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Sustainable Management of Green Waste in India through Waste-to-Energy Technologies: A Circular Economy Approach

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Abstract
India faces an escalating environmental challenge in managing rapidly increasing volumes of municipal solid waste (MSW), driven by urbanization, population growth, and economic development. Organic or green waste constitutes roughly 50% of the waste stream, and its mismanagement has contributed to landfill saturation, elevated methane emissions, and extensive ecological degradation. This paper critically examines sustainable green waste management options, with a specific focus on Waste-to-Energy (WtE) technologies such as anaerobic digestion, composting, incineration, and gasification. Using a comparative framework that integrates Life Cycle Assessment (LCA), techno-economic analysis, and carbon emission benchmarking, the study evaluates key governmental interventions, including the GOBARdhan scheme and urban WtE initiatives. The analysis indicates that decentralized biogas and composting systems deliver superior environmental performance, lower greenhouse gas emissions, and higher economic viability than conventional landfilling and most centralized thermal WtE solutions. The paper argues that embedding circular economy principles into policy and infrastructure—combined with targeted technological innovation—can help shift India's waste management system from a linear, disposal-oriented model to a resource-efficient, energy-generating ecosystem.

Keywords: Municipal Solid Waste (MSW); Green Waste Management; Waste-to-Energy (WtE); Anaerobic Digestion; Composting; Biogas Production

1. Introduction

Rapid urbanization, rising incomes, and demographic growth have substantially increased MSW generation across Indian cities and peri-urban areas. Current estimates suggest that India produces on the order of tens of millions of tonnes of MSW annually, a significant share of which remains untreated or is poorly managed. The organic fraction—including food waste, yard trimmings, and agricultural residues—typically accounts for about half of total MSW, underscoring its strategic importance for resource recovery and renewable energy generation.

Historically, waste management in India has been hampered by inadequate source segregation, limited processing infrastructure, and a strong dependence on open dumping and uncontrolled landfilling. The accumulation of organic waste in large landfills generates multiple environmental and public health risks: fugitive methane emissions from anaerobic decomposition, leachate-induced groundwater contamination, and recurrent landfill fires that aggravate urban air pollution. These impacts also undermine India's commitments to climate mitigation and sustainable urban development.

Objectives of the study:

- To systematically evaluate the performance of major green waste treatment and WtE technologies in the Indian context.
- To assess the environmental impacts and economic feasibility of these technologies using LCA-inspired indicators and techno-economic criteria.
- To develop scalable, policy-relevant recommendations for integrating green waste management into a circular economy framework.

2. Literature Review

Recent research emphasizes the need to reconceptualize organic waste as a renewable resource and a feedstock for energy and soil amendments rather than as a disposal burden. Studies report that the organic fraction of Indian MSW commonly ranges between 40% and 60%, providing substantial potential for biomethanation and compost production if appropriate collection and treatment systems are in place. Despite this potential, WtE technologies remain underutilized, with large volumes of organic waste still landfilled or dumped openly.

National data indicate that a significant share of collected waste continues to be disposed of without adequate treatment, even as processing capacity has expanded under recent missions. According to recent assessments, around 28.5% of the waste processed in India is composted, while only about 0.9% undergoes treatment via biomethanation, underscoring the limited penetration of anaerobic digestion plants. This treatment mix reflects both technological preferences and institutional constraints.

Identified research gaps:

- Limited deployment of decentralized treatment systems capable of handling segregated organic waste close to the point of generation, particularly in small towns and peri-urban areas.
- Persistent challenges in enforcing source segregation, which reduces feedstock quality and efficiency for both biological and thermal WtE technologies.
- A shortage of localized, India-specific LCA studies that account for climatic conditions, waste composition, energy mix, and socio-economic realities, especially for smaller-scale facilities.

