Carbon footprint assessment of municipal solid waste management systems: scenario analysis for a metropolitan city in India

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Abstract

The fast urbanization and consumption patterns are drastically changing leading to a marked increase in municipal solid waste (MSW) produced in developing countries, which eventually raises the environmental and climate issues. Our research focuses on analyses of greenhouse gas emissions from municipal solid waste management in Hyderabad, India, adopting an IPCC-based carbon footprint method. The city produces about 5,500 tonnes of waste each day, with biodegradable material being the largest component. The emissions from collection, transport, recycling, composting, waste-to-energy, and landfilling were recorded. Four management options were evaluated, including the current system, enhanced recycling, improved organic waste treatment, and an integrated low-carbon approach. Results suggest that landfill disposal is the significant source of emissions in general, accounting for approximately 85% of total emissions. The current system produces an annual emissions of around 1.35 million tonnes of CO_2-equivalent. Based on scenario analysis, an enhanced recycling and composting system was able to achieve reductions of 32 percent and an integrated system less dependent on landfills helped realize reductions of up to 58 percent. This study shows the significance of segregation of waste sources and resource recovery in managing waste for a sustainable, climate-resilient future.

Keywords: Municipal solid waste · Carbon footprint · Life cycle assessment · Greenhouse gas emissions · Landfill methane · Sustainable waste management

1 Introduction

Worldwide, the incidence of municipal solid waste generation (MSW) has increased substantially rapidly due to rapid urbanization, fast population growth and the evolution in consumption practices. Urban areas in developing countries are seeing massive increase in the amount of waste collected and, consequentially, there is increasing strain on waste disposal facilities. In view of the global trends, the generation of municipal waste is set to increase dramatically over the next few decades due to economic development and changing lifestyles, a figure based on current estimates developed in the global trend of town planning (World Bank 2023; UNEP 2024). Inadequate collection methods, lack of processing facilities and dependence on landfill disposal remain significant problems in most cities. Municipal solid waste management is a sanitation and environmental challenge, including a vital factor in climate change control. The waste sector is responsible for some of the world's greenhouse gas (GHG) emissions, mainly by producing methane from the anaerobic breakdown of organic materials in landfills. The estimated global warming potential of methane, which is much greater than carbon dioxide, means that landfill emissions have played a significant role in urban climate inventories, leading to methane emissions (IPCC 2021). Energy used by collectors, transporting and treating effluents and other forms of waste as well as during waste management in addition to disposal also leads to emissions in the overall carbon footprint of waste management systems (Awasthi et al. 2021; Chen and Lin 2021). In India, the amount of municipal solid waste generation has increased rapidly over the past few years, with several thousand tonnes of waste coming from large metropolitan cities daily. Despite significant increases in collection efficiency on many urban sites, scientific processing and resource recovery are limited at best, such that large amounts of the waste are still disposed of in landfills or open dumping sites (CPCB 2022). This makes for huge methane emission potential and the high fraction of biodegradable waste in Indian cities calls for innovative techniques to waste management for organic waste (Sharma et al. 2020). Numerous related studies have used Life Cycle Assessment (LCA) and carbon accounting have been employed to assess the environmental impacts of waste management systems. These studies show that recycling, composting, and waste-to-energy options can dramatically reduce emissions of greenhouse gas, by redirecting waste away from landfilling and recovering materials and energy, and in this way can greatly reduce the amount of waste generated and then extracting energy (Singh et al. 2022; Lu et al. 2023). However, prior research also presents several limitations. A lot of research has been concentrating on single treatment systems and not integrated management systems. Moreover, regional level data on growing Indian cities are scarce, and scenario-based analyses that compare various low-carbon plans remain to be produced. As global climate targets have not taken root with the emerging pace of urbanization and the pressure to meet sustainable urban growth, there continues to arise concerns over whether there are quantitative methods to aid management decisions in the field of municipal waste planning. Carbon footprint evaluation is a useful tool for detecting hot spots of emission and evaluating the advantages of different waste reduction methods. These evaluations are especially relevant in big cities, where volume and environmental consequences of waste are substantial. By this study's research goal, it attempts to bridge the research gap by the comprehensive analysis of the carbon footprint on the municipal solid waste management system, of Hyderabad, which is a emerging and growing metropolitan city in India. This study assesses the emissions from different phases in waste management and assesses alternate strategies to curb landfill use and optimize resource extraction. The rest of the paper is structured according to this order. Section 2 summarizes the study area, sources of data and methodology adopted for the carbon footprint estimation. Section 3 presents the findings and scenario and discussion of main findings and the implications for policy. In section 4, the findings and results for the sustainable management of municipal solid waste are summarized and discussed.

