used co-compost, due to a lack of information (advertising or demonstration, 40%), resources (logistical or monetary, 18%), or personal or societal factors leading to hesitation (25%). Above all, there is a lack of information flow, including about profit opportunities. The willingness to pay is shown as follows: 5.49 rupees (± 0.57) (~0.07 $) on average (Table 1), and would like to pay 4.09 rupees (± 1.45) (~0.05 $), while non-users (N = 51) would like to pay 3.81 rupees (± 1.4) (~0.05 $) per kilogram of co-compost.

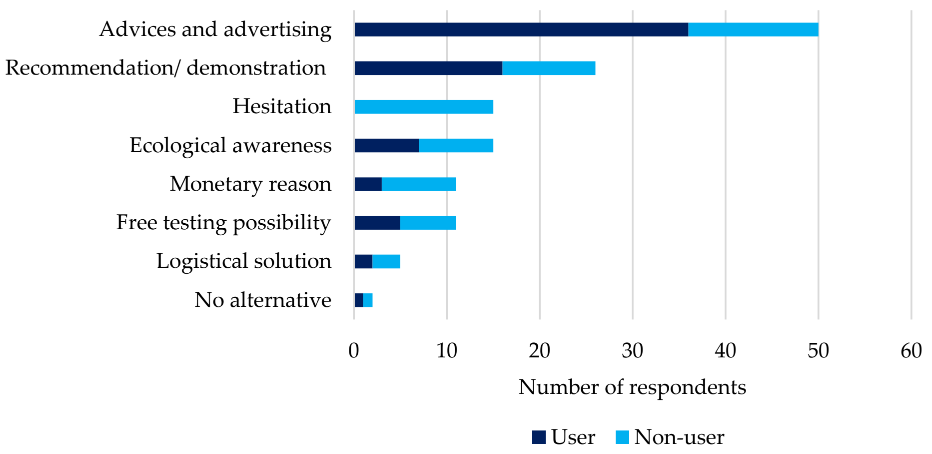


**Figure 5.** Motivation of co-compost users and non-users to try co-compost (N=120 and N=15 for multiple choices). N = number of respondents.

Co-compost is seen as needing improvement, particularly in terms of availability and information about it (20%), quality (15%), transport (12%), and price (8%). However, most users were satisfied and had no complaints or suggestions for the improvement of the co-compost.

Almost all respondents used either a septic tank or a pit latrine, and only 2% used open defecation and a public toilet. Although nearly half of the respondents indicated that they would like to try a separate toilet (53% of users and 34% of non-users), reservations were expressed (visible in Figure 6). Both users and non-users initially cited a lack of practicality, options, and space (27% each). Reluctance due to personal or societal values was higher among non-compost users (25%) than among users (12%). A lack of resources such as time, money, and labor (12% each), and a lack of knowledge (13% user and 3% non-user) were also mentioned.

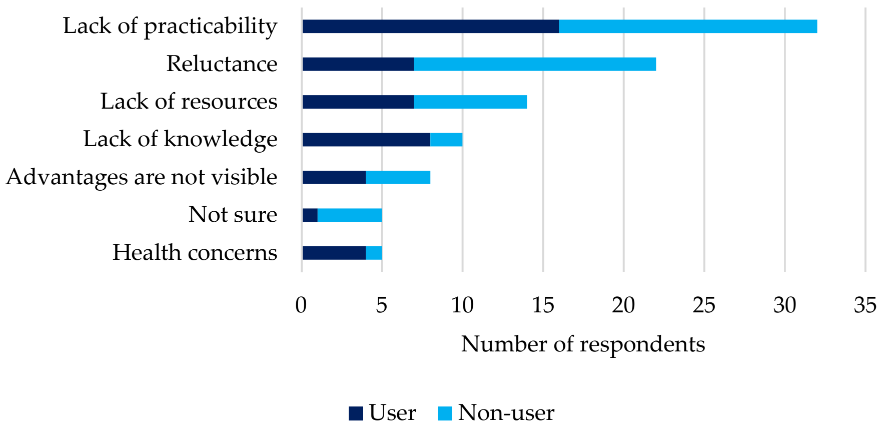


**Figure 6.** Reservations about alternative sanitary facilities using the example of a dry separating toilet.

Although the main desire of smallholder farmers (35% users, 23% non-users) is to switch to organic farming (Figure 7), most respondents do not believe that full conversion is possible for them (47% of users and 57% of non-users). On the other hand, 40% of users and 30% of non-users believe that this might be possible under certain circumstances. In total, 7% of users and 2% of non-users are already organic, and a minority think that it is entirely possible (3% users, 8% non-users).

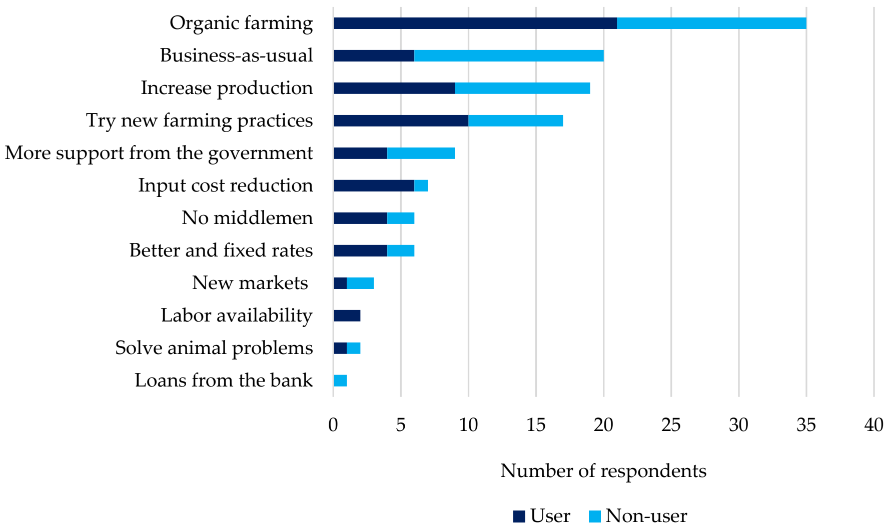


**Figure 7.** Main motivations (summarized), wishes and goals of the farmers for the future. Multiple choices possible.

The farmer' wishes showed significant differences in the answers ($p = 0.048$) (Figure 7). The second most common wish from farmers was that they would like to continue as usual, which was mostly expressed by non-users (31% versus 10% users). Other commonly cited interests were increased production (15% users, 17% non-users), new farming practices, including smart technologies (17% users, 12% non-users), and improved financial situation through support, credit, better and fixed rates, and lower input costs (24% users, 15% non-users).

## 4. Discussion

### *4.1. Alternative Circular Co-Concepts*

Farmers manage their resources well. New resources need to be identified or the link between urban and rural areas strengthened, as there are sources in rural areas. The degradation of nutrients from agricultural soils by food creates nutrient sinks in urban areas, since plant nutrients are not absorbed by a healthy human body, but are excreted in the form of feces and urine, for example [18].

Innovative, alternative circular co-concepts are considered to be promising for hygienic uses as fertilizer and wastewater treatment, and therefore, they also have positive effects on the climate, which also applies to the use of urea-separated toilets [42–44]. Here, co-concepts such as co-compost have a higher potential for sustainable soil fertility management, compared to mono-compost [23].

Alternative co-recycling systems (systems that consider different waste streams simultaneously) for black water and organic waste to those in industrial cities, which are often resource-intensive and non-circular, also have the potential to reduce pollution and improve public health [43,44]. This points to the need for action in India and globally, to leapfrog conventional concepts and embrace alternative circular ones.

### *4.2. Co-Compost for Agriculture*

Alternative co-cycle concepts that also recycle black water are suitable for sustainable soil management [23,32,42]. Many aspects can be positively influenced, such as phosphorus availability, the soil's ability to store plant-available nutrients and water, soil organic matter content, and soil pH, all of which result in improved soil fertility and crop yields [23,42]. Yield improvements from using co-compost are significant in India compared to chemical input materials [31,32], which can also be observed in other countries of the global South [23]. Economic profitability can also be given [21,45,46]. These aspects underline the results of this study. However, the effects on the amount of work and time as identified in other studies [23] could not be confirmed here. If the technical conditions are good, the microbial load can be reduced to a minimum, and the co-compost can be free of pathogen contamination [31,32]. On the other hand, if the pretreatment is inadequate, there is a risk of soil contamination [47,48].

This study shows that changes in water management and the increased use of chemicals are two major factors that have changed resource management in smallholder agriculture, mainly caused by climatic changes, the dependence on chemical resources, and their long-term unilateral use. This shows the need for resilient structures. There is a potential for alternative recycling concepts to increase agricultural resilience to environmental influences [1,29]. Promoting agricultural resilience through soil organic matter is critical in the face of climate change, as it contributes to water storage capacity and erosion resistance [23]. Research has shown that low-cost, circular approaches in India improve community resilience, reduce pollution, boost regional economies, and have positive impacts on waste and wastewater management [1]. This underscores our finding that smallholder agriculture has more resilient structures through the use of co-compost, which can have a positive impact during critical times such as pandemics. The impact of lockdowns on farmers in India varies widely due to differences in market infrastructure and regional regulations [49].

### *4.3. Attitude of Farmers*

Farmers can appreciate these mentioned visible benefits of using co-compost [23]. The use of human excrement, on the other hand, is sometimes stigmatized [21]. The societal acceptability of farmers is determined, for example, by awareness, religiosity, income, source of income, and environmental attitudes, with an overall rather positive attitude of farmers towards recycling human waste [35,50]. Obstacles to co-composting are mainly due to fears of health risks, as well as socio-cultural/religious beliefs and odor nuisance, and furthermore, collection, transport, storage, and limited information on availability, with differences between rural and urban regions [34,35]. The lack of identification with the use of co-compost, and the uneasiness towards customers [34] could not be confirmed in the results of this study. The negative perceptions of the Farmer Producer Organization were mainly driven by factors such as an insufficient availability of information [34] that approximates our findings, as well as improved crop yields, soil health, and higher income [34,35] as the main motivations of farmers. It can also be seen that people who have used co-compost before or that know others who have used it do not have negative perceptions [34], pointing to the big factors of experience and demonstration. The many different aspects depending on the context and methodology [35] show that there are recurring factors that need to be discussed anew for each region, as they partially appear in our results when implementing new systems. On the other hand, the results of this study and numerous other studies contain factors that can be considered as central aspects, regardless of the region and the methodology.

In order to establish circular bio-economy concepts, it is necessary to understand the influences of farmer attitudes [50]. In order to take a step towards nutrient recycling in agricultural systems, it is imperative that farmers socially accept human excrement for their fields [35].

### *4.4. Communication Aspects*

Communicating through participatory agricultural demonstrations, health campaigns, and participatory demonstrations could help increase knowledge, awareness, and social acceptance [35]. The keys are knowledge transfer, the mainstreaming of dissemination strategies, and promotion, and thus, the communication aspects of alternative circular bio-economy approaches such as co-composting, which play a role both in India and worldwide [21,23,25,34,50,51]. Moreover, local networks independent of co-compost are fundamental for knowledge transfer, but also for resilience against challenges [52], such as pandemic situations or climate change issues. Seeing and hearing about co-compost increases the acceptance of buying plants that have been fertilized with it [51]. Farmers would often not buy compost (in developing countries) as there is no obvious financial benefit, as chemical fertilizers are sometimes cheaper, while the demand automatically increases when farmers see the positive effects and benefits [23]. This shows that our results from Southern India can also be relevant for other regions.

### *4.5. Approach of the Methodology*

The connection between agriculture and waste management is necessary to create sustainable concepts [23]. Further work is needed to understand different contexts, particularly in the least developed countries, where sanitation can easily be linked to resource recovery, the willingness to pay, and the identification of other benefits [35]. Holistic approaches are needed to understand the barriers to adaptation, and to address the motivations of smallholder farmers [29].

Various key indicators and barriers to adaptation that are deeply embedded in the sitespecific environments of farming communities show the need for the implementation of new circular economy concepts, and qualitative and quantitative data should be integrated to understand the local conditions [29].

This is an excerpt and cannot stand on its own. These results help to broaden the picture of smallholder farmer attitudes, which should be part of new circular concepts to be implemented, although further additions are needed. Therefore, the need for more combined holistic approaches is highlighted.

## 5. Conclusions

The current situation of smallholder farmers shows that they face many challenges, and that co-compost can significantly improve this situation, and thus, the resilience. Climate change and a dependence on chemical products affects smallholder farmers' resource management in terms of water and increased chemical use.

The use of these resources can be considerably reduced by using co-compost. Therefore, water is seen as significantly less of a problem by co-compost users. In addition, in the context of agricultural problems that arise during pandemics, local networks and local economies are particularly important for smallholder farmers.

Furthermore, the results of this study underline that knowledge transfer on visible benefits is necessary for disseminating and improving circular concepts, and partially for reducing personal and social reservations. The evaluation confirms that this has an impact on experience and openness, which also has an impact on the spread of other alternative approaches, possibly in other regions. This is reflected in the increasing willingness to try new agricultural practices.

This study also shows that there is good secondary resource management through recycling via smallholder farmers or other institutions and, thus, little potential for untapped resources from agriculture.

This again underscores the need for alternative circular approaches and the use of urban nutrient sinks that both create more resilient structures for smallholder farmers and make the waste and wastewater situation sustainable, thus also benefiting the environment and society. Consequently, the study shows that smallholder farmers have significant benefits using co-compost produced nearby, which represents a great opportunity for the implementation of sustainable circular approaches. Consequently, co-composting systems, and thus, co-recycling approaches, can help to achieve sustainability for the benefit of smallholder farmers in relation to SDG 2 "Zero Hunger", SDG 12 "Responsible Consumption and Production", SDG 13 "Climate Action", SDG 6 "Water and Sanitation", and SDG 11 "Sustainable Cities and Communities".

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# Seasonal characterization of municipal solid waste for selecting feasible waste treatment technology for Guwahati city, India

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**ABSTRACT**

As quantities and composition of municipal solid waste (MSW) vary significantly with seasons, a seasonal characterization study is critical for developing an efficient MSW management system. MSW was characterized in three different seasons for selecting an appropriate waste treatment and management strategy for Guwahati city. Results of the study shows that the major components of the MSW were organics (42.2%) and plastic wastes (25.2%), which show high variations on a seasonal basis (22–49%). The chemical characterization of MSW revealed that on seasonal basis moisture content varies between 43.4% and 58.3%, pH between 5.5 and 6.5, volatile solid content from 32.9 to 58.9%, and the calorific value between 1203 and 3015 kcal/kg. Waste collected in the present study was a mixture of organics, recyclables, and inert material which is difficult and uneconomical for treatment in its present form. However, with proper waste segregation, biomethanation, and composting could be sustainable waste treatment solutions due to the high moisture and volatile content of the MSW. Due to inadequate quantity, low calorific values, requirement of skilled supervision, and high capital investment, the thermochemical conversion of MSW may not be economically feasible for the present case.

*Implications*: Present study is a novel attempt to analyze in-depth variation in the municipal solid waste (MSW) composition and properties in different seasons and how does it influence the selection and feasibility of the available waste treatment technologies. Search on Google scholar shows that only seven articles have been published till now which evaluated seasonal impact of MSW. Out to these published studies only one study have calculated energy potential of MSW on seasonal basis which is mainly restricted to incineration only. In-depth analysis of seasonal variation on anaerobic digestion, composting, refuse derived fuel (RDF), pyrolysis, and gasification is yet to determine. Furthermore, to best of our knowledge so far in India there was no such in-depth study has been published related to seasonal variation in MSW on large scale (city level). Present study provides in-depth valuable information regarding degree of variation in MSW composition and how does it affect resource recovery out of waste, which was not studied before in-depth before. Outcomes of the present study will definitely assist engineers and policymaker involved MSW management and planning for large urban areas to fulfil their sustainability goals.

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## Introduction

As the world population increases, more natural resources are being consumed for industrial production to meet the rising market demands (Ikhlayel 2018). But a high pace of economic growth and urbanization also generate mammoth heaps of Municipal Solid Waste (MSW). As per a recent World Bank report, global waste generation in year 2016 was about 2.01 billion tonnes, which is expected to be 3.4 billion tonnes by 2050 (Kaza et al. 2018). The management of MSW has been a serious environmental issue in many urban areas of developing nations. Improper dumping and burning of garbage without pollution control measures is common in many developing nations such as India. Hence, a better solution is required for resolving their waste-related problems.

India is a rapidly growing country with a 31.8% growth in urbanization in the past decade. The total MSW generated in 2016 in India was about 52 million tons, which amounts to 0.14 million tons per day (TPD). This number is rapidly increasing with the country's increasing population (Narain and Sambyal 2016). Out of this massive waste, only 68% of this waste is collected, and only 19.4% of the collected MSW is treated (Kumar et al. 2017). Due to this lack of waste collection and

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treatment, generated waste is either left on an open dumping ground or burned in most of these cities (Singhal and Goel 2021a). This poor waste management leads to various health and environmental issues in urban areas (Annepu 2012; Biswas et al. 2010). So, to reduce the amount of waste going to the landfills and its associated impacts, proper MSW management and treatment system is critical for India and other developing nations.

Integrated Solid Waste Management (ISWM) approach should be used for a sustainable waste management, which can be defined as a comprehensive waste reduction, collection, recycling, treatment, and disposal system as proposed by the United States Environmental Protection Agency (USEPA). However, waste characterization must be the first step for any successful waste management program to estimate potential materials recovery, identify sources of waste generation, facilitate the designing of waste processing equipment, estimate physical & chemical properties of the waste to select appropriate treatment and maintain compliance with the environmental regulations (Ayeleru, Okonta, and Ntuli 2018). Lately, several MSW characterization studies have been conducted to identify efficient waste treatment technologies (Ayeleru, Okonta, and Ntuli 2018; Boldrin and Christensen 2010; Gómez et al. 2009; Kumar and Goel 2009; Kumar et al. 2017; Miezah et al. 2015). However, MSW composition and quantity varies considerably with seasons which directly affects the collection (primary and secondary storage of waste) and treatment scenario. Parameters like pH, moisture content, calorific value, C/N ratio of the waste can also vary with the season (Abylkhani et al. 2019; Gómez et al. 2009), which affects the overall treatment efficiency of the conventional solid waste treatment methods like composting, bio methanation, and incineration. So, to design a sustainable solid waste management system accounting for the seasonal variation in MSW is essential. Even though several studies have published on waste characterization, only few studies were published specifically on seasonal variation in MSW. Studies by (Abylkhani et al. 2019; Denafas et al. 2014; Gómez et al. 2009; Ibikunle et al. 2020; Yenice et al. 2011), were specially focused on seasonal variation in MSW and they all found minimal to considerable variation in the MSW's physico-chemical properties and composition. Aguilar-Virgen et al. (2013) found upto 8% variation in MSW composition in winter and summers among different economical groups. Furthermore, Ibikunle et al., 2020 determined the energy recovery potential of MSW incineration including the seasonal variation in MSW properties. However, effect on seasonal variation on energy and product recovery treatment options, such as biomethanation, composting, refuse-derived fuel (RDF), pyrolysis, gasification, recycling etc., is yet to determine. A holistic approach for evaluation feasible treatment options considering seasonal variation in MSW is still missing from the literature.

The present study aims to characterize MSW on a seasonal basis and assess the variation in its properties (physical and chemical) and composition. Based on these results, feasibility of different waste treatment technologies was evaluated and discussed in-depth. The largest city in North-East India, Guwahati, was selected as the study area for waste characterization. It is being developed as part of the Smart City program Government of India (GoI). The outcome of the study will assist the local and national authorities for developing MSW management plan of urban areas. Furthermore, findings and approach used in the present study for selecting feasible waste treatment option will be applicable for other regions as well as the Guwahati city is a good example of a typical urban area in the southern Asia.

## Materials and methods

### *Study area and current waste management system*

Guwahati is the biggest city in North-eastern India as well as capital city of the state of Assam, with a population of 957,352 (Census 2011). Guwahati city is situated on the southern banks of the Brahmaputra River (on 26° 10′20″ North and 91 ° 44′ 45″ East geographical coordinates). The city receives an annual rainfall of 152 to 324 cm, with heavy rains from July to mid-October. Mid-October to March is the winter season where temperature can go also low as 11°C. While summer season is from April to June typically where temperature can go as high as 38°C. The humidity prevails throughout the year but usually highest during July and August, ranging from 76 to 94%. During the late winter month, February, and the pre-monsoon period, March–April, the humidity is low, ranging between 71% and 78% in the morning and 50–57% in the evening.

Solid waste management in the city is the responsibility of Guwahati Municipal Corporation (GMC). The entire GMC area is divided into 6 divisions and 31 municipal wards (Figure 1). The city is generating about 800 MT of MSW daily. The current waste management system of the city is shown in Figure 2. Collection of MSW is done by GMC as a primary and secondary collection of the MSW. The primary collection consists of door-to-door collection of the MSW with source segregation of the waste into wet (biodegradable and inert waste) and dry waste (recyclables). After primary collection, waste is moved to the nearest community bin or

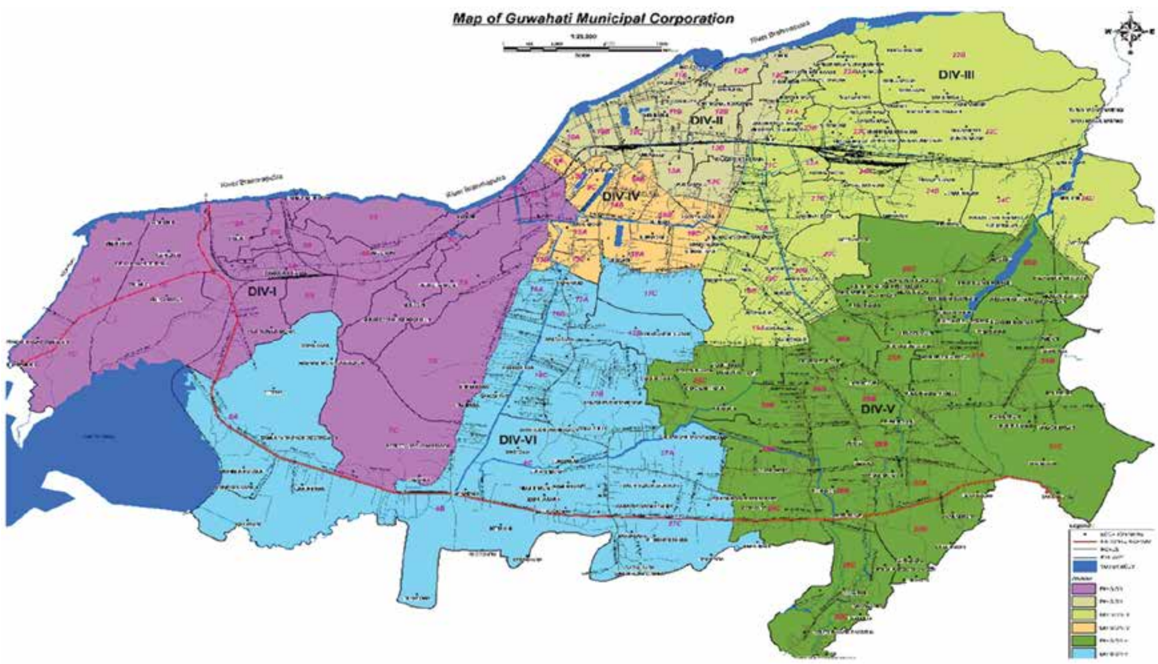


**Figure 1.** Divisional Map of Guwahati City (GMC portal, 2017).

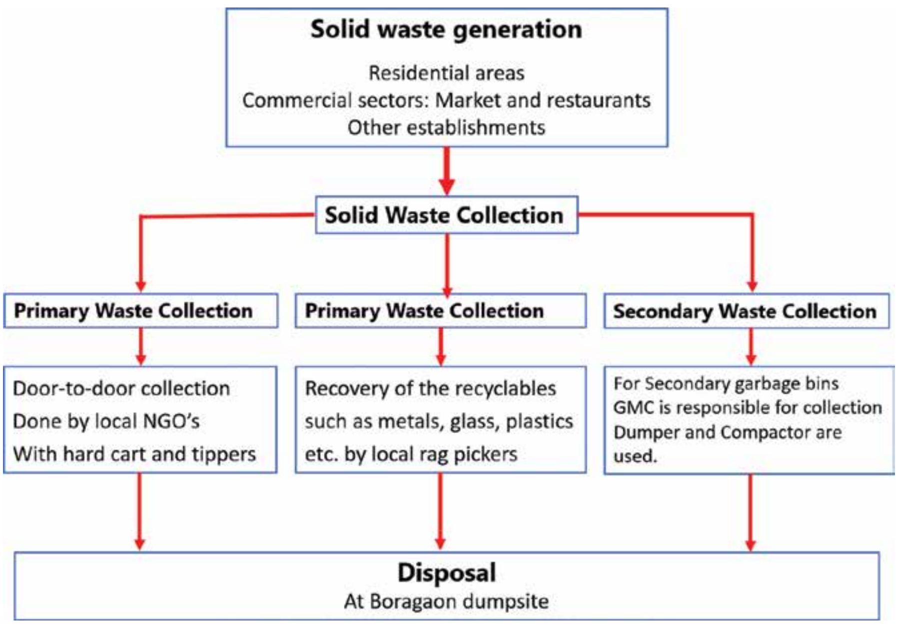


**Figure 2.** The current solid waste management system of Guwahati City.

transfer station with tricycles and mini-tipper trucks. In the secondary waste collection, MSW is collected from the community bins, storage depots, and transfer station using garbage compactor trucks. Due to good local awareness regarding SWM, fairly good amount of source segregated waste is collected from the households. Several local non-government organizations (NGOs) are mainly responsible for primary collection, which is also providing jobs to the local people. However, during secondary waste collection, all waste is mixed and put into a single community bin as there are no separate bins for the segregated waste. Currently, there is no waste treatment and sorting facility in the city due to which all the waste is dumped at Boragaon dumpsite which is basically an open dumpsite. According to SWM rules 2016, it is mandatory to source-segregate the waste into wet and dry waste that need to be treated safely afterward, which is a responsibility of the local municipalities. However, due to lack of financial resources and scientific knowledge, many of the India cities are still not able to manage their waste properly like Guwahati city. As the current waste management practices are unsustainable and the city was planned to be developed as a smart city by GoI, Guwahati was selected as the study area for the present study.

### *MSW sample collection and preparation*

To characterize the MSW generated in the city, the characterization of waste was done individually for each of the city's six divisions. Also, a representative sample was prepared by mixing the waste from all the six divisions. The sampling was carried out in accordance with ASTM-D5231 – 92 – 2016 – Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste. The sampling was done in the three different seasons- summer (March), monsoon (August), and winter (November). A total of 32 samples were collected to provide a statistical accuracy of 90% confidence (ASTM D5231 – 92, 2016). A manual sampling protocol was followed for sampling the MSW, and samples were collected from the respective dumper/compactors from their allotted divisions. A division was chosen priory and all dumpers/compactors coming from the selected division were instructed to dump the waste separately. From that dumped waste, 32 waste samples were taken from the all the dumped loads, at different depths. Around 100 kg of the waste is collected from the MSW resulting from each division. Quartering of sampling was done to obtain a representative divisional waste sample. This sampling protocol was repeated for every division in each of the three different seasons. After collecting the samples, one representative sample was prepared using the Coning and Quartering Method number of collected samples (detailed procedure and calculates are in supplementary material). Each representative sample prepared for the divisions and the city weighing in-between 10–12 kg, which was further used for physical and chemical characterization of MSW.

### *Physical composition of collected samples*

The MSW composition was determined as per ASTM D5231 – 92 (2016) in terms of the dry weight percentage. For determining MSW composition, samples were classified mainly into seven broad groups: organic, plastic, paper & cardboard, textile, glass, metal, and mixed residue. The physical composition of MSW was determined for all six divisions and representative sample for the three different seasons.

### *Chemical composition of collected samples*

For chemical characterization, collected raw samples after coning and quartering procedure were taken to the Indian Institute of Technology at Guwahati. The samples were dried in an oven at 105°C for 24 hours. After drying, samples were manually shredded, ground, and sieved to prepare samples for various chemical analyses. The chemical composition of MSW was determined through the proximate analysis and ultimate analysis. Test and methods used for chemical characterization of waste are mentioned in Table 1. After determining the physical composition of the MSW, results of the study area were compared with the MSW composition of other national and international cities. Based on the physical and chemical characterization parameters, the feasibility of treatment technologies, such as biological treatment of organic waste (biomethanation, composting), recycling, and thermal waste treatment technologies (RDF, mass incineration, gasification, pyrolysis) are discussed in detail.

