

PROJECT REPORT

Development of LCA Framework for Solid Waste Management Technologies in India



Office of the Principal Scientific Adviser
to the Government of India



PREPARED BY
IIT Madras | IISc Bangalore | IIT (BHU) Varanasi

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Office of the Principal Scientific Adviser
to the Govt. of India

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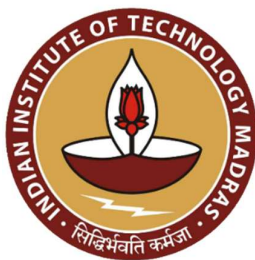
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May 2026

PREFACE

अजय के. सूद

भारत सरकार के प्रमुख वैज्ञानिक सलाहकार

Ajay K. Sood

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Foreword

Science, technology, and evidence-based innovation play a pivotal role in driving India's sustainable urban development and environmental resilience. The Office of the Principal Scientific Adviser (PSA) to the Government of India continues to strengthen this vision by fostering collaborative innovation ecosystems that bridge high-impact scientific research, civic administration, and national policy imperatives. Addressing the complex challenges of urban solid waste management requires a shift from conventional disposal mechanisms toward data-driven, circular, and scientifically validated technology frameworks tailored to India's diverse socio-economic and geographical landscapes.

Aligned with the vision of strategic national missions, including the Waste to Wealth Mission and the Swachh Bharat Mission-Urban (SBM-U), the Office of the PSA supported the national project on the *"Development of LCA framework for Solid Waste Management Technologies in India"* in 2024. Jointly undertaken by premier academic institutions—the Indian Institute of Technology (IIT) Madras, the Indian Institute of Science (IISc) Bangalore, and the Indian Institute of Technology (BHU) Varanasi—this initiative represents a landmark achievement in indigenous environmental sustainability modelling. The project successfully synergized multi-institutional expertise to develop standardized methodologies for evaluating waste processing and treatment pathways.

This report presents the scientific foundation, methodological framework, and practical tools developed under the project. A defining milestone of this initiative is the development of a dedicated Life Cycle Assessment (LCA) framework and its translation into a decision-support application. By quantifying environmental

footprints and emissions across technological life cycles, these tools provide Urban Local Bodies (ULBs) with a science-backed, objective basis for planning, technology selection, and infrastructure investment. The framework equips municipal authorities and urban planners to make evidence-based choices, accelerating the transition toward smart, resilient, and low-emission solid waste management systems across the country.

As India continues its trajectory toward climate-resilient urban growth, the adoption of standardized LCA methodologies will be vital for informing national policy, optimizing resource recovery, and achieving long-term sustainability goals. I commend the project teams at IIT Madras, IISc Bangalore, and IIT (BHU) Varanasi for their exemplary scientific rigor and collaborative commitment. I am confident that this framework and its decision-support tools will serve as an invaluable resource for ULBs, municipal leaders, and researchers, contributing meaningfully to an *Atmanirbhar Bharat* and our collective vision of *Viksit Bharat@2047*.


[Ajay Kumar Sood]

Place: New Delhi

Date: 29.09.2026

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Message

The strategic initiatives supported by the Office of the Principal Scientific Adviser (PSA) continue to strengthen India's technology ecosystem by fostering collaborative, demand-driven platforms that bring together premier academic institutions, government bodies, and civic administrations to address pressing national challenges through science and technology.

Under the project "*Development of LCA framework for Solid Waste Management Technologies in India*", supported by the Office of the Principal Scientific Adviser to the Government of India, multidisciplinary research teams successfully accelerated technology translation by bridging advanced environmental modelling with practical urban governance. The project team is commended for the detailed and thorough study carried out under the initiative. Key achievements of this initiative include the creation of an India-specific Life Cycle Assessment (LCA) inventory, standardisation of impact metrics across diverse waste treatment pathways, and the development of an interactive decision-support application tailored for Urban Local Bodies (ULBs). By translating intricate inventory data into a user-friendly digital application, this initiative empowers municipal authorities to evaluate technology trade-offs, estimate carbon footprints, and maximize resource recovery.

The successful joint execution of this project by the Indian Institute of Technology (IIT) Madras, Indian Institute of Science (IISc) Bengaluru, and Indian Institute of Technology (BHU) Varanasi demonstrates the impact of institutional synergies in tackling complex sustainability challenges. In alignment with national imperatives under the Waste to Wealth Mission and Swachh Bharat Mission-Urban, this initiative equips municipal leaders and policymakers with a science-backed basis for policy formulation, technology selection, and infrastructure investments. Moving forward, it is vital to prioritize the national interest while strengthening industry participation in technology validation, field deployment, and commercial translation to maximize real-world outcomes.

This report highlights the methodology, tools, and strategic insights generated under the project, showcasing their contribution to technology evaluation, capacity building, and evidence-based municipal planning. As ULBs adopt this framework, it will serve as a key catalyst in driving smart, resilient, and low-emission solid waste management systems, delivering lasting socio-economic and environmental impact across the nation.

Dated: 28th September, 2026


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Group photograph of the PIs with the Project Review and Monitoring Committee (PRMC) during the First PRMC Meeting held at IISc Bangalore on April 11, 2025.



Group photograph from the Stakeholders' Workshop held at IIT Madras on February 16, 2026.



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The authors sincerely thank the municipal authorities and Urban Local Bodies (ULBs) of Bengaluru, Mysuru, Tumkur, Delhi, Varanasi, and Chennai for their cooperation during field investigations, providing access to waste management facilities, and sharing relevant operational data and reports required for this study.

The authors gratefully acknowledge the Green Aadhaar team for their valuable contribution to the development of the GHG Calculator application based on the inputs from IIT Madras, IISc Bengaluru and IIT(BHU) Varanasi. We thank Dr. Abhijit Bhakte for his technical support and prompt actions to update the app based on the requirements and inputs from various stakeholders. Special thanks also go to Mr. Nikhil Panchal, Founder and CEO of Green Aadhaar, for the valuable inputs and support extended during the discussions.

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Finally, the project team appreciates all stakeholders, institutions, and individuals who directly or indirectly contributed to the successful completion of this work

EXECUTIVE SUMMARY

THE STUDY AT A GLANCE

150,000+ TPD of municipal solid waste generated in India	6 cities studied across Tier I, II and III	5 treatment technologies assessed through LCA	GHG App GHG Emission Calculator Tool for ULBs
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This study, titled “Development of LCA Framework for Solid Waste Management (SWM) Technologies in India” presents an approach to improving waste management practices in India using Life Cycle Assessment (LCA). Conducted by IISc Bangalore, IIT Madras, and IIT BHU with support from the Office of the Principal Scientific Advisor, it addresses the growing challenge of municipal solid waste (MSW), now exceeding 150,000 TPD due to rapid urbanization, population growth, and changing consumption patterns. Current waste management systems in India are largely inefficient and dependent on landfilling and open dumping, causing major environmental and public health concerns.

An LCA-based framework is developed to evaluate the environmental impacts of waste management technologies across the lifecycle—from waste generation and collection to processing and final disposal. Integrating Material Flow Analysis (MFA) and indicators such as greenhouse gas emissions, energy consumption, and pollution, it enables systematic comparison of treatment options, including composting, bio-methanation, recycling, waste-to-energy, and landfilling, to support evidence-based decision-making. The framework is applied to case studies at different urban scales—Bangalore, Mysore, Tumkur, Delhi, Varanasi, and Chennai—using primary data from field surveys and secondary institutional data. The findings show that landfilling is the dominant contributor to environmental impacts, mainly due to methane emissions, while recycling, composting, and bio-methanation offer benefits by reducing emissions and substituting conventional energy and materials. However, poor source segregation and limited processing capacity constrain these systems, so a large share of waste still goes to landfills.

This report emphasizes improved waste segregation, expansion of decentralized treatment technologies, and integration of the informal sector to enhance recycling. It highlights the need for landfill gas capture systems and recommends adopting digital tools for better data collection and monitoring. Implementing an LCA-based SWM framework can thus provide a scientific basis for policy and planning, helping India transition toward sustainable, resource-efficient, and environmentally responsible waste management aligned with circular economy principles.

Tracking MSW flow is complex because of rapid urbanization and the informal sector’s dominant role in collection and sorting, which leads to undocumented material pathways and underreported diversion. This creates major data gaps, with many zones failing to report accurate waste volumes and recycling rates, often based on estimates rather than verified data. Consequently, GHG emission reporting by ULBs is inconsistent, hindered by varied

methodologies, generic emission models, a lack of localized waste composition data, and the difficulty in measuring fugitive methane from unmanaged dumpsites. Without standardized protocols and site-specific data, municipal GHG inventories remain largely theoretical, thereby complicating climate mitigation.

To address these gaps, an LCA-based web application (GHG Emission Calculator) (<https://calc.greenaadhaar.in>) is developed to evaluate environmental impacts of waste management technologies across the lifecycle—from waste generation and collection to processing and final disposal. This enables the systematic comparison of treatment options, including composting, bio-methanation, recycling, waste-to-energy, and landfilling, with a scenario comparison feature that allows users to visualize multiple options based on carbon footprint as a key metric while allocating waste across treatments. A stakeholder workshop was organized at IIT Madras on Feb. 16, 2026 to demonstrate the GHG calculator to academics, industry, start-ups, ULBs and policymakers, and their feedback was incorporated in the current version. The report outlines the GHG calculator’s dashboard, user levels, data entry, background calculations, and output formats, and describes the validation of the app using data from the Tambaram and Avadi Municipalities in Chennai. Finally, it presents recommendations that translate study findings into actionable measures for improving municipal solid waste management performance in ULBs, corporations, and cities, identifying priority interventions to reduce environmental burdens, strengthen data reliability, and support evidence-based decision-making.

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1. PROJECT OVERVIEW AND OBJECTIVES

1.1 Background: Overview of Municipal Solid Waste (MSW) in India

India's rapidly increasing population, urbanization, and changing consumption patterns have led to a sharp rise in the quantity and complexity of municipal solid waste (MSW). Traditional waste management practices in the country have largely focused on collection and disposal, often neglecting the environmental impacts associated with the different stages of waste handling. In this context, there is a strong need for an LCA-based SWM framework that evaluates waste management options holistically, from generation to final disposal, considering their environmental and economic implications (Fig. 1.1).

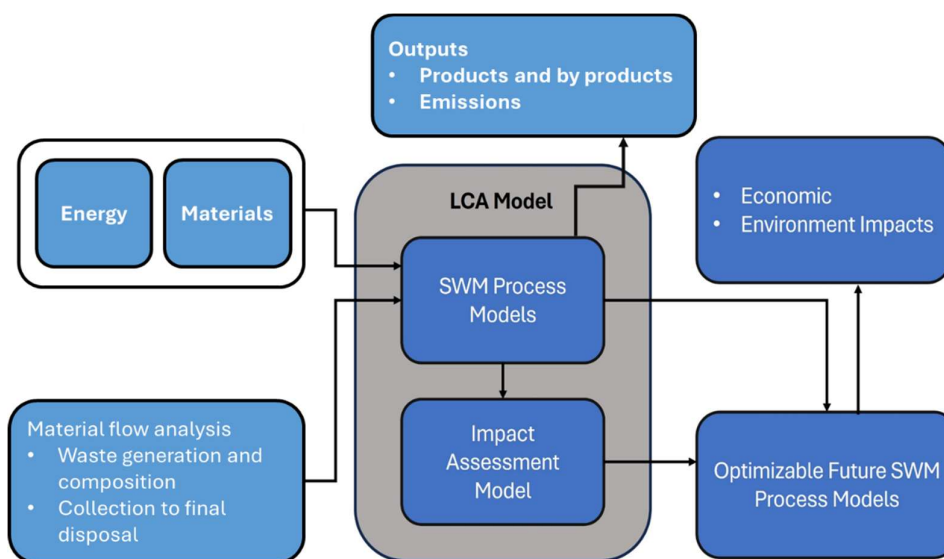


Fig. 1.1 Life cycle assessment framework for solid waste management

Furthermore, the heterogeneous composition of Indian waste, which has a high proportion of biodegradable material, requires tailored solutions that maximize resource recovery while minimizing environmental harm. An LCA-based framework can help optimize the selection of technologies such as composting and bio-methanation for organic waste and recycling systems for dry waste, thereby improving overall efficiency (Fig. 1.1). It also supports the integration of the informal sector, which plays a crucial role in recycling but is often excluded from formal planning processes.

The adoption of an LCA-based SWM framework is also aligned with national policies, such as the Solid Waste Management Rules, 2016, and initiatives, such as the Swachh Bharat Mission, which emphasize sustainable and scientific waste management practices. By incorporating LCA, policymakers can develop data-driven strategies, prioritize investments, and implement region-specific solutions that account for local conditions.

1.2 Project Consortium and Division of Responsibilities

The project aimed to generate data-driven evidence to support India's transition from current waste-disposal challenges toward a sustainable, circular economy. IIT Madras, IISc Bangalore, and IIT (BHU) Varanasi collaborated to achieve the project objectives.

The specific objectives of the work:

- **Objective I:** Identification of current waste management practices in selected sites for both fresh waste and legacy waste (Common for all teams for their respective cities)
- **Objective II:** LCA analysis of selected sites to identify the relative advantages of current and proposed waste management practices. (Common for all teams for their respective cities)
- **Objective III:** Development of a user-friendly app to enable the collection of key data from waste management facilities (Taken up by IIT Madras team)
- **Objective IV:** Development of proper SWMs practices based on discussions with the Urban Local Bodies (ULBs)

This report presents the development and application of an LCA-based framework for evaluating MSW management technologies under Indian conditions. The study focuses on assessing the environmental performance of existing waste treatment systems (Technology readiness level 9) using region-specific data collected from selected urban local bodies representing different city tiers in Bangalore, Chennai, and Delhi.

The report evaluates multiple treatment technologies, including composting, bimethanation, waste-to-energy, recycling, leachate treatment, sanitary landfilling, and biomining. The analysis considers the impacts associated with waste collection, transportation, processing, resource recovery, and final disposal.

This report also presents the structure and key functionalities of the newly developed web-based GHG emission calculator application and concludes with treatment-wise recommendations, strategic action plan with prioritization, and roadmap to transform India's municipal solid waste management systems.



2. METHODOLOGY

2.1 LCA Framework and Methodology

The research framework for developing an LCA-based framework for solid waste treatment technologies in India involves an integrated approach to evaluate the environmental performance of waste management options under Indian conditions. The framework begins with goal and scope definition, where the study objectives, boundaries, and functional units (such as treatment of one ton of municipal solid waste) are established. This is followed by LCI analysis, which includes the collection of region-specific data on waste composition, energy use, emissions, transportation, and operational parameters of treatment technologies such as composting, bio-methanation, recycling, incineration, and landfilling. The stage involves LCIA, where environmental impacts such as global warming potential, acidification, eutrophication, and human toxicity are quantified using assessment methods. The framework integrates comparative analysis to evaluate and rank waste treatment alternatives based on environmental performance, economic feasibility, and social acceptability. Sensitivity and uncertainty analyses are incorporated to ensure the robustness of the results under conditions. Finally, the interpretation phase provides insights and recommendations for policymakers, urban local bodies, and stakeholders to support informed decision-making and adoption of sustainable waste management practices. This framework is adaptable to diverse Indian contexts, enabling efficient, region-specific, and environmentally sound solid waste management strategies. The study areas are mentioned in Table 2.1.

Table 2.1 Institute and cities selected for LCA study

Institute	Cities selected
IISc Bangalore	Bangalore (Tier I), Mysore (Tier II), Tumakuru (Tier III)
IIT BHU	Delhi (Tier I), Varanasi (Tier II)
IIT Madras	Chennai (Tier I)

2.2 Data collection

The data collection strategy to develop an LCA-based framework for solid waste treatment technologies in India involves gathering primary and secondary data to ensure assessment accuracy, representativeness, and reliability. Primary data are collected through surveys, site visits, and direct measurements at waste management facilities such as composting plants, bio-methanation units, recycling centers, incinerators, and landfills, focusing on parameters such as waste composition, energy consumption, emissions, and operational efficiency. Secondary data are obtained from government reports, research publications, municipal records, and databases such as Ecoinvent, the Central Pollution Control Board, and institutions. This strategy emphasizes region-specific data collection to capture variations in waste characteristics, climate, and technological performance across India. Standardized data formats and consistent functional units ensure comparability across treatment options. Data validation, cross-checking, and gap-filling techniques address uncertainties

and missing information. This approach underpins the LCA study, enabling accurate inventory analysis and environmental impact assessment.