2.Literature Review

Municipal solid waste (MSW) management has been subjected to extensive research from the climate perspective because it's a significant contributor of greenhouse gas (GHG) emissions: especially since methane originated from organic waste decomposition under anaerobic conditions in landfills. Most recent research has focused on using Life Cycle Assessment (LCA), which offers a complete tool for quantifying the environmental impact related to a waste's collection, transportation, treatment, and disposal methods.

2.1 Emissions from landfill into Greenhouse Gases: Landfilling is still the most dominant disposal method in the development of most of the world. However, with methane production behind it, it is one of the most carbon-intensive options to consider with respect to human waste. Research suggests that with around 400 kg CO_2-equivalent per tonne produced from the filling process, landfills of organic waste are responsible for a significant share of the waste sector's carbon emissions on a global scale. In the Indian context studies in landfill emission research have found that methane generation occurs alongside first-order decay and uncontrolled disposal sites greatly increase atmospheric gas emission. Landfill gas removal to recover energy from landfill has recently emerged as a potential means of mitigating net emissions and producing renewable electric power.

2.2 Alternative Solutions: Composting and Anaerobic Digestion: Treatment of organic waste using compost and anaerobic digestion (AD) has been of interest as a low-carbon approach. Controlling for fertilizer production avoided, composting may also produce net negative emissions (approximately −41 kg CO_2/tonne). Likewise, biogas recovery in AD-based systems can mitigate the use of fossil fuels, thereby

reducing total carbon emissions. And yet literature also shines a light on trade-offs — for instance, ammonia emissions due to composting and the importance of proper process control to unlock environmental benefits.

2.3 Recycling & Resource Recovery: Recycling also reduces any production of virgin materials, thus enabling material recovery to reduce emissions. A combination of the environmental aspects made possible of recycling plastics, metals and paper in the case of recycling and also LCA studies have shown there to be significant climate benefits through energy savings in manufacturing. Integrated waste management systems that utilize segregation, recycling, and energy recovery are consistently more cost efficient than disposal-oriented, non-energy-saving systems.

2.4 Waste-to-Energy (Incineration): Waste-to-energy (WtE) technology presents both volume reduction and energy generation advantages. Where energy recovery is efficient, incineration can balance fossil fuel-based power generation, which, in turn, leads to reduced net GHG emissions. Nonetheless, the greening aspects are contingent on the efficiency, emission control system and waste composition of the plants. High moisture and organic content in MSW greatly decrease the efficiency of thermal treatment in developing areas.

2.5 Integrated waste management and LCA projects: Literature highlights the role of a combined waste treatment policy that corresponds to the waste hierarchy (reduce, re-use, recycle, recover and dispose). More recently decisions supporting assessments of the carbon footprint are used a lot more with tools such as IPCC emission factors, Land GEM models, regionally focused waste characterization data.

2.6 Research Gap: While many international studies have assessed the carbon footprint of MSW systems, there are still few, where applicable, location-specific analyses for Indian urban environments. Waste composition (high biodegradable fraction), informal recycling activities, and the maintenance or existence of open dumping provide uncertainty in emission estimates. Furthermore, limited studies contrast current practices with state-of-the-art arrangements to support policy-level decisions.

3 Materials and Methods

3.1 Research framework and approach. To estimate the greenhouse gas (GHG) emissions arising in municipal solid waste (MSW) management, this study adopts a life cycle–based carbon accounting framework. This system boundary comprises waste generation, collection, transportation, processing (recycling, composting, waste-to-energy), and final disposal. Indirect emission savings resulting from material recovery and energy substitution were also considered. The methodological framework was developed to support a comparison of scenarios and to find low-carbon management options that can be realized in large metropolitan cities with abundant organic waste.

Novelty of the approach
1. Integration of city-level waste data with standardized IPCC emission factors
2. Scenario-based evaluation of multiple treatment combinations
3. Inclusion of avoided emissions from recycling and resource recovery
4. Development of a simplified decision-support model suitable for urban planners

3.2 Study area and waste data

Hyderabad, India, was selected as the study area due to its high waste generation and rapid urban growth. The city produces approximately **5,500 tonnes of MSWper day**, equivalent to about **2.0million tonnes annually**.