## Results and discussion

### *Physical composition of MSW*

The results of the seasonal determination of the physical composition of MSW carried out at Guwahati city is shown in Table 2 and represented graphically in Figure 3, S2, S3, and S4. As per the results, in all the seasons and every division of the city, organic waste

**Table 1.** Details of tests conducted and methods followed for chemical characterization of waste.

| Sl. No. | Test name | Method | Code of practice/instrument |
|---|---|---|---|
| 1 | pH | SW846 9045 D | SW846 |
| 2 | Moisture content | Oven dry method (E871-82) | ASTM |
| 3 | Volatile solid | IS: 10158– 1982 | ISI 1982 |
| 4 | CHNS-O analysis | Combustion and Pyrolysis | EuroEA3000, CHNS-O analyzer |
| 5 | Calorific value | Laboratory bomb calorimeter | Bomb Calorimeter |

**Table 2.** Seasonal physical composition of MSW for different divisions of the city.

| Division | | 1 | 2 | 3 | 4 | 5 | 6 | Representative | Avg. |
|---|---|---|---|---|---|---|---|---|---|
| Organics | Aug | 44.00 | 40.00 | 41.00 | 34.00 | 47.00 | 40.00 | 38.00 | 40.57 |
| | Nov | 46.56 | 50.57 | 48.68 | 53.03 | 44.58 | 44.21 | 39.93 | 46.79 |
| | Mar | 40.64 | 48.78 | 39.26 | 49.67 | 50.45 | 38.58 | 48.58 | 45.14 |
| | Avg. | 43.73 | 46.45 | 42.98 | 45.57 | 47.34 | 40.93 | 42.17 | 44.17 |
| Plastics | Aug | 29.00 | 28.00 | 31.00 | 23.00 | 30.00 | 35.00 | 27.00 | 29.00 |
| | Nov | 28.16 | 23.50 | 25.20 | 22.20 | 24.96 | 25.10 | 26.73 | 25.12 |
| | Mar | 24.14 | 15.83 | 17.04 | 19.97 | 14.63 | 17.24 | 21.77 | 18.66 |
| | Avg. | 27.10 | 22.43 | 24.41 | 21.72 | 23.20 | 25.78 | 25.17 | 24.26 |
| Paper and Cardboard | Aug | 13.00 | 20.00 | 12.00 | 18.00 | 8.00 | 10.00 | 15.00 | 13.71 |
| | Nov | 11.35 | 10.33 | 16.22 | 10.33 | 12.64 | 18.87 | 18.40 | 14.03 |
| | Mar | 10.38 | 10.96 | 22.59 | 11.63 | 9.25 | 19.48 | 15.41 | 14.24 |
| | Avg. | 11.58 | 13.76 | 16.94 | 13.32 | 9.96 | 16.12 | 16.27 | 13.99 |
| Textiles | Aug | 3.00 | 2.00 | 3.00 | 20.00 | 4.00 | 9.00 | 9.00 | 7.14 |
| | Nov | 3.56 | 1.00 | 1.64 | 8.65 | 1.00 | 1.00 | 1.96 | 2.69 |
| | Mar | 3.42 | NA | 2.60 | 3.25 | 3.88 | 2.43 | 4.02 | 2.80 |
| | Avg. | 3.33 | 1 | 2.41 | 10.63 | 2.96 | 4.14 | 4.99 | 4.21 |
| Glass | Aug | 1.00 | 1.00 | 2.00 | 0.00 | 4.00 | 0.00 | 0.00 | 1.14 |
| | Nov | - | - | - | - | - | - | - | - |
| | Mar | - | - | 4.44 | - | 2.09 | 2.42 | - | 1.28 |
| | Avg. | 0.33 | 0.33 | 2.15 | 0.00 | 2.03 | 0.81 | 0.00 | 0.81 |
| Metal | Aug | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Nov | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Mar | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Avg. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Mixed residue | Aug | 10.00 | 9.00 | 11.00 | 5.00 | 7.00 | 6.00 | 11.00 | 8.43 |
| | Nov | 10.37 | 14.60 | 8.26 | 5.79 | 16.82 | 10.82 | 12.98 | 11.36 |
| | Mar | 20.75 | 24.43 | 14.07 | 15.48 | 19.70 | 19.85 | 10.22 | 17.79 |
| | Avg. | 13.71 | 16.01 | 11.11 | 8.76 | 14.51 | 12.22 | 11.40 | 12.53 |

accounts for the maximum weight percent in the overall MSW (ranging from 34 to 53 wt%). Organic waste was followed by plastics, paper, and cardboard waste in the MSW (Table 3 and Figure 3). Textile and glass accounted for 4.2 wt% and 0.8 wt%, respectively. Metals accounted for less than 0.01 wt%, because of door-to-door collection or manual scavenging of large quantities of metal waste pieces from the secondary bins by rag pickers. Due to the high percentage of recyclables and organics in MSW of the study area, recovery of recyclables and organic waste treatment methods seems to be an economical and environmentally friendly option. Table 2 shows an abrupt change in the contribution of textile waste from Division-4 in August. This may be due to local interference as division-4 is a busy market area. There is a heavy market area in division 3 and 4 while both division 3 and 1 have the major temples in the city which attracts lakhs of people from all over India. Furthermore, division 3 have all the major railway stations of the city. This could be the major reason behind the highest content of paper & cardboard and glass waste generated in division 3 compared to other divisions. While division 1 and 4 shows the highest content of plastics and textile waste respectively.

On looking at the seasonal variation in the MSW composition of the Guwahati city, organic, plastics, and mixed waste have shown significant variation. Among all types of waste, plastics have shown the most variation in the composition percentage on a seasonal basis, followed by mixed waste and organics. The highest variation in plastics and mixed waste was found in August (rainy season) and March (summers), i.e., 10.30% for plastics and 9.40% for mixed waste. The variation for organic content in MSW was up to 6.2% in the monsoon and winter seasons. The possible explanation behind these variations in MSW's composition is a change in city residents' lifestyle and consumption habits during different seasons. Besides organics, plastics, and mixed waste, other MSW components have not shown any significant variation (<5%).

## *Chemical characterization*

The proximate analysis results for summer, monsoon, and winter for all six divisions are shown in Table 4. Results shows that MSW samples have high moisture (49.5%) and volatile solid (41.3%) content, making it an attractive option for composting or biomethanation. However, the C/N ratio of the mixed waste is low (13–14) to be used directly for any organic waste treatment method. But after

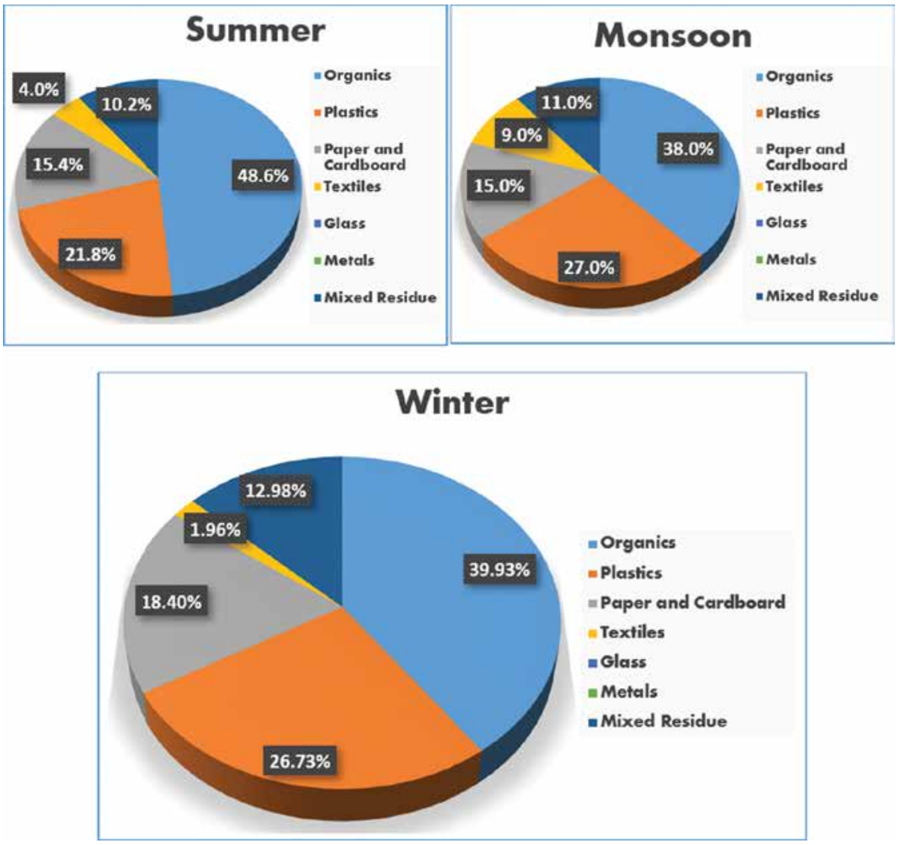


**Figure 3.** Seasonal composition of the MSW (representative sample) (a) Monsoon (b) Winter (c) Summer season.

**Table 3.** Seasonal variation of MSW composition of Guwahati city (On divisional level; *M-March, A-August, N-November*).

| Sl. No. | Contents | Lowest (%) | Highest (%) | Average (%) |
|---|---|---|---|---|
| 1 | Organics | 34.00 (A) | 53.03 (N) | 44.17 |
| 2 | Plastic | 14.63 (M) | 35.00 (A) | 24.26 |
| 3 | Cardboard + paper | 8.00 (A) | 22.59 (M) | 13.99 |
| 4 | Textile | 1.00 (N) | 20.00 (A) | 4.21 |
| 5 | Glass | 0.00 (A) | 4.44 (M) | 0.81 |
| 6 | Metal | NA | NA | NA |
| 7 | Mixed residue | 5.00 (A) | 24.43 (M) | 12.53 |

properly segregating the organic fraction of the municipal solid waste (OFMSW), the optimum range of C/N (25:1 to 30:1) can be achieved. The average pH of MSW is weakly acidic in nature (5.5–6.5), ranging from highly acidic to slightly acidic in different seasons. On average, MSW has a sufficient calorific value to be used for waste incineration or refuse-derived fuel.

While looking into the seasonal variation of MSW, parameters like pH, moisture content, and carbon-hydrogen-oxygen content varies significantly with the changing season (Table 5). As content of the organic waste is highest and inert waste (mixed waste) is lowest in the summer season, total volatile solid content, carbon content, and calorific value of MSW were highest in this season (Figure 3 and Table 4). This high calorific value could be the result of lower inert or ash fraction (mixed residue) and high organic fraction in the waste. Usually there is no to very little rain in the month of the November. But during the week of sample collection is little rainfall in the reason. As a result, there is high moisture content in the waste even in the winter season. There is not much variation in the average value of the pH, C/N ratio, and moisture content in the summer and rainy seasons. However, there is a significant difference in the percentage of volatile solids and calorific values during these two different seasons due to the change in MSW composition.

## *Comparison of MSW composition of Guwahati city with other cities*

India produces the highest amount of waste compared to other South Asian countries like Pakistan, Bangladesh, Bhutan, Afghanistan, etc. (Kaza et al. 2018). Comparing the MSW from Guwahati with other

**Table 5.** Variation in chemical characteristics of MSW in Guwahati (On divisional level; *M-March, A-August, N-November*).

| Sl. No. | Contents | Lowest (%) | Highest (%) | Average (%) |
|---|---|---|---|---|
| 1 | Moisture content (%) | 37.10 (N) | 65.70 (N) | 49.54 |
| 2 | pH | 4.90 (A) | 7.00 (N) | 5.83 |
| 3 | Volatile solids (%) | 25.70 (N) | 79.50 (M) | 41.31 |
| 4 | Calorific value (kcal/kg) | 903 (N) | 3309 (M) | 1833 |
| 5 | C (%) | 5.29 (N) | 50.18 (M) | 22.05 |
| 6 | H (%) | ND (M) | 30.37 (N) | 8.50 |
| 7 | N (%) | 0.464 (N) | 3.38 (M) | 1.69 |
| 8 | S (%) | ND | ND | ND |
| 9 | O (%) | 2.29 (A) | 11.37 (N) | 6.42 |
| 10 | C:N ratio | 5.52 (A) | 24.13 (A) | 13.32 |

cities in India and other countries is presented in Table S1 and S2 in the supplementary material. On comparing the physical composition of MSW of Guwahati with average values of South Asia (Table S1), the percentage of plastics, paper, cardboard, and textile waste was significantly higher, showing differences in living habits, product consumption, and economic conditions. Even though India belongs to lower-middle-income countries, the present study area's waste composition resembles more to the upper-middle-income countries' cities like Bangkok, Johannesburg, Chihuahua, and High-income countries' cities like Turku and Austin. Among all the countries mentioned in Table S1, the plastic component of the MSW of the present study area was found highest, and paper & cardboard waste was higher than most of the countries compared. On the contrary, the organic, glass, and metal content of the waste was relatively less to the other cities in the world. Lower organic content and higher plastic and paper waste content may represent the citizens' higher living standards or huge consumption of packaging and plastic products (Goel 2008; Kandakatla, Ranjan, and Goel 2017; Kaza et al. 2018). Though for most developing nations, organic content in the MSW is dominate in the MSW which is also true for the current case study (Yang, Xu, and Chai 2018). However, compared to other Indian cities, the percentage of plastics, paper, and cardboard were found significantly higher for study area even with the large metropolitan cities of the countries like Mumbai, Kolkata, and Delhi.

On comparing the chemical composition of the MSW of the present study, calorific value, carbon content, and C:N ratio of the MSW was lowest among all the compared city (Table S2). Also, the volatile content of Guwahati's MSW is low compares to most of the cities. Due to lower C: N ratio (<25–30) and volatile content (<50–60%), MSW in the present form (mixed form) will not be feasible for biological treatment. But with proper segregation of organic waste, these values can be improved for the biological process. The higher content of paper, plastics, and textiles compared to other Indian cities shows a high potential for recycling waste. Even though the waste's calorific value is lower than all the cities in Table S2, it may be adequate for incineration (>1700 kcal/kg) or RDF generation with proper segregation.

## *Potential treatment options for the MSW*

Appropriate waste treatment technology selection is the backbone of any efficient MSW management design. The efficiency of certain waste treatment systems depends on the certain physical and chemical properties of the waste. So, the data generated in the present waste characterization study was used for determining the efficiency of different waste treatment options. Figure 4 shows the parameters tested for determining the potential of different treatment and recycling techniques.

### *Potential for recycling*

Although recycling of the waste material is the second most preferred option in the ISWM hierarchy, the high recyclables content in the MSW from Guwahati (43.27%) implies recycling needs to be a priority. Among the recyclables, plastics and paper waste make up more than 38% of total MSW which is highest among all the cities compared in Table S1. However, this high fraction of recyclables demands proper segregation of MSW which means as per government SWM rules 2016 i.e., OFMSW and recyclables segregated as wet and dry waste respectively. Proper segregation will increase the opportunity for scientific disposal or treatment. It will also increase the recyclables' quality, leading to more revenue for the local authorities. Unlike most Indian cities, there is a relatively good source segregation system at the primary level of Guwahati's waste collection due to highly active local NGO's. But during secondary collection, all the segregated MSW is mixed into a single container. This makes the treatment of MSW challenging and renders the efforts of primary waste collection futile. Therefore, providing separate bins for recyclables and organic waste during secondary waste collection and building a material recovery facility (MRF) will improve the collection and quality of the recyclables. Besides revenue generation by selling good quality recyclables, segregated organic waste can be used for energy and compost generation by bio-methanation, composting, and incineration. Detailed plan for designing waste storage and collection is ongoing in our lab using a approach from (Singhal and Goel 2021b) and will be presented as separate manuscript.


**Figure 4.** Parameters checked for selecting potential waste treatment technologies.

Segregation of recyclables by rag pickers was observed to be practiced at the dumpsite and in different parts of the city. So, along with centralized collection and separation of recyclables, GMC should also encourage formal & informal recyclables collection with proper training. This will help in collecting good quality recyclables and create numbers of jobs for the low-income-group of the city.

### *Potential for anaerobic digestion (or biomethanation)*

Anaerobic digestion (AD) is a microbial degradation of biodegradable organic matter in the absence of oxygen that produces biogas and liquid slurry. Biogas is typically 50–70 wt% consists of methane, which can be used for energy generation. After stabilization, the waste slurry can be used as compost for soil amendment (Kumar and Samadder 2017; Surendra et al. 2014). AD is the next most preferred organic waste management & treatment option in the ISWM hierarchy. But operating a biogas plant requires skilled supervision and small fluctuations in pH and loading rates inside the reactor may disrupt the process completely. MSW of Guwahati city has a good moisture content (37–66%) for AD. But other parameters like volatile solid content (41.31%), C/N ratio (13.32), and pH (5.83) are not compatible with MSW to be used for biomethanation in unsegregated form. However, with waste segregation, all these parameters can be increased to the optimum level, i.e., volatile solids content more than 60–70%. C/N ratio is between 25:1 and 30:1. Also, the loading rate into the AD reactor needs to between 10% and 15% (wet system) and 20–40% (dry system) of dry content, which required the addition of water, which automatically increases the pH to the optimum range (6.50–7.50). With waste segregation and skilled supervision, biomethanation can be used efficiently for treating MSW of the Guwahati. Building a large biogas plant (>100 TPD) will require more capital investment compares to other treatment options like composting and RDF (Aleluia and Ferrão 2017; Lin et al. 2019). Also, there is huge fluctuations in the quality of the feedstock in different divisions and city has large area which result into huge waste transportation costs. So, for optimum biogas yield and to save waste transportation cost, a decentralized treatment system should be preferred over a centralized treatment system. The decentralized system may result in a high initial capital investment. Still, due to two-fold revenue generation (biogas and compost) and huge savings in waste transportation cost, in the long run, it seems like an economically sustainable solution.

This biogas can be used to generate electricity or can be converted into biofuel. According to Macias-Corral et al., (2008), around 37 mL methane can be generated from 1 g of OFMSW. Using that value, around 13,000 $m^3$ of methane and 21,700 $m^3$ of biogas (assuming methane content 60%) can be generated out of 353.5 tons of organic waste daily (total waste 800 ton/day and 44.2% of total MSW are organics) generated in the Guwahati city. As per Murphy et al. (Murphy and McKeogh 2004), 1 $m^3$ of biogas resulted from the AD process can generate about 2.04 kWh of electricity (conversion efficiency = 35%). So, in a single day, about

42,840 kWh of electricity can be produced from the waste, which can provide electricity to nearby 14,280 houses (average household electricity consumption is 90 kWh/month). Besides energy generation, after removing $CO_2$ and $H_2S$, methane enriched biogas containing more than 90% methane, which is somewhat like compressed natural gas (CNG). So, biogas can be used as fuel by the municipality for their waste collection fleet or used as cooking fuel for the nearby households. This will not only help in revenue generation but also help in reducing methane emission into the environment. Methane is 25 times more global warming potential (GWP) than carbon dioxide. Landfilling is one of the major sources of methane emissions in the world. So, by implementing AD treatment of MSW, huge quantities of waste can be diverted from the landfill. It will reduce methane emissions from waste, meeting India's Intended Nationally Determined Contribution (INDC) as per the Paris Climate Agreement.

### Potential of composting

Composting is the biodegradation of the organic matter in the presence of oxygen results in nutrient-rich by-products that can be used for agricultural and horticulture purposes. After biomethanation, aerobic composting is the next most preferred waste management and treatment option in the ISWM hierarchy. Around 44% of the MSW generated in the study area is organic, with volatile content of 26–80% and moisture content of 37–66%. High organic and moisture content in MSW makes composting an attractive treatment option. There is a good demand for organic fertilizer in the city's nearby areas due to major government initiatives in the North-eastern region of India regarding the promotion of traditional farming. Compared to other waste treatment technologies composting requires relatively the lowest capital investment and operational and maintenance costs (Aleluia and Ferrão 2017; Annepu 2012; Lin et al. 2019). So, centralized or decentralized composting of organic waste can be an environmentally friendly and economically sustainable option for waste treatment. Another possible composting method that can be utilized is vermicomposting. Besides feedstock quality, vermicomposting's efficiency greatly depends on the vermin's health, which can be improved in a small-size treatment plant. So, Vermicomposting could be a better option than traditional window composting in a decentralized system rather than a centralized system.

But in its current form, MSW cannot be used for composting because of the unsegregated form of the waste having a low C: N ratio (ranging 5.52 to 24.13, average 13.32) and carbon content (ranging 5.3% to 50.2%, average 22.1%). With the help of proper segregation, both values can be improved to the optimum level, i.e., 25:1 to 30:1 C: N ratio and >50–60% carbon content, respectively. If needed, OFMSW can be mixed with fruit/food waste, leaves, and animal manure to reach the optimum parameters for compost feedstock (Ayeleru, Okonta, and Ntuli 2018; Tanimu et al. 2014). Besides segregation, special consideration must be given for leachate collection and treatment due to high annual rainfall in the study area. To reduce costs related to leachate collection and treatment, centralized composting seems more economical than decentralized composting in the present case. The revenue generated from the generated compost is directly in competition with other subsidizes fertilizers in the Indian market like urea. The subsidized cost of urea is around \$77.5/ton, whereas the cost of city compost is around \$86.7/ton. To promote organic farming and organic waste compost, the government can provide a \$21.7/ton on the city compost.

### Waste incineration

Where material recovery from waste is not possible, energy recovery from waste through heat, electricity, or fuel is preferred. Incineration of waste comes after the composting, biomethanation, and RDF production in the ISWM hierarchy, so these options should be preferred over incineration. Mass incineration without any pre-treatment of MSW used for electricity generation is an economical and reliable waste treatment option (Singh et al. 2011). It can reduce the mass of the waste by 70% and volume by up to 90% and recover energy from the electricity generation's waste. Compared to other waste treatment technologies, capital investment for waste incineration is highest among all the current treatment options. According to Kumar and Samadder, 2017 capital cost is required for waste-to-energy (WTE) incineration plant 400–700 \$/tonne/MSW/year.

In contrast, as per Aleluia and Ferrão, (Aleluia and Ferrão 2017) the 2017 capital cost ranges from $USD_{2015}$ 60,097 to $USD_{2015}$ 110,581 per tons of waste processing. Also, operation expenditure per tonne is highest for incineration compares to other technologies, i.e., 5.2 to 29.9 $USD_{2015}$/ton; average 20 $USD_{2015}$/ton (Aleluia and Ferrão 2017). Since the capital investment is very high, the community's planning framework should be stable enough to allow a planning horizon of 25 years or more.

As per the World Bank report, the average calorific value of MSW for a feasible incineration operation with energy recovery should be at least 1700 kcal/kg (World Bank, 1999). According to the International Energy Agency, heating values must be greater than 1900 kcal/kg for the incineration operation to be effective and economical (Melikoglu 2013). According to the Indian SWM rules 2016, the net calorific value of waste should not be less than 1,450 kcal/kg throughout all seasons. The annual average net calorific value must not be less than 1,700 kcal/kg. The average net calorific value of MSW of Guwahati city is 1833 kcal/kg, which is appropriate for incineration as per Indian regulation and World Bank report value. However, in the rainy season average calorific value of the MSW can fall up to 1203 kcal/kg. As per waste characterization results, the waste's average moisture content was very high (average 49.5%), reaching up to high as 58.34% during the rainy season. Besides low seasonal calorific value and high moisture content, the net amount of combustible waste (42.50% of total MSW; 340 TPD) is less than 500 TPD. According to Indian regulation (SWM rules 2016), it is not economically feasible to set up an incineration plant. Due to the poor quality of feedstock and very high capital investment, installing a WTE incineration plant may not an economically feasible option for treating MSW of the Guwahati city in its present form. High moisture, variable composition, and energy content are the major difficulties the developing countries face for incinerating MSW (Annepu 2012; Kandakatla, Ranjan, and Goel 2017).

However, there are cases where MSW with low calorific values used for incineration in the WTE plant. The heating values of MSW generated in China is lower than that of India. Yet, the number of incineration plants and their capacity in China has increased more than doubled in the last decade (China Statistics Press, B. 2016). The moisture content of Japan's MSW is higher than that of India. Still, through robust source segregation, WTE contributes to more than 75% of solid waste treatment (Niyati 2015) in Japan. With proper segregation of MSW and applying some pretreatment (thermal, mechanical, or biological), the calorific value of the waste can be increased. The moisture content of waste can be reduced via flue gas recirculation, though such options needs to be studied further (Kumar and Samadder 2017).

### Refuse derived fuel (RDF)

RDF is the final product from the waste materials processed to fulfill guidelines, regulatory, or industry specifications to achieve a high calorific value as substitute fuels (Kumar and Samadder 2017). RDF is mainly used as a substitute for fossil fuels in high-energy industrial processes like power production, cement kilns, steel manufacturing, etc., to enhance these plants' economic performance (Annepu 2012). RDF could be an alternative to WTE and can be a potential waste management technology. RDF's capital investment is relatively lower than other WTE options like incineration, pyrolysis, gasification, and biomethanation (Aleluia and Ferrão 2017; Annepu 2012). Low capital investment and high combustible fraction in MSW of Guwahati city strengthen RDF's prospects as a potential waste treatment option. The average calorific value of the waste is also appropriate to be used for producing good quality RDF. The only concern is the high average moisture content of the waste, which is 49.5% and can go up to high as 65.7%. But, by proper segregation and reducing moisture content, the MSW's calorific value can be improved as RDF.

RDF could be an economically sustainable solution for waste treatment due to its huge potential to be used in nearby industries. Some cement and steel manufacturing units in the vicinity of the study area where RDF can be used as an alternative source to the coal. Also, many thermal power plants in the vicinity were closed due to corrosion of boilers due to high sulfur content in coal and difficulties in transportation of coal. These problems can be reduced by using RDF. RDF is a proven technology in India, and there are several plants operational in the country. Hyderabad (700 TPD), Vijayawada (500TPD), Jaipur (500 TPD), Chandigarh (500 TPD), Mumbai (80 TPD), Rajkot (300 TPD), Surat, Ahmedabad, Nagpur, and Kanpur are cities where RDF plants are running successfully in India (Annepu 2012). The market prices of RDF are in the range of USD 39.18 to USD 43.54 per ton. The RDF sold in the current retail market has a Gross Calorific Value (GCV) ranging from 3200 to 3800 kcal/kg. The normally used coal is usually low quality (GCV only around 50% of the RDF) and has a low cost (USD 21.77– 26.12 per ton). This low quality of coal can easily be replaced by the better quality of the RDF. This scenario makes the conversion of MSW into RDF a financially attractive treatment option.

### Pyrolysis

Pyrolysis is an advanced thermal treatment method in the absence of oxygen at the temperature range of 400–800°C. In pyrolysis, at a lower temperature (500–550°C), pyrolysis oil, wax, and tar are the major products, where at high temperature (>700°C), pyrolysis gases are the main products (Kumar and Samadder 2017). Pyrolysis can result in a 50 to 90% reduction in the waste volume. It can produce fuel in different physical forms, which can be used for energy production. Also, pyrolysis has the least Global warming potential (424 GWP) compares to other WTE options like mass incineration (424 GWP) and landfilling (746 GWP), which shows it is a more environmentally friendly option compares to other WTE options (except biomethanation-222 GWP) (Zaman 2010). For quality products from the pyrolysis process, the feedstock should be of a specific type of wastes like plastic, tire, paper, wood waste, etc. Around 40–45% of the MSW generated in Guwahati has combustible materials like paper (13.9%), plastics (24.3%), textile (4.2%), leather, etc. So, pyrolysis can be used to treat paper and plastic wastes through proper segregation of waste, which alone contributed to 38.3% of the total waste in the present case. Even though pyrolysis performs well in treating specific waste streams, only a few studies reported efficient energy recovery from MSW using pyrolysis at a commercial scale. Countries like Germany, Japan, UK, and France have some plants reporting successful MSW pyrolysis plant operations for electricity generation (Panepinto et al. 2015). Capital investment ($400–700/ton of MSW/year) and operational cost ($50–80/ton of MSW/year) of pyrolysis are very high (Kumar and Samadder 2017). Especially due to the high initial investment currently, pyrolysis hasn't been much for MSW treatment. Also, it requires skilled supervision and infrastructure, which developing countries are currently lacking. So, due to high initial investment and the need for skilled supervision thrusts that pyrolysis should only be used when other treatment options are eliminated.

### *Gasification*

Gasification is another thermal conversion technology where carbon-based material is converted into the combustible gaseous product (syngas) in an oxygen-controlled atmosphere at high temperature. Syngas is the main product from the process that can be used for energy generation or converted into liquid fuel. From an environmental impact and energy recovery prospective, pyrolysis, and gasification are more promising technologies than the incineration technology for MSW (Murphy and McKeogh 2004; Zaman 2010). Gasification and pyrolysis can reduce MSW volume up to 95% and require relatively less intensive flue gas cleaning than incineration (Yap and Nixon 2015). Even though there are not many gasification plants in India for MSW treatment, after the Indian government initiative after 2016 ("Swachh Bharat Abhiyaan"- Clean India mission), few gasification WTE plants are coming in India. All over the world, around 100 plants based on gasification technology are currently working. Japan has extensively used gasification technology (85 plants operational in 2007). Countries like the USA, Italy, UK, Germany, Norway, and Iceland have used it on a smaller scale (Panepinto et al. 2015). However, gasification technology has yet to be established at large-scale utilization across the world (predominantly in developing countries) for energy recovery from MSW due to poor efficiency of gasifiers and gas cleaning systems, high moisture content of waste, and heterogeneity in MSW composition & particle size (Kumar and Samadder 2017).

Like pyrolysis, gasification was also used mostly to treat the specific type of MSW like paper mill waste, mixed plastic waste, agricultural residue, etc. (Singh et al. 2011). Plastics and papers present in high composition (together 38.3%) in the MSW of Guwahati can effectively be used for electricity or fuel production. However, like pyrolysis, gasification also required quality feedstock, which means proper segregation of recyclables is vital for efficiently using these technologies. Besides segregation, there are other issues with using Guwahati's MSW for gasification. The moisture content of the MSW generated in Guwahati is very high (about 50%), which can also vary significantly during monsoon season and affect the waste's net calorific value. High moisture content and mixed nature of waste may lead to extensive pre-treatment of MSW (RDF), which increases the overall treatment cost of the system. The capital and operational costs for gasification are very high ($250–850/ton of MSW/year and $45–85/ton of MSW/year respectively) and may increase due to extensive pre-treatment (Kumar and Samadder 2017). Due to high capital and pre-treatment costs and high moisture content in the MSW, gasification may not be an economically sustainable waste treatment solution.

## Conclusion

The study illustrated the significance of seasonal characterization of MSW to identify an effective waste management strategy. The results of the study were compared with other global and national cities of different income-level groups. Based on the experimental result data, different waste treatment technologies were reviewed for efficient waste treatment. The study results show that organics and plastics are the major constituents of the MSW (44.2% and 24.3% of total MSW). All the physical components have shown significant variation with the changing seasons. Plastics, textiles, and mixed residue have shown the most fluctuations (10.3%, 4.44%, and 9.36% difference, respectively) in the summer and monsoon. Chemical properties like pH, volatile solids, carbon, hydrogen, nitrogen, sulfur, and oxygen content have also varied significantly with seasons. The average calorific value of MSW was 1833 kcal/kg, which was remarkably high during the summer season (3015 kcal/kg) and quite low during the rainy season (1203 kcal/kg). Compared to other cities, the percentage of plastics, and paper & cardboard waste in Guwahati's MSW was very high. In contrast, organic and other waste fraction was comparable to other cites of upper-middle-income level countries.