2.3 Material Flow Analysis

The MFA approach quantifies and tracks material flows within a system boundary over a period, making it relevant for solid waste management studies. For an LCA-based framework for waste treatment technologies in India, MFA helps map the generation, collection, segregation, processing, recycling, and disposal of municipal solid waste. It involves identifying key material streams such as organic waste, plastics, paper, metals, and inert materials and analyzing their movement through waste management stages. By applying the principle of mass balance, MFA ensures that inputs, outputs, and accumulations are accurately accounted for, thereby improving the reliability of data used in LCA. This approach enables the identification of inefficiencies, leakages, and areas for resource recovery, such as recycling and energy generation. MFA also supports decision-making by providing a clear understanding of material distribution and helping optimize waste management strategies to enhance sustainability, reduce environmental impacts, and promote circular economy practices in the Indian context.

2.4 LCA of Waste Management Technologies

The concept of LCA is based on a holistic approach that considers the cumulative environmental effects rather than focusing on a single stage of a product's life. It is typically carried out in four main phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. In summary:

- **Goal and scope** define the purpose of the study and system boundaries.
- **Inventory phase** involves data collection of inputs and outputs;
- **Impact assessment** evaluates potential environmental impacts such as global warming, resource depletion, and pollution; and
- **Interpretation phase** draws conclusions and provides recommendations.\

The LCA-based SWM framework adopted in this study is illustrated in Fig 2.1, which is also aligned with national policies such as the Solid Waste Management Rules, 2016, and initiatives like the Swachh Bharat Mission, which emphasize sustainable and scientific waste management practices.

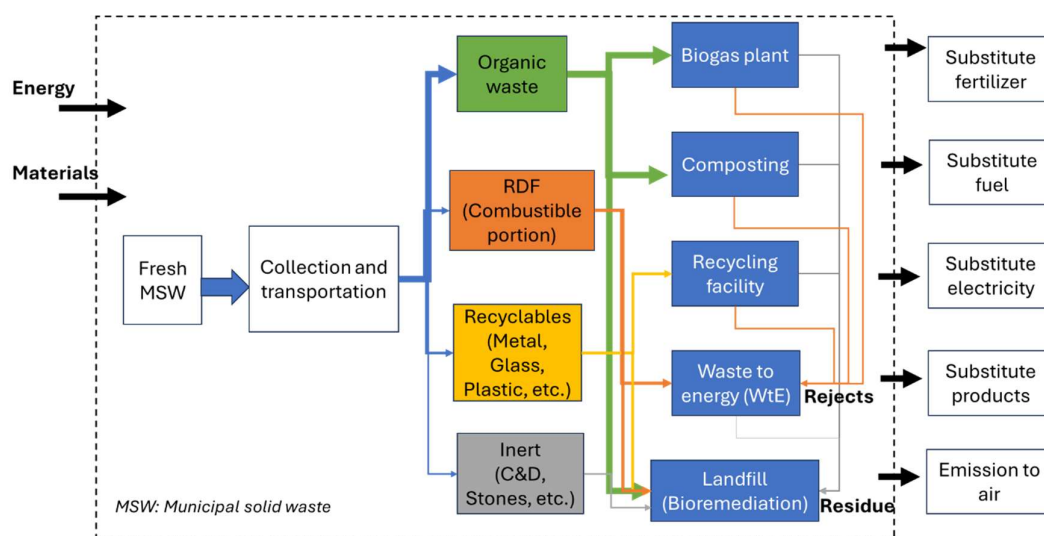


Fig. 2.1 System boundary of fresh municipal solid waste management system

2.5 Development of GHG Emission Calculator App

The project began with conceptualization and requirements definition. The team defined the scope as GHG accounting for Indian SWM technologies (collection, transport, processing, and disposal) and identified ULBs, consultants, policymakers, and researchers as target users. Through consultations with IISc, IIT Madras, IIT BHU, and potential end-users, they mapped user needs, defined functions (scenario comparison, technology-specific emission factors, regional customization, and report generation), and aligned methods with IGES EQT, MoEFCC, and CPCB guidelines.

An LCA and GHG accounting framework was designed using a modular life-cycle inventory covering cradle-to-grave SWM processes. Technology-specific emission factors were compiled from the literature, field data, and project LCAs (e.g., AD, composting, WtE, and landfilling). System boundaries, allocation rules, and biogenic carbon treatment were defined in line with ISO 14040/44 and GHG Protocol principles, and scenario logic was developed to compare baseline and alternative SWM configurations.

A web-based application architecture was selected to ensure accessibility for ULBs with varied IT capacities. The front-end supports intuitive data entry, scenario building, and results visualization, while the back-end databases securely store emission factors, process libraries, and user data. Calculation engines automate GHG computations, and the app includes role-based access, CSV/PDF export, and multilingual support (e.g., Hindi, English).

A minimum viable product was developed with core modules for data input, emission calculation, dashboards, and scenario comparison. Unit tests were run for key calculation modules (e.g., transport, biomethanation), followed by integration tests to ensure smooth interaction between the UI, databases, and engines. Internal testing also addressed UI/UX issues such as form validation, error messages, and loading states. The feature tree diagram of the app is shown in Fig 2.2.

The prototype was shared with IISc, IIT Madras, and IIT BHU for technical validation. Collaborators reviewed the data entry schema, emission factor libraries, scenario logic, and output interpretation,

leading to refinements, such as simplified forms, tooltips, and improved visualizations. Usability walkthroughs with environmental engineers and LCA practitioners further streamlined the workflow.

Case studies with pilot ULBs—Chennai, Tambaram, and Avadi—were used for real-world validation. Primary and secondary data on waste quantities, composition, transport distances, and technology performance were fed into app-based GHG calculations, which were compared against spreadsheets, literature, and prior project LCAs. Discrepancies informed updates to emission factors and calculation logic, improving accuracy and sensitivity.

Stakeholder workshops and field testing in February 2026 engaged ULB officials, NGOs, industry partners, and technocrats. The app was demonstrated and piloted in SWM master planning and technology selection exercises, generating feedback on usability, default parameters and report clarity. Stakeholders proposed features such as bulk data upload, custom emission factors, and national benchmarking. In parallel, user manuals, tutorials, FAQs, and a phased rollout with training and helpdesk support were prepared.

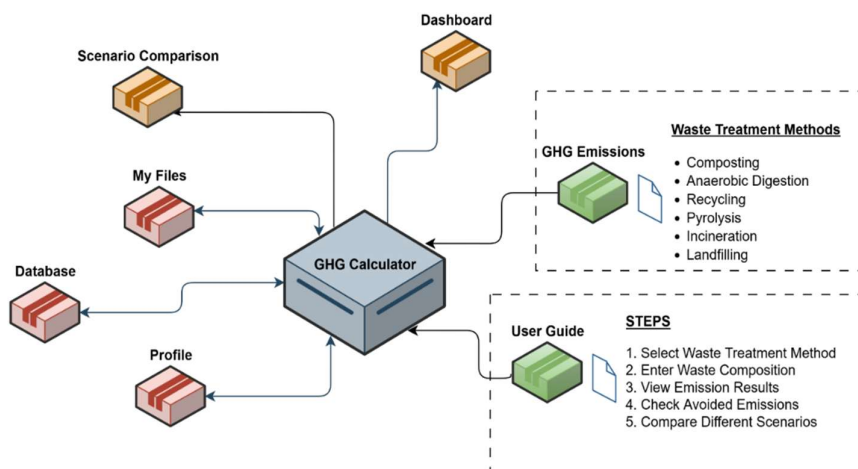


Fig. 2.2 Feature tree diagram of the GHG calculator web application

3. CASE STUDIES ON CURRENT WASTE MANAGEMENT PRACTICES

3.1 Tier I City- Bangalore

Bengaluru generates ~6,200 tons per day (TPD) of MSW, of which nearly 90% is collected through the formal system. Approximately 1,800 TPD of wet waste is processed in centralized composting facilities, producing nearly 270 TPD of compost distributed to farmers (Fig. 3.1). Additionally, approximately 70 TPD of wet waste is treated in decentralized bio-methanation plants with individual capacities of 5–10 TPD.

In the dry waste fraction, ~ 300 TPD of recyclables is recovered and sent for recycling, while another 300 TPD is sent as RDF to a waste-to-energy plant. However, a substantial amount of dry waste remains unsuitable for recycling due to contamination and poor source segregation, leading to its diversion to landfill.

Material flow analysis indicates a persistent reliance on landfills: roughly 60% of collected MSW is ultimately landfilled despite multiple processing and recovery pathways. This underscores the need to improve segregation, reduce contamination of recyclables, and expand processing capacity to divert more waste from disposal.

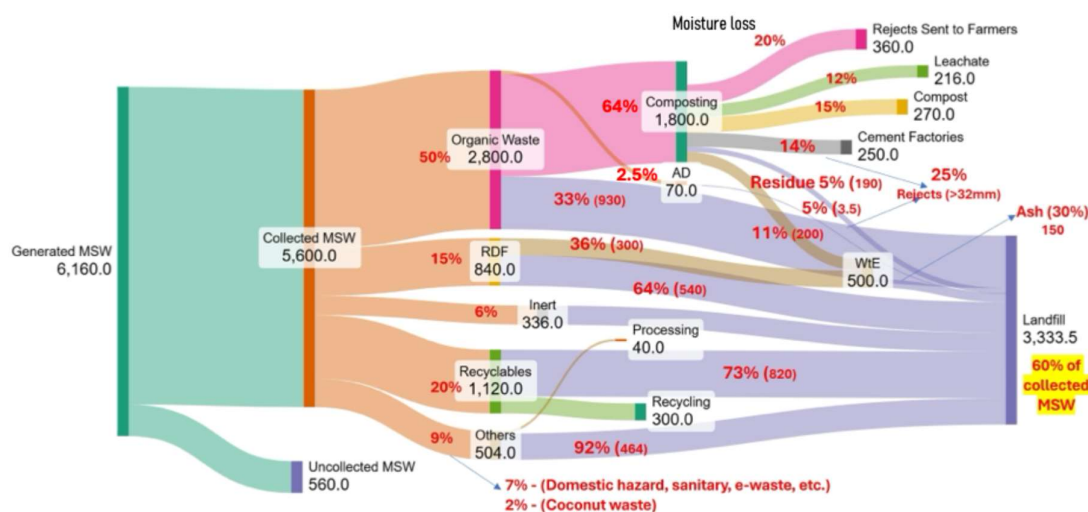


Fig. 3.1 Material flow analysis of MSW in Bangalore

The LCA results showed a net emission of 795 kg CO₂ eq. per ton of MSW. The contributions of individual treatment processes to global warming (GW) are summarized in Table 3.1. The analysis shows that landfilling dominates GW, contributing 4,532,880 kg CO₂ eq., which exceeds the emission reductions achieved through resource recovery processes. This high impact is primarily attributed to the large fraction of waste disposed in landfills (60%) and the absence of landfill gas (LFG) capture

systems. Under these conditions, landfill sites function as uncontrolled sources of methane emissions, a greenhouse gas 27–30 times more potent than carbon dioxide over 100 years.

In contrast, resource recovery pathways provide notable climate benefits. Waste diversion through composting (–2,520 kg CO₂ eq.), biogas production (–840 kg CO₂ eq.), recycling (–15,000 kg CO₂ eq.), and waste-to-energy (–62,000 kg CO₂ eq.) This results in net avoided emissions. These reductions occur primarily through material substitution, renewable energy generation, and displacement of fossil-based energy sources.

Table 3.1 Global warming (GW) contributions of solid waste management processes in Bangalore

	Waste quantity (tons)	GW (kg CO ₂ eq./ton)	Net GW (kg CO ₂ eq.)
Composting	1800	-1.4	-2520
Biogas plant (cooking)	70	-12	-840
WTE	500	-124	-62000
Landfilling	3333	1360	4532880
Recyclables	300	-50	-15000
Net emissions			4452520

These results highlight two critical priorities for reducing the climate impact of Bangalore’s waste management system.

- Substantial reduction in the landfilling rate through enhanced waste segregation, recycling, and organic waste treatment.
- Implementation of landfill gas capture and utilization systems at existing landfill sites to mitigate methane emissions and recover energy

3.2 Tier II City- Mysore

The MFA of MSW illustrates collection, processing, and disposal pathways in Mysore, with quantities in tons per day (TPD) (Fig. 3.2). Mysore generates 610 TPD of MSW, of which approximately 90% is collected. The collected waste comprises 55% organic waste (302 TPD), 36% dry waste (RDF/recyclables, 199.25 TPD), 7.5% inert materials (41.25 TPD), and 1.5% other waste (7.5 TPD).

The organic fraction is fully sent to composting facilities, producing 45 TPD of compost supplied to farmers. Approximately 30% of the composting rejects is landfilled. The RDF and recyclable fractions are only partially recovered, with 45 TPD (22.5%) directed to MRFs and the remaining 77.5% landfilled. Inert waste (41.25 TPD) and other waste (7.5 TPD) are also directly landfilled. In total, the landfill receives 233 TPD of waste, or 42% of the collected MSW, underscoring the need to improve segregation and reduce the number of rejects to lower dependence on landfills.

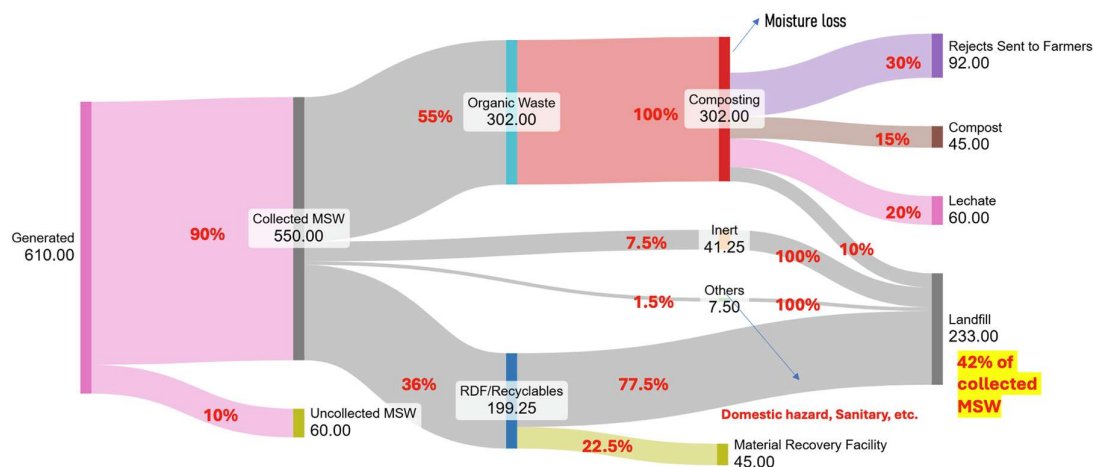


Fig. 3.2. Material flow analysis of municipal solid waste in Mysuru

Mysore demonstrated a moderate climate impact, with a net emission of 571 kg CO₂ eq. per ton of municipal solid waste managed. The contributions of the different treatment processes to GW are presented in Table 3.2. The results indicate that landfilling remains the major contributor to greenhouse gas emissions, accounting for 316,880 kg CO₂ eq. despite the city diverting a significant fraction of organic waste through composting. Approximately 42% of the collected waste is disposed of in landfills, and in the absence of landfill gas capture systems, these sites act as major sources of methane emissions.