Waste composition data were compiled from municipal reports and national databases.

Table1.The composition used in the analysis

Component	Percentage (%)
Biodegradable	52
Plastic	14
Paper	10
Glass	3
Metal	2
Inert and others	19
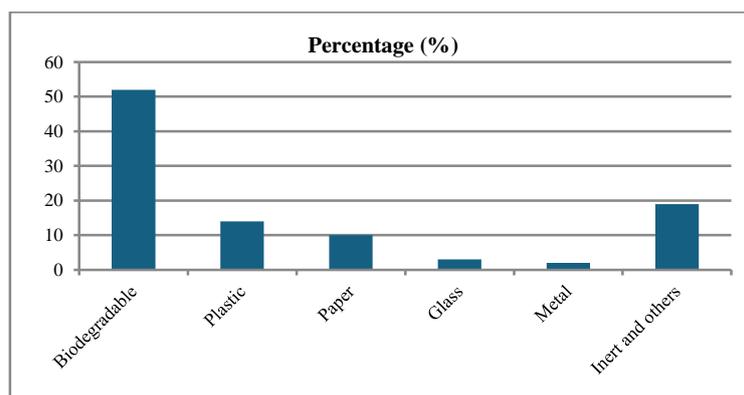
Graph1: Waste composition data

3.3 System boundary and process description

The carbon footprint estimation covered the following stages:
1. Waste collection from households and commercial areas
2. Transportation to transfer stations and treatment facilities
3. Processing through recycling, composting/biomethanation, or waste-to-energy
4. Final disposal in sanitary landfill

Open burning was not considered due to limited -verified data.

3.4 Carbon emission estimation model

Greenhouse gas emissions were calculated using the following general equation:

$$CF = \sum_{i=1}^{n} (Q_i \times EF_i)$$

where:
CF = total carbon footprint (kg CO_2-equivalent/year)
Q_i = quantity of waste treated in process *i* (ton/year)
EF_i = emission factor for process *i* (kg CO_2-eq/ton)

Table2:Emission factors adopted

Process	Emission factor (kg CO₂-eq/ton)
Collection and transport	20
Recycling (avoided emissions)	–150
Composting	50
Waste-to-energy	200
Landfill disposal	900

Emission factor (kg CO₂-eq/ton) 20 –150
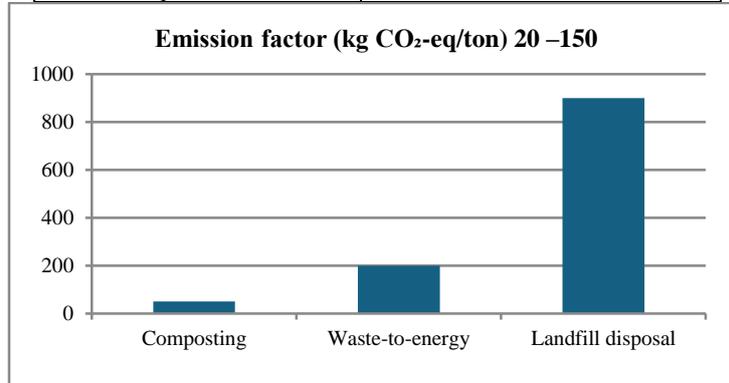
Graph2:Emission process Vs Emission factor

Negative values represent emission savings due to material or energy recovery.

3.5 Scenario modelling: To evaluate the effectiveness of alternative waste strategies, four scenarios were developed.

Our various waste management situations were developed to evaluate their contribution to emission reduction. The base case (Scenario 1) will involve 25% recycling, 20% composting or biogas, 10% waste-to-energy, and 45% landfill disposal. Scenario 2 increases recycling to 40% with a reduction in landfill disposal to 30%. For Scenario 3, organic waste treatment (using compost, biomethanation until it reaches 50%) is priority. Scenario 4 includes 40% recycling, 40% composting, 10% waste-to-energy, and 10% landfill. These are useful to understand the most effective way of reducing emissions and increasing the sustainability of waste handling. 3.5 Data analysis and computation.

All calculation was done with Microsoft Excel 2021. Mass balance analysis determined the mean total waste quantity which did not change between scenarios. The emissions of each process were calculated once again and summed to obtain annual emission contributions.