The characterization study shows that MSW generated in Guwahati city has content of recyclables. Organic fraction of MSW and combustible rejects from the recycling facility have also high potential for producing RDF. Still, proper waste segregation is essential for economic feasibility for all the waste treatment technologies and options. In the present mixed form, the MSW of the study area is difficult and costly to treat. However, other organic waste treatment technologies like anaerobic digestion and composting could become sustainable solutions with proper segregation of the organic fraction of the waste. Due to low calorific values, low quantity of available combustible waste, huge capital investment, and high operational & management costs, thermal treatment technologies were economically unsustainable for the present case as per present conditions.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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# Circular economy approach in solid waste management system to achieve UN-SDGs: Solutions for post-COVID recovery

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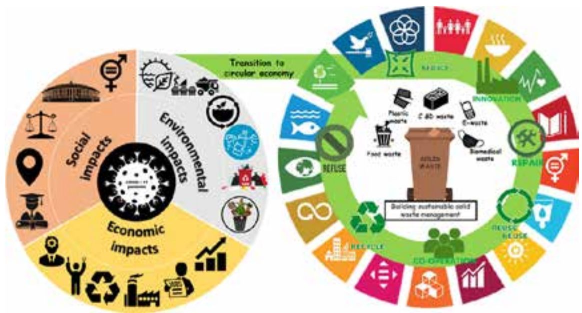
## HIGHLIGHTS

- The Paper investigated the impact of COVID-19 on the progress of the UN-SDGs.
- The guiding principles of UN-SDGs are analogous to that of circular economy (CE) based solid waste management (SWM).
- The CE based SWM have potential to create green jobs apart from bringing socio-economic benefits.
- To achieve UN-SDGs, CE based SWM should be treated as a priority.
- The COVID response fund should also be used to facilitate the transition to full adoption of circular economy model.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The COVID-19 pandemic and the ensuing socioeconomic crisis has impeded progress towards the UN Sustainable Development Goals (UN-SDGs). This paper investigates the impact of COVID 19 on the progress of the SDGs and provides insight into how green recovery stimulus, driven by circular economy (CE)-based solid waste management (SWM) could assist in attaining the intended targets of UN-SDG. It was understood in this review that the guiding principles of the UN-SDGs such as, public health, environmental concerns, resource value and economic development are similar to those that have driven the growth of waste management activities; thus, in order to achieve the goals of UN-SDG, a circular economy approach in solid waste management system should be prioritized in the post-COVID economic agenda. However, policy, technology and public involvement issues may hinder the shift to the CE model; therefore, niche growth might come from developing distinctive waste management-driven green jobs, formalizing informal waste pickers and by focusing in education and training of informal worker. The review also emphasized in creating green jobs by investing in recycling infrastructure which would enable us to address the climate change related concerns which is one of the key target of UN-SDG. The CE-based product designs and business models would emphasize multifunctional goods, extending the lifespan of products and their parts, and intelligent manufacturing to help the public and private sectors maximise product utility (thus reducing waste generation) while providing long-term economic and environmental

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benefits. The study also recommended strong policies that prioritized investments in decentralization of solid waste systems, localization of supply chains, recycling and green recovery, information sharing, and international collaboration in order to achieve the UN-SDGs.



**Contents**



## 1. Introduction

The year 2020 was marked as the start of the 'Decade of Action' by United Nations to deliver the SDGs by 2030. However, with a global death toll of over 3.4 million people (while we write) and an impending socio-economic crisis, COVID-19 has derailed the progress made so far in achieving the United Nations Sustainable Development Goals (UN SDGs) (Guan et al., 2020; Sachs et al., 2020.). Independent of the disease's real spread, every country including the high-income countries in Europe and North America have been adversely affected by the economic ramifications induced by the pandemic (Sachs et al., 2020). For instance, job hours wasted in 2020 was equal to 255 million full-time workers, resulting in $3.7 trillion in lost labour revenue (ILO, 2020). Even after investing US$ 18 trillion as an economic stimulus, global economies are projected to lose US$ 12 trillion or more by the end of the year 2021 (Gates, 2020). Moreover, the disproportionate socioeconomic implications of the COVID-19 pandemic pose a greater risk for developing nations and weaker demographics to reach their targets set by SDGs. So, in the face of a crisis, where the root causes, uneven impacts and vulnerability levels of different populations are demonstrated, the importance and the required urgency in implementation of the SDGs becomes apparent.

Solid waste management (SWM) is a crosscutting problem that influences different facets of growth in all three domains of sustainability: environment, economy, and society (Rodic and Wilson, 2017). The guiding principles of SDGs can be broadly categorized as similar to the goals that have guided the growth of SWM practices over time, namely: public health (SDG 3), environmental issues (SDG 6 & 13) and resource value (SDG 11), with more recent additions to climate change (SDG 13) (Wilson, 2007). For example, SDG 12.3 (halve the per capita global food waste at the retail and consumer levels), SDG 14 (proliferation indiscriminate use and disposal of plastic waste causing marine litter and micro plastic related concerns) cannot be met without meeting the goals of sustainable SWM. Uncollected waste and poorly disposed waste have significant health and environmental impacts (SDG 6 &13). The cost of addressing these impacts is many times higher than the actual cost of developing and operating simple, adequate waste management systems (Kaza et al., 2018). The SWM can be specifically linked to 12 out of the 17 UN-SDGs as the main utility system that more than 2 billion people currently lack (Rodic and Wilson, 2017).

Global waste is expected to grow to 3.4 billion tonnes by 2050 from the current 2.01 billion tonnes. Solid waste-related emissions are anticipated to increase to 2.38 billion tonnes of $CO_2$-equivalent per year by 2050 if no improvements are made in this sector (Kaza et al., 2018). Thus, a paradigm shift is necessary from the depletive 'produce-consume-dispose' model of the linear economy to the 'reduce-reuse-recovery-recycle-redesign-remake' model of the circular economy, which is more regenerative and restorative (can have a positive impact on SDGs 1, 3, 6 - 9, 11, and 13 - 15). The circular economy reflects a structural change that creates long-term stability, maximises the usage and circulation of commodities, resources, and nutrients (SDG12) while providing economic, environmental, and societal benefits (SDG 1, 2, 9, 13 - 15) that help the public and private sectors address both short- and long-term objectives of SDGs (Ellen MacArthur Foundation, 2020). Circular economy based SWM can be an integral component in promoting the three cornerstones of sustainable development (economic development, social inclusion, and environmental protection).

The immediate goal once pandemic starts to ebb out would be to revive economic activity without restoring old trends of environmental deterioration (Sachs et al., 2020). So, as a response to an economic slowdown brought upon by COVID, trillions of dollars in fiscal stimulus have been started to make available around the globe (Masterson, 2020; IMF, 2021). However, achieving resilient and low-carbon economic growth requires policymakers to think beyond safeguarding just national economies through crisis; but, to also take critical steps for a greater structural transition that is more robust against future global threats (Masterson, 2020). To reverse the significant setback and ensure a resilient and sustainable economic rebound, countries would need to brace for a different post-COVID economy by enabling money, labour, expertise and innovation to shift into new industries and sectors (World bank, 2020a). To meet the present needs and reserve the rights of development for future generations, a set of waste management strategies integrating the concept of sustainable development should be developed to achieve the goal of protecting the environment while yielding economic and social benefits (Wan et al., 2019).

In accordance with the preceding discussion, the objective of this paper was to present a case for how the integration of circular economy based sustainable solid waste management into the COVID-19 response could help in mitigating the impact caused by the COVID-19 pandemic to United Nation Sustainable Development Goals (UN SDGs). The first part of the paper highlights the impact of the COVID-19 pandemic on the progress of UN-SDGs. The second part of the paper elucidates in detail how sustainability goals UN-SDGs align with the that of solid waste management, and investigated the feasibility of integrating a circular economy model into a solid waste management system using a COVID-19 economic response to meet UN-SDG objectives. In addition, some major challenges hindering our transition to the circular economy were outlined along with few unique policy recommendations that can help in designing indigenous solutions for smooth transition guided by the principles of SDGs.

## 2. Implications of COVID-19 on the progress of SDGs

The objective of SDGs was to emphasize global attention and converge the efforts of society to inspect and accelerate the progress towards accomplishing the individual 169 targets spread across multiple facets of development exemplified by the 17 goals. The success of sustainable development goals could be related to two important pillars - sustainable economic growth and globalization. However, the economic slowdown due to COVID-19 has resulted in an incapacity of the industrialized countries to support the development of others. COVID-19 has also demonstrated the non-resilience of the SDGs to different global stressors. For instance, (Naidoo and Fisher, 2020) has demonstrated that almost two-thirds of the 169 targets as specified by the 17 SDGs were either under threat or not well-placed to mitigate its impacts. Moreover, around 10% are predicted to amplify the impacts of future pandemics.

The uncertainties associated with the long-term impacts of COVID-19 on economic recovery could be linked to the production factors including labour, capital stock, and productivity, along with some distributional implications (Hughes et al., 2021). The impacts hampering with the progress of SDGs could be either explicit or implicit. The explicitly affected goals are 1, 2, 3, 4, 8, 10, and 12. While some of the goals such as 5, 6, 7, 9, 11, 13, 14, 15, and 16, due to the divergence in the priorities are implicitly affected (Mukarram, 2020). The final goal of 17, would be instrumental for consolidating the global efforts and to bring back the momentum required for making up to the losses in the progress of SDGs during the post-COVID period.

### 2.1. Economic implications

The advent of the COVID-19 pandemic has resulted in an unprecedented socio-economic-ecological crisis, threatening the lives and livelihoods of people, while rewinding decades of progress. The economic recession consequent to the predicted contraction in global GDP (by 5.2%) and per-capita GDP (by 6.2%) (World Bank, 2021) has triggered a sharp increase in unemployment, underemployment, decline in labour income, and increased challenges in job quality (SDG 1). With a reduced flow of aid and resources from developed economies, the impact of the global recession will be very severe for the poorer countries. World Bank has predicted the decline in global remittances to low and middle-income countries (LMICs) by about 20% ($445 billion) in 2020 due to the pandemic and shutdown (World Bank, 2020b). The Organization for Economic Co-operation and Development (OECD) also projected that the external private finance in developing economies to lose USD 700 billion that could exceed the impact of the 2008 financial crisis by 60%, thereby risking and creating major setbacks in financing for sustainable development in developing economies (OECD, 2020,) (SDG 10). Impacts of COVID-19 on the United Nation Sustainable Development Goals is presented in Fig. 1.

The International Labour Organization (ILO) reported a reduction of working hours by 10.7% ($\approx$305 million full-time jobs) in 2020 as compared to the last quarter of 2019 (ILO Monitor, 2020). In the year 2020, 114 million people lost their jobs due to the COVID-19 pandemic and the resulting lockdown. ILO predicted workforce displacement in that 38% of the global workforce (1.25 billion workers) employed in the most vulnerable sectors (Retail trade, accommodation and food services, and manufacturing). These sectors comprising micro, small and medium-sized enterprises with little to no income security and social protection will be the hardest hit due to COVID-19. For instance, the UN World trade organization (WTO) estimates a loss of 850 million to 1.1 billion international tourist arrivals accounting for $910 million to $1.1 trillion in export revenues and 100-120 million jobs in the tourism sector (World Tourism Organization (UNWTO), 2020). With approximately 54% of the jobs in tourism held by women, who are more likely to be entrepreneurs and hold low skilled jobs in this sector, has made them the most vulnerable population for job loss (UNCTAD, 2020) (SDG 8).

### 2.2. Environmental implications

Restrictive measures on human mobility and supply chain disruptions have led to a shortage of labour in local agriculture and food-related activities thereby causing huge material losses. Especially, the reduced demand resulting from the shutdown of restaurants, catering services, food markets and public canteens have considerably limited their sales and caused increased production of perishable food wastes (FAO, 2020). Even with the partial opening of the food outlets, the volatility in the demand could also be responsible for the increase in the production of food waste (SDG 12).

The restrictions, disruptions in supply chains and confinements have forced behavioural changes worldwide. Increased locally-sourced production and online-based services have proved to support responsible consumption. Moreover, increased dependence on single-use plastics due to the false perception of hygienic superiority might retract the progress achieved by the shift to sustainable alternatives. However, with the recovery to normal, the solidity of these transitions in consumption and production would be tested (UNEP, 2020a). Disruptions in the existing waste management systems like shortage of staff, capacity constraints of treatment facilities, disruptions in the plastic recycling facilities due to the pandemic, have reduced the recycling and recovery activity (SDG 12). The increased dependence on online food and supplies delivery has raised the proportion of plastic packaging waste in the municipal solid waste stream. For example, an additional 1,47 tons of plastic waste comprising mostly takeout packaging and food delivery by Singapore's residents during their eight-week lockdown period (Bengali, 2020). An increased abundance of single-use plastic waste such as fast-food packaging, confectionary wrappers and drink bottles in the London waterways amidst the relaxation of lockdown regulations and social distancing rules (Konyn, 2020; Ro, 2020). The temporary disruptions caused in the waste collection of cities along with the inadequate infrastructure for the change in the dynamics of the waste generation have led to increased waste mismanagement, thereby resulting in pollution. However, the reduced waste generation from the commercial and industrial sectors due to the temporary halt in economic activity should also be acknowledged (UNEP, 2020b; Sharma et al., 2020) (SDG 14).

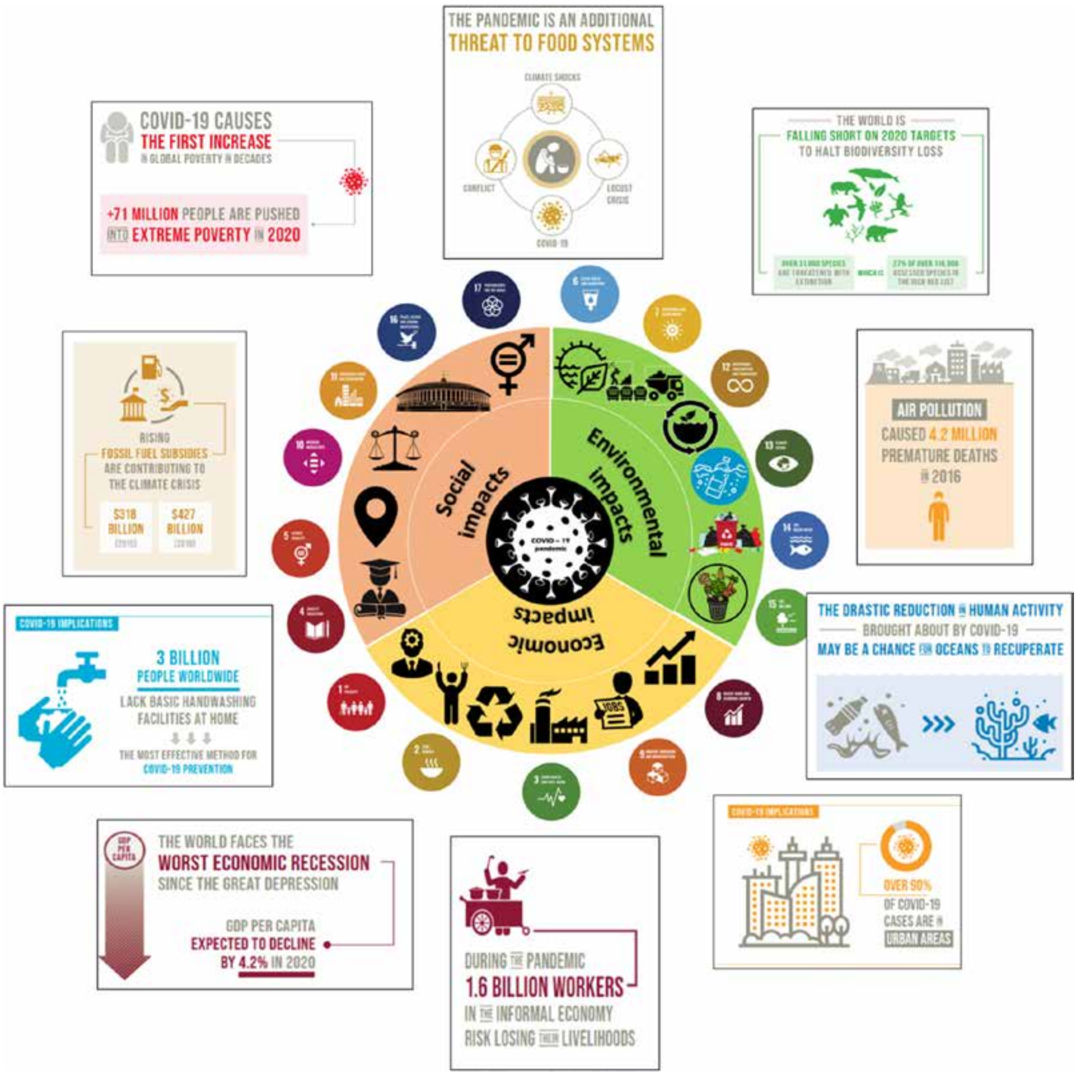


**Fig. 1.** Impact of COVID-19 on the United Nation Sustainable Development Goals (United Nations, 2020).

The health crisis induced by the COVID-19 pandemic has resulted in the generation of an enormous amount of biomedical waste (BMW). For instance, daily bio-medical waste generation in India increased by 25% in 2020 due to COVID-19 (Yearender, 2020). The increase in the use of facial tissues, gauze pieces, masks, oxygen masks, test tubes of nasopharyngeal swabs, cotton swabs, saline bags, disposable syringes, and needles to treat COVID-19 patients become part of the hazardous BMW. The used PPE is a source of potentially infectious BMW that requires special attention during waste management. The inadequacies of existing facilities like incineration to manage the increased generation of biomedical waste have also increased the risk of hazardous waste disposal in an open environment (BIR, 2020; Vanapalli et al., 2021c) (SDG 14). The health risks associated with the improper handling of infectious COVID-19 waste (especially in developing countries) for the sanitation staff due to the lack of access to safety equipment like PPE should also be taken into consideration (SDG 3, 8). Other people who are more prone to get infected from unregulated disposal of virus-laden waste in developing countries would be the informal waste collectors.

The restrictions associated with the pandemic have pushed the global workforce to work from home resulting in accelerated demand for electronics, especially in the form of information and telecommunication equipment (Laptops, mobiles, digital thermometer etc). For instance, in a survey conducted by Blancco and Joensuu, 97% of the companies were found to buy new laptops, and 77% of Americans also had to buy a new device to support remote work access (Cunningham, 2020). Even with the pandemic receding, many companies are forced to invest in better digital technology and home office setups, which has driven a huge spike in the consumption of electronic goods (Cunningham, 2020). This can be associated with an enormous rise in global electronic waste generation (SDG 3, 11, 12).

Although UN in its SDG report 2020 has predicted a 6% drop in greenhouse gases (GHGs) for 2020 due to COVID-19, United in Science, 2020 has reported atmospheric $CO_2$ concentrations of above 410 ppm during the first half of 2020, with no signs of reduction due to the pandemic. However, global fossil $CO_2$ emissions in 2020 were estimated to fall by 4 - 7% in 2020 due to COVID-19 confinement policies. For instance, their values dropped by 17% in April 2020 compared to 2019; but they have returned to within 5% (1–8% range) below 2019 levels in June (UNEP, 2020b; United Nations, 2020). Moreover, the long-term exposure to air pollution resulting in pre-existing respiratory diseases could increase the risk of mortality due to COVID-19 (Wu et al., 2020) (SDG 13).

Although with reduced industrial and commercial activity during lockdowns, there was a significant reduction in water pollution, this can be viewed as a temporary solution. Especially during the lockdown period, the temporary halting of some major industrial activities has helped to reduce the pollution load on surface waters (Yunus et al., 2020). For instance, among the 36 real-time monitoring stations of the river Ganga in India, water from 27 stations met the permissible limit, depicting the implications of reduced industrial pollution on the days of lockdown in India (Singhal and Matto, 2020). Moreover, disruptions in the waste collection services might have induced solid waste mismanagement and caused dumping into the waters (Patel et al., 2020; Yunus et al., 2020) (SDG 6). Despite the reduced activity in the sea might have caused temporary relief to direct marine pollution (Rume and Islam, 2020), the sudden rise in the daily use of single-use PPE which contain a significant portion of plastic to reduce the risk of infection has significantly increased along with the associated risks of marine pollution. With an estimated rise in the global sales of disposable face masks to $166 billion in 2020 compared to $800 million in 2019, (UNCTAD, 2020), almost 75% of it is estimated to be in landfills or end up as marine litter (UNCTAD, 2019). For instance, Oceans Asia has reported finding at least 70 face masks disposed of along a stretch of just 100 m, with an additional 30 washed up on shore on a beach in Lantau Island at the end of February (OCEANS ASIA, 2020). Further, the disintegration of plastic waste into microplastics in the oceans can adversely impact the health of aquatic biota and subsequently be ingested by humans through their food chain (Vanapalli et al., 2021b). The additional problems of plastic waste clogging of drains and canals could increase mosquito breeding, posing a risk of vector borne-diseases (Vanapalli et al., 2019).

### 2.3. Social implications

The COVID-19 poses an additional threat to the food systems, indirectly reducing purchasing power and the capacity to produce and distribute food, which affects the most vulnerable populations. According to the Food and Agriculture Organization (FAO) estimate, food systems involving the sectors of processing, services, and distribution, are estimated to lose more than 451 million jobs (35% of formal employment) (Torero, 2020) (SDG 2). Moreover, with 62% of the global workforce (2 billion) employed in the informal sector, the risk of losing their livelihoods due to the pandemic is real. Even migrant workers which represent 4.7% of the global labour force (164 million workers with approximately 50% women) (ILO, 2018) were badly affected during the ongoing crisis due to increased vulnerability due to migratory and employment status. Although the e-commerce sector which is expected to grow by USD 100.63 billion (Technavio, 2021) was absorbing some of the displaced labour, lack of income, health and social securities to the workers seems to be a depriving factor (SDG 8).

Depending on the severity of the economic contraction, the COVID-19 pandemic was forecasted to bring around 150 million into extreme poverty by 2021 (World Bank, 2020b) (SDG 1). Especially, small-scale food producers comprising 40–85% of all food producers in developing regions are hit hard by the crisis (United Nations, 2020). UN global report on the food crisis, 2021, has reported that at least 155 million people have faced food insecurity crisis in 2020 because of conflict, extreme weather events and economic shocks linked as part of the COVID-19 pandemic (IFPRI, 2020), which implies 38.2 - 80.3 million people in poor countries who rely on food imports falling into the hunger trap (Swinnen and McDermott, 2020).

### 2.4. Specific implications on solid waste management

The impacts of COVID-19 can be mainly classified into the change in waste composition, and quantity, infection risks, disposal frequency, timing (temporal), and spatial distribution. The variations in the waste generation rates, frequency and demands at places of collection have stifled the existing treatment facilities, thereby restricted their adaption to the sudden changes. Also, the decision associated with whether to continue or avoid the recycling considering the safety concerns of the workers against infection was difficult. The technoeconomic uncertainties related to the volume changes, ambiguous policies and guidelines, duration of the emergency, and the constraints with accommodation of safety measures have led many leading recycling programs to suspend services (Fan et al., 2021). The price drop in the secondary materials and the decrease in the demand for primary material could be the key reasons for the decline in the profit of the waste to materials industry in China by 43% during the COVID-19 pandemic (Zhou et al., 2021). However, with the advantage of achieving energy recovery and safe disposal of waste, waste to energy (WTE) industry has compensated the other options of management with non-hazardous municipal solid waste along with hazardous and non-hazardous medical waste during the pandemic and is expected to be booming post COVID-19 pandemic. In spite of the safety advantages of WTE, the environmental superiority of waste to material over of incineration in the waste management hierarchy poses a dilemma to zero waste and source separation and could not be seen in line with the concept of sustainable waste management as proposed by the SDGs.

The solid waste industry is expected to be confronted with declining revenue and rise in operational cost post pandemic in the short-term. For instance, an estimated 55.8 billion $CNY \cdot a^{-1}$ reduction in the turnover of the thirty listed companies in the solid waste industry was predicted by ARIMA-Intervention model in the year 2020 (Zhou et al., 2021). This can be attributed to the overall global economic recession which in turn restricts the monetary support from governments and waste producers who were also affected by the pandemic. Also, the change in the policies and shift in the allocation of funds to indispensable sectors and services affected during the pandemic could compromise the action plans associated with waste generation reduction, promotion of recycling, and elevating level of waste management systems as depicted in the 2030 agenda of SDGs.

## 3. Circular economy based sustainable solid waste management as a tool for accelerating the progress of achieving SDGs

Geissdoerfer et al. defined circular economy (CE) as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops (Geissdoerfer et al., 2016). Incorporating CE principles in waste management systems could enable the recovery of economic growth. The CE system strives to integrate the three pillars of sustainable development (economic, environmental and social) through a symbiotic approach to recover energy and material from waste, design durable products and extend the service life of systems. This regenerative model can bring a balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations (Geissdoerfer et al., 2016).

The circular economy needs a smarter approach to bend the linear flow of material (Fig. 2) to avoid disposal and this transition requires swift actions and strong policies. A framework based on 10 common circular economy strategies (i.e., recover, recycling, repurpose, remanufacture, refurbish, repair, re-use, reduce, rethink, refuse) or 10 R is often proposed to transit into a circular economy (Morseletto, 2020). Morseletto organized the idea of 10R into three groups approach: (a) useful application of materials; (b) extend the lifespan of products and their parts; (c) smarter product manufacturing and use (Morseletto, 2020) (Fig. 3).

The first approach in dealing with the linear flow is to introduce the concept of refuse, rethink, and reduce for smarter product use and manufacture. 'Refuse' refers to making a product redundant by abandoning its function or by offering the same function with a different product. 'Rethink', signifies the importance of making a product more intensive through product sharing or by promoting multi-functional products

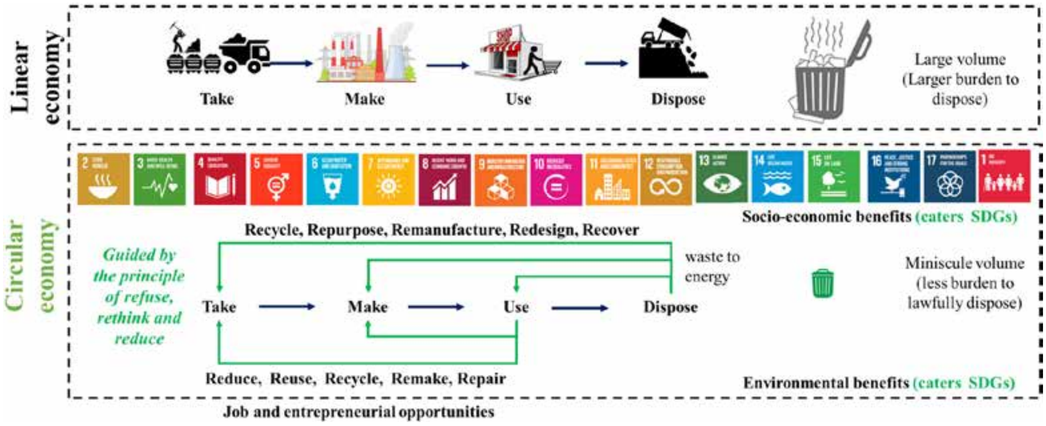


**Fig. 2.** The difference between linear and circular economy showing ways to achieve SDGs.

into the market. The concept of 'Reduce' infers increasing the efficacy of the products or by consuming fewer natural resources in its manufacture.

The second approach of dealing with the linear material flow is by making sure the products manufactured along with their parts have extended lifespans. This could be achieved by the principles of reuse, repair, refurbish, remanufacture, and repurpose. By reusing the same product after disposal that can still fulfill its original function by another consumer. Repairing and maintaining the defective product so it can be used with its original function. Refurbishing and restoration of an old product can bring its utility back. The used parts of the discarded product could be remanufactured into a new product with the same function. Repurposing the use of a discarded product or its parts could be converted into a new product with a different function. Manufacturing

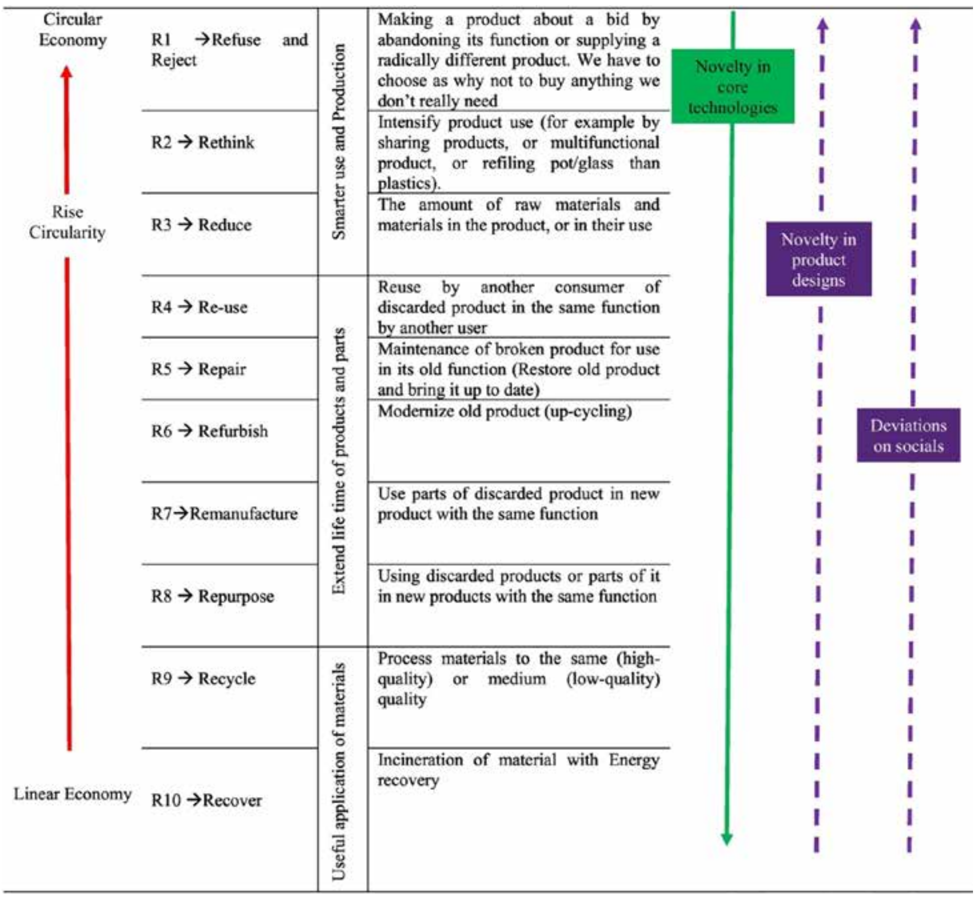


**Fig. 3.** Concept of 10R during the implementation of circular economy based solid waste management (Zorpas, 2020) (with permission from Elsevier Licence number 5041781434699).

products that encourage reparability, upgradability will encourage sufficiency, modest growth rates, which could further help slow resource loops and reduce waste generation (Bocken et al., 2016).