3. Methodology

3.1 Data acquisition

The study is based on secondary data derived from authoritative national sources, including reports by the Ministry of New and Renewable Energy (MNRE), NITI Aayog, and the Central Pollution Control Board (CPCB), supplemented by technical documentation under Swachh Bharat Mission (Urban and Rural) and the GOBARdhan programme. Peer-reviewed articles and case studies on WtE technologies in India and other developing countries provide additional empirical evidence and technology performance benchmarks.

3.2 Technological scope

The analysis covers four main green waste treatment and WtE pathways that are currently relevant to the Indian context:

1. Composting (centralized and decentralized systems)
2. Anaerobic digestion for biogas and compressed biogas (CBG) production
3. Mass-burn incineration for heat and power
4. Gasification and pyrolysis for syngas and bio-oil generation

3.3 Analytical framework

A comparative framework inspired by Life Cycle Assessment is used to evaluate environmental performance across technologies using indicators such as greenhouse gas emissions, energy recovery, and potential impacts on soil and air quality. Techno-economic analysis considers capital and operating costs, scalability, and context-specific suitability, while carbon emission benchmarking assesses each option's contribution to climate mitigation relative to conventional landfilling. Where available, documented case studies are used to calibrate performance assumptions and contextualize the results.

4. Green Waste Disposal Technologies

4.1 Anaerobic digestion (biogas and CBG)

Anaerobic digestion (AD) is a controlled biological process in which microorganisms degrade organic matter in the absence of oxygen to generate a methane-rich biogas and a nutrient-rich digestate. The biogas can be used directly for cooking, heating, or power generation, or it can be upgraded to CBG for injection into gas grids and use as a transport fuel, while the digestate can serve as an organic fertilizer. Under the GOBARdhan scheme and associated policies, India has committed to developing more than 500 biogas and CBG plants, and recent implementation data indicate that this milestone has been surpassed, signalling strong policy momentum for AD-based WtE.

4.2 Composting

Composting is an aerobic biological process in which organic waste is converted into stable, humus-like material that can be used as a soil amendment. The technology is relatively low-cost, can be implemented at multiple scales, and is particularly suitable for segregated kitchen and garden waste streams. Municipalities across India have piloted centralized compost plants and smaller ward-level or community composting units, often in combination with garden waste and market residues.

4.3 Incineration

Incineration involves the high-temperature combustion of mixed MSW to generate heat and electricity, typically in large, centralized plants. In the Indian context, the high moisture content and significant organic fraction of municipal waste generally result in low calorific value, which undermines combustion efficiency and often necessitates auxiliary fuel use. In addition, incineration requires stringent flue gas treatment and robust emissions control systems to address particulate matter and toxic pollutants, which increases capital and operating costs and raises concerns about local air quality.

4.4 Gasification and pyrolysis

Gasification and pyrolysis are advanced thermochemical processes that operate at high temperatures with limited or no oxygen to convert biomass and suitable waste streams into syngas, bio-oil, and char. These technologies can achieve high energy efficiency when fed with well-characterized, high-calorific feedstocks, but they are less compatible with heterogeneous, high-moisture MSW without extensive pre-treatment. High capital costs, the need for skilled operation, and feedstock constraints currently limit the broad deployment of these systems for mixed municipal green waste in India.

5. Case Study: Decentralized Urban Waste-to-Energy

Emerging urban climate and waste management strategies in large metropolitan areas such as Mumbai increasingly favor decentralized organic waste processing models. Ward-level biogas plants and composting facilities have been deployed to treat segregated kitchen and garden waste close to the point of generation, converting it into usable energy and organic fertilizer while reducing the need for long-distance transport. These initiatives help lower fuel consumption and associated vehicular emissions, reduce the volume of waste sent to central landfills, and demonstrate practical pathways for operationalizing circular economy concepts at the city scale.

6. Results and Techno-Economic Analysis

The comparative assessment highlights distinct differences among technologies in terms of cost, energy recovery, emissions, and suitability for Indian waste characteristics.

