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Comprehensive Analysis of Waste Management Practices in India

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Abstract: Economic growth in countries like India has led to a sharp rise in waste generation. An effective solid waste management (SWM) system requires collection, segregation, transport, and scientific disposal of waste. Among these, safe transportation and environmentally sound disposal are especially important, as they directly affect public health, environmental protection, and opportunities for green jobs and industrial growth. However, current SWM practices in India remain largely inefficient due to gaps in infrastructure, lack of public awareness, and weak implementation of policies. This paper reviews key waste management methods, incineration, pyrolysis, gasification, composting, and landfilling, assessing their feasibility, challenges, and environmental impact. Waste-to-Energy (WtE) technologies are discussed as a potential dual solution to the problems of waste disposal and energy shortage. The study aims to guide planners and policymakers by providing a clear overview of technological options, their challenges, and their role in sustainable development. It emphasizes decentralized approaches, energy recovery, and practical pathways for creating waste management systems that are both environmentally sustainable and economically viable.

Keywords: Infrastructure, Environment, Waste to Energy, Landfill, Refuse-Drive-Fuel, Sustainable Development

1. Introduction

Urban growth and industrial growth in India have rapidly led to the generation of a vast quantity of municipal solid waste (MSW) that contributes to the considerable stress on natural resources and urban services. Improperly maintained, mismanaged, and disrespectful waste also places a burden on the costs urban local bodies (ULBs) must incur and also contributes to negative environmental outcomes. India's demographic and economic trajectory directly explains the scale of its waste management challenge. With a population of over 1.4 billion and an annual urban growth rate of 2.3%, nearly 50% of Indians are projected to live in cities by 2036. This rapid urbanization, coupled with rising income levels, has led to significant changes in consumption patterns and waste composition. The Central Pollution Control Board (CPCB, 2022) estimates that India generates more than 150,000 metric tonnes of municipal solid waste daily, of which only 70% is collected and less than 30% is treated scientifically.

The key challenges in handling waste in India have been related to outdated technology, lack

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of qualified personnel, and lack of support facilities. Poor or no source segregation alone further complicates the shortcomings of poorly-designed MSW management systems.

As there is more demand for energy supply, there is a shift towards alternative sources of energy, especially energy from waste. If managed and operated in an efficient manner, waste can be a potential source of energy. In addition, the three pillars of waste management, of "reduce, reuse, recycle" still apply.

Waste management techniques in India include landfilling, incineration, and pyrolysis for waste-to-energy conversion. However, it is landfill and open dumping that continue to be the dominant practises, with significant impacts in the realms of pollution and groundwater contamination, as well as emissions of greenhouse gases. There is an urgent need for scientifically driven, economically feasible, and environmentally sustainable waste management systems. In this scenario, the concept of WtE technologies hold considerable potential for converting waste into energy, thus promoting sustainability and reducing environmental hazards.

The Swachh Bharat Mission (SBM), launched in 2014, has been pivotal in shaping India's national waste management framework. While its primary focus was on eliminating open defecation and improving sanitation infrastructure, the mission also laid strong emphasis on solid waste management, particularly segregation at source, door-to-door collection, and scientific processing of waste. Under SBM-Urban 2.0, launched in 2021, the government has moved beyond sanitation to promote 100% source segregation, material recovery facilities, and the integration of waste-to-energy technologies. By encouraging municipalities to set up biomethanation plants, composting units, and Refuse-Derived Fuel (RDF) projects, SBM links local sanitation drives with broader goals of energy recovery and climate change mitigation.

1.1 Waste Management Practices in India

India, being the second most populous country, produces over 150,000 metric tonnes of waste daily, according to estimates from the Central Pollution Control Board (CPCB, 2022**)**. Of this, approximately 70% is collected, while only 25–30% is scientifically processed, with the remainder disposed of through open dumping or poorly managed landfills. This amount of waste has great potential to generate energy. However, generating energy from waste is a complicated process that requires a high level of infrastructure, proper funding, and skilled staff. According to the Ministry of New and Renewable Energy (MNRE), approximately 50% of Indian MSW is biodegradable, 30% inert, and 20% recyclable. The high organic content leads to substantial methane emissions and leachate generation.

Currently, the most commonly used disposal methods, landfilling and open dumping are preferred due to low operational costs, despite their adverse long-term effects on health and ecology. Waste conversion methods are generally categorized into thermal and biochemical processes. Thermal methods include incineration, pyrolysis, and gasification, while biochemical methods comprise composting, biomethanation, and anaerobic digestion.

It is evident that waste management practices in India are still at a nascent stage as current practices are not able to deal with the rate at which waste is generating. Various types of conversion practices are followed in the country based on the quantity and composition of the waste.