The third approach is to increase the useful application of the materials. The principle of recycling and recovery is critical in this approach and it is where most of the circular policies (and targets) are currently concentrated (Ghisellini et al., 2016). The strategies of recovery and recycle are often considered as efficient solid waste management techniques in the waste management hierarchy as compared to landfilling, or combustion without heat recovery (Morseletto, 2020).

It is self-evident that the process of green recovery post pandemic would still need to focus on job creation. Investments in recycling, reuse, remanufacturing, maintenance refurbishing and repair services prevent cities from sinking in their garbage while quickly creating jobs for vulnerable groups (Gulati et al., 2020). The global annual waste generation rate is expected to rise from 2 billion tons per year to 3.4 billion tons per year by the year 2050 (Kaza et al., 2018). For every 1000 metric tons of waste, 3 to 20 recycling, reuse and recovery jobs are needed vs. 0.1 landfill and incineration jobs (Goldstein et al., 2011). According to the International Labour Organization (ILO, 2018), by 2030, 45 million workers in the waste management sector could be added, as well as 50 million jobs in related circular economy services like repair and remanufacturing, if the world shifts to more recycle, reuse, and repair via a circular economy scenario (IISD, 2020; Gulati et al., 2020). Investments in recycling infrastructure can also offer opportunities to address climate change related issues apart from creating additional jobs.

### 3.1. Linking solid waste management and UN-SDGs

Poor waste management involves anything from a lack of effective recycling systems and infrastructure to unregulated disposal of waste which pollutes the air, water, and soil (SDG 12, 13, 14). Non-scientific landfills and waste dumps that are open and unsanitary lead to air pollution and contamination of ground water (SDG 11, 13). Debris dispersal pollutes habitats, and toxic chemicals from electronic waste or industrial garbage put a strain on urban dwellers' health and the climate (SDG 3, 13). Around 44% of the global waste generated is organic waste (mostly food and green water) (Kaza et al., 2018), and this percentage is even higher in most of the developing nations. The major disposal option currently followed around the world is open dumping (around 33%). Recycling accounts for just 13.5% while, composting and incineration accounts for 5.5% and 11.1%, respectively. The current global trends of waste composition, treatment and disposal options are presented in Fig. 4. It was estimated that 1.6 billion tons of carbon dioxide equivalent ($CO_2$-equivalent) of greenhouse gas (GHG) emissions were emitted from solid waste management and disposal in 2016, which accounted for about 5% of the global GHG emissions. Among the waste management components, waste disposal and treatment accounts for the highest amounts of carbon emissions sector as per European Union data (Eurostat, 2020). Without sectorial improvements, solid waste-related emissions are projected to rise to 2.6 billion tons of $CO_2$-equivalent of GHGs by 2050 (Kaza et al., 2018).

Each component of solid waste presents both challenges and opportunities. Waste management using a market-based sustainability approach would help in making the cities clean and green while also bringing direct economic benefits to the people involved in it (SDG 8). The additional socio-environmental benefits like improved living standards, breathable air, clean water and land, health and education could also be achieved which are the major goals of UN-SDGs. Municipalities in low-income countries are spending about 20% of their budgets on waste management, on average—yet over 90% of waste in low-income countries is still openly dumped or burned (Kaza et al., 2018). It has been estimated that a 10 to 15% reduction in global greenhouse gas emissions could be achieved through landfill mitigation and diversion, energy from waste, recycling, and other types of improved solid waste management. Also, including waste prevention could potentially increase this contribution to 15–20% (Wilson, 2007).

The case study (Nizami et al., 2017a, 2017b, 2017c) of Madinah City with the focus on energy, economic and environmental savings by adopting waste recycling found out that the estimated around 10,200 tons of methane ($CH_4$) emissions and 254,600 Mt.$CO_2$ eq. of global warming potential (GWP) can also be saved. In addition, carbon credit revenue of US $5.92 million, and landfill diversion worth of US $32.78 million can be achieved with net revenue of US $49.01 million every year only by recycling 24.21% of MSW in Madinah city (Nizami et al., 2017a, 2017b, 2017c). In another similar study Nizami et al. found out

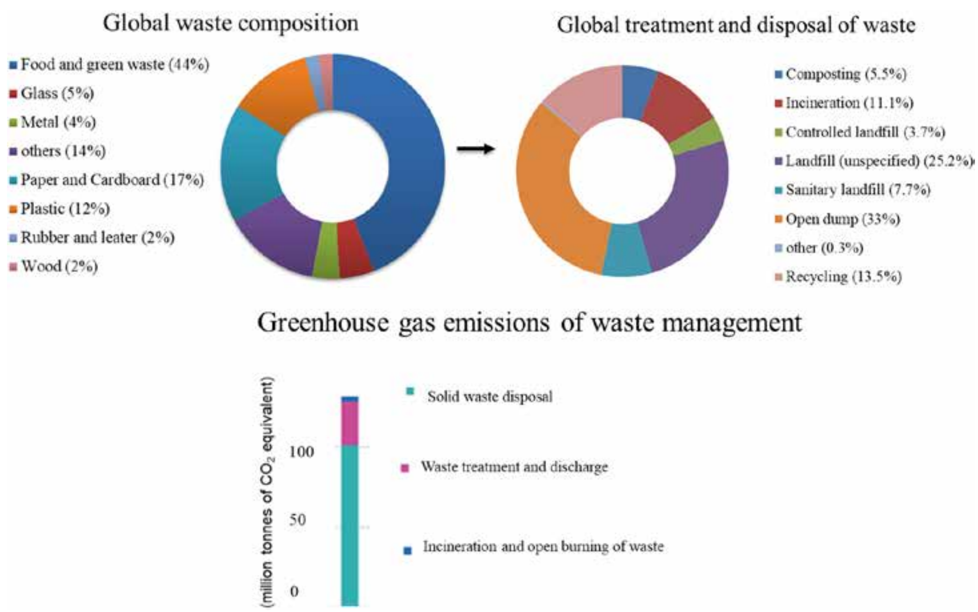


**Fig. 4.** Global waste composition and treatment and disposal trends (Eurostat, 2020; Kaza et al., 2018).

that by adopting waste-based biorefinery and recycling, the holy city of Makkah can reduce the global warming potential (GWP) of 1.15 million Mt.$CO_2$ eq while generating total revenue of 758 million SAR (Nizami et al., 2017a, 2017b, 2017c). So, understanding the prospects of each component of solid waste, from economic, social, and environmental perspectives is important to integrate the necessary responses that could help achieve SDGs. Table 1 present the link between the components of solid waste management and UN Sustainable development goals.

*3.1.1. Food waste*

The mismatch between substantial amounts of food produced and its limited consumption has severe environmental, social, and economic implications. Estimates suggest that 8-10% of global greenhouse gas emissions are associated with unconsumed food (Environmental protection England, 2020) (SDG 13). The UN report estimates 17% of the global food production ends up being wasted, which amounts to 931 million metric tons (1.03 billion tons) of food. Ironically, an estimated 821 million people went hungry during the year 2017 (SDG 2) (Hub ISK, 2019). The SDG 12.3 aims at halving per capita global food waste at the retail and consumer levels and reducing food losses along the production and supply chains, including post-harvest losses. During the pandemic, the broken food chains, panic buying and stock piling contributed to an increase in food loss and wastage, while lockdown mechanisms, unemployability, unprecedented health, economic and social crisis contributed to an increase in hunger (FAO, 2020; Sharma et al., 2020). World Food Programme estimated that the COVID-19 pandemic has doubled the number of people suffering from acute hunger i.e., about 130 million along with the 135 million people already suffering from hunger due to climate change, man-made conflicts and economic turndowns (Ellen Macarthur Foundation, 2019) (SDG 2). While food loss and waste contribute to about $940 billion in annual economic loss, optimisation of these systems can create substantial monetary benefits for farmers, companies, and households. So, the development of sustainable agriculture approaches including reduction in food waste will play a major role in achieving SDG13 (Climate Action).

Post COVID-19, the goal of achieving "Zero Hunger, SDG2" needs to be reinforced by understanding interconnectivity between economic, environmental dimensions of food systems to develop sustainable solutions integrating the circular economy model and food waste management. Efficient policies will promote that bring out circular economy-based applications like material and energy recovery, development of secondary products, designing green solutions, infrastructure development, industry interactions, and employment creation which can help in achieving the SDGs. Across the supply chains and production processes, the application of circularity principles can bring additional economic opportunities (SDG 8). Post COVID-19 pandemic, the EU Commission aims to develop a contingency plan from the stock of lessons to reinforce their 'Farm to Fork' strategy, this aims to accelerate the transition towards sustainable food systems to achieve neutral or positive environmental impact, mitigate climate change, reverse the loss of biodiversity, ensure food security, nutrition and public health, preserve affordability and promote fair trade (BINNS, 2019). The transition to these systems will equip and enable the governments to achieve a combination of SDG indicators viz., SDG 2 (end hunger, malnutrition, food security, agriculture, fair trade), SDG 6 (Water use efficiency, wastewater treatment), SDG 8 (economic growth; productivity, employability), SDG 12 (Food loss and Wastage), SDG 13 (Adapt climate change measures), SDG 15 (forest and land degradation, loss of biodiversity, natural habitats). Food waste, on the other hand, accounts for 8% of annual anthropogenic GHGs emissions; development of circular economy strategies would enable annual savings of 1.7 billion tonnes of $CO_2$ (Hub ISK, 2019). Development of enhanced collection, redistribution and valorisation systems will enable the development of economic opportunities from the organic material. It is estimated that an annual economic opportunity of USD 155-405 billion by 2030 can be achieved by the reduction of food waste (Ellen Macarthur Foundation, 2019). The establishment of food banks and distribution centres will equip in reducing hunger and improving food security. Processing waste to new products provides an economic opportunity; For example in 2019, Renewal mill raised USD 2.5 million by developing a flour producing venture using soya milk and tofu by-products (Hub ISK, 2019). Ananas Anam developed a leather-like material (Pinate) from pineapple leaves (Hub ISK, 2019); National university of science and technology, Russia development of bio-polymer ceramic composite from egg shells for fixing implants and bone defaults in the skull (BINNS, 2019) are few innovations in transforming food by-products for material use in the bioeconomy. Development of valorisation mechanisms like composting, anaerobic digestion and hydrothermal carbonization for inedible food and unavoidable food waste can also be other viable options of resource recovery and job creation (Sharma et al., 2021; Sharma and Dubey, 2020a, 2020b). For example, (Waqas et al., 2018) concluded that the composting of food waste not only provides sustainable management to MSW in Gulf countries but has a potential to fulfill compost demand in the region that was estimated to be about 500,000 tons per year in 2015 only in KSA with total net savings of US $70.72 million per year.

As depicted in Fig. 5, food waste prevention policies need to be devised based on the geographic and regional-specific conditions by integrating community needs, food supply variations, waste generation rate, behaviour and attitudes of stakeholders. Policy directives requires a multi-facet approach to address logical, infrastructure and social aspects associated with waste prevention. Public participation, performance indicators, political willingness, uncertainty on policy outcomes are the challenges in the implementation of food waste prevention policies. The economic component in policy should emphasizes notions like food waste as a resource and impacts on the environment along with other behavioural intervention. Logistic based policies should include economic incentives like tax benefits, subsidies to improve food packaging, labelling, mandating targets on waste prevention, designing waste collection systems, promoting redistribution and donation. The social component empowers people to understand food safety, nutrition values, food shopping, routine planning, and waste sorting and resource recovery.

*3.1.2. Plastic waste*

The surmounting amount of plastic pollution has already harnessed enough attention for its proliferation in the environment. (Virto, 2018) reported that 80% of marine litter is composed of waste plastics and estimated that by the year 2050, oceans will carry more plastic than fish (SDG 14). The advent of COVID-19 was estimated to result in the generation of 1.6 million tonnes/day of plastic waste since the outbreak (Benson et al., 2021). The rise in the use of single-use plastics can be associated with our fixation for hygiene, fear of contraction of virus from reused materials, and extensive demand for plastic packaged products which in turn has resulted in the generation of substantial amounts of waste plastics.

Addressing the issue of plastics from the value chain perspective not only minimizes environmental pollution, but also the consumption of fossil fuel - since 20% of total oil production is used for plastic production (Syberg et al., 2021). So, development of innovative products that facilitate harmonized standards relating to sustainable and circular design should be one of the major goals of legislations. For instance, Canadian Strategy on "Zero Plastic Waste" incorporates a directive on extended producer responsibility, which encourages producers to design and develop products that are easier to incorporate in the circular value chain. The development of products based on renewable resources like bioplastics from organic waste streams reduces plastic production from fossil fuels is an example of shift towards a circular economy (European commission, 2017). In the food and beverage sector, alternate solutions are being designed to reduce the usage of single-use plastics. For example, trials are underway to test paper bottle by Coco-cola

**Table 1**
Linking components of solid waste management to achieve UN Sustainable development goals.

| Waste management goal[a] | Sustainable development goal | Indicator |
|---|---|---|
| Primary (Directly achievable goals) | | |
| Reduction of food waste and loss. | Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture | 2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round.<br>2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.<br>2. c Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, to help limit extreme food price volatility. |
| Informal Sector Integration.<br>Waste collection services<br>Eliminate open dumping and open burning | Goal 3. Ensure healthy lives and promote well-being for all at all ages | 3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination. |
| Creating technical and Nontechnical jobs<br>Upgradations in managerial and Administrative positions<br>Informal sector integration | Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all | 8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors.<br>8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services.<br>8.5 By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value<br>8.8 Protect labour rights and promote safe and secure working environments for all workers, including migrant workers, in particular, women migrants, and those in precarious employment |
| Development of waste treatment technologies.<br>Biomaterials from food waste | Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation | 9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all<br>9.3 Increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, including affordable credit, and their integration into value chains and markets<br>9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities |
| Waste collection services | Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable | 11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums<br>11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management<br>11.b By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels<br>11.c Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials |
| Landfill waste diversion<br>Waste recycling, Remanufacturing and reusing approaches<br>Creation of green jobs (technical and non-technical) | Goal 12. Ensure sustainable consumption and production patterns | 12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses<br>12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, following agreed international frameworks, and significantly reduce their release to air, water and soil to minimize their adverse impacts on human health and the environment<br>12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse<br>12.a Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production |
| Clean and green waste treatment technologies | Goal 13. Take urgent action to combat climate change and its impacts | 13.2 Integrate climate change measures into national policies, strategies and planning |
| Plastic waste management | Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development | 14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution |

(continued on next page)

**Table 1** (*continued*)

| Waste management goal[a] | Sustainable development goal | Indicator |
|---|---|---|
| Eliminating unregulated open dumping and open burning | Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss | 15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements |
| Development of waste treatment technologies | Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development | 17.7 Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed<br>17.17 Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships |
| Secondary (indirectly achievable goals) | | |
| Informal Sector Integration | Goal 1. End poverty in all its forms everywhere | 1.1 By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day<br>1.2 By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions<br>1.b Create sound policy frameworks at the national, regional and international levels, based on pro-poor and gender-sensitive development strategies, to support accelerated investment in poverty eradication actions |
| Waste education and training | Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all | 4.3 By 2030, ensure equal access for all women and men to affordable and quality technical, vocational and tertiary education, including university<br>4.4 By 2030, substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs and entrepreneurship |
| Creating technical and nontechnical jobs<br>Upgradations in managerial and administrative positions<br>Informal sector integration | Goal 5. Achieve gender equality and empower all women and girls | 5.1 End all forms of discrimination against all women and girls everywhere<br>5.5 Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic and public life<br>5.c Adopt and strengthen sound policies and enforceable legislation for the promotion of gender equality and the empowerment of all women and girls at all levels |
| Harnessing energy via biological and thermal conversion methods | Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all | 7.2 By 2030, increase substantially the share of renewable energy in the global energy mix<br>7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology and promote investment in energy infrastructure and clean energy technology |

[a] Adopted with modification from (Wilson et al., 2015).

to eliminate plastic from packaging (BBC News, 2021). The EU Single-use plastic directive aims to reduce the utilization of food containers and cups for beverage by adopting and promoting reusable alternatives by 2026 (Climate Action Tracker, 2020). UK government is encouraging a shift towards multi-use products by levying taxes on single-use plastics that come into enforcement from 2022 (Environmental Protection England, 2020).

Recycling promotes local development by re-internalizing jobs within a region. A plant that produces 50,000 metric tonnes of recycled plastic employs about 30 people on average (d'Ambrières, 2019). By developing an efficient recycling system, a local industry can emerge and recover material, energy and so economic value from recycling waste plastics. However, due to the technical constraints in plastic waste recycling systems compared to a relatively simple conventional waste disposal system, recycling is often considered a costly option. So, to encourage such environmentally sustainable ventures, this additional cost must be covered by producers and consumers of plastic goods through extended producer responsibility (EPR) (d'Ambrières, 2019). Moreover, transition to economic and environmentally sustainable technologies such as pyrolysis with a potential to deliver by-products of good commercial value can enhance material and energy recovery from plastic waste following circular economy principles (Vanapalli et al., 2021a). Plastic material flows to different processing methods, associated financial equation of different processing methods, and the EPR concept is presented in Fig. 6.

Development of waste handling capacities and infrastructure will equip handling the increased waste. Policies on material recovery and energy recovery, extended producer responsibility and integration of the informal sector improve the economic activity and equip in employment creation. An overview of the key drivers for integrating the pillars of sustainability and governance to circular economy approaches in plastic waste management to achieve sustainable development goals is presented in Fig. 6.

Extended producer responsibility, increasing investor's confidence, incentivizing responsible consumer behaviour equip in the long-term economic viability of plastics recycling. EU directive on packaging and packaging waste amended in 2018 promotes recycling and reuse of packaging waste facilitating the transition towards circular economy (Climate Action Tracker, 2020). EU directive on single-use plastic is adopting measures to develop separate collection systems for individual waste streams (ex: beverage bottles) to increase the recycling rate. Globally, in 2016 around 41% of the plastics were mismanaged and it is estimated to increase by 56% in 2040. Integration of the plastic recycling systems with circular economy approaches reduces GHG emissions by 25%, entry of plastics into the ocean by 80%, generates savings by about USD 200 billion per year and creates an additional 7 lakh employment opportunities (Ellen Macarthur Foundation, 2019).

The transition to these systems will enable the governments to directly achieve a combination of SDG indicators viz., SDG 8 (Annual growth rate of real GDP per capita; Proportion of informal employment

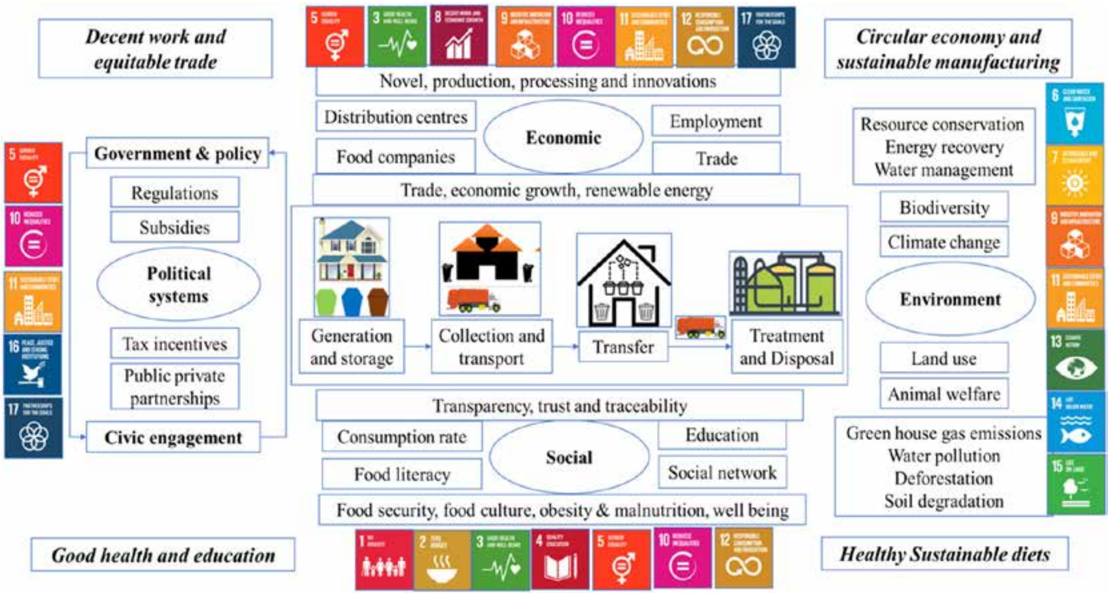


**Fig. 5.** Food waste prevention policies with multi-facet approach to address logical, infrastructure and social aspects associated with waste prevention.

in non-agriculture employment; Unemployment rate, by sex, age and persons with disabilities); SDG 9 (Manufacturing employment as a proportion of total employment; Proportion of small-scale industries in total industry value added), SDG 11 (Urban solid waste collection and discharge), SDG 12 (reduction of waste generation through prevention), SDG 13 (Adapt climate change measures), SDG 14 (Preventing marine pollution). On the other hand, SDG 1 (decreasing poverty level), SDG 2 (end hunger) and SDG 5 (Gender equality) are also influenced indirectly.

*3.1.3. Construction and demolition waste*

Building and infrastructure sector contributes to environmental impacts by utilizing natural resources and energy during its design lifetime. The building sector accounts for utilizing 32% of the total global energy, extraction of 40% of natural resources in industrialized countries, consumption of 70% of electricity, 12% of potable water, occupies 45–65% of landfills, 30% of GHG emissions in operation phase, and 18% in material utilization and transportation phases (Umar et al., 2012; Zou et al., 2019). Designing energy-efficient buildings improves indoor

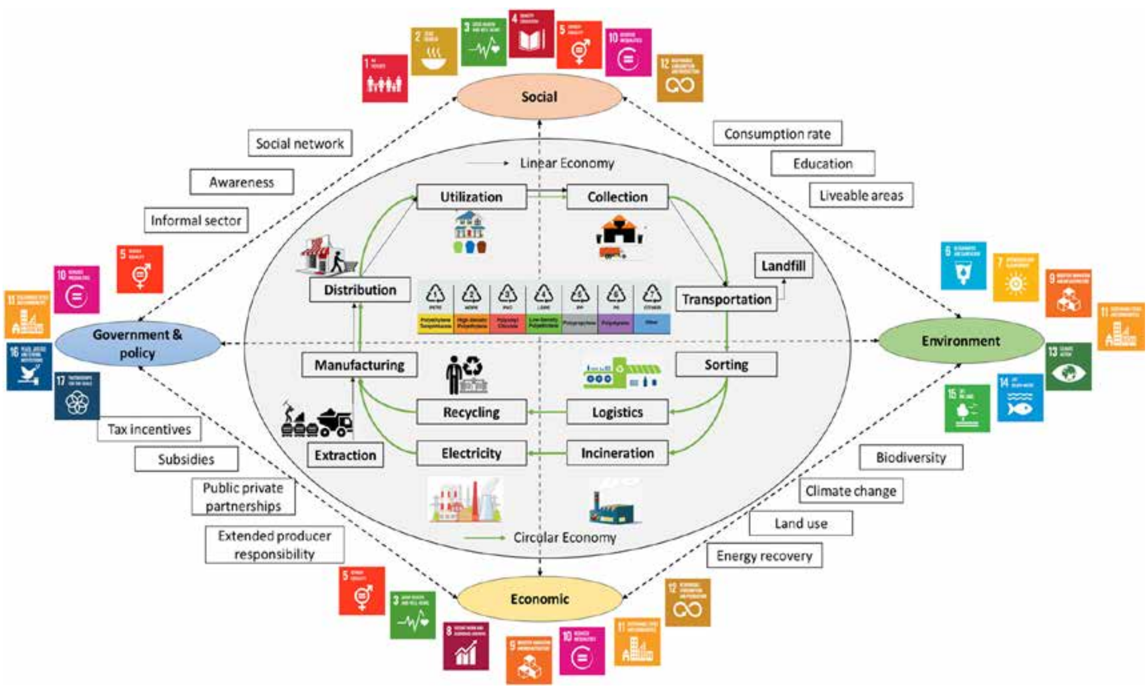


**Fig. 6.** An overview of the key drivers for integrating the pillars of sustainability and governance to circular economy approaches in plastic waste management.

comfort levels, minimizes reduce energy consumption and reduces overall building cost. The SDG 11 (Urban solid waste collection and discharge) and SDG 13 (Climate Change) and energy policies aiming to promote sustainable construction and global environment well-being can be achieved through the application of energy-efficient systems. Alawneh et al. (2018) reported that the application of LEED v2.2 water efficiency credits, energy and atmosphere standards in the design of green buildings contribute to the realization of seven SDGs (6, 7, 8, 9, 12, 13, and 15).

Investments of USD 1 million in the green construction sector for a low carbon-built environment would create 8 - 21 vs. 3 jobs in the fossil fuel sector. These green building sectors hold up to 58% of the emission abatement potential in cities globally (Gulati et al., 2020). Green design also aims to reduce building waste that usually ends up in landfills, which should be one of the major aims during the construction process.

Construction and building materials are the major components contributing to buildings total energy consumption and GHG emissions during their lifetime. The utilization of local building materials or recycled materials minimizes the construction cost by about 60%. The development of a low-cost housing design enables housing access to low-income people at affordable cost. This approach equips in reduction of poverty (SDG1), clean water and sanitation (SDG6), industry innovation and infrastructure (SDG9), reduce inequalities (SDG10), development of resilient local community (SDG11) and combating climate change (SDG13). Good health and promoting the well-being of communities - the goal of SDG3 can be achieved by improving the indoor environment in the buildings and workspaces. Selection and promotion of green materials in the indoor environment promotes well-being and prevents low progression and long duration diseases. Innovations in building materials and construction practices lead to sharing of knowledge, development of partnerships and strengthening of bilateral relationships. Programs are being designed and developed at regional, national, and international levels to educate, assist and train construction stakeholders. This will equip in achieving the goals and targets of SDG 17 (partnerships for goals) (Nubholz et al., 2019). In the construction industry, replacing virgin material with recycled material equips in reducing 14-18% GHG emissions by 2050 in G7 countries. The utilization of recycled aggregate reduces emissions by 40% and recycled steel by 90% providing scope for reducing the risk of future climate crisis (Masterson, 2020). Incorporation of circular economy approaches in construction and demolition waste systems promotes transition towards the recycling of C&D waste, reduces stress on natural resources, lowers greenhouse gas emissions and improves job opportunities as shown in Fig. 7.

### 3.1.4. Biomedical waste

The use of disposable items to reduce viral transmission is a necessary part of controlling the spread of the virus. However, with the number of people requiring access to health care and increasing during the pandemic and as the vaccination drives gather pace across all countries, there is a tremendous surge in the quantum of biomedical waste generation. With an endeavour to reduce health problems (SDG 3), it is essential to have a safe and reliable method of segregation and disposal of BMW, because of its higher potential for infections and injuries. On average 0.5 kg/bed/day of hazardous waste is generated in developed countries and in developing countries, 0.2 kg/bed/day of hazardous waste is generated (WHO, 2018). As per the World Health Organization (WHO), 85% of BMW is non-hazardous and 15% of BMW includes potentially infectious waste (WHO, 2020.). Apart from the associated health risks, improper handling and disposal practices of BMW can cause adverse environmental effects including soil and groundwater contamination, killing beneficial microbes in septic systems, physical injuries through sharps, etc.(Sharma et al., 2020). Such situations are more predominant in developing countries that lack the necessary infrastructure leading to the dumping of infected or hazardous waste along with other municipal solid waste. So, during the pandemic where the risks are higher, crucial steps will be access to the appropriate treatment facility and safe disposal of waste, which would control the related health and environmental hazards (Sangkham, 2020).