Table 1: Comparative performance of key WtE technologies for green waste in India

Technology	Capital / O&M Cost	Energy / Resource Efficiency	Emission Profile	Contextual Suitability
Composting	Low	Medium	Very Low	Suitable for rural areas, peri-urban zones, and decentralized urban applications.
Anaerobic Digestion	Medium	High	Low	Well-suited for segregated wet waste; co-produces energy and fertilizer.
Incineration	High	Medium	High	Limited viability due to high moisture and low calorific value of typical MSW.
Gasification	High	High	Medium	Applicable mainly to specialized, high-calorific

Technology	Capital / O&M Cost	Energy / Resource Efficiency	Emission Profile	Contextual Suitability
				biomass or pre-treated streams.

Key findings:

- A combined strategy that prioritizes anaerobic digestion for wet organic waste and composting for residual biodegradable fractions emerges as the most environmentally and economically robust option for India's prevailing waste composition.
- Conventional landfilling of untreated organic waste remains the least efficient and most environmentally damaging pathway, due to methane emissions, leachate generation, and land requirements.
- Decentralized infrastructures, when supported by effective source segregation, consistently perform better than large centralized plants by reducing transport costs, mitigating local pollution hotspots, and enhancing community participation.

7. Discussion

7.1 Operational challenges

The large-scale adoption of WtE technologies in India continues to face several systemic barriers. Foremost among these is inadequate source segregation, which leads to contaminated feedstock and lowers the efficiency and reliability of both biological and thermal treatment facilities. High moisture content and variable composition further complicate thermal processes such as incineration and gasification, while limited institutional capacity and financing constraints affect the operation and maintenance of existing plants. Additionally, gaps in enforcement of regulations and low levels of public awareness about waste separation and organic waste valorization hinder the scaling of decentralized solutions.

7.2 Strategic opportunities

Despite these challenges, the abundance of biodegradable waste offers substantial opportunities for renewable energy generation and soil health improvement. Scaling up AD and composting could reduce reliance on fossil fuels, support local energy security, and help substitute chemical fertilizers with organic amendments, particularly in peri-urban and rural regions. Decentralized, community-managed WtE systems can also create local employment, improve urban cleanliness, and embed circular economy principles into everyday waste practices. Integrating digital tools—such as IoT-based monitoring and AI-enabled route optimization—offers additional potential to increase operational efficiency and transparency along the waste management value chain.

8. Policy Implications and Future Scope

Existing policy frameworks, including Swachh Bharat Mission (Urban and Rural) and the GOBARdhan scheme, have laid an important foundation for expanding organic waste treatment and WtE infrastructure. To fully realize the potential of green waste, policy evolution should prioritize mandatory and verifiable source segregation, backed by suitable enforcement mechanisms and behavioral change initiatives. Financial instruments—such as viability gap funding, results-based incentives, and carbon market linkages—are needed to catalyze investment in decentralized AD and composting, particularly at the ward and panchayat levels.

In the medium to long term, integrating digital tracking platforms and AI-enabled decision-support tools can improve plant performance, monitor feedstock flows, and enhance accountability in municipal waste systems. Further research should focus on India-specific LCA studies across different scales and regions, comparative assessments of centralized versus decentralized systems, and socio-economic analyses of community participation and livelihood generation in circular waste management models.

9. Conclusion

Organic or green waste, traditionally treated as a liability, represents a significant opportunity for India to advance sustainable energy generation, climate mitigation, and improved urban governance. Given that the organic fraction constitutes a substantial share of MSW, shifting this stream into WtE pathways can markedly reduce landfill dependence and associated greenhouse gas emissions. Among available options, anaerobic digestion and decentralized composting stand out as context-appropriate, cost-effective, and environmentally sound strategies aligned with Indian waste characteristics and policy priorities.

Embedding these technologies within a broader circular economy framework—supported by robust policy, digital innovation, and community engagement—can transform green waste into a local renewable resource, simultaneously strengthening environmental sustainability, energy security, and economic resilience.

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