1.1.1 Incineration

Incineration is effective for reducing waste volume (by up to 70–90%) and generating energy. However, it releases pollutants such as SO_x and CO_x, contributing to air pollution and health risks. Additionally, incineration produces ash as a residue, which may contain hazardous materials, including heavy and volatile metals. Therefore, it is essential for incinerator plants to be equipped with emission control instruments. This practice typically operates within a temperature range of 750 to 1000 degrees Celsius. While incineration does not completely destroy waste, it transforms it into various new forms and reduces its volume. Additionally, incinerator ash may contain hazardous substances, necessitating emission control mechanisms. India's incineration-based WtE footprint has grown but remains concentrated in large urban agglomerations. As of December 2024, 14 municipal WtE plants are operational nationwide with an aggregate design throughput of 17,600 TPD and 202 MW of grid-connected capacity. Delhi alone operates four plants (Okhla, Ghazipur, Narela-Bawana, Tehkhand).

1.1.2 Pyrolysis

Pyrolysis is a thermal degradation process conducted in the absence of oxygen, producing pyrolysis oil, gas, and char. The pyrolysis process can be classified into three types based on their parameters: fast, conventional, and flash pyrolysis. The process produces pyrolysis gas as the product. It involves the thermal decomposition of organic matter, which further produces fuel and chemicals. It is particularly suitable for plastic waste and can contribute to fuel production, offering a promising solution for turning plastic waste into useful products. Several pyrolysis plants have been set up in a country where pyrolysis oil is produced, which is further used for industrial and chemical applications. However, high capital costs and greenhouse gas emissions remain major challenges. Indian Oil Corporation and other public enterprises are currently exploring the viability of pyrolysis-based fuel production. Thus, this process is playing a significant role in the energy transition by converting waste into valuable resources. To address the financial barriers, policy interventions such as capital subsidies, tax incentives, and low-interest green financing could be implemented to make pyrolysis more accessible. Moreover, promoting public–private partnerships (PPPs) would enable cost-sharing between government bodies and private investors, reducing the burden on municipalities while ensuring technical expertise and operational efficiency. Establishing long-term power purchase agreements and creating a stable market for pyrolysis-derived fuels could further attract private sector participation and enhance economic viability.

1.1.3 Gasification

Gasification can be defined as the conversion of solid or liquid carbon-containing matter into combustible products using a gasification agent. Gasification converts organic or fossil-based carbonaceous materials into syngas, a mixture of CO, H_2, and hydrocarbons, using a controlled amount of oxygen or steam. The syngas can be utilized for electricity generation or as a feedstock in chemical industries. This process involves the combustion of the mass to produce gas. The main product gases of this process are CO_2 and H_2O, which are then reduced into CO and H_2 using charcoal. This process also produces methane and hydrocarbons. Depending on operational parameters, the gasification system mainly comprises a Gasifier, which produces gas, an Energy Recovery System, and a Cleanup system. It is a more feasible option for generating energy from biomass and treating industrial waste. Direct gasification occurs in the presence of an oxidant gasification agent, while indirect gasification occurs in its absence. Indirect gasification requires an external source of energy, and steam is used as an indirect gasification agent. Gasifier units in Rajasthan and New Delhi exemplify localized energy recovery through gasification. Gasifier units in Rajasthan and New Delhi exemplify localized energy recovery through gasification. Nevertheless, the high initial investment required for gasification technology often deters large-scale adoption in India. These barriers can be mitigated through supportive policy frameworks that provide fiscal incentives, viability gap funding, and dedicated waste-to-energy funds. Encouraging PPP models would facilitate risk-sharing, bring in private capital, and ensure technical innovation. Additionally, integrating gasification projects within broader renewable energy policies, along with assured feed-in tariffs for electricity generated from syngas, could improve financial returns and make the technology more attractive for both urban local bodies and investors.