Table 3.2 Global warming (GW) contributions of solid waste management processes in Mysore

	Waste quantity (tons)	GW (kg CO ₂ eq./ton)	Net GW (kg CO ₂ eq.)
Composting	302	-1.4	-422.8
Landfilling	233	1360	316880
Recyclables	45	-50	-2250
Net emissions			314207

Mysore's waste management system achieves better diversion of organic waste than many Indian cities, but continued reliance on uncontrolled landfilling limits the climate benefits. Transitioning to a more integrated circular system with improved recycling and methane recovery could substantially reduce the city's greenhouse gas emissions.

3.3 Tier III City Tumkur

The MFA of MSW in TCC indicates a total waste generation of approximately 150 TPD, of which approximately 140 TPD (~90%) is collected through the formal municipal system, while 10 TPD (~10%) remains uncollected (Fig. 3.13). Wet waste constitutes the major fraction (90 TPD, ~64%), followed by dry waste (35 TPD, 25%), mixed waste (14 TPD), and sanitary waste (1 TPD). The wet waste stream is entirely directed to composting facilities (90 TPD). The dry waste fraction (35 TPD) is processed at the

MRF. Sanitary waste (1 TPD, 0.7%) is separately collected and treated through incineration by the Ramky group.

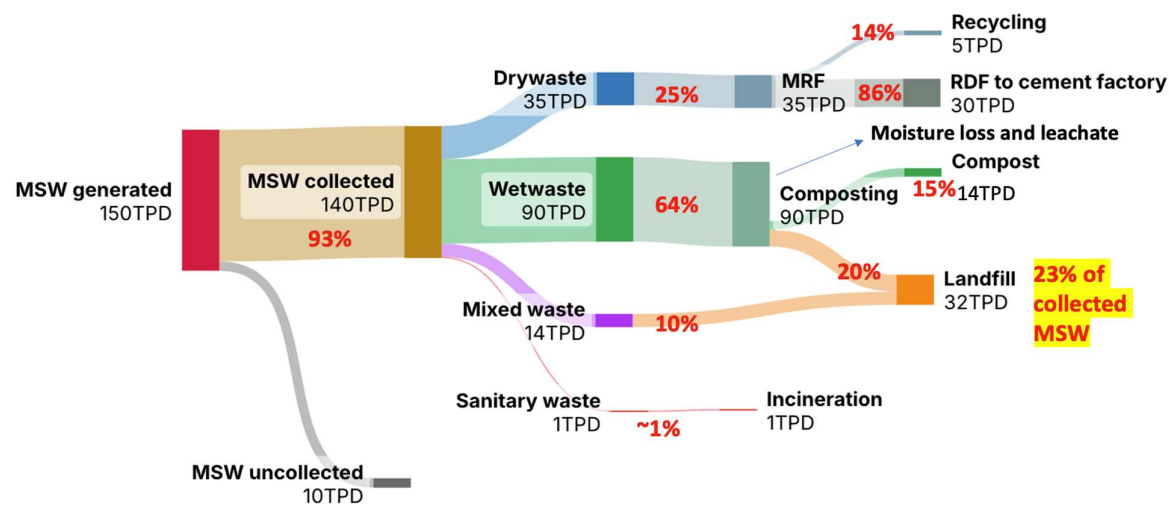


Fig. 3.3 Material flow analysis of municipal solid waste in Tumkur

Tumkur had net emissions of 39,424 kg CO₂ eq., corresponding to 282 kg CO₂ eq. per ton of municipal solid waste managed. The contributions of individual treatment processes to GW are presented in Table 3.3. Landfilling remains the primary source, contributing 43,520 kg CO₂ eq., but the overall impact is lower because only ~23% of waste is landfilled. By diverting about 77% of collected waste to resource recovery pathways—composting, WTE (cement factories), and recycling—Tumkur reduces methane emissions from landfill disposal.

Table 3.3 Global warming (GW) of solid waste management practices in Tumakuru

	Waste processed (tons)	GW (kg CO ₂ eq./ton)	Net GW (kg CO ₂ eq.)
Composting	90	-1.4	-126
Cement factory (WTE)	30	-124	-3720
Landfilling	32	1360	43520
Recyclables	5	50	-250
Net emissions			39424

Tumkur's waste management system highlights the importance of prioritizing waste segregation and diversion strategies, particularly composting, recycling, and energy recovery, to reduce reliance on landfilling. Further improvements could be achieved through enhanced recycling infrastructure and the introduction of landfill gas recovery systems.

3.4 Tier I City- Delhi

Delhi generates nearly 11320 TPD of MSW (as per annual reports of DPCC 2023-24), all collected through the formal system. Nearly 74% of the total waste is processed through five routes: WTE (54%), composting (17%), MRF (<1%), and bio-methanation (<1%), while nearly 40% is landfilled (Fig. 3.18). Of the dry waste, approximately 6000 TPD is sent to four WTE plants, generating nearly 80 MW of electricity and 800 TPD of bottom ash. The total wet waste collected, approximately 2000 TPD, is processed through composting, generating nearly 450 TPD of compost used as fertilizer. In addition, nearly 50 TPD of wet waste is sent to a bio-methanation facility with an individual capacity of 5 TPD.

The material flow analysis shows that nearly 40% of the total waste continues to be sent to landfills. Despite various treatment routes and recovery pathways, nearly half of the generated waste still goes to landfill, highlighting the urgent need for better segregation to prevent the diversion of waste to landfill sites.

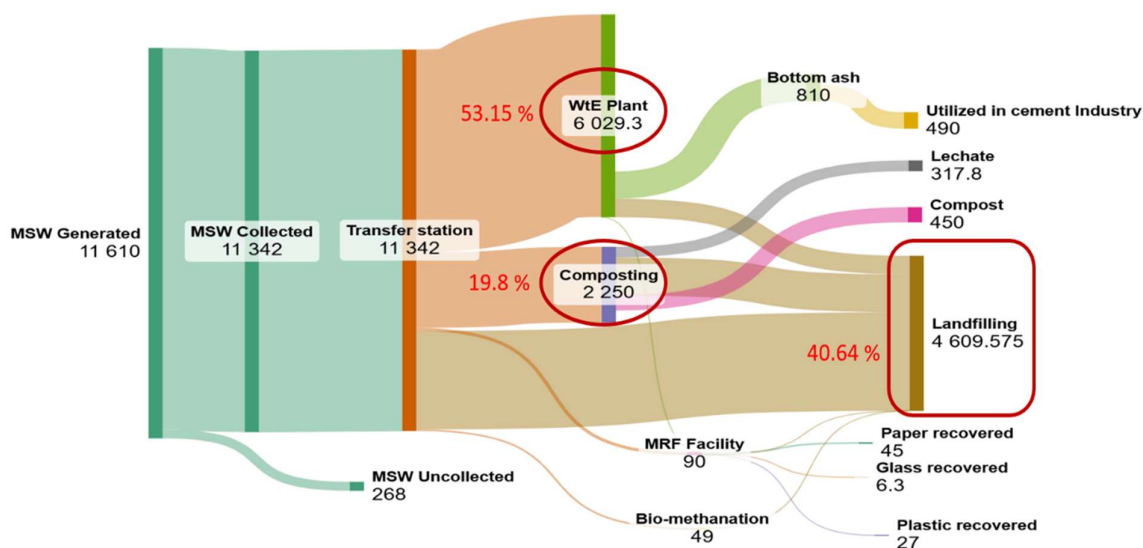


Fig. 3.4 Material Flow Analysis of current waste management practices in Delhi

A comparative life cycle assessment (LCA) was performed to examine the environmental implications of two MSW management configurations implemented in the Delhi region. The first configuration served as the reference (baseline) scenario 1, in which the environmental impacts arising from waste collection, transportation, treatment, and final disposal were assessed without considering the environmental benefits associated with resource recovery. In contrast, the second configuration (scenario 2) adopted a system expansion approach by integrating avoided burden credits resulting from resource recovery activities. These credits included electricity generated from waste-to-energy (WTE) and bio-methanation facilities, the substitution of chemical fertilizers through compost produced in composting plants, and the replacement of virgin raw materials through material recovery at material recovery facilities (MRFs). The results are summarized in Table 3.4.

Table 3.4 Global Warming Potential (GWP) contribution of MSW management technologies

Waste Management Strategy	Waste Processed (TPD)	Scenario 1 GWP (kgCO ₂ eq.)	Scenario 2 GWP (kgCO ₂ eq.)
WTE	6023	$\sim 6 \times 10^6$	$\sim 4.5 \times 10^6$
Composting	2250	$\sim 2 \times 10^6$	$\sim 1 \times 10^6$
MRF	90	$\sim 1.1 \times 10^3$	$\sim -0.5 \times 10^3$
Landfilling	2930	$\sim 7 \times 10^6$	$\sim 1.75 \times 10^6$

3.5 Tier II City Varanasi

Varanasi generates nearly 1070 TPD of MSW, of which ~90% is collected through a formal collection system. Nearly 74% of the total waste generated is processed through four major treatment routes: WTE (38%), composting (18%), MRF (<1%), and bio-methanation (<1%), and nearly 41% of the waste is landfilled (Fig. 3.5).

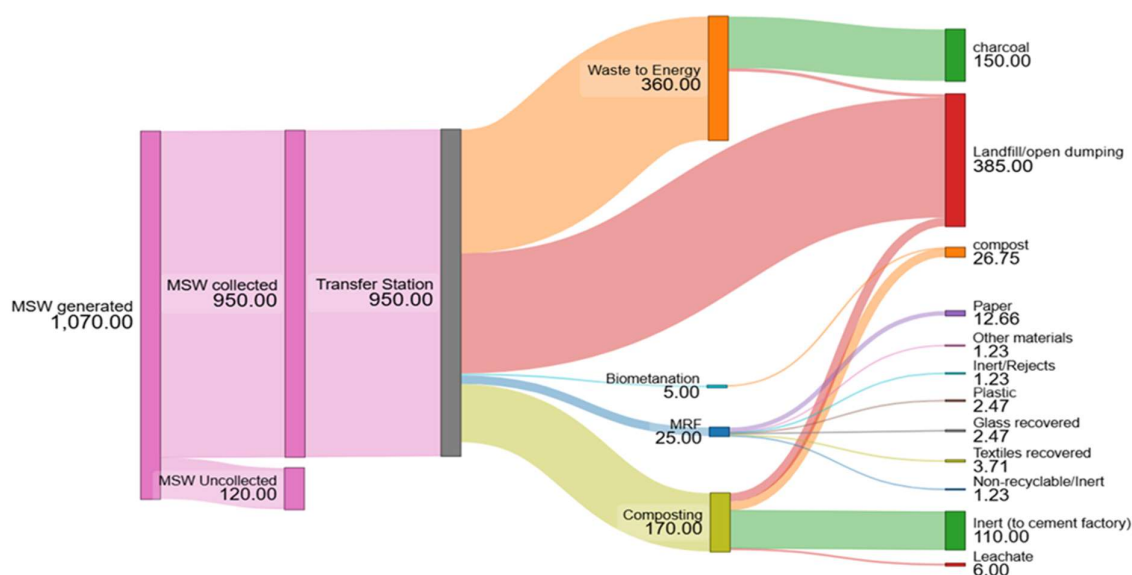


Fig. 3.5 Material Flow Analysis of current waste management practices in Varanasi

In the dry waste fraction approximately 360 TPD is sent to WTE plants and generating coal nearly 150 TPD. The total wet waste collected, approximately 170 TPD is processed through composting process. This treatment facility generates approximately 26 TPD of compost, which is further utilized as fertilizer. In addition, nearly 5 TPD of wet waste is sent to a bio-methanation facility with an individual capacity of 5 TPD.

3.6 Tier I City Chennai

The Sankey diagram (Fig. 3.6) summarizes Chennai's municipal solid waste flows at approximately 6,100 TPD, of which approximately 5,700 tons is collected, and approximately 400 tons remains uncollected or leaks from the system. Of the collected stream, approximately one quarter (1,396 TPD)

is segregated at the source, and three-quarters (4,306 TPD) remain mixed, yielding a combined composition of approximately 2,916 TPD of wet, 2,194.93 TPD of dry, 520.48 TPD of inert, and 70.59 TPD of domestic hazardous waste. Only modest fractions of the wet and dry streams are processed through resource-recovery routes (micro-composting, windrow composting, bio-CNG, coconut/garden waste treatment, RRCs, baling, incineration, and pyrolysis), while the dominant pathway remains disposal, with approximately 2,329.85 TPD of wet residues and 1,904.31 TPD of dry residues sent to landfills, together with nearly all inert and hazardous fractions. In total, approximately 4,754.64 TPD of residual waste is landfilled, split between Kodungaiyur ($\approx 2,204$ TPD) and Perungudi ($\approx 2,550.64$ TPD), highlighting a system that is still strongly landfill-dependent- despite the presence of multiple recovery and treatment options.

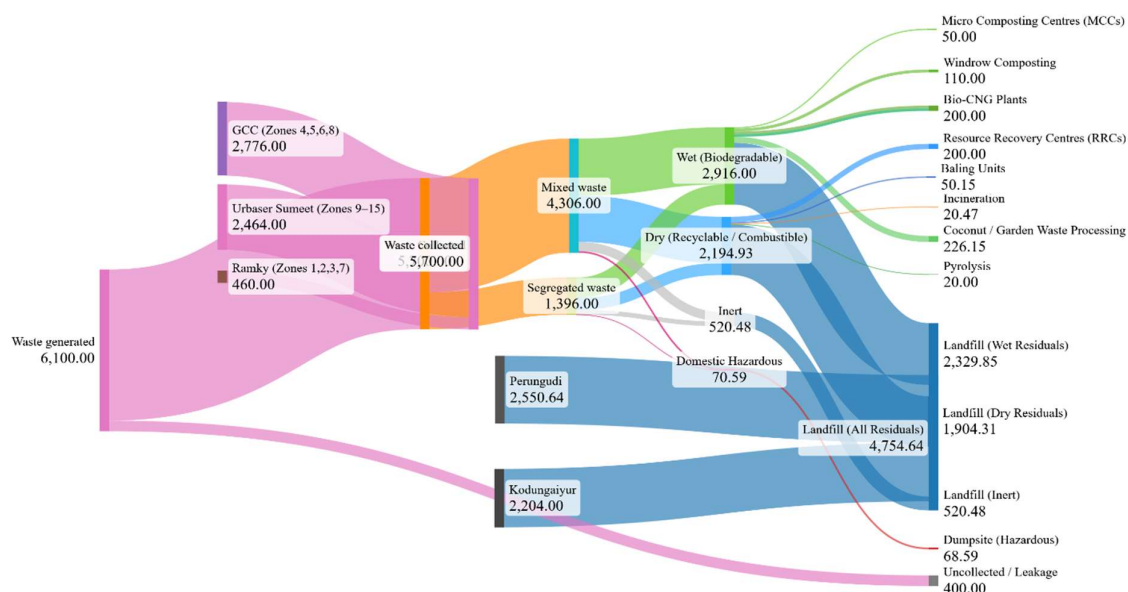


Fig. 3.6 Material flow analysis of current waste management practices in Chennai

The LCA of the selected solid waste management facilities available in the city, including two biomethanation plants of 100 TPD and a composting plant of 110 TPD. Table 3.5 presents the global warming contribution associated with selected solid waste management, expressed per ton of waste treated and as net daily emissions for the corresponding facility capacities. Composting of 110 TPD of organic waste exhibited a negative specific GWP of -5.62 kg CO₂-eq./ton, yielding a net climate benefit of -562 kg CO₂-eq., which reflects avoided emissions due to the displacement of synthetic fertilizers and reduced methane generation compared to unmanaged decomposition. In contrast, biogas plants configured for transportation and cooking fuel each treated 100 TPD and showed positive GWPs of 46.34 and 51.76 kg CO₂-eq./ton, respectively, corresponding to net burdens of 4,634 and 5,176 kg CO₂-eq.