Sensitivity analysis was performed by varying landfill emission factors by ±10% in order to evaluate robustness of the results.
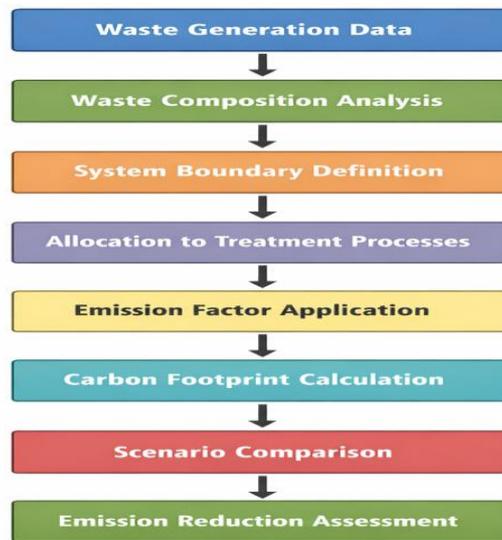
3.6 Flowchart of methodology

Figure1:A flowchart with the following sequence
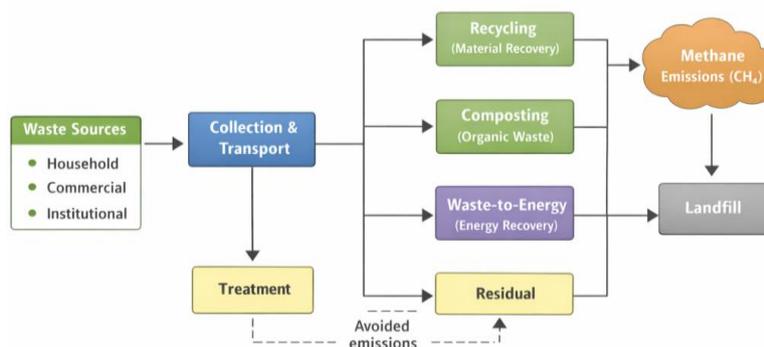
3.7 Block diagram of system

Figure 2 :Municipal waste management Flowchart and emission

3.9 Software, hardware, and tools

1) Software: Microsoft Excel (calculation and graphs)
2) Statistical analysis: Built-in Excel functions
3) Diagram preparation: MS Visio / PowerPoint
4) Hardware: Standard personal computer (8 GB RAM, Windows environment)

No specialized computational resources were required, making the method suitable for municipal-level applications.

3.10 Justification of methodology

The IPCC-based emission factor method was selected because:

It is widely accepted for national and urban GHG inventories

It requires limited data compared to full LCA software

It is suitable for developing regions where detailed operational data are unavailable

It enables rapid scenario evaluation for policy decision support

4 Results and discussion

## 4.1 Carbon footprint of baseline system

The total annual emissions from the current system were estimated to be approximately 1.35 million tonnes CO_2-equivalent. Landfill emissions accounted for nearly 85% of the total, indicating that methane generation from organic waste is the dominant contributor.

4.2 Scenario comparison

Table 3 Emission reduction under different scenarios

Scenario	Emissions (million t CO_2-eq/year)	Reduction (%)
Baseline	1.35	–
Enhanced recycling	1.05	22
Organic treatment	0.92	32
Integrated system	0.57	58

The integrated system showed the highest emission reduction due to significant diversion of waste from landfills.
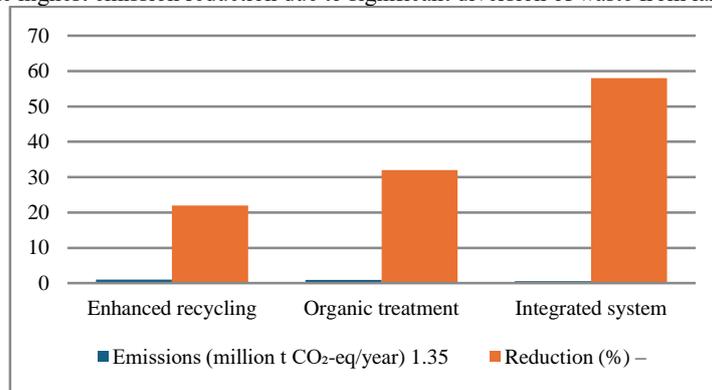
Graph3: Emission reduction due to significant diversion of waste from landfills

4.3 Discussion: Increasing recycling reduces emissions by avoiding the production of virgin materials. Similarly, composting and biomethanation reduce methane generation by treating organic waste under controlled conditions. The results highlight that source segregation plays a critical role in improving the efficiency of recycling and organic waste processing.