1.1.4 Composting

Composting can be defined as the decomposition of waste under aerobic conditions. Composting is a widely accepted method for treating biodegradable waste, particularly in areas where organic matter exceeds 50% of total waste composition. It involves microbial decomposition under aerobic conditions to produce nutrient-rich compost. The main advantage of this process is the application of biomass at a lower cost with higher efficiency. In this process, microorganisms such as bacteria and fungi are used to degrade the organic matter. Composting reduces the transportation and disposal costs of waste. It involves the decomposition of organic matter through biological processes, which further produces nutrient-rich humus. It simply involves putting together all residues to generate humus. Usually, kitchen waste and agricultural residues are utilized in the composting method. In India, both traditional and modern composting methods are followed. Traditional methods include vermicomposting and pit composting, while modern methods include aerobic composting. Composed products are widely used in organic farming in India as they provide nutrients to the soil, reduce dependency on chemical fertilizers, and further improve soil productivity and health. Composting can also be utilized for biogas production through anaerobic digestion. Despite its environmental benefits, composting in India suffers from unscientific techniques, poor source segregation, and limited public awareness. Various biogas plants are set up in the country, especially in rural areas, to provide energy. Gujarat and Maharashtra have taken commendable steps by promoting large-scale biogas and composting plants. As they are frontrunners in using renewable sources of energy, and they have been successful in producing biogas using biomethanation and anaerobic digestion methods. However, major barriers in this way are improper separation, limited awareness regarding composting methods, low levels of infrastructure and technology for composting operations.

1.2 Landfilling method in India

Landfilling remains the most prevalent waste disposal method in India, with over 80% of waste ending up in landfills. However, this method is highly unorganized and unhygienic as most sites are unmanaged, lacking leachate treatment, soil layering, or gas monitoring systems. These sites contribute significantly to air and water pollution, especially in peri-urban areas where land availability is increasingly scarce due to urban expansion.

To provide a clearer comparison of the strengths and limitations of major waste-to-energy (WtE) and disposal technologies in the Indian context, a comparative table has been developed. This table summarizes relative costs, energy yields, major challenges, and adoption trends.

Table 1: Comparative Analysis of Waste-to-Energy and Disposal Technologies in India

Technology	Relative Cost	Energy Yield	Key Challenges	Adoption in India
Incineration	High	Moderate	Ash disposal	Delhi, Bengaluru
Pyrolysis	Very high	High	GHG emissions	Limited pilot project
Gasification	High	High	Complex logistics	Rajsthan, New Delhi
Composting	Low	Low	Low awareness	Gujrat, Maharastra
Landfilling	Low	None	Groundwater pollution	Still dominant

As Table 1 indicates, while incineration and gasification offer moderate to high energy yields, they face significant operational and environmental challenges. Composting remains cost-effective but depends heavily on source segregation. Landfilling, despite being unsustainable, continues to dominate due to its low immediate cost and lack of infrastructure for alternatives.

2. Review of Literature

The technological, infrastructure, and policy obstacles to effective waste management are highlighted in the literature on solid waste management in India.

2.1 Technological Approaches

Research on waste management technologies in India highlights both potential and limitations. In urban India, these studies draw attention to the inefficiencies of current systems and advocate WtE as a dual solution to waste overload and energy constraint. Singh et al. (2011), Kothari et al. (2010) and Saini et al. (2022) stress the necessity of integrated Waste-to-Energy (WtE) models. Belgiorno et al. (2003) discuss pyrolysis and gasification as feasible methods, though constrained by high start-up costs and operational complexities. Incineration, while reducing waste volume by 70–90%, produces toxic ash and air pollutants (Mukherjee et al., 2021). Composting and biomethanation, as noted by Thomas and Soren (2020), are more suitable for biodegradable waste, with Gujarat and Maharashtra successfully implementing large-scale systems.

2.2 Policy and Institutional Frameworks

Policy frameworks such as the Solid Waste Management Rules (2016) provide a regulatory foundation but remain weak in implementation due to funding shortages and bureaucratic inefficiencies. Scholars identify the administrative and infrastructural barriers that preclude Urban Local Bodies (ULBs) from managing waste better. Gupta et al. (1998) and Kumar & Sharma (2014) underline the infrastructural barriers such as inadequate collection facilities and outdated landfill systems. Khan et al. (2022[a]) emphasize the need for integrating energy recovery with policy reforms, highlighting Refuse-Derived Fuel (RDF) as a promising alternative if segregation systems are enforced.

2.3 Behavioral and Social Barriers

Several studies underscore that waste management is not only a technical issue but also a behavioral challenge. The literature also reflects growing awareness of the need for behavioural change in waste practices. Nandan et al. (2017) argue that citizen participation and segregation at source are crucial, while Khan et al. (2022[b]) highlight unregulated dumping and burning as major contributors to urban pollution. Mor et al. (2006) emphasize the health risks of unmanaged landfills. Effective awareness campaigns and community-level participation remain indispensable to ensure policy success.