Table 3.5 Global warming (GW) contribution of solid waste management processes in Chennai

Facility	Waste quantity (TPD)	GWP kg CO ₂ eq./ton	Net GWP kg CO ₂ eq.
Composting	110	-5.62	-562
Biogas plant (Transportation fuel)	100	46.34	4634
Biogas plant (Cooking fuel)	100	51.76	5176
Landfill	4700	1110	5217000

Across all cities, landfilling without gas capture emerged as the dominant contributor to GHG emissions, whereas resource recovery pathways consistently provided net emission reductions through material substitution and renewable energy generation. The findings demonstrate that increasing waste diversion, improving segregation efficiency, and integrating energy recovery systems are critical for reducing the climate footprint of MSW management. They further highlight the need for a systemic transition toward a circular waste management framework that prioritizes enhancing recycling and organic waste treatment, minimizing landfilling, and implementing landfill gas-capture systems. These measures are essential for achieving substantial and sustained reductions in greenhouse gas emissions across urban waste management systems in India.



4. SALIENT LCA RESULTS

4.1 Composting

4.1.1 Composting: System Boundary and Scenarios

In this study, life-cycle assessment (LCA) was used as an analytical framework to compare OFMSW management alternatives. The LCA was performed using SimaPro (version 9.6.0.1). The functional unit was the treatment of 1 ton of OFMSW (Colón et al., 2010; Serafini et al., 2025a). The LCA model includes the operation stage, collection and transportation of OFMSW, composting of waste, leachate handling, transportation of compost and liquid manure, and substitution of synthetic fertilizer with compost and liquid manure (Fig. 4.1) (Nanlin et al., 2023; Tian et al., 2025).

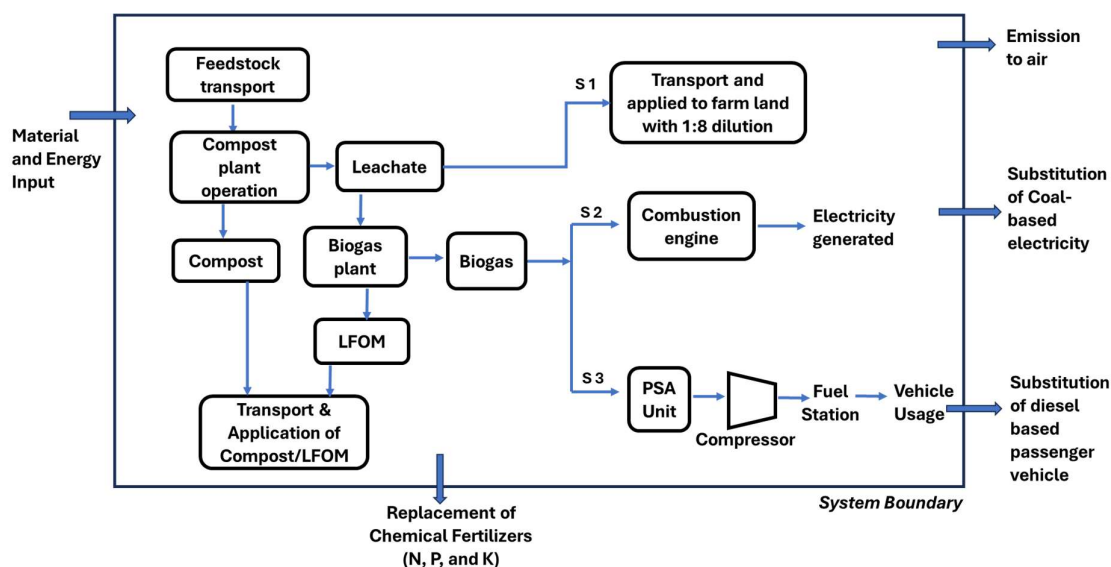


Fig. 4.1 System boundary of the compost plant life cycle assessment

End-of-life processes, such as compost application and energy displacement, were included to ensure a cradle-to-grave perspective (Biancini et al., 2022; Khandelwal et al., 2019). For the assessment of environmental impacts, the ReCiPe 2016 (H) method was employed for both midpoint estimations (Singh et al., 2020).

Scenarios Studied

- S1- Composting without energy recovery from leachate
- S2- Composting with energy recovery from leachate (biogas to electricity)
- S3- Composting with energy recovery from leachate (biogas to compressed biogas for vehicle fuel)

4.1.2 Composting: Global Warming Potential

The global warming (GW) of a compost plant per tonne of OFMSW is shown in Fig. 4.2. The result highlights individual contributions of various activities, the most significant contribution in gross emission (or total GW without credit) being associated with composting process

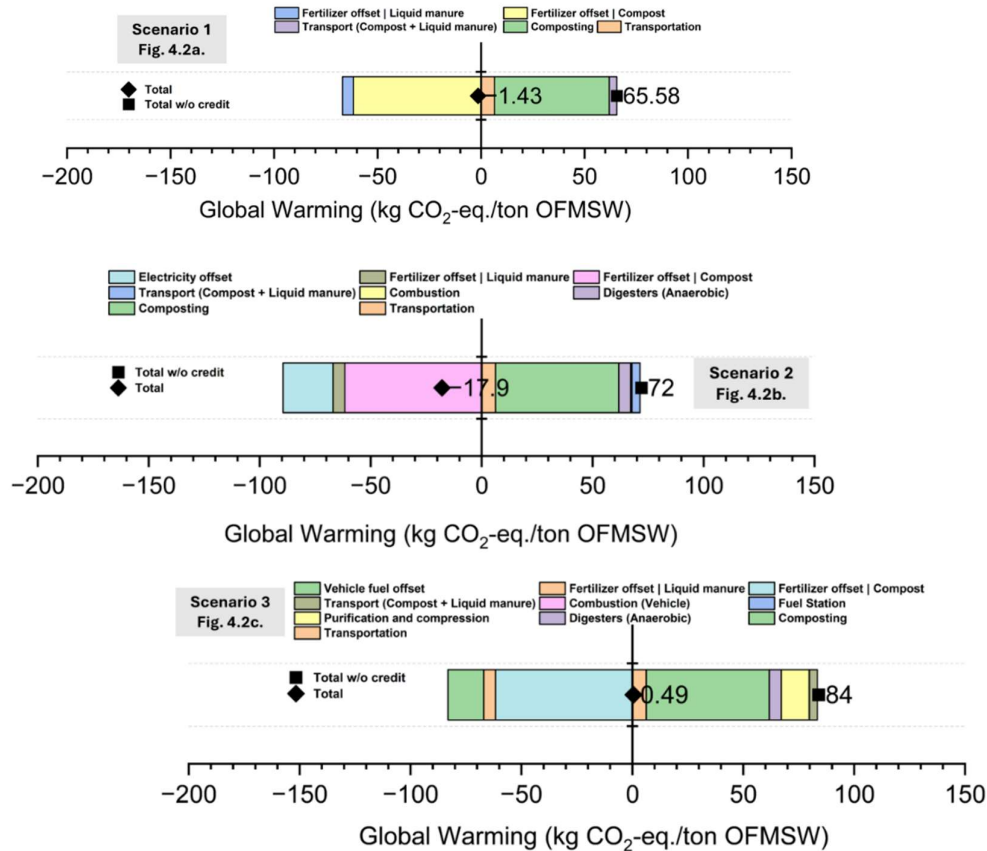


Fig. 4.2 Impact on global warming from compost plant based on organic fraction of municipal solid waste a) scenario 1 – composting without energy recovery from leachate b) scenario 2 - composting with energy recovery from leachate (biogas to electricity) c) scenario 3 - composting with energy recovery from leachate (upgraded biomethane used as vehicle fuel)

Scenario 2 (energy recovery from leachate for electricity generation) emerged as the most environmentally favorable option, demonstrating a net-negative carbon footprint of -17.9 kg CO₂ eq. Scenario 3 (energy recovery from leachate for CBG production) resulted in a somewhat net-positive footprint of 0.491 kg CO₂ eq. indicating near climate neutrality. This study shows that the environmental sustainability of OFMSW composting systems is governed not only by waste stabilization but also by the effective valorization of all outputs, particularly compost leachate. By integrating leachate-based energy recovery into the life cycle boundary, the analysis highlights a major opportunity to enhance the climate performance of composting facilities.

4.2 Biogas/ Biomethanation Plant

4.2.1 Biogas Plant: System Boundary and Scenarios

The system boundary of treatment of OFMSW in biogas plant in this study follows cradle-to-grave approach (Fig. 4.3) which includes all major operational processes of the biogas plant. This study also identifies the hotspots along the biogas system for various scenarios, where most environmental loads are associated. Specifically, five scenarios were considered based on the most common end-uses of biogas in India:

- **Scenario 1:** Biogas flaring
- **Scenario 2:** Electricity generation from biogas
- **Scenario 3:** Biogas directly used as cooking fuel in nearby areas
- **Scenario 4:** Upgraded biomethane (CBG) used as cooking fuel
- **Scenario 5:** Upgraded biomethane (CBG) used as vehicle fuel

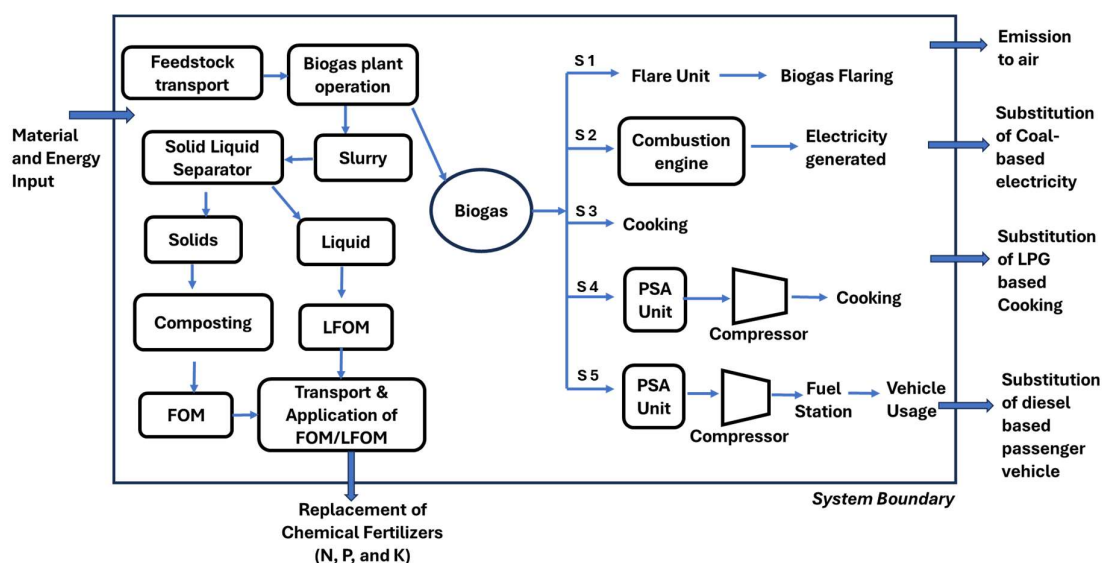


Fig. 4.3 System boundary of the biogas plant life cycle assessment

4.2.2 Biogas Plant: Global Warming Potential

The comparative analysis of the GW for various treatment scenarios of organic fraction of municipal solid waste (OFMSW) in a biogas plant (Fig. 4.4) clearly shows that while flaring of biogas results in a net positive GW of 13 kg CO₂-eq., all other scenarios demonstrate a net negative GW, indicating increasing overall environmental benefits. The most significant level of GW reduction is achieved when biogas is converted to electricity while displacing coal-based electricity, leading to a net GW of -123 kg CO₂-eq. Directly utilizing biogas for cooking (unpurified) also yields a substantial net GW of -108 kg CO₂-eq. Even after purification and bottling, using biogas for cooking (purified) still results in a negative GW of -12 kg CO₂-eq., which is less impactful than direct use. Lastly, utilizing biogas as vehicle fuel also provides a net negative GW of -11 kg CO₂-eq. while being the most economic option so far.

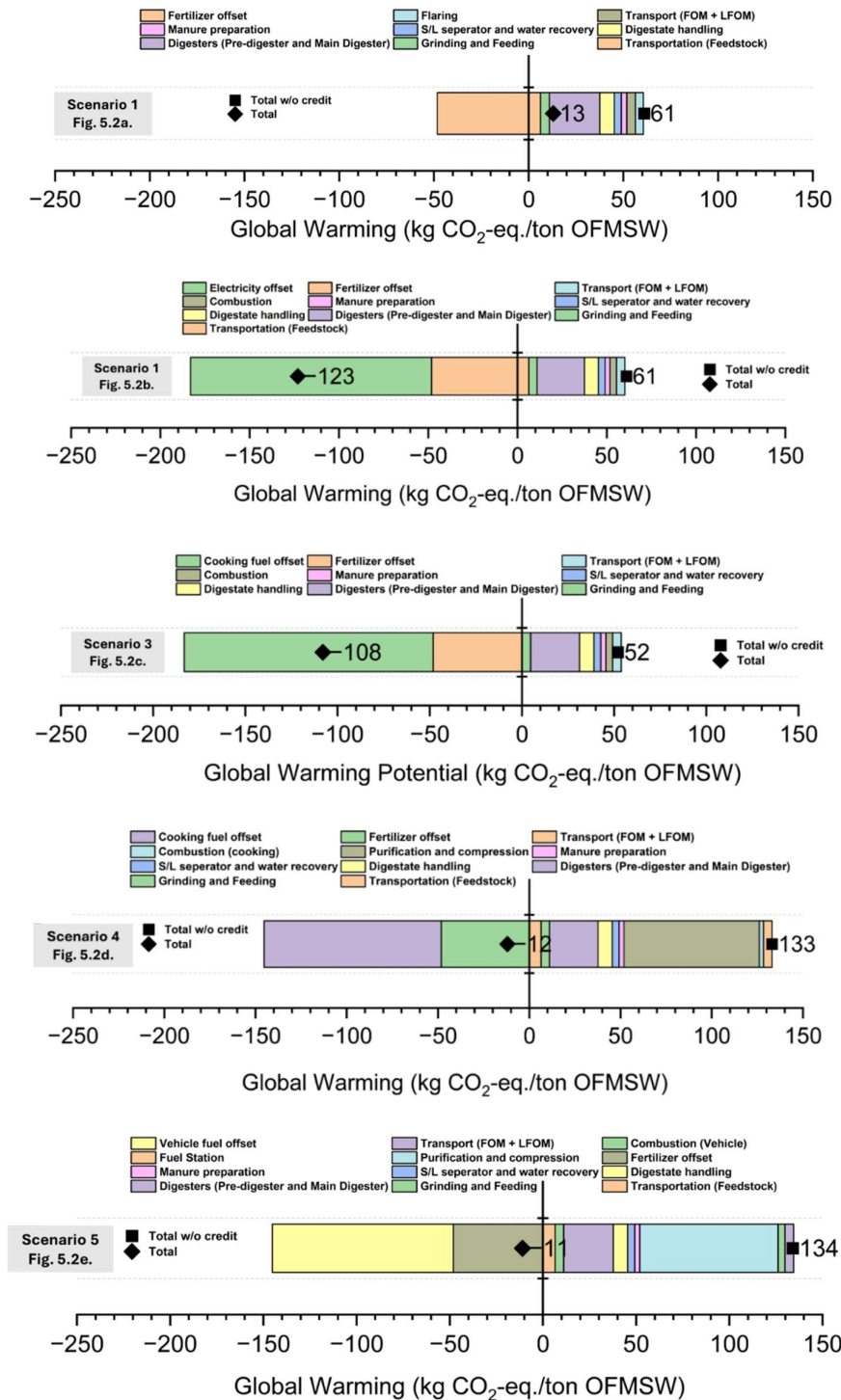


Fig. 4.4 Impact on global warming from biogas plant based on organic fraction of municipal solid waste a) scenario 1 - flaring of biogas b) scenario 2 - biogas to electricity c) scenario 3 - biogas directly used as cooking fuel d) scenario 4 - upgraded biomethane used as cooking fuel and e) scenario 5 - upgraded biomethane used as vehicle fuel

Using biogas to generate electricity presents significant economic hurdles. A critical barrier is that the marginal economic return (price of biogas-based electricity 5-7 Rs. /kWh) often leads to very low

profitability. This financial strain is compounded by direct competition from cheaper electricity generated by large, established power plants. Without significant government subsidies or guaranteed high feed-in tariffs, these biogas-to-electricity projects frequently struggle to be economically viable. When used as a direct cooking fuel, biogas faces a different set of logistical challenges. The limitation is that biogas plants for cooking must be installed exactly where the fuel will be consumed, such as in a household's backyard or a community kitchen, making large, centralized production plants for widespread distribution impractical. It should be noted that the ability to purify and compress the biogas as CBG opens avenues for commercial distribution to areas creating a high-value marketable product that improves energy access. Furthermore, this comparison underscores that energy recovery and fossil fuel displacement are crucial for maximizing the climate change mitigation potential of anaerobic digestion plants, with electricity generation offering the highest GW reduction.