The global market for medical waste management is expected to have a strong demand for additional capacity building and advanced solutions. Success in healthcare waste management will speed progress

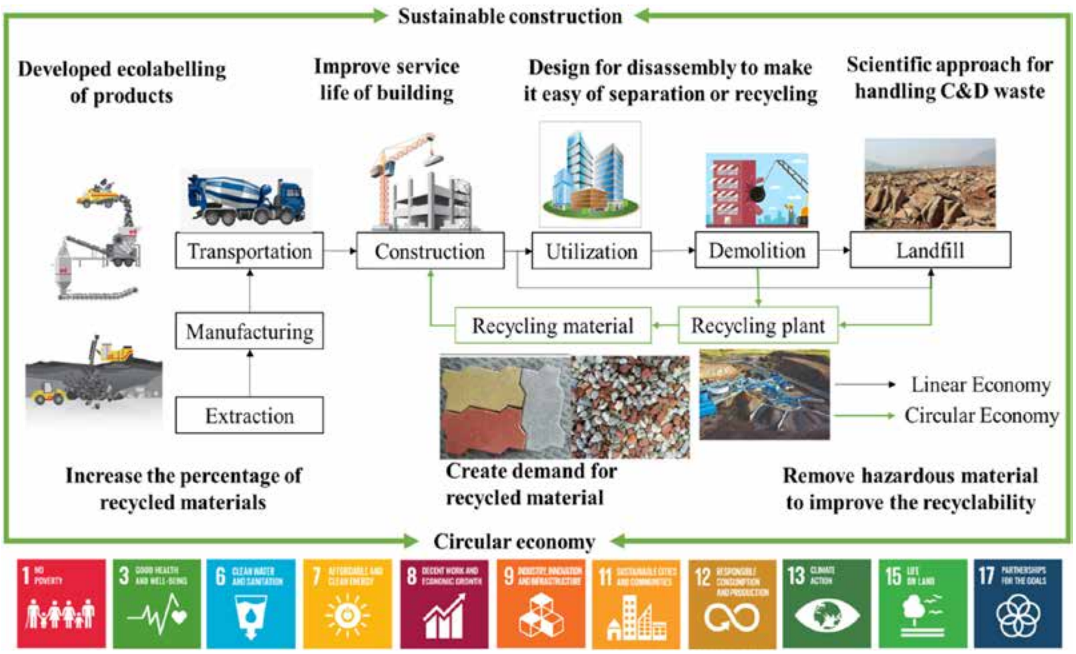


**Fig. 7.** Incorporation of circular economy approaches in construction and demolition waste management.

towards meeting several of the UN Sustainable Development Goals, particularly: (3) Good health and wellbeing, (6) Clean water and sanitation, (8) Decent work and economic growth (12) Responsible consumption and production and (13) Climate action. Healthcare waste management is one area that has been persistently under-recognised and under-resourced, with enormous knock-on effects for workers, patients and the community. Solving this problem would remove direct and indirect threats to the health of over half the world's population (SDG 3). The WHO, recognizing the interrelation between waste and water, has incorporated healthcare waste management into its water, sanitation and health program for healthcare. To be truly successful, this program must implement waste treatment technologies that do not create toxic residues or emissions in their own right (SDG 6). Despite carrying out a task vital to society, waste workers are too often underpaid, under-educated and under-protected. In many cases, not only do workers lack a living wage, but working conditions violate their human right to a safe working environment. There needs to be a step-change in the way healthcare waste management and its workers are viewed. It needs to be recognised as an essential public service, with professional standards, vaccinations, training, decent conditions, a living wage and respect for the men and women that carry it out (SDG 8).

Sustainable choice of products that are inclined to the principles of circular economy is also necessary. The healthcare sector needs to leverage its buying power to ensure that the materials it purchases generate minimal amounts of toxic, non-repairable, non-recyclable waste. By advocating for the replacement of these products with safer alternatives, the healthcare system can help kick-start the global circular economy. Minimizing waste, segregating at source, avoiding incineration, and recycling all conserve resources and energy. Research conducted by HCWH proved that autoclaving waste has $CO_2$ emissions at least fifteen times lower than waste incineration (Health Care Without Harm, 2020). Organic wastes produce methane gas as they degrade, but if this is done in a controlled manner in a biodigester, the methane can be captured for use as a biofuel. Because methane has a stronger greenhouse effect than carbon dioxide, burning it reduces the $CO_2$ emissions of the waste, which can help in the mitigation of climate change. Sustainable healthcare waste management technologies such as bio-digestion and autoclaving can also play a role in making healthcare systems more resilient to disasters (SDG 12). Treatment through microwave technology, as used in the Sterilwave equipment, is considered a reliable, clean and modern solution with low operating costs (Sterilwave, 2020.). Finally, a regional network can be developed to share experiences and lessons learned to accomplish the BMW management system and overcome the obstacles not only for this pandemic but also beyond.

### 3.1.5. Electronic waste

Fuelled by higher consumption rates of electric and electronic equipment, shorter life spans, and few options for repair, global production of E-waste is predicted to double by 2045 from an existing amount of 53.6 Mt. in 2019 (an average of 7.3 kg per capita) (Forti et al., 2020; Cunningham, 2020). Moreover, with the increased remote working resulting in higher demands for robust technical infrastructure and digital transformation across business models, E-waste is expected to see a sudden surge due to the pandemic (Cunningham, 2020). Irregular E-waste disposal can be associated with health and environmental hazard, due to the presence of toxic additives and hazardous substances, which are harmful to human health and well-being (Ranganathan, 2018). Economically, E-waste is an 'urban mine' with the potential to recover several precious, critical, and other noncritical metals (Iron, copper, and gold) that, if recycled, can be used as secondary raw materials (Fig. 8). The value of raw materials in the global e-waste generated in 2019 is equal to an approximate value of USD 57 billion (Forti et al., 2020) (SDG 8). There is also an increasing momentum in technologies that enable higher yields and quality of material recovery in these outer loops. So, capturing residual value or utility is central to reaching a circular economy for electronics. If the materials in e-waste are not recycled, they cannot substitute primary raw materials and reduce GHG emissions (SDG 13) from extraction and refinement of primary raw materials. A total of 98 Mt. of $CO_2$-equivalents were released into the atmosphere from discarded fridges and air-conditioners that were not managed in an environmentally sound manner (SDG 3, 11, 12, 13). This is approximately 0.3% of global energy-related emissions in 2019 (Swinnen and McDermott, 2020). E-waste contains several toxic additives or hazardous substances, such as mercury, brominated flame retardants (BFR), and chlorofluorocarbons

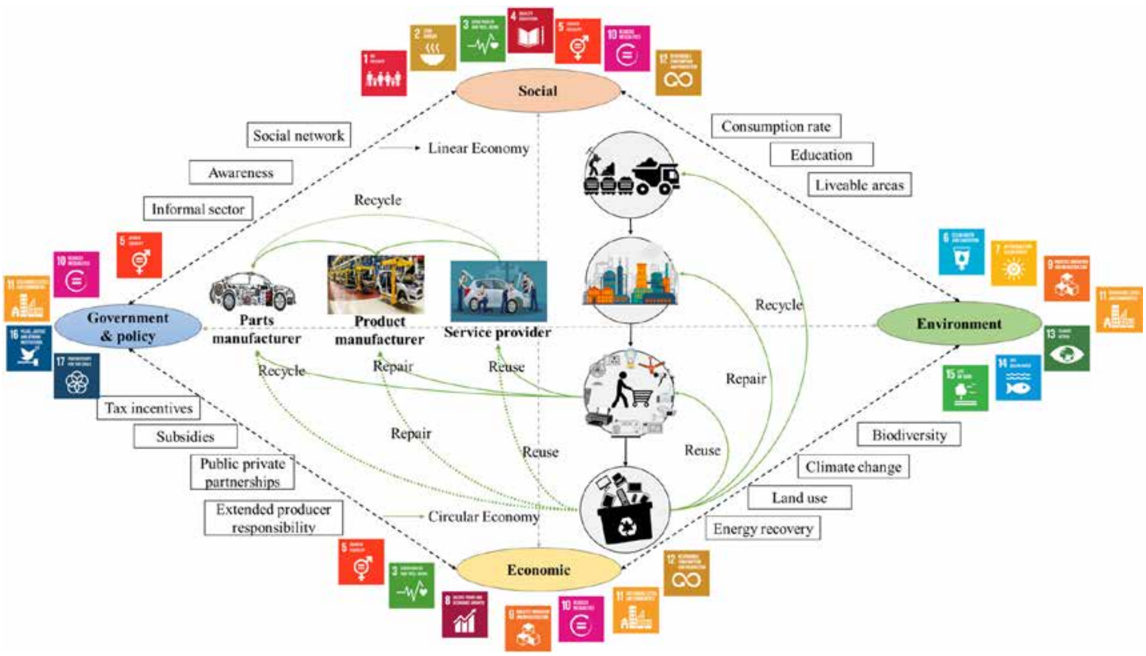


**Fig. 8.** Circular economy approaches in management of electronic waste.

(CFCs), or hydrochlorofluorocarbons (HCFCs). A total of 50 t of mercury and 71 kt of BFR plastics are found in globally undocumented flows of *E*-waste annually, which are largely released into the environment and impacts the health of the exposed workers (Forti et al., 2020) (SDG 3). E-waste management closely relates to many SDGs, such as SDG 8 on decent work and economic growth, SDG 3 on good health and well-being, SDG 6 on clean waste and sanitation, and SDG 14 on life below water. Given the high raw material demand for the production of electrical and electronic equipment (EEE), E-waste also closely relates to the SDG indicators on the material footprint (SDGs 8.4.1 and 12.1.1), and the SDGs on the domestic material consumption (SDGs 8.4.2 and 12.2.2). Relatively general indicators are being used to measure progress towards these SDGs.

By contrast, a more specific sub-indicator has to be recognised for monitoring growth in the E-waste stream, which is of particular concern due to both its potential hazardousness and its high residual value. Business models in which the manufacturer retains ownership and responsibility for the product, have led to high rates of recovery and reuse in products such as modems (Morseletto, 2020). Adapting such business models can help in the capture of greater value in electronic products, while developing a new type of relationship with customers, and keeping valuable resources in use for longer. Substantially greater efforts are urgently required to ensure smarter and more sustainable global production, consumption, and disposal of electrical and electronic equipment.

### *3.2. Focus on the informal sector*

Development of policies and frameworks which will emphasize the role of the informal sector through circular economy approaches will enable us to achieve gender equality, improvement of occupational health, reduce inequalities, eradication of poverty and hunger as shown in Fig. 9. The global informal economy provides an earning livelihood to over 2 billion workers (62% of working personal) in the year 2020. Informal employment represents 18% in high-income countries, 67% in middle-income countries and 90% in low-income countries. The larger proportion of women of low and low-middle income countries in informal employment puts them in a more vulnerable situation compared to the male population (ILO, 2018). The ILO estimated that 400 million informal sector workers are at the risk of abject poverty. The women waste pickers relatively faced challenges in collecting due to movement restriction and selling waste due to reduced prices (Chakraborty, 2015). In Delhi, a single informal waste picker collects about 10-15 kg daily of waste by foot and 50–60 kg of waste on a tricycle. In 2018, it was estimated that 20% of waste in the cities is being recycled through informal waste picking. Pandemic and lockdown lead to a decrease in informal activity due to fear of transmission due to lack of protective equipment (WIEGO, 2020).

With only 30-70% of the waste collected undergoes processing and treatment in low-income and middle-income group countries, open dumps and unsanitary landfills provides eminent scope for itinerant waste pickers to recover valuable recyclables for their livelihood. This informal recycling reduces the associated environmental pollution from waste in the landfills and adds value to the recycling sector while harnessing increased informal employability opportunities (Aparcana, 2017; Fei et al., 2016). Despite these benefits, the informal sector faces severe negative socio-economic conditions. However, due to the social, economic, legal, managerial, and political constraints, the formalization process has not been successful to the full extent. So, policy makers and local authorities have been on the task of developing mechanisms to integrate the informal sector based on individual country contexts.

For instance, European Union estimates with an investment of $90 trillion (Gopalakrishnan et al., 2019) the application of CE principles in waste management will create up to three million jobs by 2030 and help in reaching the targets of the Paris Agreement. A UK study estimated that implementation of higher recycling, reuse and remanufacturing rates will result in a 0.15–0.28% decrease in unemployment by 2030 in a conservative to ambitious scenario (Masterson, 2020; WRAP, 2015). Meyer (2012) also estimated that improvement of point resource efficiency in the EU could create approximately 1.5 lakh additional jobs and an additional increase of resource efficiency up to 25% which could create up to 2.6 million jobs.

## 4. Challenges and barriers in transiting to circular economy and policy recommendations

The circular economy model is expected to face challenges of uncertainty, competing claims and promises and high rates of failure and pioneer burn-out (Olleros, 1986). The 'liability of newness' causes such

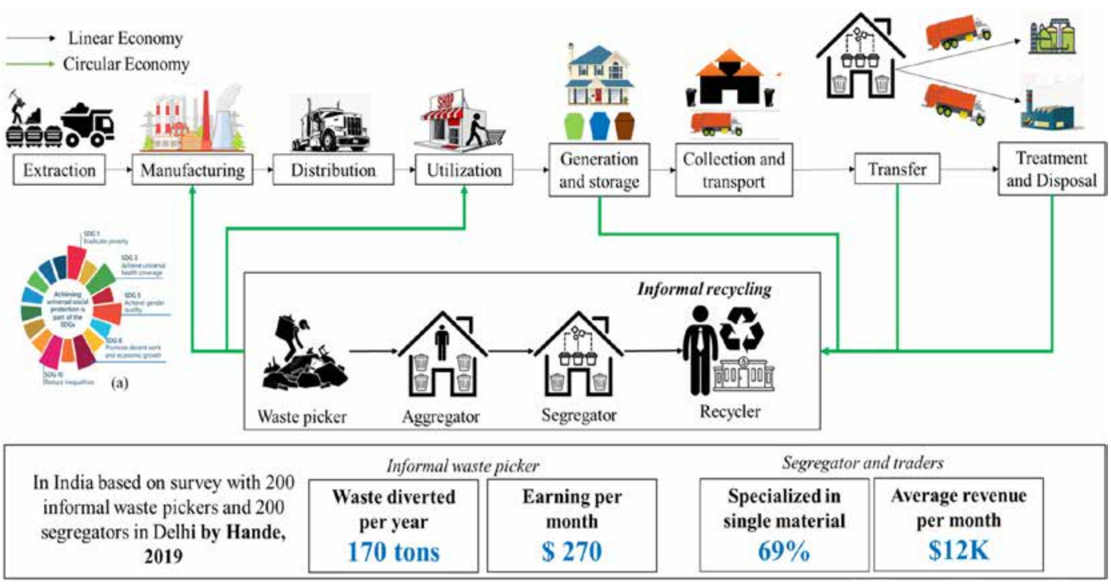


**Fig. 9.** The role of the informal sector in designing supply chain by incorporating circular economy approaches(Hande, 2019; ILO, 2018; Valencia, 2019).

radical ideas to be viewed as strange, unstable, or unknown, reducing their cultural credibility, social recognition, and financial capital (Michael and Mary, 2001). If we aim to overcome the current fragmentation of initiatives and their tendency to remain isolated or short-lived, more and more sustainability experiments, local projects, urban experiments, and living laboratories should be prioritized and funded for achieving their full potential for lasting and wide-ranging change (Michael and Mary, 2001; Turnheim et al., 2018). Research, innovation, trial and error, and real-world demonstration could act as catalysts for niche development (Geels, 2019). These transitions come about through the interplay between processes at niche, system, and landscape levels (Geels, 2019). Geels (Geels, 2019) has classified the socio-technical transitions that take several decades into four phases with different core activities and struggles (Fig. 10). They are: (a) Research and Development (experimentation phase) (b) Foothold establishment by innovation (stabilization phase) (c) Diffusion of innovation into mainstream markets (diffusion, disruption phase) (d) new economic model replaces the old one, and becomes institutionalized and anchored in regulatory programmes, user habits, views of normality, professional standards, and technical capabilities (institutionalisation, anchoring phase). Policy and technological limitation along with reluctant public participation could hinder transition to circular economy. However, if post COVID stimuli is directed for the development of a specific green job-driven by waste management system, formalization of informal waste pickers, investment in recycling infrastructure, research and development of new product designs and business models, intelligent manufacturing could result in initial creation of the niche which could help in realization of circular economy in few decades.

### 4.1. Barriers

Some of the massive barriers hindering the implementation of the circular economy to make it “business as usual” can be categorized into three groups: (1) policy; (2) technology and (3) public participation (Geng and Doberstein, 2010).

#### 4.1.1. Policy barriers

From a policy perspective, many countries lack a centralised platform for promoting the circular economy. The existing fragmented regulatory systems in some of the developing countries have been detrimental against corporate enthusiasm to develop environmentally friendly technologies and products. For instance, in the case of China, policies such as a high corporate value-added taxing system on recycled products (Mao and Kang, 2005), low effluent discharge fees have encouraged rapid industrial development based on short-term economic benefits (Geng and Doberstein, 2010). Moreover, the tax loopholes associated with the regulation and control of consumption behaviour, discourage the development of a systematic public attitude towards green consumption (Ren, 2005). Further, the lack of detailed policies encouraging green production, technologies, and consumption and in some cases, ambiguities in their stringent implementation have created a platform for regular relapses over environmental compliances as committed by many emerging informal recycling/recovery enterprises (Dutta and Goel, 2021; Puckett and Smith, 2002). Unbalanced regional development also makes the initiation and implementation of a national policy unrealistic and impractical in all sectors and regions at the same time. Adoption of a systematic iterative approach that considers collecting relevant experiences and lessons from pilot studies planned and carefully monitored in key areas could help in setting up national regulations and standards through gradual promotion of the concept to new sectors and regions (Geng and Doberstein, 2010).

#### 4.1.2. Technology barriers

Although it is quite evident that innovations in eco-design, cleaner production, and life cycle assessment, will help revolutionise the related fields of biotechnology, information technology and materials science

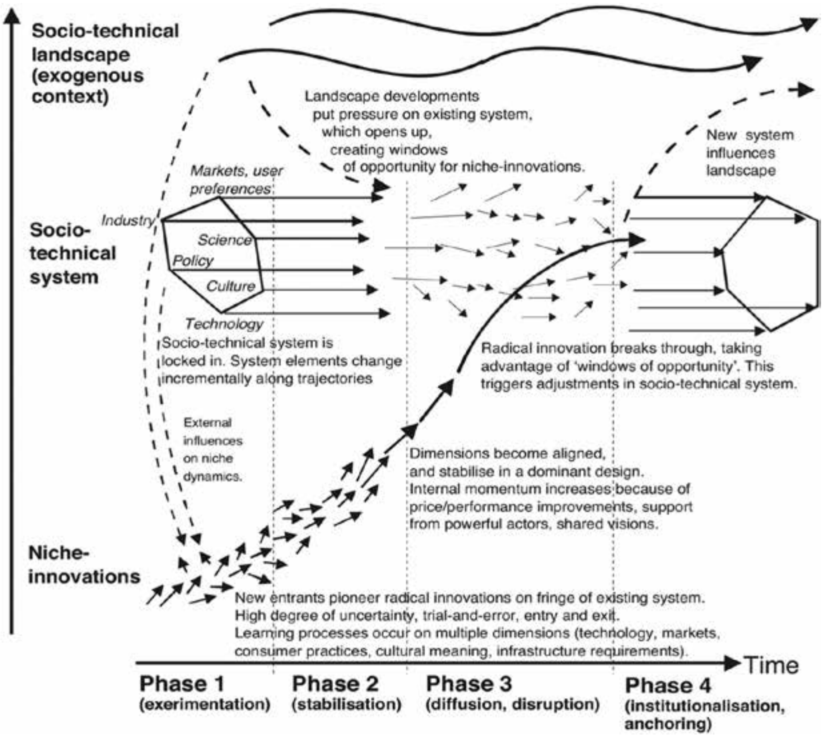


**Fig. 10.** Multi-level perspective on socio-technical transitions (Geels, 2019) (with permission from Elsevier Licence number 5041790223993).

(Chen and Bacareza, 1995), global demand for environmentally superior technologies is still weak, with inadequate technical capabilities and financial resources (Banks, 1994). Moreover, constraints in efficient training and financial support have limited the sustainability in technology transfers from developed to developing countries (Geng and Wu, 2000). The fragmented management frameworks often create an information barrier with zero collaboration among various stakeholders causing systemic restriction in ease of access to information needed to the corporate world for effective planning and management. This in turn discourages their interest in the creation of scenarios for optimal reduction, reuse, and recycling.

*4.1.3. Public participation barriers*

The array of potential contributions from every consumer in the implementation of a circular economy is mostly limited by the lack of necessary human and institutional capacities to encourage public participation in a growing economy (Geng and Doberstein, 2010). Due to the relative infancy of the circular economy concept, inadequate understanding of its principles by governments and industries alike creates a lack of appreciation for its benefits leading to inaction. Periodic implementation of awareness campaigns to build an understanding of the concept, accompanied by an objective review of the shared experiences from different parts of the world could boost public association to the circular economy. Moreover, clearly enunciated short-, medium- and long-term goals designed to directly address the needs and create the overall conditions for the circular economy, followed up with regular assessment should be specifically considered for capacity building at various levels of implementation (Geng and Doberstein, 2010). Development of functional eco-industrial networks as part of an industrial symbiosis could also be an effective way to complement traditional technical assistance (Gao et al., 2006). Building better communication between all stakeholders, and adoption of innovative public participation programmes could facilitate proficiency in the implementation of the circular economy.

*4.2. Policy recommendations*

Post COVID climate-mitigation stimulus should focus on adopting changes that accelerate change to a low carbon-based economy (Climate Action Tracker, 2020). Climate Action Tracker has suggested strategies that invest in green energy infrastructure - including energy efficiency and low and zero-carbon energy supply technologies - have the strongest effect on reducing emissions, irrespective of an optimistic or pessimistic economic recovery by 2030 (Climate Action Tracker, 2020). Economic equality, access to healthcare facility, access to quality education and creating equal economic and livelihood opportunities need to be immediate and long-term priorities of post COVID-19 planning. Focus on achieving sustainable development goals and the creation of a more inclusive society should be the centre of the post COVID-19 recovery model. As a science-driven design, this new economic model would prevent the extortion of climate change and all other environmental disasters. Policy instruments for waste and resource management should be steered using the idea of economic instrument, social instrument, and direct regulation and enforcement as presented in Fig. 11.

Policy recommendations intended for policymakers

1. The COVID -19 response funds should focus on support for the elimination of open dumping and burning, creation and development of infrastructure for sound management of hazardous waste, formalizing informal waste pickers into recycling business, education and training of informal workers regarding safety standards and health protection, and creation of green jobs. This would address both unemployment and environmental degradation, thereby create better livelihood opportunities, and education for children and better healthcare facility for women, especially in developing nations. The funding could be redirected through governmental and non-governmental organizations (NGOs) which are closely working in these areas.
2. In developing nations SWM services are often provided by individuals and small and medium enterprises. The COVID response fund should make provision to support them which will improve livelihoods and directly contribute to SDGs 1 and 8.
3. The COVID response should also focus on improving the wages of women involved in the informal sector of waste management, who are often not paid equally. Formalizing the informal waste picker and providing mechanisms to initiate the benefits of modern healthcare service like health insurance should also be the priority of COVID-19 response strategy. The focus should also be on imparting education to the children of informal workers, this will directly influence in achieving some of the major SDGs (SDG 3,5 and 5)
4. Food losses in the supply chain should be reduced by prioritising local production, local storage and local combustion; therefore, COVID-19 response strategy should make plans to develop this infrastructure. By doing so, the possible future pandemic could be fought well. Technology-based innovative solutions to address food loss and food waste should also be a part of post COVID recovery (SDG 12.3)
5. The COVID response fund should support behaviour change and awareness programs to motivate waste reduction, source-separation and reuse through extensive communication, outreach activities and international collaboration (SDG 17).
6. Ensure access to adequate, safe, and affordable solid waste collection services for all. Uncollected waste is often dumped in waterways or burned in the open air, thus directly causing pollution and contamination (SDG 6,11and 13).
7. Foster in strengthening the prioritization to invest in green sectors, localization of supply chains, and decentralization of waste systems with bottom-to-top approach, commitment towards recycling and green recovery, regional coordination on the environment and natural resource (SDG7, 11 and 12). Subsidies and tax exemptions to promote investments in waste infrastructure (SDG 12).
8. Post COVID response in the development of initiatives on capacity building, direct benefit transfer and welfare policies for informal sector to improve both recycling rate and well-being (SDG 1, 2, 3 and 8).
9. With the current trend of "planned obsolescence" - deliberately designing products with flaws, technical limitations, incompatibility, obstacles for repair to promote new replacement within few years of their purchase there is an increased concern of wastage of energy and resources. Challenging this corporate unsustainability strategy to make technically durable products with high recyclability should be the focus of premium business models. Legislating a complete

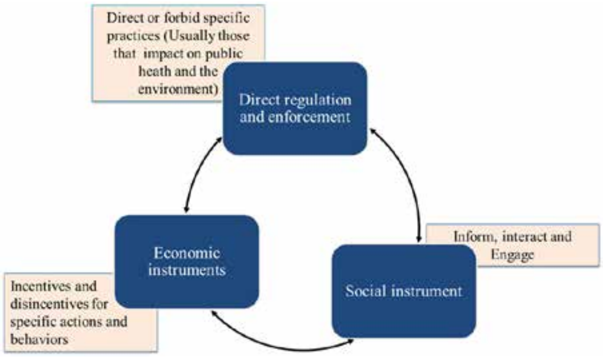


**Fig. 11.** Policy instruments for waste and resource management (Wilson et al., 2015).

ban on all forms of 'Planned obsolescence' (systemic, perceived, programmed, legal, etc.,) and recognizing 'sustainable consumption' as a consumer right. Further, a labelling system indicating the durability of a device can be mandated, so that the consumer has the choice between a cheap product and an expensive durable product (SDG 12).

10. Selection of waste to energy technologies depend on regional waste characterization (Nizami et al., 2017a). Post COVID response should address the challenges and innovation in adopting waste to energy (renewable energy) (SDG 7) technology in developing nations through knowledge sharing and international collaboration (SDG 17). Waste in developing countries is a promising source of energy and value-added products. Waste biorefineries can achieve a circular economy, especially in developing countries (Nizami et al., 2017a). Waste-to-energy has the potential to add new green jobs while quickly aiding the quest for a renewable energy source (Nizami et al., 2017b) (SDG 7).

## 5. Conclusion

This study focused on the effects of COVID-19 and the ensuing socio-economic crisis on the United Nations Sustainable Development Goals (UN-SDGs). Furthermore, this paper intended to investigate the feasibility of integrating a circular economy model into a solid waste management system using a COVID-19 economic response for meeting UN-SDG objectives. The review found that the COVID-19 has seriously impacted the progress made in achieving UN-SDGs. Inadequate waste management systems which are inextricably associated with several UN-SDGs, have been the source of health and environmental concerns, thus necessitating the serious attention of policymakers. According to the study, because the guiding principles of UN-SDGs such as managing public health and environmental concerns are analogous to that of waste management operations, thus tackling the latter would help us achieve the former. The review emphasized that the proposed fiscal stimulus for an economic rebound should incorporate a framework based on circular economy strategies such as recovery, recycling, repurpose, remanufacture, refurbish, repair, re-use, reduce, rethink, refuse into product designs and business models in order to speed up the process of achieving SDGs in a post-COVID world. The review also highlighted the importance of understanding the prospects of different component of solid waste: food waste, plastic waste, construction waste, biomedical waste, electronic waste which presents both challenges and opportunities to integrate the necessary responses that could help the public and private sectors address both short and long-term objectives of UN-SDGs. The review also found that management of solid waste using a market-based sustainable approach would help in bringing direct economic benefits to the people through job creation and help in achieving additional socio-environmental benefits like improved living standards, breathable air, clean water and land, health and education which are the major goals of UN-SDGs. Despite the hurdles to adopt circular economy-based solid waste management, the study emphasized that post-COVID economic response measures may be leveraged as an opportunity to catalyse the transition towards its full adoption worldwide. The study also highlighted that if the post-COVID-19 recovery model revolves on the central premise of easing the transition to circular economy-based solid waste management, it will enable the UN-SDGs be met on schedule.

The paper also presented the policy recommendation that would help policy makers worldwide to make transition to circular economy based solid waste management. The paper recommended in improving the living standard and formalizing the informal waste pickers in developing nations in order to realize UN-SDGs by focusing in education, training, capacity building and healthcare facilities using a COVID -19 response funds. The paper also recommended that the COVID response should also focus on facilitating behavioural changes, outreach activities and international collaboration to tackle solid waste management woes. The paper also recommended legislating a total prohibition on all kinds of planned obsolescence and recognizing sustainable consumption as a consumer right. This would not only assist to minimize waste generation, it would also assure energy and resource conservation, both of which are important UN-SDGs. Moreover, to achieve some of the major UNSDGs, the study emphasized that investments in waste biorefinery and waste to energy in developing nations should be prioritized as a COVID-19 response strategy since they have the potential to create green jobs and foster entrepreneurial opportunities.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# SCOPE OF PRIVATE PARTICIPATION IN MUNICIPAL SOLID WASTE MANAGEMENT: THE CASE OF INDIA

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**ABSTRACT**

*In the coming decades the urban sector will play a crucial role in sustaining the momentum of India's economic growth. Expansion of urban infrastructure and provision of amenity services at a satisfactory level would be important challenge to the Urban Local Bodies (ULBs). One such major concerns centers around the management of municipal solid waste. If the public authority has to bear the full responsibility of this waste management, it would impose a severe burden on the public money. So, the scope for private participation needs to be explored. The Municipal Solid Waste Management (MSWM) and Handling Rule, 2000 recommended segregation of wastes at source (WaS) through the introduction of public-private-partnership. This paper examines the relative importance of source-segregation vis-à-vis private participation in enhancing efficiency of Municipal Solid Waste Management by using ULB level data on three states of India, viz., Maharashtra, Himachal Pradesh and Odisha. The analysis is expected to indicate direction for more specific as well as effective policy interventions.*

**Keywords:** Municipal Solid Waste Management, Missing Market, Public Good, Efficiency Analysis, Public-Private Partnership

## Section 1: Introduction

The amount of waste generation in all over the world is rising rapidly and though it is positively correlated with the growth of urban population[1] the increase in the volume of per capita waste generation due to increased consumption also deserves serious attention of the policymakers (Karak, Bhagat and Bhattacharyya, 2012). Not only the scale and intensity of waste generation is on the rise, what is more disturbing is the change in the composition of waste. The naturally treatable bio-degradable components in wastes are yielding to the pressure of chemical and non-bio-degradable

[1] *For instance, Thanh, Matsui and Fujiwara (2010) conducted a study in Vietnam and found high correlation between waste generation and population density and urbanization rate.*

materials demanding costly technological intervention in the process of treatment. This is imposing further burden on the public fund.

Proper management of household waste is one of the key areas of intervention of local governments. Households find it easy, convenient & space saving to dispose the waste out of their premises to get rid of the pollution from garbage by transferring it from private space to the public domain. This attitude is typically termed as "not-in-my-backyard". To internalize, at least partially, the externality of household waste needs to be separated at source, reused and recycled at different stages of primary disposal, collection, treatment and final disposal. This approach will perfectly fit-in the polluter pay principle. Here, regulatory challenge lies in designing the mechanism to make the household own up the post consumption garbage, i.e., send the garbage management cost, at least partially, back from public to private domain. The source-separated-waste would require further processing before it can be disposed in a manner that minimizes the cost of waste handling and management.