5 Results and Discussion

5.1 Waste generation and process allocation: The annual municipal solid waste generation for the study area was estimated at approximately 2.0 million tonnes. Based on the existing management structure, the distribution of waste across different treatment processes is presented in Table 4.

Table 4:Waste allocation under baseline condition

Treatment option	Percentage (%)	Quantity (ton/year)
Recycling	25	500,000
Composting/Biomethanation	20	400,000
Waste-to-energy	10	200,000
Landfill disposal	45	900,000

The large share of landfill disposal indicates a strong dependence on final disposal rather than resource recovery.
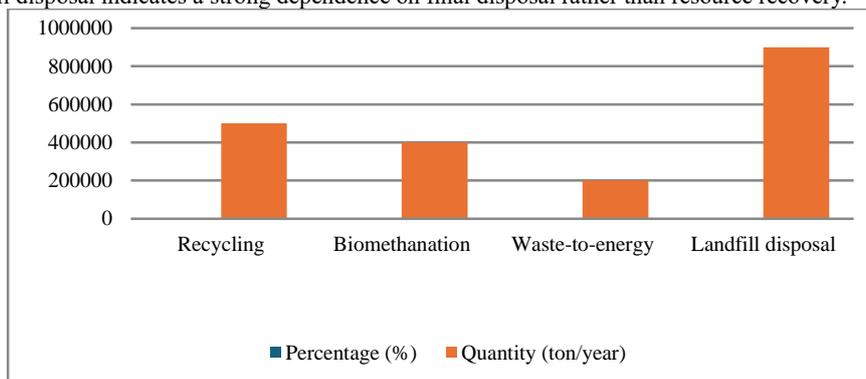
Graph4: Distribution of waste across different treatment processes

5.2 Carbon footprint of baseline system: The emissions from each waste management stage were calculated using the emission factors described in the methodology. The results are summarized in Table 5.

Table 5 Carbon emissions under baseline scenario

Process	Emission factor (kg CO_2-eq/ton)	Emissions (t CO_2-eq/year)
Collection & transport	20	40,000
Recycling (avoided)	−150	−75,000
Composting	50	20,000
Waste-to-energy	200	40,000
Landfill	900	1,350,000

**Total net emissions ≈ 1.35 million t CO_2-eq/year**

Landfill disposal alone contributed nearly 85% of the total emissions, confirming that methane generation from organic waste is the dominant climate impact source. The negative value for recycling represents avoided emissions due to reduced production of virgin materials.

5.3 Scenario analysis: To evaluate emission reduction potential, alternative waste management scenarios were developed. The results are presented in Table 6.

Table 6 Emission comparison across scenarios

Scenario	Total emissions (million t CO_2-eq/year)	Reduction (%)
Baseline	1.35	–
Enhanced recycling	1.05	22
Improved organic treatment	0.92	32
Integrated low-carbon system	0.57	58

The integrated scenario demonstrated the highest reduction due to significant diversion of waste from landfill and increased resource recovery.
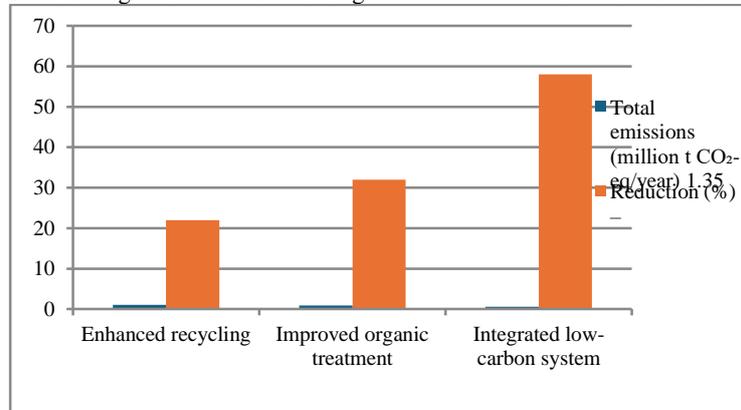
Graph 5: Should illustrate emission contributions from each process under the baseline scenario

5.4 Contribution analysis

Key observations:

1. Landfill emissions dominate due to methane formation from biodegradable waste.
2. Collection and transportation contribute a relatively small portion of total emissions.
3. Recycling provides substantial emission savings.
4. Organic waste treatment significantly lowers methane generation when landfill disposal is reduced.