4.3 Waste to Energy Plant

4.3.1 Waste to Energy: System Boundary and Scenarios

The spatial boundary of the operation stage included several key processes: collection and transportation of MSW to the plant, processing of waste via power generation through incineration coupled to high-pressure steam turbine, treatment of flue gas, disposal of residual bottom and fly ash to an engineered landfill, and environmental credits gained from the substitution of coal-based electricity. Three distinct scenarios were modelled to provide a comprehensive comparison (Fig. 4.5).

- Scenario 1: Conventional WTE without carbon capture.
- Scenario 2: WTE with carbon capture and storage (CCS)
- Scenario 3: WTE with carbon capture and utilization (CCU)

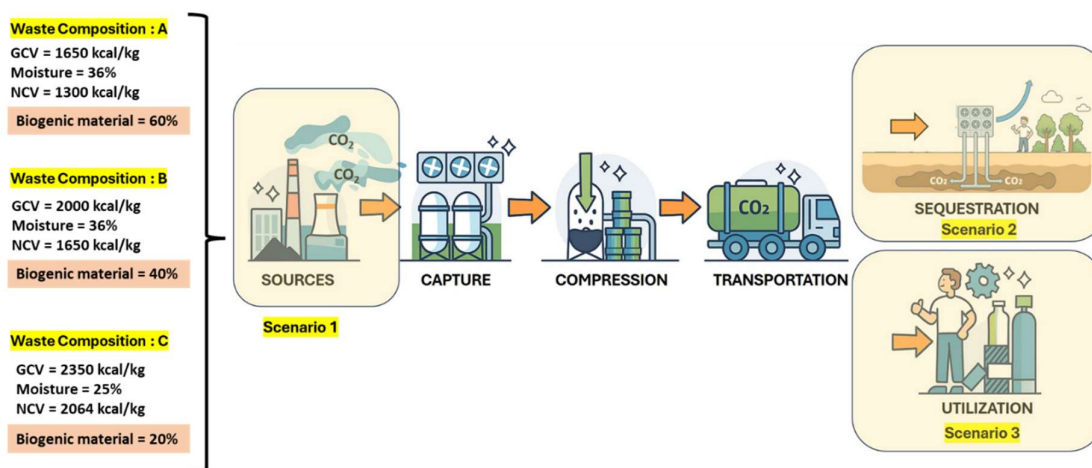


Fig. 4.5 Process flow of various Scenarios of waste to energy plant based on municipal solid waste

4.3.2 Waste to Energy: Global Warming Potential

For Scenario 1 i.e., WTE plant (without carbon capture), the GW depends on the biogenic fraction, GCV and moisture content of waste. Overall, the net GW from waste to energy plants producing only power

for offsetting coal-based electricity is in the range of -124 to -139 kg CO₂-eq./ton (Fig. 4.6) and for offsetting grid-mix electricity is 13 to 79 kg CO₂-eq.

The net GW from waste to energy plants producing power with CCS (Scenario 2) for offsetting coal-based electricity is in the range of -739 to -1030 kg CO₂-eq./ton (Fig. 5.5) and for offsetting grid-mix electricity is in the range of -609 to -819 kg CO₂-eq. This confirms that CCS is a highly effective strategy for significantly mitigating the carbon footprint of WTE facilities, regardless of the precise biogenic fraction, GCV, or moisture content of the waste within the analyzed ranges.

In Scenario 3, which involves carbon capture and utilization (CCU), the overall carbon footprint of the WTE plant remained almost identical to that observed in Scenario 2 (carbon capture and storage - CCS).

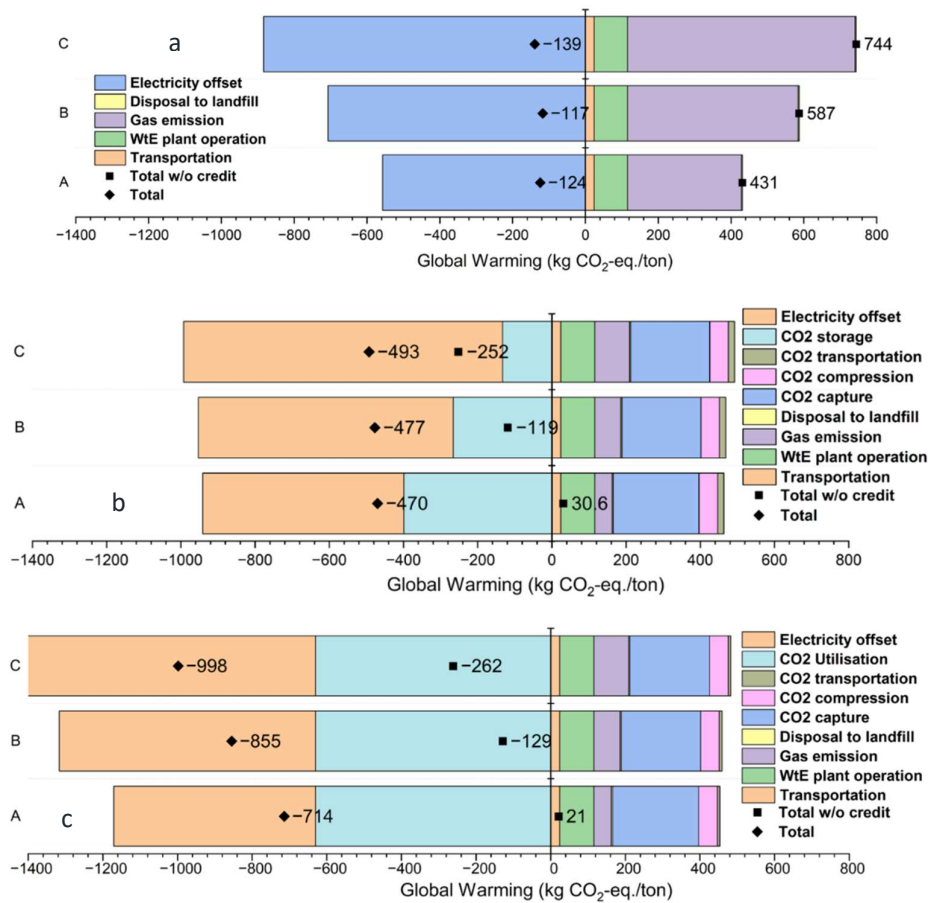


Fig. 4.6 Impact on global warming from waste to energy plant a) producing only power without carbon capture b) coupled with combined heat and power with carbon capture and storage c) coupled with combined heat and power with carbon capture and utilization (Waste composition A) represents 60% biogenic mass of GCV – 1650 kcal/kg and moisture 36% B) represents 40% biogenic mass of GCV – 2000 kcal/kg and moisture 36% C) represents 20% biogenic mass of GCV – 2350 kcal/kg and moisture 25%)

4.4 Landfill with and without Bioremediation

4.4.1 Landfill: System Boundary and Scenarios

The system boundaries were defined as cradle-to-grave, encompassing collection, transport, treatment, LFG recovery for utilization, and leachate handling. For Open Dumping (OD) and Sanitary Landfill (SLF), the focus was on traditional practices without energy recovery (Fig 4.7). Six scenarios were considered based on the most common MSW disposal practices in OD and SLF in India:

- Open Dumping (OD/S1),
- Sanitary Landfilling with leachate treatment and passive gas venting (SLF_LT/S2),
- SLF with Leachate Recirculation and Flaring (SLF_LR_F/S3),
- SLF with electricity generation (SLF_LR_ELE/S4), and
- SLF with bio-CNG production (SLF_LR_BCNG/S5)—. The bio-CNG production scenario was subdivided into two sub-scenarios, utilizing bio-CNG as vehicle fuel (VF) and cooking fuel (CF), named as SLF_LR_BCNG_VF (S5a) and SLF_LR_BCNG_CF (S5b), respectively.

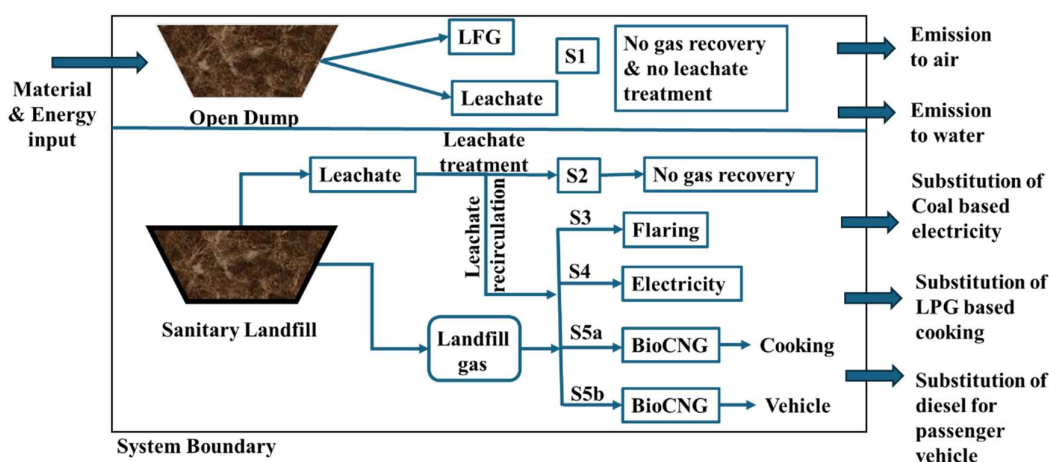


Fig. 4.7 System boundary of the different scenarios for life cycle assessment, a) Open dumping, b) Sanitary landfill with leachate treatment, c) Sanitary landfill with leachate recirculation and LFG flaring, d) Sanitary landfill with leachate recirculation and electricity generation from LFG, e) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as vehicle fuel or as cooking fuel

4.4.2 Landfill: Global Warming Potential

The GW of six scenarios are presented in (Fig. 4.8 a-e). The results highlight the main contributions of various activities, with surface emissions making the most significant contribution to gross emissions. The significant reduction in GW in scenarios 4 and 5 (Fig.4.8 e and f) is primarily driven by the substantial "LPG offset," which represents the avoided emissions from displacing LPG-based cooking with bio-CNG. The considerable offsets from replacing fossil fuels ensure that the overall system is almost carbon-neutral, highlighting its potential for sustainable waste management and decarbonization of household cooking

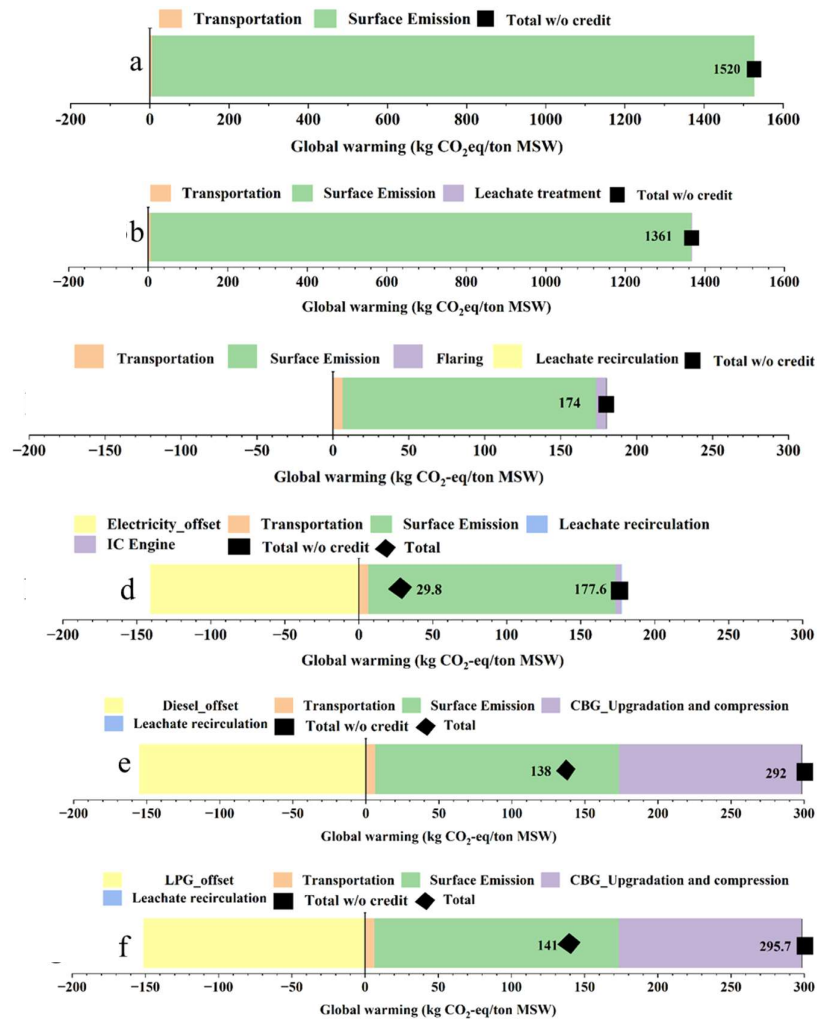


Fig. 4.8 Impact on global warming from different landfilling scenarios a) Open dumping, b) Sanitary landfill with leachate treatment, c) Sanitary landfill with leachate recirculation and LFG flaring, d) Sanitary landfill with leachate recirculation and electricity generation from LFG, e) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as vehicle fuel, f) Sanitary landfill with leachate recirculation and bioCNG (BCNG) used as cooking fuel

4.5 Biomining

4.5.1 System Boundary and Scenarios

- Scenario 1: Current baseline scenario -biomining with SLM and RDF recovery
- Scenario 2: Enhanced biomining material recovery - recyclable fractions and ash from WTE plant

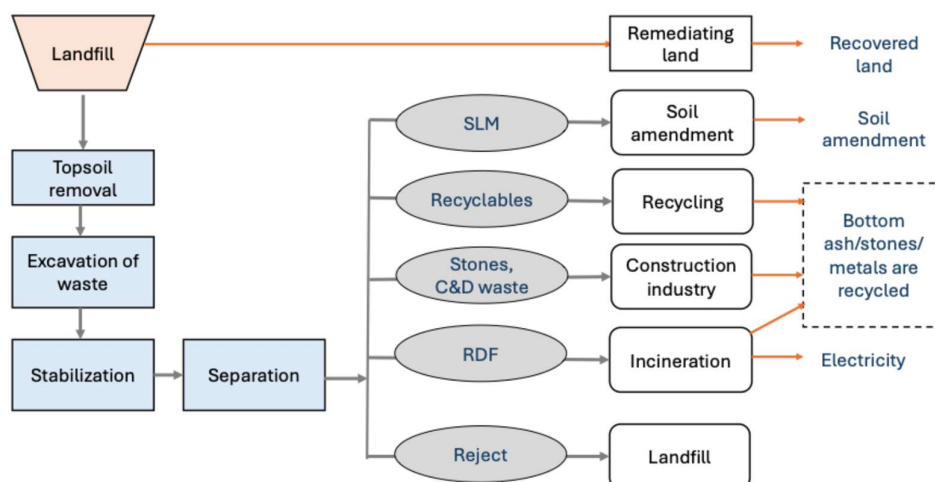


Fig. 4.9 System boundary of Biomining

4.5.2 Practical implications

The Central Pollution Control Board (CPCB) guidelines (2019) establish a necessary foundation for legacy waste handling. However, to move beyond ad hoc remediation, these guidelines must be transitioned into a regulatory framework with verifiable performance metrics. Currently, the lack of mandatory stabilization thresholds and recovery targets leads to sub-optimal environmental outcomes and the "secondary dumping" of unprocessed fractions. By establishing quantifiable key performance indicators (KPIs), regulatory bodies, such as the State Pollution Control Boards (SPCBs), can ensure that dumpsite remediation contributes to a true circular economy. The major issues or gaps in the guidelines and their corresponding recommendations are listed in Table 4.1.