Keeping in consideration the heterogeneity of composition, the household waste can be identified and classified from a holistic 'public bad' to a number of 'private bad(s)', according to different re-use and treatment options, then participation of private agents also becomes feasible and profitable through public-private-partnership. Thus, a market for waste handling would emerge. The information about the consumers' preferences is now provided by the market so that the producer can extract the full value of public good from all types of consumers (Auster, 1977). Household would do the primary processing and it would subsequently be picked up by the waste treatment firms for further processing and there will be partial resource recovery. Here instead of direct involvement in processing and handling waste the local governments would act more as a coordinator to ensure efficient outcome. Thus the efficiency in service provision would be contingent on commoditization (Fullerton and Stavins, 1998; Nalebuff, 1997) of waste disposal services and this would in turn depend on the pre-conditions for evolving markets, where they are otherwise missing. If this premise is correct then in high-income countries where the pre-conditions for market hold better, there one may expect to observe a higher degree of private involvement in municipal solid waste management leading to greater efficiency compared to any urban area of a developing country. This involvement would come from both the generator of waste, i.e., the households (as a separate entity) and the collector cum processor of waste, i.e., the private agents. The developing countries are experiencing some public-private-partnership in waste management but surprisingly enough that fails to have any long lasting impact on the efficiency of waste management. That is mostly because here the private involvement is not coming from within the system due to the presence of adequate incentives for participation rather they are the off-shoot of some flagship programs sponsored by the outside agencies. In most cases once the trial period is over the private participation erodes and the system goes back to square one.

In this backdrop, this paper examines the performance of some selected states of India in managing their municipal solid waste with the conviction that the lessons from this study could be generalized to understand the problems and prospects of Municipal Solid Waste Management (MSWM) in any developing country. The rest of the paper is organized as follows: section 2 discusses the required economic conditions to ensure private participation on a win-win basis, and briefly presents the prevailing situation in India. Section 3 states the research questions and the analytical approach adopted to answer them in terms of specific methods and available data. Section 4 estimates efficiency scores of the Urban Local Bodies (ULBs) by applying Stochastic Frontier Analysis (SFA) technique, section 5 attempts to explain the predicted scores in terms of different proxies of stakeholders' involvement (both households and private agents) and finally section 6 concludes the paper by discussing its policy implications.

## Section 2: Prospect of Solid Waste Management through Market

In any ULB the management of solid waste involves participation of at least three different types of stakeholders, viz., the regulator, the provider and the beneficiary. In some cases the regulator and the provider may be the same entity and in some other cases, the responsibility may be vested on different agencies. As the scale and scope of the operation increases, it can be shown that separation between regulator and provider could save some dead weight loss by avoiding some net leakage from the system. However, this separation may lead to the classical principal-agent problem where the persons entrusted with the responsibility of service provision neither have any specific reward for efficient involvement nor any threat or penalty for underperformance, here shirking is a major concern leading to leakage and inefficiency. Some resource burden can be shifted to the beneficiaries in the form of source segregation. There exist two types of beneficiaries: one participates in the process from the self interest and termed as 'active user' and the other type does not participate actively, tries to free-ride and is termed as 'passive user' of the service. Now, this free-riding tendency is difficult to prevent due to large monitoring cost. The free-riding can be done in either of the two ways: mixed waste disposal and/or illegal dumping. There is a serious revelation problem. Hence, inefficiency gets into the process. The final outcome largely depends on the transparency and effectiveness of the market signals, which is crucial to ensure low transaction cost. To achieve efficiency, the beneficiaries as a group should also be involved in this entire process of waste management through in-house active involvement. If the wastes can be segregated at source, then with different types of specific waste some specific types of recycling/ re-use practices can be planned and if the coverage of the facility is large enough then market may evolve in different directions through the channel of public-private partnerships. The municipal solid waste will no longer be an indivisible whole but it will be a collection of divisible specific products. The management through market mode, if possible, will be more effective in reducing the extent of free-riding. The increasing cost of MSWM led the local authorities in several countries to seek partnership with the private enterprises as a cost-cutting as well as efficiency- enhancing practice.

### *Scope of Public-Private-Partnership*

To control the tendency to free-ride the regulator has to design an incentive that maintain 3R (reduce-reuse-recycle). The Market Based Instruments (MBIs)provide incentives to the households for achieving this. The incentives work on both the passive as well the active users to participate in source segregation and proper primary disposal. The MBIs role is to reveal the consumers preference to the producers. In the absence of any knowledge about preference of specific individual the under provision of the service carries over even with the zero cost of exclusion (Oakland, 1974). When MBI gets into the process it promotes internal monitoring from within the process. As a result, the monitoring cost will gradually be eliminated from the system, the transaction cost will go down and so will be the net leakage. To remove the shirking induces inefficiency, the ULB can outsource part of service to the private agents that in turn will reduce some financial burden of ULBs. Such Public-Private Partnership (PPP)[2] is likely to act as an alternative tool of governance and management in the urban waste sector. The MBIs can be introduced in the system when the habit of source segregation and proper primary disposal among the beneficiaries has already been promoted by the regulator (or ULB). Once the habit develops completely the private entities can easily enter and participate in the process.

The problem with PPPs arises when output specification is not clearly defined or not consistent with the infrastructure needs that PPP intends to satisfy (Lossa, Spangnolo and Vellez, 2013). The output specification is the basis of a contract design. The desired contract structure should depend on the type of good or service produce (Rausser and Stevens, 2009). The ownership or property rights give the owner complete control and bargaining power and clearly defined contract helps in the specification of exact terms and conditions (Grossman and Hart, 1986). The property right erodes the transaction cost associated with the negotiation that helps the market to work smoothly and efficiently. Once the ownership is clearly defined, the private owner will directly extract the benefits from cost reduction (Shleifer and Vishny, 1994)[3].

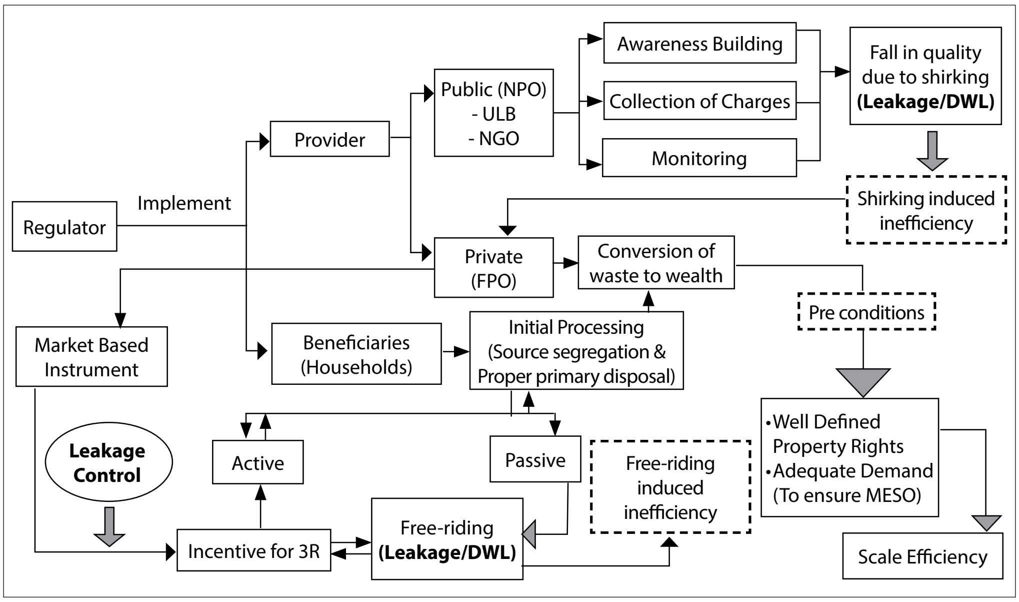
The allocation of property rights can determine whether the partnership will operate efficiently (Bester 2009). The effective allocation occurs through the change in structure of commodity from public bad to private bad(s) that ensures the responsibility sharing between multi-level agents (Shekdar, 2009). This responsibility sharing emerges through the commoditization of SWM service. If the management and handling of MSW is considered as a single mixed product, then this holistic approach would lead to high transaction cost as the mixed waste is not amenable to any subsequent treatment to be converted into something reusable and the only way to manage it is by throwing it away in the dumping ground. Given the land scarcity in the urban area this option is no longer viable. In fact, two necessary pre-conditions need to be fulfilled to guarantee a profitable involvement of the private: (a) clearly defined property right that acts as guiding incentives to achieve better internalization of externalities (Demsetz, 1967) over the waste to be collected and processed and (b) sufficiently large

[2]*In general the PPP is defined as the structural, organizational and management changes of public service by the private sectors (Jamali, 2004). Therefore, a PPP implies cooperation between public and private actors to develop products or services sharing risks, costs and benefits (Klijn et al., 2008).*

[3]*The problem in public service is that tough the regulators have some control but they do not enjoy the property or proprietary rights. Their only motivation is to protect public interest with some remote incentive of reelected in the position. In the absence of this incentive there would be a co-ordination failure among the institutions.*

coverage of the service to ensure minimum efficient scale of operation (Chart 1)[4]. Here, involvement of private will call for source-segregation of waste as a necessary pre-condition that will allow market to operate in each specific line of waste product, leaving the overall promotional and monitoring role in the hand of the public authority[5]. Problems related to transaction costs involved in such contracting out are emphasized in the empirical analysis by Bel and Fageda (2010). By defining the property right, the MBIs actually remove the transaction cost and create favourable environment for securing efficiency. At the same time, to ensure positive profit there should be adequate demand for the service. In gaining positive profit, the private enterprises have to operate at the minimum efficient scale. The extensive outreach will help to ensure this scale efficiency. Moreover, the competitive pressure and the benchmarking set by the private providers ensure the efficiency in public service (Bel and Warner, 2008). The competition works in two ways: it reduces excessive public supply of private service (Thompson, 1968) on the one hand and on the other hand, it provides incentives for cost reduction (Shleifer, 1998) under secured private property rights. The government plays the role of a negotiator between the consumer and private enterprise to ensure this efficiency.

**Chart 1: Leakage Control and Private Involvement in Solid Waste Management**




*Source: Author's understandings*

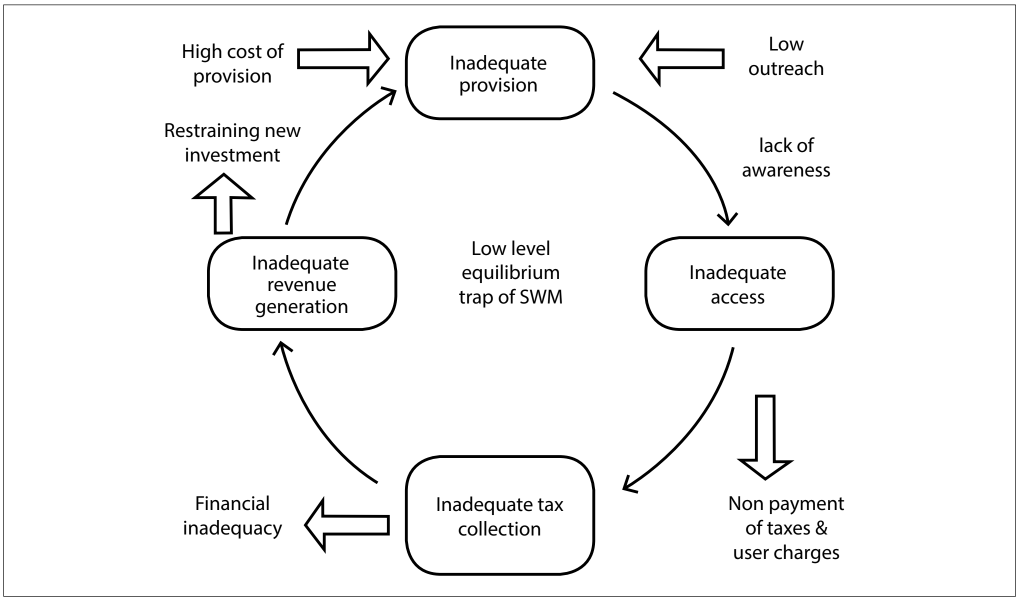
[4]*Boyne (1998) emphasizes the need for expanding coverage to ensure attainment of the scale economy for sustenance of private involvement*

[5]*Private provision of public good under laissez-faire is not sufficient condition for efficient resource allocation (Karni, 1976).*

*Low Level Equilibrium Trap in the Developing Countries*

The ongoing Solid Waste Management (SWM) practices of developing countries fail to meet these preconditions for private participation. Primarily, the absence of waste segregation at source and door-step collection services creates hindrance in identifying specific wastes as utility-bearing commodities. Moreover, the limited coverage does not encourage the emergence of a market for SWM service and on the whole, the system suffers from the problem of a low-level equilibrium trap from which it is difficult to overcome without any big institutional push. The idea is extracted from Charti and Aziz (2012) where the cycle starts from low use of municipal services and finally results in low level of service provision.

**Chart 2: Low Level Equilibrium Trap of SWM**




*Source: Author's understandings*

This vicious cycle (Chart 2) starts from the poor delivery and low quality of services and also ends up there. The cycle runs as follows: the cost of provision in the developing countries is very high due to low outreach. The risk involved in expanding the outreach comes from high monitoring cost. Due to lack of awareness among the potential beneficiaries whatever provision is created is not fully accessed. So, the actual use rate is even more inadequate. This inadequacy culminates into narrow tax base and poor revenue generation. This hinders further investment in infrastructure and network development. So, there is no effective way of cost reduction, outreach expansion and quality improvement. The system gets clasped into a vicious cycle.

One way of breaking this low-level-equilibrium trap is the incorporation of market principles in provision of a public service like MSWM. The coverage has also to be sufficiently extensive to satisfy the demand adequacy condition. Given the market size and the technology of waste management, the derived market of waste products may face either perfect competition or a natural monopoly and for the latter coverage expansion will help further in cost saving through appropriation of the scale economy present due to the falling average cost. In fact, whatever be the market structure the regulator will always impose 'average cost pricing rule' to protect the interest of the beneficiaries against the threat of surplus extraction by the provider (Figures 1 & 2). So it will not be an unregulated free market but one under strong monitoring with PPP.

It is apparent from Figure 1 that in a perfectly competitive market when the demand for the service in terms of coverage and accessibility is low (D0-D0), then there is demand inadequacy and the minimum price at which the average cost will be covered is not backed by any positive demand. So, private provision of the service is not possible. However, with an expansion of coverage and building up of proper awareness the access rate is likely to go up and the demand curve will shift to the right to (D1-D1) where the supply curve (S1-S1) cuts the demand curve from below, indicating a stable equilibrium with optimal access A* and optimal service charge C*.

**Figure 1: Private Participation: Perfect Competition**

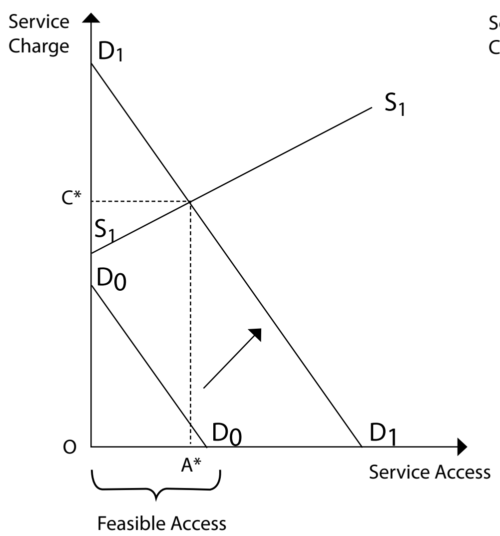
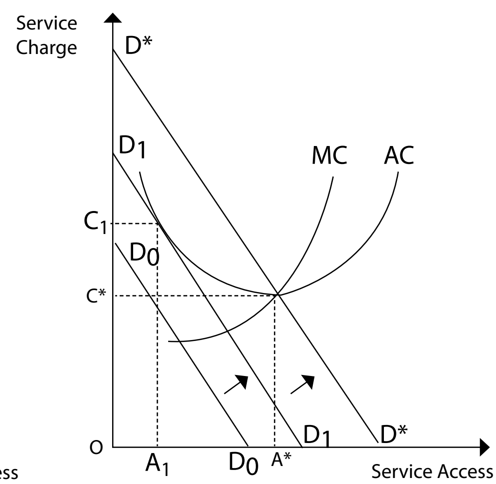



**Figure 2: Private Participation: Natural Monopoly**




*Source: Author's understandings*

Figure 2 describes the case of a natural monopoly[6]. Here the average cost curve is falling up to the access level A* and there is a presence of network externalities leading to scale economy advantage. If the demand is adequate (D*-D*) not only private participation will be attractive, there will be a reduction in the average cost of provision and the service can be provided with greater economic efficiency. It is important to note that we are considering the case of average cost pricing to ensure that the private agents would not behave as profit-sharks but will participate only against socially optimal prices to break-even and would thereby eliminate the burden of subsidy from the public fund. In fact, (D1-D1) would be the minimum acceptable demand (outreach) that would make the private participation attractive. The range of demand between D*D* and D1D1 is defining the feasible zone. Demand like (D0-D0) would be inadequate for emergence of a market.

*Initiative in Public Private Partnership in India*

In India generation of solid waste has increased significantly over the few decades. The per capita waste generation is increased at a rate of 1.3 percent per anum (Agarwal, Pandey and Agarwal, 2011). Some of the ULBs are found to outsource different segment of MSW collection and treatment process. At some places, contracts are given to private operators for door-step collection and transportation. In some cases, the responsibility of door-step collection is vested on the NGOs against some monthly payment e.g., Vejalpur, Gujarat, (MoUD, 2012). Municipal authorities outsource secondary storage and/or transportation to avoid investing in vehicles and equipment and to avail of a more efficient system. In such an arrangement, the private firm provides container and/or vehicles with drivers as well as fuel (examples can be found in Ahmedabad, Surat and Mumbai) (DEA, 2009). Generally, municipal authorities are not equipped to handle treatment and disposal of waste, which are highly technical operations. Private sector participation is preferred for waste processing. Cities such as Kolkata, Hyderabad, Vijayawada, Ahmedabad, Trivandrum, Thane and Jaipur are examples of such contracts for the construction of compost plants or waste to energy plants[7]. The private firm is given time-bound contracts on mutually agreed terms and conditions (Asnani 2006)[8]. In the following sections an attempt has been made to study the relationship between efficiency in MSWM in India and the presence of involvement of the private partners.

## Section 3: Research Question

*The present study is focused on four broad objectives:* (a) an assessment of the nature of technical efficiency of different ULBs in managing municipal solid wastes by applying Stochastic Frontier Analysis (SFA), (b) identification of the factors influencing this efficiency score by applying OLS regression, (c) importance of waste segregation vis-à-vis private participation in enhancing this

[6]*Given the scale of operation, there may not have the scope to accommodate more than one service provider in an economically meaningful way. This is the case of natural monopoly where we observe falling average cost over a very long stretch of output.*

[7] *In most such cases, the municipal authority provides land on lease rent basis and free garbage at the plant site.*

[8] *Cities such as Mysore, Calicut, Kochi, Shillong and Puri have adopted the design, build and operate (DBO) model for setting up compost plant. Under this arrangement, the municipal authorities provide funds, land, and garbage whereas the private authority is responsible for designing, building and operating the facility. The ownership of the plant remains with the municipality. The private firm is given time-bound contracts on mutually agreed terms and conditions.*

efficiency score through data exploration and (d) the marginal effect of different pre-conditions of market in influencing the probability of private participation in terms of LOGIT analysis.

*Data:* To estimate technical efficiency scores the data on output and input variables are required. Here, control should be given to the scale of operation of the service, which may have significant influence on the production efficiency. This scale can be assessed in terms of both population density and service-coverage. Besides, direct input and output related information one needs to gather information on the presence of regulatory instruments and private participation.

Recognizing the growing importance of improving efficiency in delivery of basic services in the cities, the Government of India has launched a series of initiatives aimed at enabling urban local bodies to meet the unprecedented challenges that they face today. These include schemes such as the Jawaharlal Nehru National Urban Renewal Mission, Urban Infrastructure Development Scheme for Small and Medium Towns, Capacity Building for Urban Local Bodies, etc. Investments in urban infrastructure have, however, not always resulted in corresponding improvements in levels of service delivery. There is, therefore, a need for a shift in focus towards service delivery. The Ministry of Urban Development initiated an exercise to develop standardized Service Level Benchmarks (SLB) with respect to basic municipal services in the year 2006. These benchmarks on the agreed aspects would help performance improvements in the identified service sectors by (i) helping local decision-makers identify gaps, plan and prioritize improvement measures; (ii) enabling the identification and transfer of best practice; (iii) enhancing accountability to customers for service delivery levels; (iv) providing a framework that can underlie contracts/agreements with service providers; and making it possible to link decision-making on financial allocations to service outcomes. The Handbook for the year 2010-11 provides information on 1400 ULBs spread over 13 major Indian states, viz., Andhra Pradesh (AP), Bihar (BIH), Chhattisgarh (CHGR), Gujarat (GUJ), Himachal Pradesh (HP), Karnataka (KAR), Kerala (KER), Madhya Pradesh (MP), Maharashtra (MAH), Orissa (ORI), Rajasthan (RAJ), Tripura (TRI) and Uttar Pradesh (UP) on a number of outcome indicators like household coverage, collection efficiency, extent of treatment, extent of scientific disposal, along with some instruments like extent of cost recovery, extent of source segregation, efficiency in collecting charges and redressing customer complaints, etc. Since the purpose of this report was setting the benchmark and compare actual performance with the pre-fixed norms, hence all the indicators were normalized and expressed in percentage terms (MoUD, 2010).

The input data for waste management is collected from the annual reports of State Pollution Control Boards (SPCB). The reports provide information on available collection and transportation vehicles for waste management. Following the classification suggested in the Solid Waste Management Manual, different types of collection vehicles like tricycle, hand carts and collection bins can be clubbed together and different transportation vehicles like tractor, truck, lorry, compactor, etc. can also be clubbed. Information on the presence of private initiatives in the form of PPP was collected from the Action Plan Proposals of the State Pollution Control Boards. Finally, from the website of the Census of India information was downloaded on the total number of households in each ULB and population density of each ULB for the year 2011. Table 1 reports the indicators of solid waste management from the SLB Handbook.

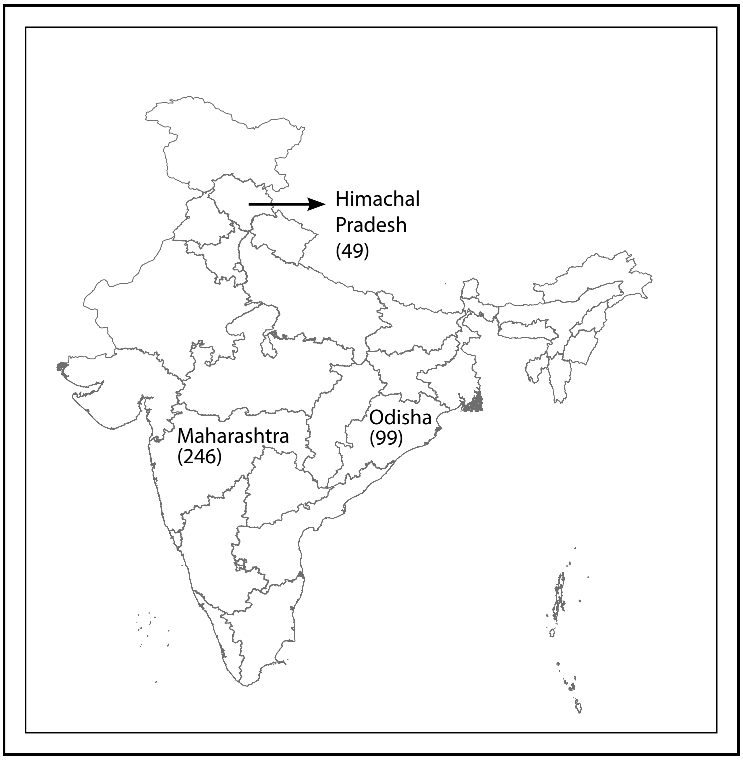
**Table 1: Indicator of Solid Waste Management: SLB Handbook**

| Categories (Variables) | Description | Benchmark |
|---|---|---|
| Household level coverage (COV) | Percentage of households and establishments that are covered by a daily door step collection system by the ULB itself or ULB approved service providers. | 100% |
| Efficiency of collection of MSW (COL) | The total waste collected by the ULB and authorized service providers versus the total waste generated within the ULB, excluding the waste at recycling and processing point. | 100% |
| Extent of MSW recovered (TREAT) | The total quantum of waste intake by the waste processing facilities operated by the ULB or other authorized institution excluding the inert materials versus the total waste collected from households establishments and common collection points by any authorized service providers. | 80% |
| Extent of scientific disposal (SCI) | The amount of waste that is disposed in landfills that have been designed, built, operated and maintained as per standards lad down by the central agencies. The data is expressed as a percentage of the total quantum waste disposed at landfill sites. | 100% |
| Extent of cost recovery (COST) | The indicator denotes the extent to which the ULB is able to recover all operating expenses that is defined as the total annual operating revenues from SWM as a percentage of the total operating expenses on SWM. | 100% |
| Extent of segregation (SEG) | The total quantum of waste that arrives in a segregated manner at the treatment or disposal site as a percentage of total waste collected from households. | 100% |
| Efficiency in redressal of customer complaints (RED) | The total number of SWM related complaints redressed within 24 hours of receipt of the complaints as a percentage of the total number of complaints received during the month. | 80% |
| Efficiency in collection of charges (CHRG | Efficiency in collection is defined as current year revenues collected, expressed as a percentage of total operating revenues. | 90% |

*Source: MoUD (2010)*

Reliable data on collection and transportation equipments were available only for three out of fourteen states, viz., MAH, ORI and HP (Map 1). Total 394 sample points have been collated from these different sources on which the total data set was available. Number of observations from MAH was 246, from ORI 99 and from HP 49, respectively. These three states are completely different in terms of state characteristics. According to the fact-sheet available in the official website of the Planning Commission of India, MAH is an industrially developed state, while for HP agriculture and tourism explain a significant part of state domestic product, ORI is amongst the least developed states of the country (http://planningcommission.nic.in/data/...). In terms of coverage and collection efficiency reported in the benchmark study MAH is a good performer [65 percent coverage with 75 percent efficiency], HP is a bad performer [13 percent coverage with 70 percent efficiency] and ORI is a moderate performer [40 percent coverage with 55 percent efficiency] making the effective outreach 49 percent, 9 percent and 22 percent, respectively.

**Map 1: Selected States of India**




*Source: Constructed from Google Image*

*Data Description:* The industrially developed state MAH performs better in terms of outreach and market related variables i.e. SEG, RED and CHRG. The percentage of ULB with private participation is also higher in MAH compared to ORI and HP. These three state samples would be considered collectively in the subsequent analysis to predict the prospect of efficiency in the MSWM for India as a whole and no inter-state comparison would be attempted.

**Table 2: Solid Waste Management Practices: Across State**

| Variables | Description | Mean Values | | |
|---|---|---|---|---|
| | | MAH | ORI | HP |
| COL | % of waste collected | 74.91 | 58.02 | 69.35 |
| TREAT | % of waste treated | 17.23 | 25.02 | 11.04 |
| CL_V | Collection vehicle per 1,00,000 population | 21.44 | 47.78 | 11.39 |
| TR_V | Transportation vehicle per 1,00,000 population | 19.50 | 14.29 | 25.76 |
| COST | % of operating cost recovered | 8.85 | 0.10 | 3.15 |
| DNSITY | Population density per sq. km. | 6453.82 | 2392.71 | 2470.66 |
| OUT | % of area covered/ outreach | 65.78 | 43.94 | 17.36 |
| SEG | % of source segregated waste | 24.53 | 1.92 | 9.95 |
| RED | % of complaints redressed within a day | 63.52 | 47.38 | 67.29 |
| CHRG | % of revenue share collected from the household | 10.78 | 0.71 | 11.76 |
| PPP | Presence of private participation | 46.34 | 24.24 | 20.41 |

*Source: Ministry of Urban development (2012a), SAP of SPCB (2011) & Census (2011)*

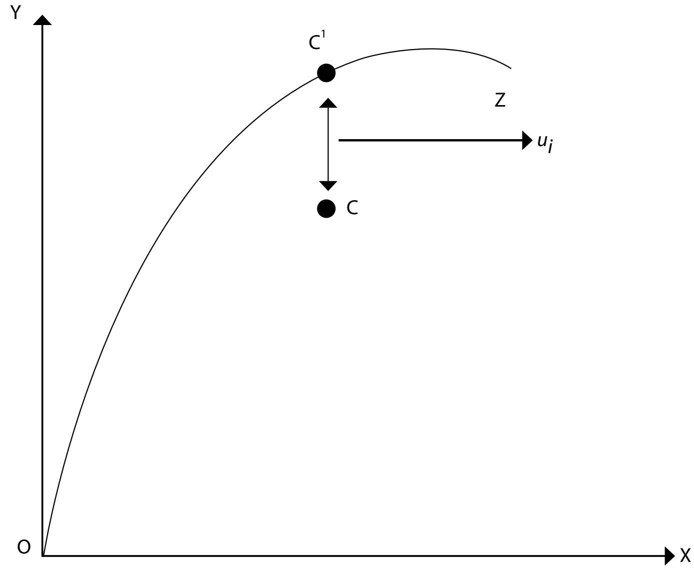
## Section 4: Technical Efficiency Score: an Application of SFA

Technical or productive efficiency refers to the firm's ability to produce as much as without any reference to the input prices. It is an index expressed as the ratio of actual output *(y)* and the output that would results if the inputs are used efficiently ($\acute{y}$).The ratio

$u = \frac{Actual\ Production}{Efficient\ Production} = \frac{y}{\acute{y}}$ would serve as a measure of technical efficiency (TE).

Technical Effeciency (TE) lies between 0 and 1. The reciprocal of $u$ is the gain in output as a result of a movement from inefficient to efficient production point. Thus $u$ is the distance from point of operation of a production unit to the projected point on the frontier (Figure 3).