These findings are consistent with previous studies that highlight landfill avoidance as the most effective strategy for reducing waste-sector emissions.

5.5 Effect of organic waste management: Given that biodegradable waste constitutes more than 50% of the total waste stream, increasing composting and biomethanation showed considerable climate benefits. Scenario 3 reduced emissions by 32%, indicating that decentralized organic waste processing can play a major role in emission mitigation for Indian cities.

In addition to emission reduction, organic treatment improves soil quality and reduces the burden on landfill infrastructure.

5.6 Sensitivity analysis

Table7 sensitivity analysis was performed by varying landfill emission factors by ±10%.

Condition	Total emissions (million t CO_2-eq/year)
−10% landfill factor	1.23
Baseline	1.35
+10% landfill factor	1.47

The results indicate that total emissions are highly sensitive to landfill performance, further emphasizing the importance of landfill gas control and waste diversion.

5.7 Policy and practical implications: The analysis provides several insights for urban waste planning:

1. Source segregation is essential to improve recycling and organic waste treatment efficiency.
2. Decentralized composting and biomethanation should be expanded for high-organic waste cities.
3. Material recovery systems need strengthening to increase recycling rates.
4. Landfill disposal should be limited to inert and non-recyclable residues.
5. Carbon footprint evaluation can be integrated into municipal decision-making to support climate action plans.

5.8 Comparison with previous studies

The emission reduction potential observed in this study (32–58%) falls within the range reported in earlier LCA-based studies for developing countries. Similar research has shown that integrated waste management systems can reduce greenhouse gas emissions by 30–70% compared to landfill-dominated systems.

The results confirm that waste diversion and resource recovery are key strategies for achieving low-carbon urban waste management.

6 Conclusion and Future Work: Based on an IPCC-based life cycle technique, the present study employed a detailed carbon footprint assessment of the municipal solid waste management system developed for a large urban community. Ground-breaking methods that tested potential mitigations for the associated impacts of climate change, encompassing greenhouse gas emissions from collection, transport, recycling, composting and waste-to-energy and landfill disposal, were analyzed.

The current waste management system generates 1.35 million tonnes of CO_2-equivalent every year, with landfill disposal as the primary source of emission representing almost 85% of the total emissions. The high biodegradable fraction in the waste stream produces a lot of methane when put in the landfill. Scenario analysis showed to achieve significant reduction in emissions by improving recycling rates and increasing organic waste treatment. An integrated approach to waste disposal with increased recycling and composting whilst minimizing landfill dependence showed up to 58% reduction in emissions as relative to the current system.

This study emphasizes the core principles of source segregation and material recovery and decentralized organic waste processing as key components of low-carbon urban waste management. From a policy perspective, the study recommends addressing landfill disposal as a priority area of concern for municipal authorities. For example, assessing the carbon footprint can be included in the urban planning process, guiding how evidence-based decision making can be taken in accordance with CO2 emissions and contribute to national and global climate mitigation goals for sustainable cities. It is a useful, but somewhat limited, study.

The analysis also drew on aggregated waste data and standard emission factors in light of relatively limited facility-level operational data. Waste composition, seasonality and efficiency gains of treatment plants were largely not modelled. Besides, informal recycling, which plays a significant role in most Indian cities, was investigated in a generalized manner. These limitations can be overcome by future research integrating site-specific operational data, dynamic waste generation patterns and full modeling of the landfill gas recovery system. As for advanced life cycle assessment tools, GIS, and optimization techniques, such a more accurate geographically relevant carbon footprint estimation needs better integration. Techno-economic analysis of decentralized waste treatment systems and evaluation of policy instruments (e.g., carbon credits, extended producer responsibility) could also be relevant elements in guiding and encouraging sustainable waste management planning. It is also shown in this study that a transition from a disposal-based approach towards integrated resource recovery might help reduce greenhouse gas emissions significantly, with the possibility of aiding and facilitating climate-resilient, sustainable cities.

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