Table 4.1 Issues or gap and proposed recommendation

Issues/Gap	Recommendation
Lack of formal standards for stabilization condition	Establish stabilization thresholds before further processing: Moisture < 25%, Organic content < 10%, Bulk density > 1.0 t/m ³
Lack of defined drying period and operational conditions	Specify 8–12 weeks drying, depending on climate; mandatory aeration and periodic windrow-turning (Min 2 times/week) to ensure active stabilization
No standards for monsoon / rainy-season operations	Define rain-resilient operational protocols: temporary covered processing zones, storm-water diversion, rapid transfer to covered dryers
Lack of on-site air quality monitoring	Mandatory monitoring for methane, PM10 and PM2.5, and odor control; use of dust suppression systems
Absence of leachate management directives	Leachate collection, storage, and on-site treatment must be operational throughout remediation; groundwater protection monitoring required
No requirement for performance audits of processing machinery	Enforce quarterly performance audits: throughput capacity, breakdown frequency, emission norms for excavators/screens
No requirement of baling of RDF before transportation	Mandatory baling/compaction of RDF prior to transport; covered transportation to minimize litter and combustion risk

Issues/Gap	Recommendation
Low calorific value RDF fraction (<1500 kcal/kg) usage provision	Introduce pre-processing/blending standards to improve calorific value: drying, shredding, etc.
Insufficient emphasis on resource recovery	Min. Recovery: >50% of the total mined volume (by mass) diverted from landfills.
Weak enforcement and accountability	Convert guidelines into legally binding rules; impose penalties for delays, and incentive schemes for high-performing municipalities
Inadequate post-remediation land-use guidelines	Issue clear safe land-use certification criteria: prioritized use for green buffers, solar parks, industrial utilities; residential use only after long-term monitoring

4.5.3 Carbon Credit Based on Landfill Age

Analysis shows that biomining is most carbon-efficient for "young" legacy waste. As a site reaches 40+ years, the waste largely stabilizes, and emissions from energy-intensive excavation machinery may nearly equal the emissions saved (Fig. 4.10), creating a "carbon-neutral" or "carbon-positive" operation that may not qualify for credits or meet the 'additionality' requirements of standard carbon accounting protocols. To achieve a verifiable carbon credit, emissions avoided through methane avoidance and displacement of fossil-fuel-based electricity must exceed operational emissions from fuel for excavators, electricity for trommel screens, and transport of segregated fractions.

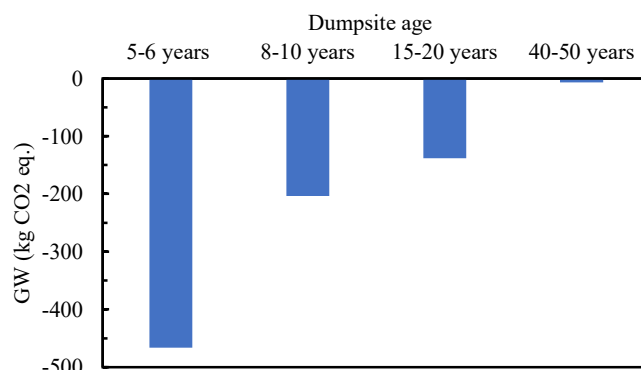


Fig. 4.10 Net emissions from dumpsites based on their age

To achieve a carbon credit, avoided emissions (methane avoidance and displacement of coal (electricity generation)) should exceed operational emissions. Combining carbon credit value and real estate value of reclaimed land may show that if a 40-year-old site has zero carbon credits, it is "profitable" because of land recovery. Revenue from recovered materials alone is insufficient to offset excavation, processing, and transportation costs, making LFM dependent on value streams such as land reclamation benefits and carbon credits. LFM carbon credit eligibility is linked to landfill age and residual biodegradability, as older dumpsites may offer limited methane avoidance potential. These interdependencies highlight the need for an assessment framework that considers environmental performance, economic feasibility, and policy relevance.

5. GHG CALCULATOR APP

The developed web-based GHG Calculator, tentatively named **ENVISAGE (Environmental Navigation & Vision for Impact Scenario Analysis and GHG Estimation)**, is designed to estimate GHG and SLCP emissions associated with municipal solid waste management systems (Fig. 5.1). The application is accessible at <https://calc.greenaadhaar.in/login>; the key features and functionalities of the application can be explored by selecting “Continue without login” on the login page.

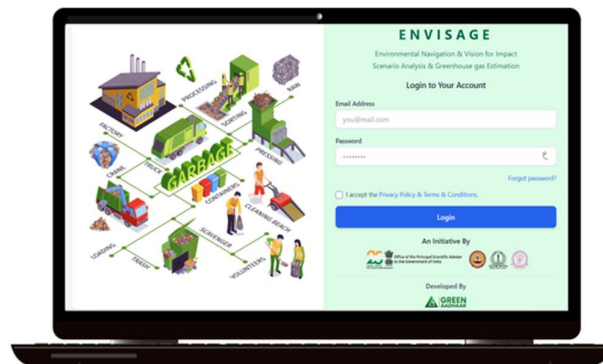


Fig. 5.1 The homepage of the developed GHG Calculator platform

The application framework is based on the Emission Quantification Tool (EQT) developed by the Institute for Global Environmental Strategies (IGES), Japan. The structure and workflow of the GHG calculator app are shown in Fig. 5.2.

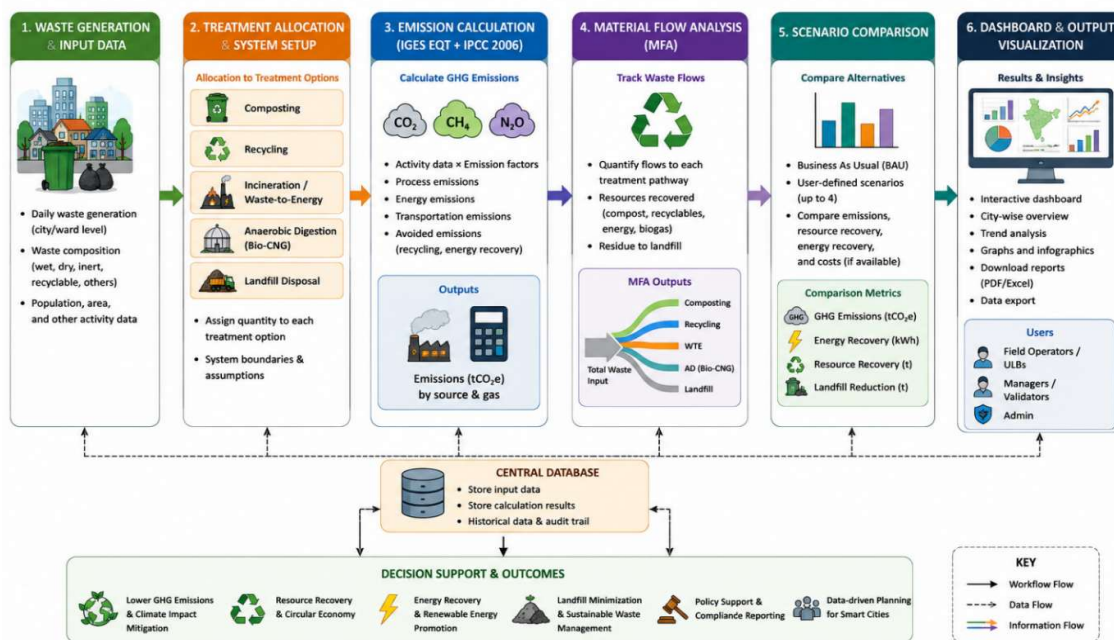


Fig. 5.2 Workflow of the GHG Calculator

5.1 Avadi Scenario Comparison

Four alternative management strategies were developed for Avadi and evaluated against the BAU case. The alternatives comprised a composting-intensive strategy (S1), an anaerobic digestion-intensive strategy (S2), a waste-to-energy intensive strategy (S3), and an integrated approach with minimum landfill disposal (S4). The total quantity of waste considered under all scenarios was maintained at 286.5 TPD to ensure consistency in comparison. Fig. 5.3 depicts the user interface of scenario comparison module showing waste allocation of Avadi.

Figs. 5.4–5.7 show the results of the GHG calculator depicting the waste collection and composition metrics, scenario-wise waste allocation, overall GHG emission for all the scenarios, individual emissions, and process-specific emissions, respectively.

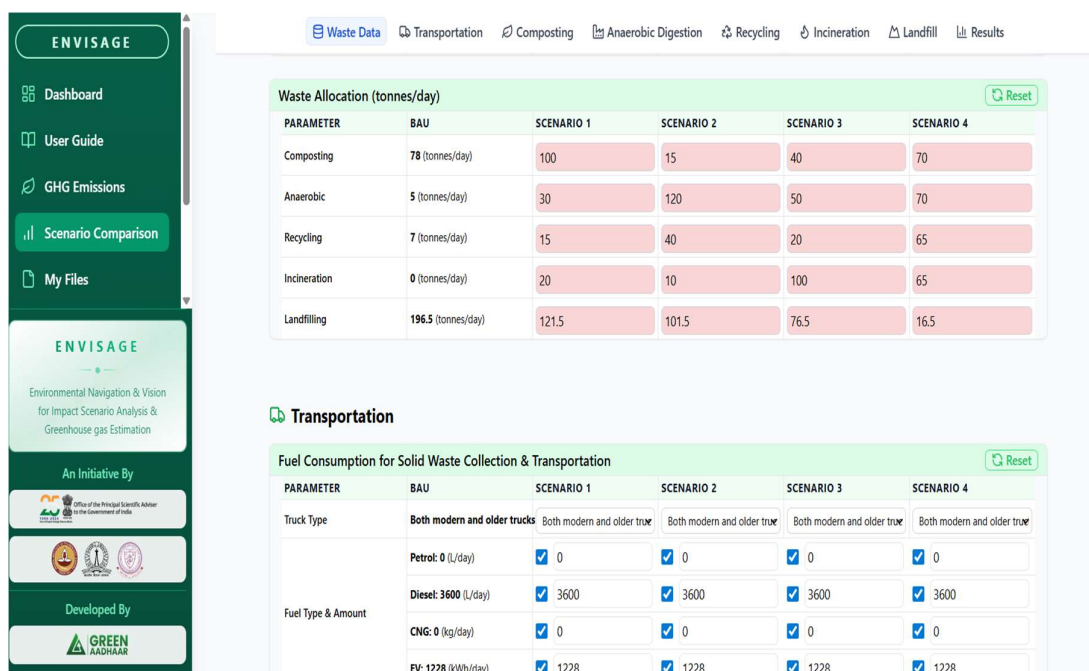
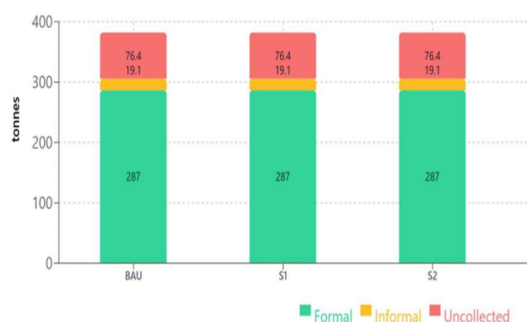
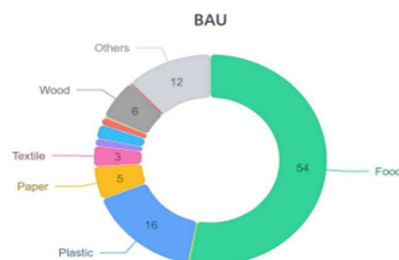


Fig. 5.3 Scenario comparison module showing waste allocation for Avadi

Waste Collection Summary



Waste Composition (% by Weight)



Waste Allocation (tonnes)

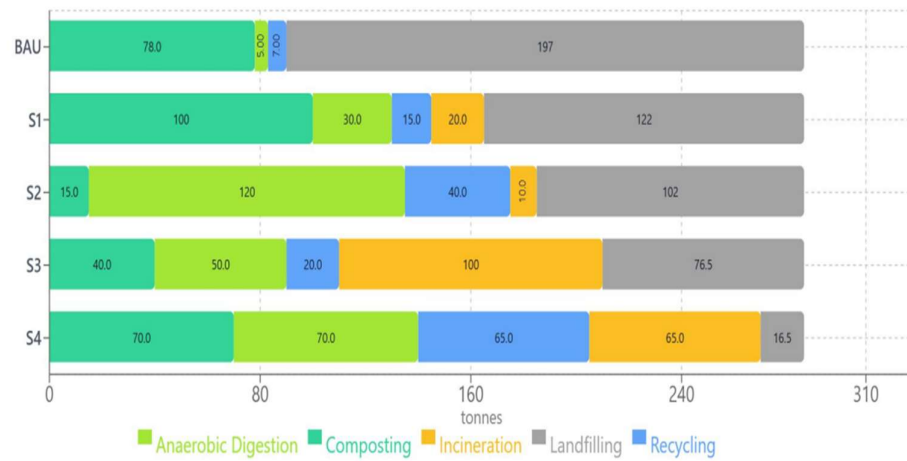


Fig. 5.5 Scenario-wise waste allocation in Avadi

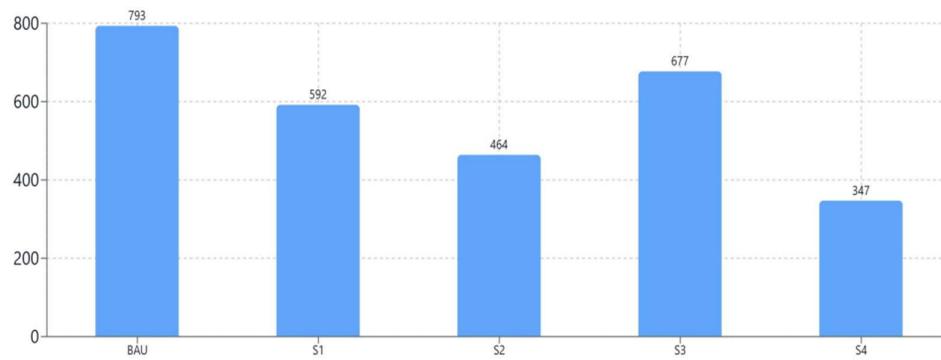
Total Emissions by Scenario (kgCO₂e/tonne)

Fig. 5.6 Greenhouse gas emissions under alternative scenarios in Avadi

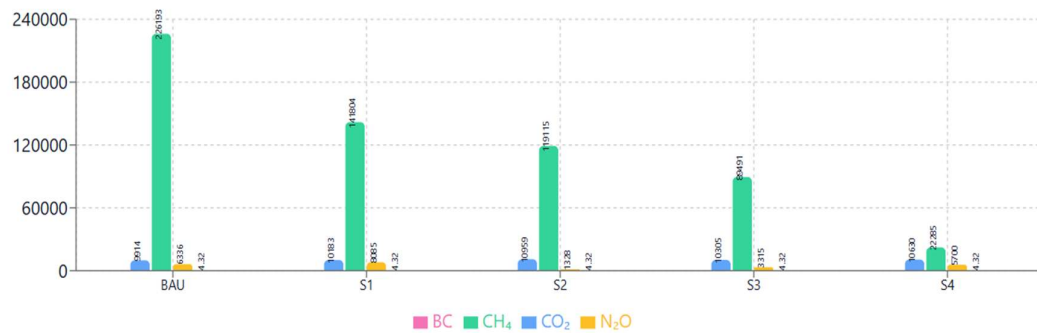
Individual Emissions by Gas (kgCO₂e; BC kg)

Fig. 5.7 Gas-wise emission comparison for Avadi scenarios

Table 5.1 summarise the comparative assessment of alternative waste management scenarios for Avadi

Table 5.1 Comparative assessment of alternative waste management scenarios for Avadi

	Emissions	Reduction	Ranking
BAU	793.31 kgCO ₂ e/ton	-	Rank 5
S1- Composting ↑	591.75 kgCO ₂ e/ton	25.4 %	Rank 3
S2 – AD ↑	463.96 kgCO ₂ e/ton	41.5 %	Rank 2
S3 - WtE ↑	677.16 kgCO ₂ e/ton	14.6 %	Rank 4
S4 - (Integrated) Landfill ↓	347.20 kgCO₂e/ton	56.2 %	Rank 1-BEST

Overall, the integrated strategy (S4) emerged as the most environmentally preferable option for Avadi, achieving the highest reduction in GHG emissions among all the alternatives considered. Based on emission reduction performance, the scenarios were ranked in the order **S4 (56.2%) > S2 (41.5%) > S1 (25.4%) > S3 (14.6%) > BAU**. The superior performance of S4 can be attributed to the balanced integration of multiple treatment technologies, enhanced resource recovery, increased energy recovery, and extensive diversion of waste away from the landfill. In contrast, the waste-to-energy intensive strategy (S3) exhibited the least improvement among the alternative scenarios owing to comparatively higher emissions associated with thermal treatment.