**Figure 3: Technical Efficiency**




*Source: Author's understandings*

There are alternative approaches to measure technical efficiency. Broadly, they can be grouped under parametric and non-parametric. The parametric approach requires the imposition of specific functional form for a production frontier and some associated assumptions like independently and identically distributed normal errors, which have to be uncorrelated with the independent variables. In contrast, the nonparametric approach does not require any functional form. It is based on the set of behavioral assumptions regarding the production structure. To evaluate the efficiency of interventions designed for the proper provision of a number of public services like the operation of public transport, water supply in urban areas, management of sewage and solid waste by the municipalities, etc. both DEA and SFA techniques have frequently been used in the literature. This paper concentrates only on the parametric methods. The Stochastic Frontier Production Function (SFPF) takes care of the effect of such unobserved random influences beyond the control of any individual production unit. So, it is expected to produce more robust estimates of *TE*[9].

[9] *For a detailed survey see Bandyopadhyaya and Majumder (2013).*

*Stochastic Frontier Production Function:* To overcome the deficiencies associated with the measure of technical (in)efficiency in Deterministic Production Frontier Method (DPFM)[10], the SFPF considers the following specification of the production function: suppose there are $k$ inputs $(X_1, X_2, \ldots, X_k)$, indexed by *j*, needed to produce a single output *Y* and there are *N* producing units indexed by i. The production frontier model may be written as:

$$\hat{Y}_i = f(X_i;\beta) \ldots\ldots\ldots\ldots (1)$$

Here $\hat{Y}_i$ is the maximum output of producer *i*, $f(X_i;\beta)$ is the production frontier, $X_i$ is the vector of $k$ inputs and $\beta$ is the corresponding technology parameters. The actual production level will be represented as:

$$Y_i = f(X_i;\beta)\mu \ldots\ldots\ldots\ldots (2)$$, with μ representing TE.

By presuming a Cobb-Douglas functional form equation (1) can be written as a log-linear form

$$\ln f(X_i;\beta) = \beta_0 + \sum_{j=1}^{k} \beta_j \ln X_{ji} \ldots\ldots\ldots\ldots (3)$$

Denoting ($\ln X_{ji}$) as $x_{ji}$ and ($\ln Y_i$) as $y_i$, the logarithm of observed output can be written as

$$y_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ji} - u_i \ldots\ldots\ldots\ldots (3)'$$

Here ui is the index of technical inefficiency of the ith producing unit distributed independently and normally with mean 0 and variance $\sigma_u^2$. Thus it should be assumed that $u_i \geq 0$ for each i to ensure $Y_i \leq f(X_i;\beta)$ as for a particular vector of inputs the observed level of corresponding output for any firm cannot exceed the frontier. Thus the specification of distribution is needed for this one sided inefficiency error component [in view of the fact that TEi = exp(-ui)]. This can follow different alternative specifications like exponential distribution, truncated normal distribution, gamma distribution or half-normal distribution. Here, ui is distributed independently and normally with mean 0 and variance $\sigma_u^2$, truncated at zero i.e. ui ~ idN+(0, $\sigma_u^2$) Though *ui* is capturing the extent of technical inefficiency, in this deterministic frame there is no scope to accommodate the possibility of random fluctuations in production those are beyond the control of any individual producer. As proposed by Aigner Lovell and Schmidt (1977) and Meeusen and Van Den Broeck (1977), the SFPF is able to capture these unobserved random factors provided an independent random term v is incorporated

[10]*Corrected Ordinary Least Square Method, Goal Programming Approach and Modified Ordinary Least Squares Method are the types of DPFM.*

in the production frontier itself. This $v$ would be independently and identically normally distributed with zero mean and constant variance $\sigma_v^2$. By adding this random error term v to the non-negative variable u and assuming them to be uncorrelated equation (3) can be written as,

$$y_i = \left[\beta_0 + \sum_{j=1}^{k} \beta_j x_{ji}\right] + (v_i - u_i) \ldots\ldots\ldots \text{(4)}$$

$$y_i = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ij} + \varepsilon_i \ldots\ldots \text{(4)'}$$

Thus,

$$\mathrm{TE_i} = \exp(-u_i) = \left[\frac{Y_i}{f(X_i;\beta)\exp(v_i)}\right] \ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

The joint density of $u$ and $v$ is: $f(u,v) = \dfrac{2}{2\pi\sigma_u\sigma_v}\exp\left\{-\dfrac{u^2}{2\sigma_u^2} - \dfrac{v^2}{2\sigma_v^2}\right\} \ldots\ldots\ \text{(6)}$

Since $v = (\varepsilon + u)$, the joint density for u and $\varepsilon$ is:

$$f(u,\varepsilon) = \frac{2}{2\pi\sigma_u\sigma_v}\exp\left\{-\frac{u^2}{2\sigma_u^2} - \frac{(\varepsilon+u)^2}{2\sigma_v^2}\right\} \ldots\ldots \text{(6)'}$$

The marginal density of $\varepsilon$ is:

$$f(\varepsilon) = \int_0^{\infty} f(u,\varepsilon)\,du$$

$$= \frac{2}{\sqrt{2\pi}\sigma}\left[1 - \Phi\left(\frac{\varepsilon\lambda}{\sigma}\right)\right]\exp\left\{-\frac{\varepsilon^2}{2\sigma^2}\right\} = \frac{2}{\sigma}\phi\left(\frac{\varepsilon}{\sigma}\right)\Phi\left(-\frac{\varepsilon\lambda}{\sigma}\right) \ldots\ldots \text{(7)}$$

where $\sigma = \left(\sigma_u^2 + \sigma_v^2\right)^{1/2}$ and $\lambda = \frac{\sigma_u}{\sigma_v}$

The log-likelihood function of the sample of N urban local bodies (ULBs) is:

$$\ln L = CONS - N \ln \sigma + \sum_{i=1}^{N} \ln \Phi\left(-\frac{\varepsilon_i \lambda}{\sigma}\right) - \frac{1}{2\sigma^2} \sum_{i=1}^{N} \varepsilon_i \quad \text{.................(8)}$$

The conditional distribution of $u|\varepsilon$ is:

$$f(u \mid \varepsilon) = \frac{f(u,\varepsilon)}{f(\varepsilon)}$$

$$\left. \frac{1}{\sqrt{2\pi}\sigma_*} \exp\left\{-\frac{(u-\mu_*)^2}{2\sigma_*^2}\right\} \middle/ \left[1 - \Phi\left(-\frac{\mu_*}{\sigma_*}\right)\right] \right. \quad \text{....... (9)}$$

$$\text{where: } \mu_* = -\frac{\varepsilon \sigma_u^2}{\sigma^2} \ \& \ \sigma_*^2 = \frac{\sigma_u^2 \sigma_v^2}{\sigma^2}$$

Estimated technical efficiency of the i[th] ULB:

$$TE_i = E\left(\exp\{-u_i\} \mid \varepsilon_i\right)$$

$$= \left[\frac{1 - \Phi(\sigma_* - \mu_{*i}/\sigma_*)}{1 - \Phi\left(-\mu_{*i}/\sigma_*\right)}\right] \exp\left\{-\mu_{*i} + \frac{1}{2}\sigma_*^2\right\} \quad \text{....... (10)}$$

## Section 5: Estimation and Results

*Prediction of efficiency scores:* To apply SFA the first task is to define the output and input variables. The waste management can be considered proper if the waste is collected and treated. So, the outcome variable is defined as CTREAT which is a numerical product of COL and TREAT. Collection vehicle per 1, 00,000 population (CL_V) and transportation vehicle per 1, 00,000 population (TR_V) are taken as proxy for capital input in a flow form. There was no direct information available on the labor use. The only related information available was the percentage of operating cost recovered (COST). Therefore, a strong implicit assumption is made that the major share of the operating cost is the labor cost and hence, COST is taken as a proxy for labor input. To give control to the variation in efficiency score due to the scale of operation, two additional variables have been incorporated as the percentage of coverage (OUT) and population density (DNSITY), where the former would represent the extensive margin and the latter would represent the intensity. In fact, the ultimate scale of operation would depend on both area covered and the density of households. The SFA results are reported in Table 3.

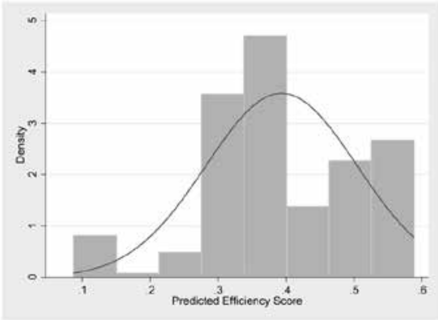
**Table 3: Efficiency Score: SFA**

| Covariates | Study Variable: [CTREAT] | |
|---|---|---|
| | Coef. | z-statistics |
| CL_V | -0.002 | -0.03 |
| TR_V | 0.08** | 2.07 |
| COST | 0.034*** | 3.66 |
| OUT | 0.01*** | 3.22 |
| DNSITY | 0.00005*** | 2.57 |
| CONSTANT | 0.60 | 0.82 |
| **Diagnostics** | | |
| Wald $\chi^2$ | | 35.52*** |
| df | | 388 |

*Source: Ministry of Urban development (2012a), SAP of SPCB (2011) & Census (2011)*
**** Significant at less than 1 percent, ** Significant at less than 5 percent*

It has been found that among the inputs TR_V and COST are more important than CL_V. Both the indicators of scale, viz., OUT and DNSITY are significant at less than one percent level. The Wald-$\chi^2$ value is also significant enough to make the regression result acceptable. The predicted efficiency score is plotted in Figure-4. It ranges from 0.09 to 0.59. The mean value is closed to the median value, making the distribution almost symmetric.

**Figure 4: Histogram of Predicted Efficiency Score**




Mean = 0.39
Median = 0.37
Min = 0.09
Max = 0.59

*Source: Ministry of Urban development (2012a), SAP of SPCB (2011) & Census (2011)*

*Determinants of Efficiency Scores:* It is expected that an active participation of household in waste management will have a favorable impact on efficiency (coefficient of SEG is likely to be positive). In the presence of proper monitoring payment of charges can be expected to make beneficiaries more aware about the worth of the service and develop resistance against free-riding (coefficient of CHRGE is likely to be positive). Finally, the active households are quality conscious and the speed of grievance redressal is very important for them (coefficient of RED is likely to be positive). The increase in this speed reduces the transaction cost of monitoring and, hence, enhances efficiency. The OLS regression results are reported in Table-4.

**Table 4: Determinants of Efficiency Score: OLS Regression**

| Study Variable | Covariates | | |
|---|---|---|---|
| Predicted Efficiency Score | SEG | RED | CHRGE |
| Coefficients | 0.0012*** | 0.0013*** | 0.000021 |
| df | F | | $\bar{R}^2$ |
| 390 | 29.99** | | 0.19 |

**** Significant at less than 1 percent, ** Significant at less than 5 percent*
*Source: Ministry of Urban development (2012a), SAP of SPCB (2011) & Census (2011)*

It is evident from the regression results that both SEG and RED are contributing to the enhancement of efficiency in a significant way. However, CHRGE as an explanatory factor fails our expectation. Here the sign is positive but statistically insignificant. This may indicate inadequacy of monitoring. In that case private involvement in the entire process will encourage impersonal self-enforced governance, where in the best self-interest all the agents will behave in a responsible way and all inefficiency enhancing transaction costs will be eliminated from the system.

*Determinants of Private Participation:* Whether private participation will on its own contribute to an enhancement of efficiency or some pre-conditions needed to be fulfilled for it to be effective is our moot question. The variable SEG has been converted to a dummy variable DSEG in terms of its presence/absence. A four-way classification of the sample observations is done according to the presence-absence of SEG and PPP and for each cluster the median (predicted) efficiency score has been calculated (Table-5).

**Table 5: Segregation, PPP: Median Efficiency Score**

| PPP (Y/N): Median Value [count] | DSEG (Y/N): Median Value [count] | | | |
|---|---|---|---|---|
| | Absent | Present | Median Difference (PEARSON'S $x^2$) | Total (#) |
| Absent | 0.351 [n = 159] | 0.394 [n = 87] | 0.043*** (11.115) | 0.362 [n = 246] |
| Present | 0.346 [n = 221] | 0.469 [n = 173] | 0.123*** (24.981) | 0.386 [n = 148] |
| Median Difference (Pearson's $x^2$) | -0.005 (0.392) | 0.075*** (7.911) | 0.118*** (18.75) | 0.024* (3.51) |
| Total (#) | 0.349 [n = 221] | 0.443 [n = 173] | 0.094*** (24.74) | 394 |

**** Significant at less than 1 percent & * Significant at less than 10 percent*
*Source: Ministry of Urban development (2012a), SAP of SPCB (2011) & Census (2011)*

When SEG is absent introduction of PPP fails to improve the predicted median efficiency score to any significant extent. In fact, it has gone down from 0.351 to 0.349, though the difference is not statistically significant. However, when SEG is present, the introduction of PPP leads to an improvement of the predicted median efficiency score by 0.075 points, where the Pearson's $\chi^2$ of this difference is strongly statically significant (at less than one percent level). In contrary, the marginal effect of SEG is always very strong on the efficiency score irrespective of the presence or absence of PPP. Thus, SEG is a precondition for PPP to be effective. The mixed MSW produced by the households is not very attractive to the private agents from the commercial perspective. However, if the waste is separated at source then different component of waste can be utilized in different types of production process generating marketable use value. For example the bio-degradable waste can be composted to produce manure. Reusable paper, plastic, glass etc. can be utilized as inputs for subsequent production of different art and craft objects and so on. So, some intermediaries will have incentive to collect source segregated wastes from the households and supply to the producer using them as productive inputs, provided their exclusive buying and selling rights can be defined over the transaction, the scale of operation is sufficiently large and specific charges can be collected against the service. The highest marginal effect on the predicted median efficiency score is observed when the (no-SEG, no-PPP) group is compared with the (yes-SEG, yes-PPP) group.

If the regulator can create markets in waste based production, then in the presence of a defined group of demanders and suppliers no external monitoring would be needed to ensure efficiency of SWM. However, the next pertinent question would be the identity of the regulator who will assign property rights to the private players. Obviously, in this case it would be the ULB. The ULB's may auction the franchisee right of door-step collection of source separated wastes from the households, subsequent transportation disposal and final treatment of the reusable or recyclable waste. However, the part that has no future market demand in its original and/or transformed state will remain the sole responsibility of the public local body. Thus, private cannot replace public altogether, but can have efficiency enhancing partnership with the later.

Three market based instruments at the disposal of the regulator have been considered here, viz., SEG, RED and CHRGE and their marginal influence on the PPP is estimated in terms of a LOGIT regression (table-6). The sample adequacy has also been tested in terms of Kendall's τ-a and Somer's D-statistics. Consistent to our expectation the marginal effect of SEG is the highest, both in magnitude and statistical power, followed by that of RED. However, CHRGE does not reveal any significant impact on the likelihood of PPP initiation. Here the design of the fee structure becomes crucially important and the dataset used in this research did not have sufficient information on the fee-structure.

**Table 6: LOGIT for PPP**

| Study Variable | Covariates | | | |
|---|---|---|---|---|
| **PPP (Y/N)** | **SEG** | | **RED** | **CHRGE** |
| Marginal effects | 0.0037*** | | 0.0018* | 0.0016 |
| **Diagnostics** | | | | |
| **df** | **LR** | **Pseudo $R^2$** | **Kendall's τ-a** | **Somers' D (z – statistics)** |
| 390 | 24.47*** | 0.05 | 0.15*** | 5.85*** |

**** Significant at less than 1 percent, * Significant at less than 10 percent*
*Source: Ministry of Urban development (2012a), SAP of SPCB (2011) & Census (2011)*

## Section 6: Conclusion

The study shows that the efficiency of MSWM can be enhanced manifold by incorporating private participation in the collection, transportation and treatment process. It also identified the pre-conditions that generally make private participation feasible as well as mutually gainful. The first requirement is a wide spread service outreach, followed by source-segregated wastes. These two conditions, if satisfied would help to define property rights on specific wastes and the missing market for the collection and treatment of specific wastes would evolve, where the treated waste can be put into subsequent uses after suitable transformations and modifications. The finer requirements would be the designing of a specific tariff structure, assurance of quality against payment, etc. Though, at present the presence of PPP in the MSWM service of the developing bloc is not very prominent, in view of the rapid urbanization and need for cost effective provision of solid waste management services there is very high potential of market solution in this sector under well-designed regulation.

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# WASTE MANAGEMENT INITIATIVES IN INDIA FOR HUMAN WELL BEING

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**Abstract**

The objectives of writing this paper is to study the current practices related to the various waste management initiatives taken in India for human wellbeing. The other purpose is to provide some suggestions and recommendations to improve the waste management practices in Indian towns. This paper is based on secondary research. Existing reports related to waste management and recommendations of planners/NGOs/consultants/government accountability agencies/key industry experts/ for improving the system are studied. It offers deep knowledge about the various waste management initiatives in India and find out the scope for improvement in the management of waste for the welfare of the society. The paper attempts to understand the important role played by the formal sector engaged in waste management in our country. This work is original and could be further extended.

**Keywords:** India, Recycling, Waste Disposal, Waste Management

## Introduction

"There are few things certain in life – one is death, second is change and the other is waste." No one can stop these things to take place in our lives. But with better management we can prepare ourselves. Here we will talk about waste and waste management. Each of us has a right to clean air, water and food. This right can be fulfilled by maintaining a clear and healthy environment. Now for the first question, what is waste? Any material which is not needed by the owner, producer or processor is waste. Generally, waste is defined as at the end of the product life cycle and is disposed of in landfills. Most businesses define waste as "anything that does not create value" (BSR, 2010). In a common man's eye anything that is unwanted or not useful is garbage or waste. However scientifically speaking there is no waste as such in the world. Almost all the components of solid waste have some potential if it is converted or treated in a scientific manner. Hence we can define solid waste as "Organic or inorganic waste materials produced out of household or commercial activities, that have lost their value in the eyes of the first owner but which may be of great value to somebody else." (Robinson, W.D.1986). Generation of waste is inevitable in every habitation howsoever big or small. Since the dawn of civilization humanity has gradually deviated from nature & today there has been a drastic change in the lifestyle of human society. Direct reflection of this change is found in the nature & quantity of garbage that a community generates. We can dispose the waste or reuse the waste and can earn money through proper management. Indian cities which are fast competing with global economies in their drive for fast economic development have so far failed to effectively manage the huge quantity of waste generated. There are about 593 districts and approximately 5,000 towns in India. About 27.8 percent of India's total population of more than 1 billion (as per Census 2001) lives in urban areas. The projected urban population percentage is 33.4 percent by the year 2026. The quantum of waste generated in Indian towns and cities is increasing day-by-day on account of its increasing population and increased GDP. The annual quantity of solid waste generated in Indian cities has increased from six million tons in 1947 to 48 million tons in 1997 with an annual growth rate of 4.25 percent, and it is expected to increase to 300 million tons by 2,047 (CPCB, 1998).

Population explosion, coupled with improved life style of people, results in increased generation of solid wastes in urban as well as rural areas of the country. In India like all other sectors there is a marked distinction between the solid waste from urban & rural areas. However, due to ever-increasing urbanization, fast adoption of 'use & throw concept'& equally fast communication between urban & rural areas the gap between the two is diminishing. The solid waste from rural areas is more of a biodegradable nature & the same from urban areas contains more non-biodegradable components like plastics & packaging. The repugnant attitude towards solid waste & its management is however, common in both the sectors. Universally 'making garbage out of sight' is the commonly followed practice.

In India, the urban local bodies, popularly known as the municipal corporations/councils, are responsible for management of activities related to public health. However, with increasing public and political awareness as well as new possibilities opened by economic growth, solid waste management is starting to receive due attention. The various initiatives taken by government, NGOs, private companies, and local public drastically increased in the past few decades. Nonetheless, land filling is still the dominant solid waste management option for the United States as well as many other countries like India around the world. It is well known that waste management policies, as they exist now, are not sustainable in the long term. Thus, waste management is undergoing drastic change to offer more options that are more sustainable. We look at these options in the hope of offering the waste management industry a more economically viable and socially acceptable solution to our current waste management dilemma. This paper outlines various advances in the area of waste management. It focuses on current practices related to waste management initiatives taken by India. It also highlights some initiatives taken by the US federal government, states and industry groups. The purpose of this paper is to gain knowledge about various initiatives in both countries and locate the scope for improvement in the management of waste.

**Classification of waste**

There may be different types of waste such as Domestic waste, Factory waste, Waste from oil factory, E-waste, Construction waste, Agricultural waste, Food processing waste, Bio-medical waste, Nuclear waste, Slaughter house waste etc. We can classify waste as follows:

- Solid waste- vegetable waste, kitchen waste, household waste etc.
- E-waste- discarded electronic devices such as computer, TV, music systems etc.
- Liquid waste- water used for different industries, tanneries, distilleries, thermal power plants
- Plastic waste- plastic bags, bottles, bucket, etc.
- Metal waste- unused metal sheet, metal scraps etc.
- Nuclear waste- unused materials from nuclear power plants

Further we can group all these types of waste into wet waste (Biodegradable) and dry waste (Non Biodegradable).

**Wet waste (Biodegradable)** includes the following:

- Kitchen waste including food waste of all kinds, cooked and uncooked, including eggshells and bones
- Flower and fruit waste including juice peels and house-plant waste
- Garden sweeping or yard waste consisting of green/dry leaves
- Sanitary wastes
- Green waste from vegetable & fruit vendors/shops
- Waste from food & tea stalls/shops etc.

**Dry waste (Non-biodegradable)** includes the following:

- Paper and plastic, all kinds
- Cardboard and cartons
- Containers of all kinds excluding those containing hazardous material
- Packaging of all kinds
- Glass of all kinds
- Metals of all kinds
- Rags, rubber
- House sweeping (dust etc.)
- Ashes
- Foils, wrappings, pouches, sachets and tetra packs (rinsed)
- Discarded electronic items from offices, colonies viz. cassettes, computer diskettes, printer cartridges and electronic parts.
- Discarded clothing, furniture and equipment

In addition to the above wastes, another type of waste called **"Domestic Hazardous Waste"** may also be generated at the household level. These include used aerosol cans, batteries, and household kitchen and drain cleaning agents, car batteries and car care products, cosmetic items, chemical-based insecticides/pesticides, light bulbs, tube-lights and compact fluorescent lamps (CFL), paint, oil, lubricant and their empty containers. Waste that is considered hazardous is first required by the EPA to meet the legal definition of solid waste. The EPA incorporates hazardous waste into three categories. The first category are source-specific wastes, the second category is nonspecific wastes, and third, commercial chemical products. Generally, hazardous waste "is waste that is dangerous or potentially harmful to our health or the environment. Hazardous wastes can be liquids, solids, gases, or sludge. They can be discarded commercial products, like cleaning fluids or pesticides, or the by-products of manufacturing processes (EPA Wastes Website, 2010).

Similarly there is **"Non Hazardous waste".** There are many definitions of hazardous and non-hazardous waste within the US federal government, states and industry groups. The Department of Defense (DOD) and The Environmental Protection Agency (EPA) define waste as "the extravagant, careless, or needless expenditure of DOD funds or the consumption of DOD property that results from deficient practices, systems, controls, or decisions. In addition, "abuse is the manner in which resources or programs are managed that creates or perpetuates waste and it includes improper practices not involving prosecutable fraud" (EPA Wastes Website, 2010)**.** The Environmental Protection Agency (EPA) defines solid non-hazardous waste as "any garbage or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semi-solid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities" (EPA Wastes Website, 2010). The definition of non-hazardous waste can also include financial waste. In 2009 the US Presidential Executive Order, Reducing Improper Payments and Eliminating Waste in Federal Programs was initiated to eliminate payment error, waste, fraud and abuse in major Federal government programs due to public zero tolerance of fraud, waste and abuse. This Executive Order is based upon a transparent, participatory and collaborative comprehensive framework between the government and public.

**Disposal vs. Management**

There are common practices to dispose waste from ordinary people. But disposal of waste is becoming a serious and vexing problem for any human habitation all over the world. Disposing solid waste out of sight does not solve the problem but indirectly increases the same manifold and at a certain point it goes beyond the control of everybody. The consequences of this practice such as health hazards, pollution of soil, water, air & food, unpleasant surroundings, loss of precious resources that could be obtained from the solid waste, etc. are well known. That's why it is essential to focus on proper management of waste all over the world. Waste management has become a subject of concern globally and nationally. The More advanced the human settlements, the more complex the waste management. There is a continuous search for sound solutions for this problem but it is increasingly realized that solutions based on technological advances without human intervention cannot sustain for long and it in turn results in complicating the matters further. Management of solid waste which generally involves proper segregation and scientific recycling of all the components is in fact the ideal way of dealing with solid waste. Solid waste management (SWM) is a commonly used name and defined as the application of techniques to ensure an orderly execution of the various functions of collection, transport, processing, treatment and disposal of solid waste (Robinson, 1986). It has developed from its early beginnings of mere dumping to a sophisticated range of options including re-use, recycling, incineration with energy recovery, advanced landfill design and engineering and a range of alternative technologies. It aims at an overall waste management system which is the best environmentally, economically sustainable for a particular region and socially acceptable (World Resource Foundation, 1996; McDougall et al., 2001). This not only avoids the above referred consequences but it gives economic or monetary returns in some or the other forms.

**Basic principles of Solid Waste Management**

1) 4Rs: Refuse, Reduce, Reuse & Recycle

- Refuse: Do not buy anything which we do not really need.
- Reduce - Reduce the amount of garbage generated. Alter our lifestyle so that minimum garbage is generated.
- Reuse - Reuse everything to its maximum after properly cleaning it. Make secondary use of different articles.
- Recycle – Keep things which can be recycled to be given to rag pickers or waste pickers (Kabadiwallahs).Convert the recyclable garbage into manures or other useful products.

2) Segregation at source: Store organic or biodegradable and inorganic or non biodegradable solid waste in different bins. Recycle of all the components with minimum labor and cost.

3) Different treatments for different types of solid wastes: One must apply the techniques which are suitable to the given type of garbage. For example the technique suitable for general market waste may not be suitable for slaughter house waste.

4) Treatment at nearest possible point: The solid waste should be treated in as decentralized manner as possible. The garbage generated should be treated preferably at the site of generation i.e. every house.

Based on the above principles, an ideal Solid Waste Management for a village could be as under.

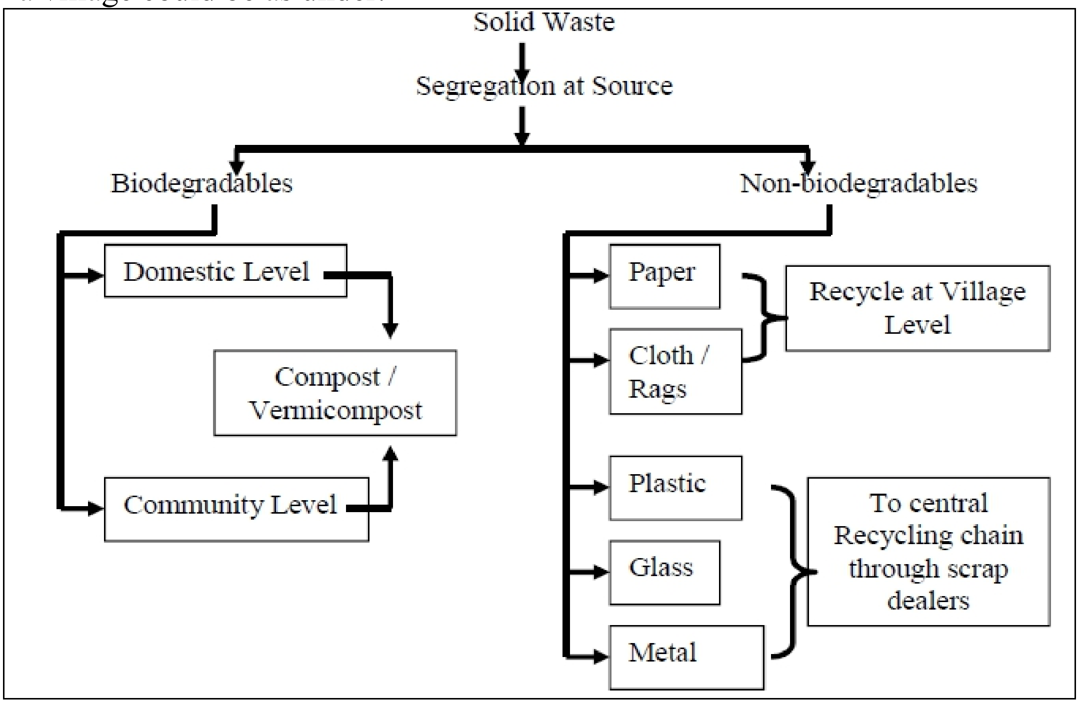


Figure 1- An ideal Solid Waste Management at a glance
Source- Shrikant M.Navrekar, “Sustainable Solid waste Management: Need of the hour”

**Waste Management System in India**

Waste management market comprises of four segments - Municipal Waste, Industrial Waste, Bio- Medical Waste and Electronic Waste Market. All these four types of waste are governed by different laws and policies as is the nature of the waste. In India waste management practice depend upon actual waste generation, primary storage, primary collection, secondary collection and transportation, recycling activity, Treatment and disposal. In India, municipality corporations play very important role in waste management in each city along with public health department. Municipal Corporation is responsible for the management of the MSW generated in the city, among its other duties. The public health department is responsible for sanitation, street cleansing, epidemic control and food adulteration. There is a clear and strong hierarchy of posts in the Municipal Corporation. The highest authority of Municipal Corporation rests with the Mayor, who is elected to the post for tenure of five years. Under the Mayor, there is a City Commissioner. Under the city commissioner, there is Executive Officer who supervises various departments such as public health, water works, public works, house tax, lights, projection tax, demand and a workshop, which, in turn, all are headed by their own department heads. The staffs in the Public health department are as follows: Health officer, Chief sanitary and food inspector, Sanitary and food inspectors, Sanitary supervisor, Sweepers, etc. The entire operation of solid waste management (SWM) system is performed under four headings, namely, street cleansing, collection, transportation and disposal. The cleansing and collection operations are conducted by the public health department of city Municipality Corporation, while transportation and disposal of waste are carried out by the transportation department of city Municipality Corporation. The entire city can be divided in to different zones. These zones are further divided into different sanitary wards for the purpose of solid waste collection and transport operations. Currently waste management in India mostly means a picking up waste from residential and industrial areas and dumping it at landfill sites. The authorities, usually municipal, are obligated to handle solid waste generated within their respective boundaries; the usual practice followed is of lifting solid waste from the point of generation and hauling to distant places known as dumping grounds and/or landfill sites for discarding. The treatment given to waste once thus emptied is restricted to spreading the heap over larger space so as to take away the waste from the public gaze. Waste collection is usually done on a contract basis. In most cities it is done by rag pickers, small- time contractors and municipalities.