The literature indicates that while technological options are available, infrastructural weaknesses, inadequate enforcement of policies, and behavioral gaps hinder sustainable waste management. These studies collectively suggest that unless awareness campaigns, infrastructure development, and policy reforms are aligned, sustainable waste management will remain a distant goal. Recent research (Gupta et al., 2015; Dutt & Sundaravadivel, 2022; Patwa & Kazmi, 2023) highlights how decentralized models, life cycle assessment tools, and WtE advancements are shaping India's next generation of waste management policies. However, they note that its success depends on well-functioning waste segregation systems and logistical efficiency. Despite technological advancements, the existing body of literature reveals significant implementation gaps. While policies such as the Solid Waste Management Rules (2016) provide a framework, practical execution remains weak due to funding shortages, bureaucratic delays, and insufficient public–private partnerships. As a result, scholars call for region-specific, decentralized, and community-participatory models to meet the rising waste challenges of India's urban centres.

3. Objectives of the Study:

i. To evaluate the effectiveness and environmental impact of various waste treatment technologies such as incineration, pyrolysis, gasification, composting, and landfilling.
ii. To evaluate the technical, financial, and policy barriers to the effective implementation of Waste-to-Energy (WtE) technologies in India.
iii. To identify infrastructural, administrative, and behavioral challenges in implementing scientific waste management systems.
iv. To propose integrated and decentralized waste management models tailored to India's urban and rural contexts.

4. Methodology

A qualitative research approach based on secondary data analysis has been adopted for the study. The research primarily relies on published reports, government documents, academic journals, policy briefs, and technical papers relevant to waste management practices in India. These include reports from the Central Pollution Control Board (CPCB), Ministry of Environment, Forest and Climate Change (MoEFCC), Ministry of Housing and Urban Affairs (MoHUA), Swachh Bharat Mission (SBM) documents, and scholarly research articles from peer-reviewed journals. The study relies on secondary data rather than primary data collection due to both practical and analytical considerations. Given the vast geographical diversity of India and the significant differences in waste management practices across urban and rural areas, conducting a comprehensive primary survey would have been resource-intensive and time-consuming, limiting the scope of coverage. Secondary data, in contrast, provided access to a wide range of government reports, national policy documents, and peer-reviewed studies that have already systematically captured waste management challenges and practices across different regions. This approach allowed for a comparative, holistic, and cost-effective analysis, while ensuring the study remains grounded in credible and large-scale datasets.

Selection Criteria: The documents and reports were selected based on their relevance, credibility, and publication timeframe. Priority was given to government policy documents, peer-reviewed journal articles, and technical reports published within the last 15–20 years, with classic references included were historically significant. Studies focusing on India's waste management practices, technological feasibility, and policy frameworks were emphasized, while global literature was included selectively for comparative insights.

Data Analysis: The collected data were systematically reviewed and categorized into thematic areas such as waste-to-energy technologies, composting, landfilling, policy frameworks, and institutional challenges. A comparative analysis was conducted to identify gaps between technological potential and actual implementation. In addition, cross-referencing among government reports and academic studies helped ensure validity and reduce bias in interpretation.

5. Findings:

The Prevalence of Non-Scientific Methods: In spite of existing policy frameworks and available technology, waste management in the majority of Indian cities still relies heavily on unscientific techniques such as open dumping and unsanitary landfilling, which raises serious environmental and health issues.

Inadequate Waste Segregation at Source: Data reveal that a substantial volume of municipal solid waste remains largely unsorted at the point of generation. This marginalizes recycling, composting, and Waste-to-Energy (WtE) operations.

Infrastructure and Management Deficiencies: Often Urban Local Bodies (ULBs) do not have enough infrastructure, trained personnel or financial resources available for developing sustainable waste management activities. Many WtE and biomethanation projects have closed down because of the absence of logistical planning, and a lack of source segregation.

Technological Potential vs. Ground Realities: While advanced methods like pyrolysis, gasification, and anaerobic digestion offer promise, their adoption remains limited due to high costs, operational complexity, and lack of public awareness. Composting, though environmentally friendly, suffers from inconsistent execution and public participation.

Waste-to-Energy as an Emerging Solution: WtE technologies are being promoted under national missions like Swachh Bharat and Smart Cities, but large-scale success is contingent upon robust segregation practices, consistent supply chains, and public-private partnerships.

Need for Decentralized Models: Data suggests that decentralized and community-based waste management systems are more sustainable and context-appropriate, especially for medium and small towns where centralized systems are not economically viable.

Importance of Behavioral Change and Public Participation: The literature highlights that successful waste management is not only a technical issue but also a social one. Long-term improvement requires sustained awareness campaigns, behavioral change initiatives, and citizen engagement.

To ensure clarity in understanding how research objectives were addressed, the following table maps each objective with its corresponding key findings.