5.2 Tambaram Scenario Comparison

Four alternative management approaches were developed for Tambaram, similar to Avadi, and assessed in relation to the existing waste management system to examine their potential for reducing GHG emissions. The alternatives include a composting-oriented strategy (S1), an anaerobic digestion-oriented strategy (S2), a waste-to-energy-based strategy (S3), and an integrated resource recovery strategy with minimum landfill disposal (S4). The quantity of waste considered under each alternative was maintained at 455.25 TPD to ensure uniformity in assessment. Fig. 5.8 depict the user interface for scenario comparison module and how to do the waste allocation for different scenarios.

Fig. 5.9, 5.10, 5.11, and 5.12 show the results of the GHG calculator depicting the waste collection and composition metrics, scenario-wise waste allocation, overall GHG emissions for all the scenarios, and individual and process-specific emissions, respectively.

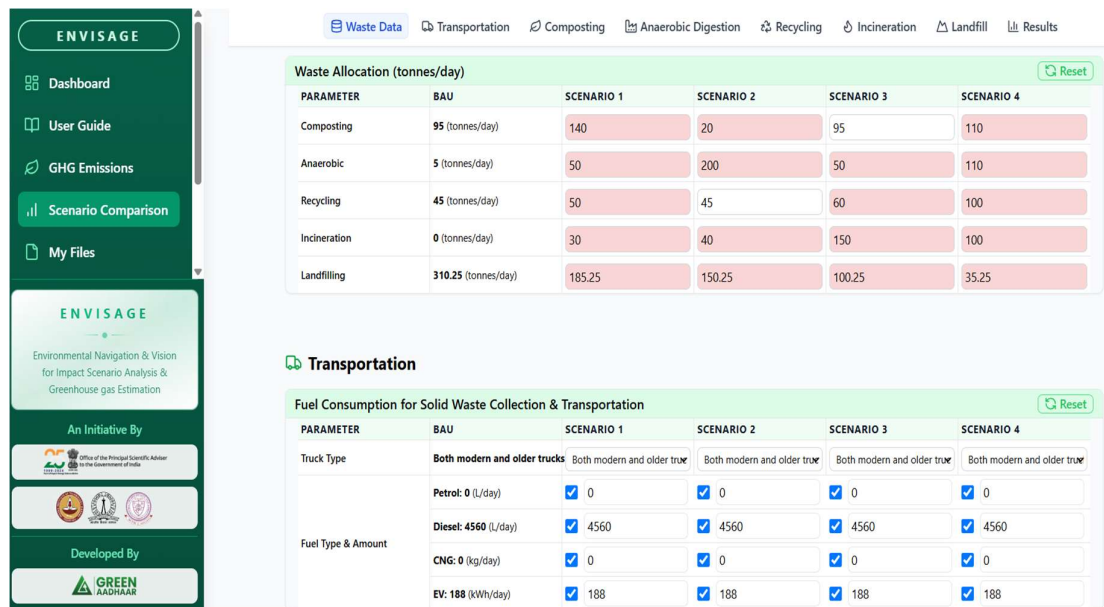
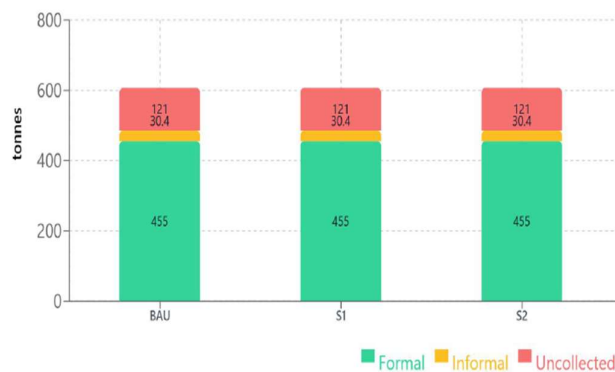


Fig. 5.8 Scenario waste allocation interface for Tambram

Waste Collection Summary



Waste Composition (% by Weight)

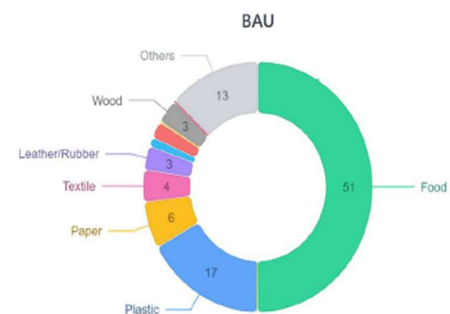


Fig. 5.9 Waste collection and waste composition metrics under different scenarios for Tambram

Waste Allocation (tonnes)

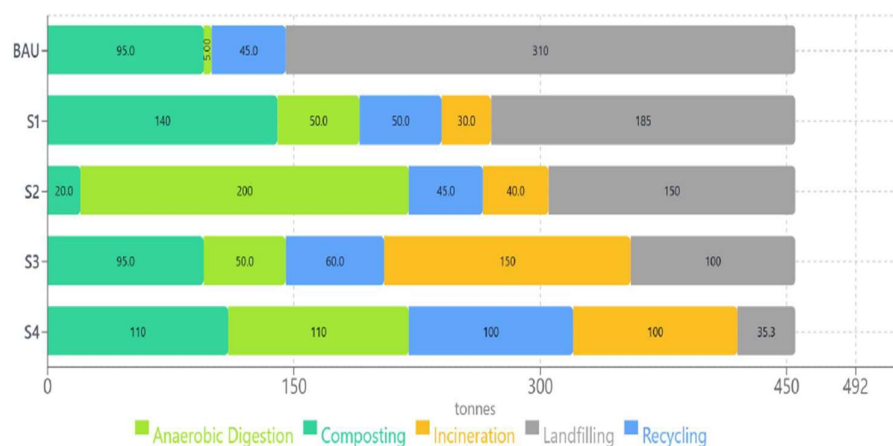


Fig. 5.10 Scenario-wise waste allocation in Tambaram

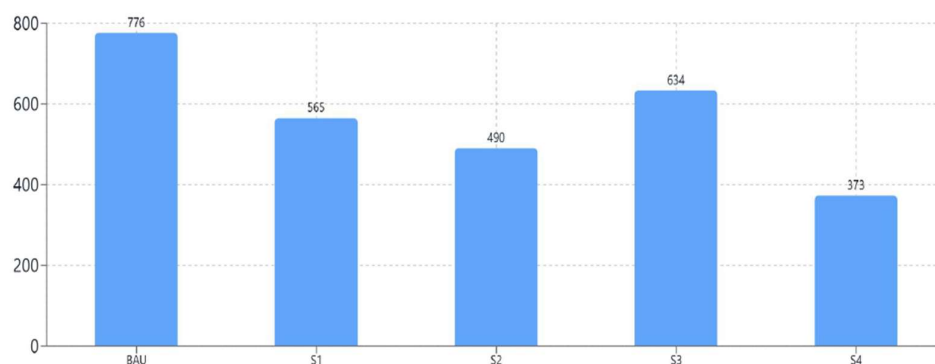
Total Emissions by Scenario (kgCO₂e/tonne)

Fig. 5.11 Greenhouse gas emissions under alternative scenarios in Tambaram

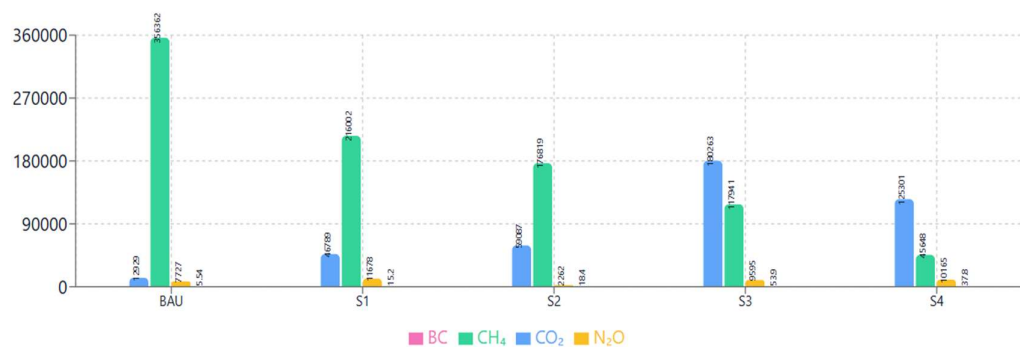
Individual Emissions by Gas (kgCO₂e; BC kg)

Fig. 5.12 Gas-wise emission comparison for Tambaram scenarios

Table 5.2 summarizes the comparative assessment of alternative waste management scenarios for Tambaram.

Table 5.2 Comparative assessment of alternative waste management scenarios for Tambaram

Scenario	Emissions	Reduction	Ranking
BAU	776.40 kgCO ₂ e/ton	-	Rank 5
S1- Composting ↑	565.21 kgCO ₂ e/ton	27.2 %	Rank 3
S2 – AD ↑	490.46 kgCO ₂ e/ton	36.8 %	Rank 2
S3 – WtE ↑	633.85 kgCO ₂ e/ton	18.4 %	Rank 4
S4 - (Integrated) Landfill ↓	372.97 kgCO₂e/ton	51.9 %	Rank 1-BEST

Overall, the integrated strategy (S4) emerged as the most sustainable option for Tambaram, very similar to the Avadi case, achieving the maximum reduction in GHG emissions among all the alternatives evaluated. Based on the emission reduction performance, the scenarios can be ranked as follows: **S4 (51.9%) > S2 (36.8%) > S1 (27.2%) > S3 (18.4%) > BAU**. The superior performance of S4 can be attributed to the combined benefits of resource recovery, biological treatment, energy recovery, and significant reduction in landfill disposal. Conversely, the waste-to-energy intensive strategy (S3) demonstrated the least improvement among the alternative options due to the relatively higher direct emissions associated with thermal treatment.



6. KEY RECOMMENDATIONS

6.1 Preamble

The recommendations from this study are grounded in life cycle assessment (LCA) outcomes, wherein the approach aligns operational choices with measurable impacts, such as greenhouse gas (GHG) emissions, resource recovery efficiency, and disposal-related losses. The LCA identified the principal environmental hotspots across the municipal solid waste processing ecosystem, with treatment-stage emissions and unmanaged disposal accounting for the largest share of GHG burdens. Quantitative results show that processes that fail to capture methane (landfills, poorly managed biogas plants) and high-carbon thermal treatments without emission controls are dominant contributors to global warming potential. Hotspots concentrate where organic degradation, uncontrolled combustion, or inefficient energy recovery occur, specifically open dumping, unmanaged landfills, and sub-optimally operated biogas and composting facilities. Collection and transportation contribute non-trivially to emissions where routing inefficiencies, vehicle idling, and high diesel dependence persist; however, their relative impact is lower than that of disposal-stage methane emissions. Gaps in plant-level operational reporting, variable waste composition datasets, and non-standardized emission factors undermine comparability between cities and technologies.

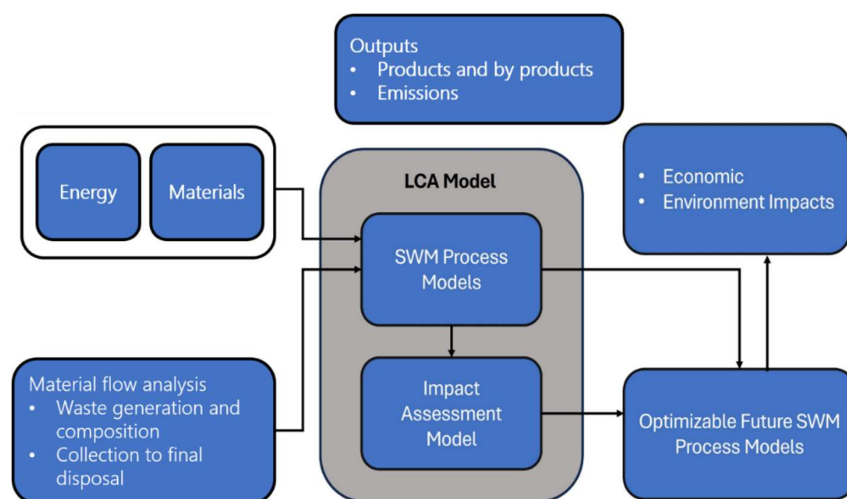


Fig. 6.1 Life cycle assessment (LCA) framework for solid waste management processes

6.2 Key Challenges Identified

The key challenges identified and limitations of the existing SWM systems are illustrated in Fig. 6.2, which are as follows:

- Inconsistencies in waste generation and composition data: The ULBs in India depend hugely on historic thumb-rule estimates of waste composition in a specific region over different periods of the year. This does not include the varying waste composition due to rapid urbanization and evolving regulations on waste management practices.

- Incomplete plant-level operational reporting, especially for throughput, rejects, energy use, methane capture, and residue management. The lack of actual waste handled vs. installed plant capacity data limits the outcomes of LCA models and city-wise planning.
- Lack of reliable emissions data: Daily datasets of gaseous, liquid (leachate), and solid residue emissions vis-à-vis the type/composition of waste processed in bio-gas, composting, landfills, and waste-to-energy plants are lacking.

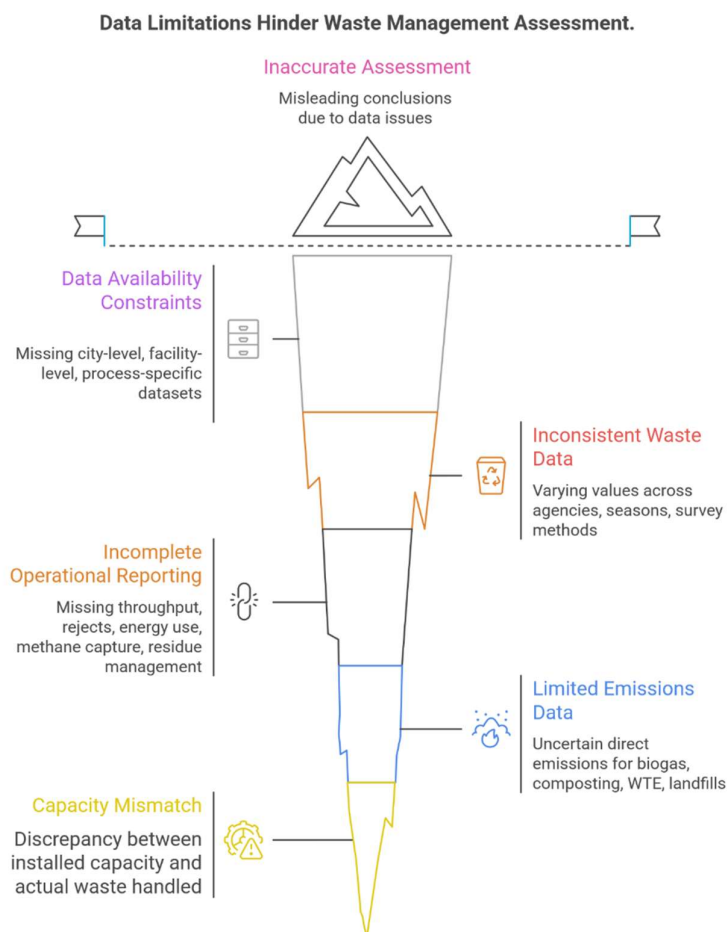


Fig. 6.2 Effect of data quality challenges and limitations on SWM assessment

6.3 Recommendations for Data Collection and Monitoring

- Standardization of data collection and reporting across municipalities, treatment facilities, and regulatory agencies with uniform definitions, units, sampling procedures, and digitalization of data collection and entry are vital to improve traceability, support centralized databases, and create a stronger foundation for consistent LCA-based policy evaluation.
- Periodic measurement of waste quantity and composition is necessary rather than estimated through static or thumb rules. Digitalization of waste collected, segregated, transported, and processed is necessary to avoid data manipulations often done through handwritten records. This also helps establish a reasonable mass balance in ULBs.