Waste Collection in India:
Primarily by the city municipality

- No gradation of waste product eg bio-degradable, glasses, poly bags, paper shreds etc.
- Dumps these wastes to the city outskirts

Local raddiwala / kabadiwala (Rag pickers)

- Collecting small iron pieces by magnets
- Collecting glass bottles
- Collecting paper for recycling

In Delhi - MCD- Sophisticated DWM (Delhi Waste Management) vehicle

There are different sweepers employed in street sweeping and primary waste collection in each city. Each sweeper is responsible for the daily cleansing of a fixed area, usually a street including all side lanes. Domestic solid waste is usually thrown on the streets directly or in plastic bags from where road sweepers collect it into heaps. These waste are then transported by hand-cart trolley to the nearby open dumps or to bins, or directly by tractor trolley to the out-skirt of the cities. The road sweepers are equipped with a broom, pan, favda (spade/showel), hand-carts, panji (small pointed hand-rake), gayti (pointed small spade to clean road-side open drains) and buckets. The waste from street cleansing is collected in wheelbarrows and thereafter; it is dumped into roadside bins or at open dumping space along with household waste. Municipal workers collect waste from collection points (open dumping spaces or bins) into various vehicles including tractors and bull carts and haul it to disposal sites. In some cases, the workers collect the MSW from the collection points using chabra (wooden baskets) and transfer it into the vehicles manually. Normally, bull carts make only one or two trips a day to the final disposal site; a tractor makes two or three trips per day whereas refuse collectors/dumper placers make four trips. Finally recycling and reuse takes place by recycling units in different cities. Recycling is related to processing of a waste item into usable forms. The concept of recycling and reuse is well embedded in India largely due to prevailing socio-economic conditions and partly due to traditional practices. In India some cities have become a hub for recycling activities as considerable amounts of recyclable materials also come from adjoining towns and villages. Recycling industry mainly process paper, plastic, glass and metals. But recycling is not a solution to all problems. It is not a solution to managing every kind of waste material. For many items recycling technologies are unavailable or unsafe. In some cases, cost of recycling is too high. Recycling forms a big part of informal sector engaged in solid waste management. Waste recycling has, in fact, both organized and unorganized sections. The lower segments working as waste and dump-pickers, itinerant waste buyers, and small traders come under the unorganized segment, while the big traders, wholesalers and manufacturers come under the organized segment of the waste-recycling sector.

**Waste Management Initiatives in India**

During the recent past, the management of solid waste has received considerable attention from the Central and State Governments and local (municipal) authorities in India. A number of partnerships/alliances are found to exist in the field of solid waste management in Indian cities. These alliances are public-private, community-public and private-private arrangements. To identify the status of existing alliances in the study area, it is first necessary to identify the various actors working in the field of waste management. These actors can be grouped as under:

- Public sector: this comprises of local authority and local public departments at city level;
- Private-formal sector: this constitutes large and small registered enterprises doing collection, transport, treatment, and disposal and recycling;
- Private-informal sector: this constitutes the small-scale, non-recognized private sector and comprises of waste-pickers, dump-pickers, itinerant-waste buyers, traders and non-registered small-scale enterprises; and
- Community representatives in the form of NGOs, etc.

These actors enter into partnerships for providing various activities related to solid waste management. These partnerships can be as follows:

- public-private (Local Authority and private enterprises);
- public-community (Local Authority and NGOs); etc
- private-private (waste-pickers, itinerant-waste buyers, waste traders and dealers, wholesalers, small scale and large scale recycling enterprises); and
- Public-private-community (Local Authority, private enterprises and NGOs).

National Solid Waste Association of India (NSWAI) is the only leading professional non-profit organization in the field of Solid Waste Management including Toxic and Hazardous Waste and also Biomedical Waste in India. It was formed on January 25, 1996. NSWAI helps the Ministry of Environment and Forest (MoEF), New Delhi in various fields of solid waste management makes policies and action plans and is entrusted the responsibility of collecting information and various data related to solid waste management from the municipalities of Urban Class-I cities(population more than 1Lakh) and Urban Class-II cities(population above 50,000), collate and disseminate the information to website which is linked to national and international organizations. The association is a member of the International Solid Waste Association (ISWA), Copenhagen, Denmark and provides forum for exchange of information and expertise in the field of Solid Waste Management at the national and international level.

The other regulatory framework for waste management is related to Indian government Initiatives for waste management under Jawaharlal Nehru National Urban Renewal Mission (JNNURM), Urban Infrastructure Development Scheme for Small & Medium Towns (UIDSSMT), "Recycled Plastics Manufacture and Usage Rules (1999) amended and now known as The Plastics Manufacture and Usage (Amendment) Rules (2003), "Draft Guidelines for Sanitation in Slaughter Houses (1998)" by Central Pollution Control Board (CPCB), Non-biodegradable Garbage (Control) Ordinance, 2006, Municipal Solid Wastes (Management and Handling) Rules, 2000, etc. At the national policy level, the ministry of environment and forests has legislated the Municipal Waste Management and Handling Rules 2000. This law details the practices to be followed by the various municipalities for managing urban waste. Other recent policy documents include the Ministry of Urban Affairs' Shukla Committee's Report (January 2000) the Supreme Court appointed Burman Committee's Report (March 1999), and the Report of the National Plastic Waste Management Task Force (August 1997). In order to get a sense of the current status of sanitation in India's cities, a survey was initiated by the Ministry of Urban Development as a part of the National Rating and Award Scheme for Sanitation in Indian Cities. The methods used for the survey can be found on the Ministry of Urban Development website. The Government of India announced the National Urban Sanitation Policy (NUSP) in 2008. As a part of this, the government proposes to encourage states to develop their own sanitation strategies to tackle their own sanitation problems and meet the goals of the NUSP. The rating and award scheme has been taken up under this policy initiative.

The first major initiative was taken by the Honorable Supreme Court of India in 1998, which resulted in formation of an expert committee to study the status of SWM in Indian cities. This Committee identified the deficiencies/gaps in the existing SWM system in the country and prepared the Interim Report in 1999 on SWM Practices for few cities. As a second major initiative, in conformance with Sections 3, 6 and 25 of the Environment Protection Act of 1986, and on the basis on the recommendations by the Committee, the Ministry of Environment and Forests (MoEF) of the Government of India, developed and issued Municipal Solid Waste (Management and Handling) Rules (MoUD, 2000). These rules aim at standardization and enforcement of SWM practices in urban areas. These rules dictate that "Every municipal authority shall, within the territorial area of the municipality, be responsible for the implementation of the provisions of these rules and infrastructure development for collection, storage segregation, transportation, processing and disposal of municipal solid wastes". The municipal authorities are further required to submit a detailed annual report on waste management to the Secretary-in charge of the Department of Urban Development of the concerned State in case of a metropolitan city; or to the District Magistrate or the Deputy Commissioner concerned in case of all other towns and cities every year. As per NSWAI, there are 303 projects till September 2009 running in the country related to waste management, environment and others. The CPCB in collaboration with National Environmental Engineering Research Institute (NEERI), Nagpur has undertaken a detailed survey of 59 cities in the country to assess the existing status of solid waste management in these cities (MoEF –India). The objective of the survey was to assess the compliance status of 59 cities with Municipal Solid Wastes (Management and Handling) Rules, 2000 and initiatives taken for improving solid waste management practices. The 59 cities selected for study cover 35 metro cities. It has been observed that initiatives for collection of waste from house-to-house and waste segregation has been undertaken in only seven cities, privatization of transportation of waste has been done in 11 cities and waste processing facilities have been set up in 15 cities. Ten waste processing facilities are based on composting; one of these composting facilities has provision for energy recovery also, four are based on vermin-compositing, and one facility employs pelletisation and energy recovery technology. In relation to hospital waste the Government of India (Notification, 1998) specifies that Hospital Waste Management is part of hospital hygiene and maintenance activities. This involves management of a range of activities, which are mainly engineering functions, such as collection, transportation, operation/treatment of processing systems, and disposal of waste. If the infectious component gets mixed with the general non-infectious waste, the entire mass becomes potentially infectious. Before the notification of Bio-Medical Solid Waste (Management and Handling) Rules 1998, now amended, waste from houses, streets, shops, offices, industries and hospitals was the responsibility of municipal or governmental authorities, but now it has become mandatory for hospitals, clinics, other medical institutions and veterinary institutions to dispose of bio-medical solid waste as per the Law. Besides all these initiatives Delhi Waste Management (DWM) was formed in 2004 as a Special Purpose Vehicle (SPV) in the Public Private Partnership (PPP) format for collection, segregation and transportation to landfill sites of municipal waste. Over 1000 employees are employed as a part of this initiative. The overall initiatives related to waste management in India can be summed up as follows in the table 1.

**Table -1**
**India's Waste Management Initiatives**

| | |
|---|---|
| **Policy and Regulation** | |
| Institutional Framework | • Central Level<br>• State Level<br>• Other Organizations/Associations |
| Legal Framework | • 74th Constitutional Amendment Act, 1992<br>• Management and Handling Rules<br>• Environment (Protection) Act, 1986<br>• National Environment Tribunal Act, 1995<br>• National Environment Appellate Authority Act, 1997<br>• Water (Prevention & Control of Pollution) Act, 1974<br>• Water (Prevention & Control of Pollution) Cess Act, 1977 |
| Environmental Norms | • Existing Environmental Standards<br>• Recently Notified Environmental Standards |
| Policy Initiatives | • National Urban Sanitation Policy, 2008<br>• National Environment Policy, 2006<br>• Policy Statement for Abatement of Pollution, 1992<br>• National Conservation Strategy and Policy Statement on Environment and Development, 1992<br>• Law Commission Recommendation<br>• Ecomark Scheme, 1991 |
| **Key Government Programmes** | |
| JNNURM | • Programme Scope and Structure<br>• Funding<br>• Experience So Far<br>• Experience on Reforms<br>• Issues and Challenges |
| Total Sanitation Campaign | • Programme Scope and Structure<br>• Funding<br>• Experience So Far<br>• Issues and Challenges |
| MNRE's Waste-to-Energy Programmes | • Programme Scope and Structure<br>• Experience So Far<br>• Issues and Challenges |
| Other Programmes | • Integrated Low Cost Sanitation Scheme<br>• National Biogas and Manure Management Programme |
| **Technology and Practices** | |
| Traditional Technologies | • Landfills<br>• Waste Incineration<br>• Sanitation |

| | |
|---|---|
| Key Projects | • Kolkata: SWM Improvement Project<br>• Kanchrapara: SWM through Citizens' Participation<br>• Kollam: MSW Management Project<br>• Chennai: MSW Project<br>• Navi Mumbai: MSW Management Project<br>• Gurgaon: Ultra Modern Waste Management Plant<br>• Namakkal: Zero Garbage Status<br>• Suryapet: Dustbin Free and Zero Garbage Town<br>• Visakhapatnam: SWM Though Citizens Participation<br>• Thiruvananthapuram: Decentralised SWM<br>• CIDCO: SWM System at Areas Adjoining Navi Mumbai |
| Key Initiatives | • Chennai: GPRS Equipped Waste Bin<br>• Ahmedabad: Tapping Methane Gas<br>• Goa: Solid Waste Management Corporation<br>• Nagpur: Bye-Laws to Collect Waste Generated in Hotels<br>• Nagpur: Management of Construction Debris<br>• Akola: CBO for Waste Management<br>• Yavatmal: Door-to-Door Collection of Solid Waste |
| **Rural Waste Management** | |
| Key Projects | • Tamil Nadu: Zero Waste Mgt. at Vellore District<br>• Maharashtra: Slwm at Dhamner Village<br>• Gujarat: Greywater Mgt. at Fathepura Village<br>• Maharashtra: Greywater Mgt. at Wadgaon Village<br>• Nashik: Wastepaper to Pepwood<br>• Kerala: Post-NGP Initiatives at Kattapana Village |
| **Industrial Solid Waste Mgt.** | |
| Key Projects | • Andhra Pradesh: 3.66-MW Power Generation Project<br>• Uttar Pradesh: 6-MW Biomass Cogeneration Power Plant<br>• Other WTE Projects<br>• Kolkata: Waste Minimisation of Small-Scale Industrial Units<br>• Himachal Pradesh: Waste Treatment Plant |
| **Liquid Waste Management** | |
| Key projects | • Municipal Liquid Waste<br>• Other Noteworthy Water Reuse and Recycling Projects<br>• Industrial Liquid Waste |

Source- India Infrastructure report (2009)

**Initiatives taken by Private Companies**

There are various private companies that are providing complete solutions for waste management. For example Subhash Projects and Marketing Limited (SPML) is a leading Engineering and Infrastructure development organization with 26 years in Water, Power and Infrastructure. Today SPML is surging ahead in Urban Infrastructure, Solid Waste Management, Water and Waste Water Systems, Cross Country Pipelines, Ports and SEZs, through BOOT/PPP initiatives. “SPML Enviro” is an integrated environment solution provider arm of Subhash Projects and Marketing Limited (SPML). It provides complete solution in relation to collection, transportation & disposal of municipal / hazardous waste, segregation and recycling of municipal waste, construction & management of sanitary landfill, construction & operation of compost plant and waste to energy plant at the Delhi airport and Hyderabad Airport. SPML Enviro has invested in the necessary resources and partnerships to provide solid and water treatment solutions. It expertise includes solid waste-to-resources’ solutions – universal, industrial and medical waste. SPML Enviro has teamed up with PEAT International, North Illinois, USA, a waste-to-resources company specializing in treating and converting waste to usable resources. PEAT's proprietary Plasma Thermal Destruction Recovery (PTDR) technology is an environmentally friendly process, that converts wastes into non-toxic synthetic gas (which is a valuable source of alternative energy) and other useful end-products. The PTDR is a proven, cost-effective, environmentally clean and commercially viable solution for waste remediation. SPML Enviro together with its joint-venture partners, has proven capabilities to successfully execute projects on turn-key basis involving Okhla sewage treatment plant, Delhi Jal Board, Bewana common effluent treatment, Delhi State Industrial Development Corporation, Delhi State Industrial Development Corporation, Yelahanka primary/tertiary sewage treatment plant, Bangalore Water Supply and Sewerage Board, Okhla common effluent treatment plant, Sewage treatment plant, Mysore, Karnataka water supply and sewerage board, etc. SPML has also formed a joint venture with the US based Company INSITUFORM Technologies (INC.). INSITUFORM is a pioneer in sewer rehabilitation projects world wide. The Company brings with them a No Dig Technology, that eliminates replacement of old sewers. In this, pipe within a pipe concept - a liner is inserted into the sewer, which makes it as good as new.

**Initiatives taken by Indian corporate**

In India, there are various initiatives taken by many corporations. For example HCL Info system believes that the producers of electronic goods are responsible for facilitating an environmental friendly disposal, once the product has reached the end of its life. HCL Info system supports the ongoing initiative for separate e-waste legislation in India. HCL has been working on an easy, convenient and safe programme for recycling of e-waste in India. HCL has created the online process of e-waste recycling request registration, where customers (both individual and corporate) can register their requests for disposal of their e-waste. Apart from corporate customers, HCL has extended its e-waste collection program to retail customers also through its HCL Touch spread points spread across the country HCL extends the recycling facility to its users regardless of the fact, when and where they purchased the product. To promote recycling of electronic waste, Nokia India launched a 'Take Back' campaign where customers can drop their old handset in the company’s stores and win gifts. The take-back campaign is aimed at educating mobile phone users on the importance of recycling e-waste. As a part of this initiative, Nokia encourage mobile phone users to dispose their used handsets and accessories such as charges and handsets, regardless of the brand, at any of the recycling bins set up across Nokia Priority Dealers and Nokia Care Centers. ITC Ltd has chosen energy management, environmental & waste management and social & farm forestry as major focus areas for CSR. Specific processes include recycling/reuse of paper mill back water for dilution of bleached pulp, recycling of paper machine primary clarifier outlet water for miscellaneous uses, etc. These are few examples to show that Indian corporate is not behind in producing initiatives related to waste management.

**Challenges in India**

Key issues and challenges include lack of collection and segregation at source, scarcity of land, dumping of e-waste, lack of awareness, etc. Simple dumping of mixed waste is the practice followed practically everywhere and especially in the developing countries as they cannot mobilize financial resources for applying expensive technology propounded by the developed countries.

In India, “The new Municipal Solid Waste Management Rules 2000”, which came into effect from January 2004, fail, even to manage waste in a cyclic process. Waste management still is a linear system of collection and disposal, creating health and environmental hazards. Urban India is likely to face a massive waste disposal problem in the coming years. Until now, the problem of waste has been seen as one of cleaning and disposing as rubbish. But a closer look at the current and future scenario reveals that waste needs to be treated holistically, recognizing its natural resource roots as well as health impacts. Waste can be wealth, which has tremendous potential not only for generating livelihoods for the urban poor but can also enrich the earth through composting and recycling rather than spreading pollution as has been the case. Increasing urban migration and a high density of population will make waste management a difficult issue to handle in the near future, if a new paradigm for approaching it is not created.

A strong need felt on private sector participation in waste management but we can not ignore the risk of private sector participation. Risks of private sector involvement may include a lack of transparency, a commercial failure that would then lead to disturbance of public services, or low cooperation between stakeholders. Another important questions is that how effective are the public-private partnerships? We remember that Chennai based corporation and French conglomerate Onyx partnered for garbage collection. But we really don't know how effective it was in practical sense. The Corporation paid heavy amount for garbage clearance. But there were complaints against the company. In any case the company was simply collecting garbage and dumping it on the dumpsites. There is no engineering miracle in collecting and dumping waste. The way forward is proper waste management policies which must be adopted and responsibilities of each are defined in proper manner and correctly watched, if the municipal authorities get the private companies (like onyx) to composting and recycling wastes rather than just dumping it.

There have been a variety of policy responses to the problem of urban solid waste in India, especially over the past few years, yet sustainable solutions either of organic or inorganic waste remains untapped and unattended. For developing countries, recycling of waste is the most economically viable option available both in terms of employment generation for the urban poor with no skills and investment. All policy documents as well as legislation dealing with urban solid waste mention or acknowledge recycling as one of the ways of diverting waste, but they do so in a piece-meal manner and do not address the framework needed to enable this to happen. Critical issues such as industry responsibility, a critical paradigm to enable sustainable recycling and to catalyze waste reduction through, say better packing, have not been touched upon. Recycling of only some types of materials like plastics, paper and metals is not enough. Many types of new materials mainly used for packaging are not, or indeed cannot be, recycled in the low-end technology being employed. Besides, there are serious issues of poor occupational safety provisions of the waste pickers as well as workers.

In India, new and expensive technologies are being pushed to deal with our urban waste problem, ignoring their environmental and social implications. It is particularly true in the case of thermal treatment of waste using technologies such as gasification, incineration, pyrolysis or pellatisation. Indian waste content does not provide enough fuel value (caloric value) for profitable energy production. It needs the addition of auxiliary fuel or energy. Such technologies put communities to risk and are opposed widely. For example, the United States has not been able to install a new incinerator for the past five years, while costs for burning garbage have escalated astronomically with rising environmental standards in other countries. While the more developed countries are doing away with incinerators because of high costs (due to higher standards of emission control), developing countries have become potential markets for dumping such technologies.

**Suggestions for future improvement**

The political will is the first priority. Generally Government bodies and municipalities give priority to present problems which they face but do not think for future problems due to environmental decay. Their view is that, they will solve problems when they will face it but not now. Because doing something for environment does not provide political gains or assure next time seat. Now questions is that how can we change this mentality? We believe there should be a positive approach for a long time planning and implementation. Legislation and its effective enforcement is a key to sustainability for which the framework requires to be established.

Efforts to improve waste storage and collection are required. This can be done when each household and locality are provided standard bins that are placed outside for ease of collection. In areas where this is not appropriate, centrally located waste collection points should be established that are shared by a number of households. Wastes need o be increasingly sorted at the source, to separate materials that can be recycled and to educe the amount of wastes requiring collection and disposal. Co-operation is required among communities, the informal sector, the formal waste collectors and the authorities. An effective Solid Waste Management system should aim at minimizing manual handling and 100 % collection & transportation of solid wastes should be achieved.

In solid waste management, one thing became very clear that segregation at source is to be practiced. There are lots of initiatives to manage wastes but goes in vein because of not identifying wealth in wastes. In India, we cannot afford sanitary land filling as land is precious here and there are lot of municipalities who do not have land as trenching ground. The source segregation needs lot of study on human behavior against waste littering. A continuous sensitization programme is to be planned according to the sentiments of the residents towards their city and ultimately it will work as wonders. If waste segregation is practiced, the potential threats can be minimized directly. Besides, the quality of materials retrieved will be better due to absence of mixing. The pickers can thus, fetch better money on the materials retrieved besides having lesser threats of catching diseases, cuts and wounds encountered in the usual practice of waste picking.

The adoption and transfer of the technologies from the developed countries without adapting them to the local or regional perspective would be fallacious on the part of the developing countries. Therefore, the technical aspects for a waste management would have to take into account many points for planning and implementation of strategies according to situation of the country. It would call for the strengthening of the management sector which has to go hand in hand with technical planning.

General public can play a very important role. Public participation is necessary for a proper waste management system. Changes in the habits of segregation, littering, can change the approach towards wastes. For example in a heritage town of West Bengal, there was a movement related to waste management. Within a span of two years it successfully sensitized residents for segregation at source and not littering in open areas. Now the city is really becoming clean and other people are also participating in the movement.

In order to improve the system efficiency and increase the coverage to 100 percent in each city, it is recommended to explore alternative arrangements for collection of waste like involving private operators. A mechanism to generate revenue from the citizens should also be developed. However, the approach to public-private partnerships pursued in the developed countries cannot be replicated for Indian towns in general. This approach can only be implemented after some modifications taking into account the local conditions.

There may be separate parallel decentralized schemes by the government. Financial support by the community based on decentralized schemes will provide the right impetus for the development of waste management method. For example the municipality of Bangalore has a parallel scheme, “Swaccha Bangalore”, which levies mandatory fees for all households, businesses and educational institutions to increase its financial resources. These user fees imply that the residents will expect the municipality to provide proper waste collection services. It integrates them into the overall waste management strategy in all localities thereby helping to reduce the amount of wastes going outside the locality. The levying of waste collection and disposal fees should be based on waste generation rates and according to the economic standard of the area, whilst considering the nature of the waste wherever necessary. However, these fees should not be levied solely to meet the financial lacunae for management and the equipment demand.

In India waste management could materialize only if service delivery will be linked to private sector participation. “It is imperative that the private sector comes forward and enables the public sector stakeholders to devise appropriate frameworks that result in a win-win for both sides.” Although there are some initiatives taken by corporate but there is strong needs that all corporate must come forward to take first step. At least they should manage their industrial waste rather littering and throwing in the rivers as we can find many examples in Indian cities like Kanpur, Varanasi, Agra, etc. The private sector could also play an important role in building the capacities of municipal bodies. Solid waste management, along with recycling, presents plenty of opportunities for partnerships. For example, EXNORA is an NGO in Chennai that focuses on the environment through their solid waste management program, which works in municipalities throughout Tamil Nadu.

In fact, despite the lack of proper legal and financial support by public agencies, the informal sector has a firm standing and gives an invaluable service to a large section of the society in relation to waste management. There is an urgent need to understand the vital role of this informal sector engaged in municipal solid waste management, study their socio-economic conditions, and to integrate them with the formal sector to achieve sustainable solid waste management on one hand and improve their living conditions on the other.

The possible future policy options available with the policy makers for management of municipal solid waste are to promote either/all of the existing alliances between private-private enterprises, private-public enterprises and private-public-community. The selected scenario should be based on socio-economic, environmental and health considerations. It should fulfill the basic goal of recycling the maximum waste generated, creating maximum employment through cleaner methods without bringing any threat/reducing the potential health hazards to the lower rung of the waste recycling sector and improving their socio-economic conditions, as well.

Another option is to promote formation of micro-enterprises among the waste-recycling sector through various policies. It is observed from various case studies of developing countries like Latin America, Egypt, etc. that if waste pickers and recyclers get official recognition from the local authorities and they organize themselves and institutionalize their activities, there is an overall improvement in the living conditions of these people. Micro-enterprises in the field of solid waste management sector are a new process in India and only few examples are available. The Self Employed Women’s Association (SEWA), Ahmedabad, India successfully improved the living conditions of women paper pickers, by organizing them into cooperatives and by searching for easily accessible raw materials in bulk quantity.

There are several missing links and many loose ends both in terms of management, technology and professional skill. The solutions need thorough understanding, for example, deployment of competent persons qualified in solid waste management (real hard taskmasters and not people who turn up with a handkerchief to cover their nose to keep the stink away), application of efficient combination of waste handling equipments in cost effective manner and streamlining of the handling of waste at various stages throughout its journey from source of generation to ultimate safe disposal site, without intermediate dumping and accumulation of waste for days together. A flawless continuous flow sheet of waste management has to be developed. Matching financial support, discipline and attitudinal change in all concerned will obviously be the key for effective and successful waste management in India.

In India the landfill, sometimes described as `sanitary landfill', does not go beyond filling up of low-lying areas with stinking waste conveniently bypassing the recommended requirements for `sanitary landfill'. In the end, anything that is emptied at dumping or landfill sites continues to cause serious environmental depredation. The developed countries do boast that they handle their waste in a more scientific manner at landfill sites by laying the dumping grounds with a vulcanized plastic sheet to avoid leaching of toxic digested and undigested waste into the ground underneath. In our countries authorities practicing landfill do declare that they assiduously implement requirements for recommended landfill to assuage citizen concern.

The quantum of solid waste is ever increasing due to many reasons. Plastics waste is a significant portion of the total municipal solid waste (MSW). Recycling of plastics should be carried in such a manner to minimize the pollution level during the process and as a result to enhance the efficiency of the process and conserve the energy. Newer techniques related to recycling and reuse of plastic can be adopted.

Any new paradigm should include a cradle-to-grave approach with responsibility being shared by many stakeholders, including product manufacturers, consumers, communities, the recycling industry, trade, municipalities and the urban poor. The Ministry of Urban Development and Poverty Alleviation, as well as Agriculture, should develop the market for compost, and if required provide subsidies for compost manure – first to provide organic soil nutrients to the farmers and to solve the urban waste problem which continuously is polluting land through uncontrolled dumping.

In order to make proper waste management activity sustain in true sense, following other points need to be given attention to –

**1)** Region specific planning: Looking at the geographical, topographical and cultural diversity of the country it can be divided into five regions such as

Northern region, Eastern region, Western region, Central region and Southern region. Each of these regions has different structure. Hence all the activities should be planned & implemented on regional basis.
**2)** Planning from below: To make Solid Waste Management a success in true sense, the planning as well as implementation should start from general public level planning followed by block level planning, district level planning and state level planning.
**3)** Involvement of self help groups, youth groups and small entrepreneurs: The general public level waste management units can be run by self help groups, youth groups or small entrepreneurs. This will help in making the programme self supportive and sustainable.
**4)** Well planned and effective training policy: Technical training at all levels (General public to state) forms the backbone of a successful waste management programme. Adequate training must be given to all those concerned prior to actual launching of the programme in the field.

## Conclusion

It is suffice to say that we require a more stringent integrated and strategic waste prevention framework to effectively address wastage related issues. There is an urgent need to build upon existing systems instead of attempting to replace them blindly with models from developed countries. To prevent any epidemic and to make each city a healthy city-economically and environmentally, there is an urgent need for a well-defined strategic waste management plan and a strong implementation of the same in India. To achieve financial sustainability, socio-economic and environmental goals in the field of waste management, there is a need to systematically analyze the strengths and weaknesses of the community as well as the municipal corporation, based on which an effective waste management system can be evolved with the participation of various stakeholders in India. The public apathy can be altered by awareness building campaigns and educational measures. Sensitization of the community is also essential to achieve the above objectives and we need to act and act fast as every city in India is already a hotbed of many contagious diseases, most of which are caused by ineffective waste management.

All these above said suggestions are given in relation to India and will be effective only when we individually feel the responsibility of making environment clean. As general public, we can not do much in policy and regulations formulation, adoption of newer technologies related to recycling and other waste management options but we can play a very important role in this process if we can adopt only few tips. Here are a few tips to achieve this goal.

1. Keep ourself informed: It is important that we are in the know about what is happening on the environment front. Read about how untreated sewage is thrown into the rivers, attend public lectures about air pollution, & keep in touch with new policies that affect our environment. The more informed we are, the better equipped we are to fight such issues.

2. Consume less: Motto: Refuse…..Reduce….Reuse… Recycle .This means consuming fewer resources, reusing whatever we can and finally recycling what cannot be reused. This process greatly reduces the garbage.

3. Say 'No' to plastic bags: One of the biggest sources of pollution in Indian cities is the ubiquitous plastic bag. Refuse to accept one. Instead, carry a cloth shopping bag with us.

4. Separate our garbage: India has one of the world's most efficient recycling mechanisms. Use the service of our raddiwalla. Newspapers, bottle cans and other such recyclables can fetch us money and in the process we can help to save the environment. Rag pickers, too, perform a vital function for the city. Kitchen garbage (biodegradable) should be separated from non-biodegradable waste.

5. Compost our organic waste: Start a vermiculture bin. We can convince our neighbors to start a vermiculture bin also to produce manure.

6. Stop burning garbage: Ask our neighbors to desist from burning solid wastes. It may seem harmless but smoke emitted from leaves contributes to air pollution. Also, when there are plastic in the heap, it emits dangerous toxic fumes. Leaves can be converted to fertilizer through composting & plastic can be recycled.

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