Table 2: Mapping Objectives to Findings

Objective	Key Findings
	Incineration reduces waste volume but produces toxic ash; Pyrolysis is useful for plastics but costly; Gasification enables energy recovery but demands infrastructure and skilled labor; Composting is cost-effective but suffers from poor segregation.
Explore the role of WtE	WtE projects (Delhi, Bengaluru) show potential but depend heavily on source segregation and reliable supply chains.
Identify challenges	ULBs lack infrastructure, trained personnel, and financial resources; behavioral resistance to segregation; poor enforcement of SWM Rules 2016.
Propose models	Decentralized community-based composting and biogas plants (e.g., Gujarat, Maharashtra) demonstrate greater sustainability compared to centralized systems.

6. Suggestions

Currently, there are various technologies available for waste treatment, each with its own set of positive and negative consequences. The selection criteria for a viable option depend on the quantity and composition of the waste. The major challenge in effective waste management lies in the collection and segregation of waste. Inefficient collection and segregation reduce the efficiency of recycling and treatment processes. Therefore, this study highlights several suggestive points based on research:

- Investment in Waste to Energy Projects: Specific funding mechanisms should be promoted to overcome the high capital costs associated with these projects. These may include government incentives such as viability gap funding (VGF), capital subsidies, and tax exemptions on renewable energy infrastructure**.**
- Amendments to the Solid Waste Management (SWM) Rules, 2016: To address the gaps in implementation of the SWM Rules (2016), this act should focus on strengthening source segregation, mandating decentralized bio-waste management, improving Waste-to-Energy feedstock quality, introduce QR/RFID-based waste tracking and open dashboards minimizing landfilling.
- Scientific Up gradation of Dumping Sites: Modernizing existing landfill sites with leachate control, gas collection, and soil layering.
- Capacity Building: Training programs for sanitation workers and municipal staff to improve efficiency and awareness.
- Infrastructure Development: Enhancing collection, segregation, and transportation facilities.
- Promotion of Integrated Waste Management: Adoption of region-specific, technology-integrated solutions.
- Encouragement of Composting and Recycling: Community-level composting and material recovery facilities.
- Waste Segregation at Source: Incentivizing households and institutions to segregate waste.

- Extended Producer Responsibility (EPR): Holding manufacturers accountable for post-consumer waste management.

7. Conclusion

Waste-to-Energy generation represents a vital component of India's strategy to achieve Sustainable Development Goals (SDGs), particularly concerning clean energy and sustainable cities. With increasing awareness and a changing mindset among people, the waste-to-energy generation model has become more viable in the current scenario. Many initiatives, in the form of pilot projects and large-scale plants, have been set up in India. Despite various initiatives, several technological and operational barriers persist:

- **Incineration:** High emissions and hazardous ash residues demand stricter emission controls and investment in advanced flue-gas cleaning technologies.
- **Pyrolysis:** High capital costs and limited market pathways for pyrolysis oil call for targeted subsidies, PPP investment, and stronger demand creation through industrial applications.
- **Gasification:** Complex operation and high initial investment require viability gap funding, integration into renewable energy policy, and capacity building for operators.
- **Composting:** Limited public awareness and improper segregation at source highlight the need for decentralized, community-driven composting initiatives and educational campaigns.
- **Landfilling:** Poorly managed sites lacking leachate treatment and gas recovery systems underscore the urgent need for scientific upgrading and strict enforcement of landfill regulations.

Next Steps: Hence, there is a need for a micro-based plan to achieve higher targets. Primary door-to-door collection and proper segregation of waste at the source are essential for achieving waste-to-energy generation targets. The Government of India, within its waste management and handling rules of 2016, has given special emphasis to the waste-to-energy generation process. This includes all elements from waste collection to treatment, which may bring sustainability to the environment and economy, thus shift from disposal-oriented to recovery-centric models is urgently needed, supported by policy integration, monitoring frameworks, and financial incentives. With a robust regulatory framework and active public participation, India can transform its waste crisis into an opportunity for sustainable growth. This paradigm shift requires an attitudinal change among people and an effective regulatory and monitoring framework for waste management. Each of these methods requires tailored interventions, emission control frameworks for incineration, green financing for pyrolysis and gasification, decentralized models for composting, and modernization of landfills with proper monitoring systems. Cross-cutting solutions include robust segregation at source, sustained awareness campaigns, and capacity building for municipal staff and sanitation workers.

Call to Action: Policymakers must now move beyond piecemeal approaches and prioritize an integrated, decentralized, and financially viable waste management strategy. This requires aligning regulatory frameworks with innovative financing, incentivizing private participation, and ensuring accountability at the local level. Without urgent, coordinated action, India risks perpetuating unsustainable waste practices, but with bold policy choices and strong governance, the country can transform its waste crisis into an opportunity for sustainable growth and environmental leadership.

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