- Methane and GHG monitoring: Improving gaseous leakage quantification is critical in all waste management processes, because even small methane losses can substantially alter the climate performance.

Fig. 6.3 illustrates a standardized approach to address data reporting gaps in the LCA of SWM systems.

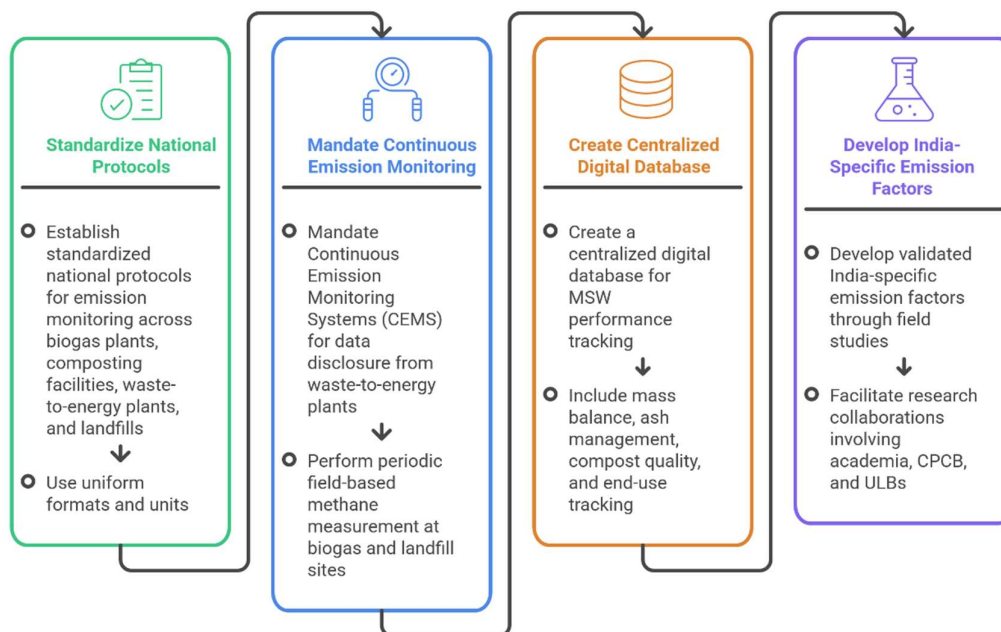


Fig. 6.3 A standardized approach to address data reporting gaps in LCA of SWM facilities

6.4 Recommendations on Treatment Technologies

This study evaluated treatment technologies using LCA methodology, including biomethanation, composting, waste-to-energy, landfill and landfill gas management, biomining, and leachate treatment and reuse. Fig. 6.4 illustrates the recommendations for SWM activities and treatment technologies. Biomethanation environmental performance can be improved by maximizing biogas utilization as compressed biogas (CBG), cooking fuel, or electricity, while controlling fugitive methane emissions across digestion and purification stages. Digestate valorization requires processing and conversion to value-added products (including biochar and biofuels) to improve technoeconomic viability. Purification-intensive pathways upgrade biomethane for cooking or vehicle fuel, but offer lower benefits due to methane slip and higher energy inputs, especially at medium scales within 100 TPD input. Environmental sustainability of organic fraction of MSW composting systems depends on waste stabilization and valorization of compost leachate. Integrating leachate-based energy recovery into the life cycle boundary highlights an opportunity to enhance the climate performance of facilities. Composting combined with anaerobic digestion of leachate and biogas-to-electricity generation is the best option from environmental and LCA perspectives. LCA studies of landfills and landfill gas management demonstrate that landfill-based energy recovery enhances the environmental and economic performance of MSW systems. Open dumping exhibits the highest warming impact, whereas electricity generation from landfill gas reduces emissions through avoided coal-based power generation. Economic analysis proves that electricity generation yields the highest revenue surplus and

shortest payback period (< 4 years), and a positive net present value when carbon credits and tax revenues are included. Therefore, landfill sites should prioritize landfill gas capture, leachate recirculation, and electricity generation as decarbonization efforts to reduce long-term environmental burdens and improve site stability.

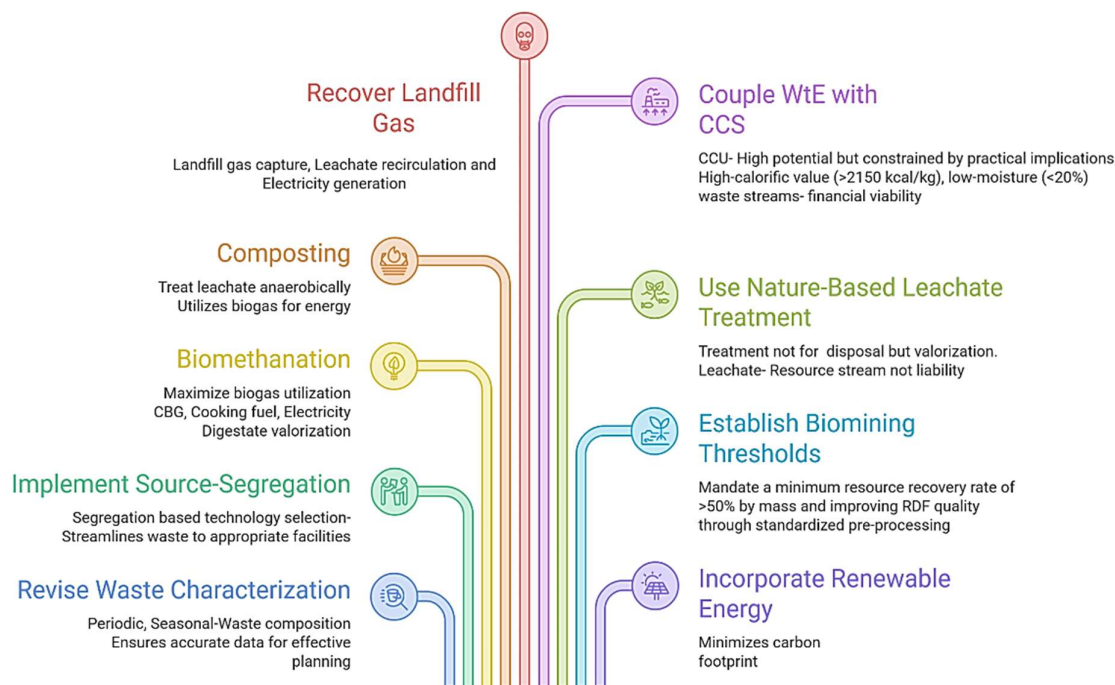


Fig. 6.4 Key recommendations on various solid waste management technologies

Our analysis shows that biomining should focus on waste excavation, land reclamation, and improving the efficiency of mechanical systems during processing. Optimizing trommel performance, energy use, and material separation is necessary to reduce the environmental burden of biomining and improve recovery. These interventions affect refuse-derived fuel (RDF), a high-calorific-value feedstock for WtE, and recyclable fractions diverted to MRF. Without verifiable metrics, such as stabilization thresholds (Moisture < 25%, Organic content < 10%) and drying periods (8–12 weeks), biomining risks "secondary landfilling" and sub-optimal recovery. To achieve a circular economy, we recommend mandating a resource recovery rate of >50% by mass and improving RDF quality through standardized pre-processing. Financial analysis at sites like Mandur shows that biomining is not self-sustaining through material recovery alone. Economic feasibility depends on land reclamation credits and avoided costs (e.g., tipping fees and long-term maintenance). Furthermore, carbon credit potential is sensitive to landfill age; younger sites offer methane avoidance, while sites over 40 years old may become carbon-neutral, with operational emissions offsetting savings. Frameworks on leachate treatment advocate "treatment for disposal"; however, a shift is required toward "treatment for valorization," where leachate is managed as a resource stream rather than a waste liability. Sustainable strategies must prioritize nutrient recovery, water reuse, energy generation, and design tailored to landfill age and leachate characteristics. Guidelines should promote the reuse of treated effluent for non-potable

applications such as dust suppression, industrial washing, or greenbelt irrigation to reduce freshwater demand, rather than targeting drinking water quality.

6.5 Implementation: Prioritization and Roadmap

Prioritization of technology should be based on a combination of environmental benefits, implementation cost, technical readiness, and institutional feasibility, as described in Fig. 6.5.

- In the short term (0–1 year), priority should be given to strict enforcement of source segregation, digitalization of waste collection, movement, and segregation, optimization of existing plant capacities, strengthening of data monitoring systems, and establishment of BAU scenarios of GHG emissions across different cities to support informed decision-making.
- The medium term (1–3 years) should focus on expanding treatment infrastructure, improving operational efficiencies, and maximizing resource recovery and utilization, supported by robust market mechanisms for the recovered products.
- In the long term (3–7 years), LCA-based evidence should lead to a shift from disposal-oriented practices to a resource-efficient, technology-driven, and circular waste management system. This includes a transition towards engineered landfill systems with proper environmental controls, power generation from landfill gas, widespread adoption of biomethanation and composting for wet waste streams, and maximum resource recovery from different non-biodegradable wastes, alongside the development of sustainable financing mechanisms such as carbon credits.

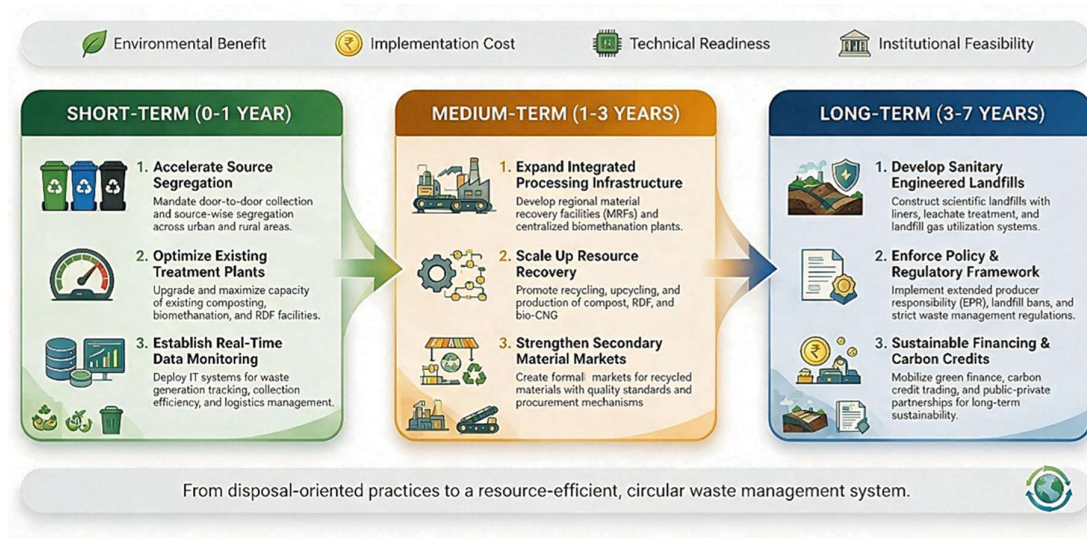


Fig. 6.5 Strategic action plan for solid waste management transformation in India

Press Release

Office of Principal Scientific Adviser to Govt

Principal Scientific Adviser to the Government of India, Prof. Ajay Kumar Sood, Launches Digital Platform to Optimise Waste Management in Cities

Posted On: 17 SEP 2026 9:44AM by PIB Delhi

Prof. Ajay Kumar Sood, Principal Scientific Adviser (PSA) to the Government of India, chaired a meeting on 16 September 2026 to review the outcomes and recommendations of the project 'Development of LCA Framework for Solid Waste Management (SWM) Technologies in India'. Dr Parvinder Maini, Scientific Secretary, also graced the meeting, which brought together Dr Vishal Chaudhary, Scientist 'F'; Dr Hafsa Ahmad, Scientist 'D', from the Office of the PSA; Ms. Shravanthi, Deputy Adviser, Central Public Health and Environmental Engineering Organisation, Ministry of Housing and Urban Affairs; and Prof. M.S. Mohan Kumar, Prof. (Retd.), Department of Civil Engineering, IISc Bengaluru and Chair, Project Review Monitoring Committee. The project consortium included Prof. Lakshminarayana Rao and Prof. Chanakya Hoysall from IISc Bengaluru, Prof. R. Vinu from IIT Madras, and Prof. R. S. Singh from IIT (BHU) Varanasi, along with key research associates responsible for LCA modelling, GHG accounting, and digital tool development. Representatives from invited Urban Local Bodies (ULBs) also joined the meeting virtually.



Aligned with the vision of national missions like the Waste to Wealth Mission and the Swachh Bharat Mission-Urban, the Office of the PSA supported the project in 2024, which was jointly undertaken by IISc Bengaluru, IIT Madras, and IIT (BHU) Varanasi. It sought to develop a contextual and nationally relevant Life Cycle Assessment (LCA) framework, along with a GHG calculator web application, to help ULBs plan, compare, and optimise solid waste management systems with lower carbon footprints.



The project team presented findings from the LCA study covering a wide range of waste management technologies, supported by case studies from Bengaluru, Mysuru, Tumakuru, Chennai, Delhi, and Varanasi. A demonstration video of the GHG calculator app showcased its key features and how it can help ULBs quantify emissions associated with different SWM technologies and operating scenarios. The team also presented scenario comparison modules for evaluating alternative waste management pathways and identifying low-carbon options, along with detailed LCA insights into Indian SWM technologies such as biomining, anaerobic digestion, waste-to-energy, and landfilling.

The GHG calculator app developed under this project supports and enables the following-

- The user-friendly GHG calculator app designed specifically for Urban Local Bodies (ULBs) seamlessly analyses emissions from existing solid waste management practices.
- The app features common waste management processes like anaerobic digestion, incineration (waste-to-energy), composting, recycling and landfilling
- The app provides net emissions, avoided emissions, logistic emissions, carbon footprint, different GHG emission data (methane, carbondioxide, NOx, black carbon)
- The app helps the ULBs to visualize different best practice waste management scenarios that result in minimum GHG emissions with the lowest carbon footprint
- The app can be used for environmental assessment of new projects, detailed project reports (DPRs) from various consultants, and to fill in mandatory environmental performance metrics needed for tenders.

Prof. Sood emphasised the importance of the LCA framework and the application developed under the project. He noted that these tools can provide ULBs with a science-backed basis for planning and support their transition towards smart, resilient and low-emission solid waste management systems across the country.

Dr Maini highlighted the project's alignment with the Swachh Bharat Mission-Urban and stressed the need for institutional mechanisms that can support the wider implementation of such solutions across the country.

The project also proposed strategic recommendations for improving the efficiency of existing and future SWM systems, along with a national roadmap for India's transition towards climate-resilient, low-emission waste management.



The report titled 'Development of LCA Framework for Solid Waste Management (SWM) Technologies in India' which was released during the meeting, is available at https://psa.gov.in/CMS/web/sites/default/files/publication/Integrated_Report_IISc_BHU_IITM_Final%20%281%29.pdf

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