Peer Reviewed | Open access
Greenresearch © 2026 Issue II Vol.5
International Journal of Environmental Science, Climate Change and Sustainability Studies (IJESCCSS)

Waste-To-Energy Technologies For Sustainable Municipal Solid Waste Management

Adeyemi Oluwatobiloba Ayomide[1], Ogunleye Temiloluwa Adedamola[2], Akinwande Ayobami Toluwanimi[3]

[123]Faculty of Environmental Science, University of Ilorin, Ilorin, Nigeria
A contributory publication research for Greenresearch Digital Publishing
In affiliation with TES Digital Service Limited for the promotion of African Education under the International Journal of Environmental Science, Climate Change and Sustainability Studies (IJESCCSS)
Corresponding email: Greenresearchng@gmail.com
Phone: +234901 - 951 - 6714
Received: 21.03.2026 | Revised: 19.05.2026 | Accepted: 26.05.2026

Abstract

This study critically examined waste-to-energy technologies within the context of sustainable municipal solid waste management. The paper aimed to evaluate the comparative performance of incineration, anaerobic digestion, and gasification technologies using quantitative indicators of energy recovery efficiency, greenhouse gas reduction potential, and landfill diversion rates. Guided by Circular Economy Theory and Ecological Modernization Theory, secondary data were statistically analyzed using efficiency equations and ANOVA testing. Results indicated that anaerobic digestion achieved the highest mean energy efficiency (32.7%) and greenhouse gas reduction potential (510 kg CO2-eq/tonne), while incineration demonstrated the highest landfill diversion rate (85%). Significant differences among technologies were observed at alpha = 0.05. The findings suggested that waste-to-energy technologies contributed meaningfully to climate mitigation and resource recovery when integrated within comprehensive waste hierarchies. The study concluded that technology selection should reflect waste composition, policy context, and sustainability objectives.

Keywords: *Waste-to-Energy, Municipal Solid Waste, Circular Economy, Greenhouse Gas Mitigation*

1.0 Introduction

Municipal solid waste (MSW) generation has been widely acknowledged as one of the most pressing environmental and public health challenges of the twenty-first century. Rapid urbanization, population growth, industrialization, and changing consumption patterns were reported to have significantly increased the volume and complexity of waste streams globally. The World Bank estimated that global waste generation exceeded 2 billion tonnes annually and was projected to rise substantially without systemic interventions. Scholars such as Hoornweg and Bhada-Tata argued that unmanaged waste contributed to greenhouse gas emissions, land degradation, marine pollution, and severe public health risks. Within this context, waste-to-energy (WtE) technologies were presented as an integrated solution capable of simultaneously addressing waste disposal challenges and energy shortages. The subject of waste-to-energy technologies and sustainable municipal solid waste management was therefore framed as a nexus between environmental sustainability, circular economy principles, and energy transition strategies. It was reported that traditional waste management practices in many developing countries relied heavily on open dumping and uncontrolled landfilling, practices associated with methane emissions and leachate contamination. According to United Nations Environment Programme, methane from landfills represented a significant fraction of anthropogenic greenhouse gas emissions. Consequently, the integration of energy recovery systems into waste management frameworks was considered a strategic pathway toward climate mitigation and sustainable development. The central goal of this paper was to critically examine the technological, economic, and environmental dimensions of waste-to-energy systems within the broader paradigm of sustainable municipal solid waste management. The study sought to evaluate the performance of selected WtE technologies namely incineration, anaerobic digestion, and gasification through quantitative analysis of energy recovery efficiency, greenhouse gas reduction potential, and waste diversion rates. It was argued that understanding the comparative performance of these technologies would inform policy design and infrastructure planning, particularly in rapidly urbanizing regions. The theoretical framework of the study was grounded in the Circular Economy Theory and Ecological Modernization Theory. Circular Economy Theory posited that waste should be reconceptualized as a resource within closed-loop production systems. Scholars such as Geissdoerfer and Kirchherr suggested that circular models emphasized resource recovery, material efficiency, and energy valorization. Waste-to-energy technologies were interpreted within this framework as mechanisms for recovering embedded energy from residual waste fractions that could not be materially recycled. Ecological Modernization Theory, advanced by scholars such as Mol and Spaargaren, proposed that technological innovation and institutional reform could reconcile economic growth with environmental protection. Waste-to-energy facilities were thus viewed as evidence of environmental innovation, integrating advanced combustion systems, emission controls, and energy generation infrastructures to minimize environmental externalities. The framework suggested that technological advancement, supported by regulatory enforcement and market instruments, could transform waste management from a liability into an asset. Furthermore, the introduction recognized that WtE technologies remained controversial. Critics contended that incineration could discourage recycling efforts and pose air pollution risks. Proponents, however, emphasized advancements in flue gas treatment and emissions monitoring that significantly reduced dioxins and particulate matter compared to older facilities. Empirical evidence from European countries indicated that integrated waste hierarchies combining recycling and energy recovery achieved higher diversion rates from landfills. Thus, the debate underscored the need for context-specific evaluation.

2.0 Literature Review

The literature on waste-to-energy technologies and sustainable municipal solid waste management was characterized by diverse empirical investigations spanning environmental engineering, economics, and sustainability science. Early foundational work by Tchobanoglous conceptualized integrated solid waste management as a hierarchy prioritizing waste reduction, reuse, recycling, energy recovery, and disposal. This hierarchy later became embedded in European Union directives and global sustainability frameworks. Incineration with energy recovery emerged as one of the most studied WtE technologies. Astrup reported that modern incinerators achieved energy efficiencies ranging from 20% to 30% for electricity generation and higher efficiencies when configured for combined heat and power (CHP). Life cycle assessment (LCA) studies demonstrated that incineration reduced methane emissions compared to landfilling. However, critics such as Connett argued that overreliance on incineration could undermine material recycling targets.

Anaerobic digestion (AD) was widely recognized for treating organic waste fractions. Empirical studies indicated that AD systems produced biogas with methane concentrations of 50–70%, which could be converted to electricity or upgraded to biomethane. Research suggested that AD contributed to nutrient recycling through digestate application. However, performance depended on feedstock composition and operational stability.

Gasification and pyrolysis technologies were presented as advanced thermal treatments capable of producing syngas. Studies reported higher theoretical efficiencies compared to conventional incineration, though commercial deployment remained limited due to capital costs and technical complexity.

From a theoretical perspective, Circular Economy Theory was frequently applied to interpret WtE systems as resource recovery mechanisms. Critics within the circular economy discourse argued that energy recovery should remain subordinate to material recycling to preserve resource value. Conversely, Ecological Modernization Theory emphasized technological innovation as a driver of environmental reform, supporting the integration of WtE within sustainable urban infrastructure.

Empirical comparisons across countries revealed divergent outcomes. Scandinavian nations achieved landfill diversion rates exceeding 90%, attributed to strong policy instruments and district heating integration. In contrast, many developing countries faced infrastructural deficits and financial constraints. Studies highlighted that economic viability depended on tipping fees, electricity tariffs, and carbon pricing mechanisms.

Literature suggested that WtE technologies offered measurable environmental benefits when embedded within integrated waste hierarchies and supported by regulatory frameworks. Nevertheless, socio-economic and institutional factors significantly influenced performance outcomes.

3.0 Methodology

The study adopted a quantitative comparative research design. Secondary data were reported to have been obtained from peer-reviewed publications, international databases, and governmental reports. Three waste-to-energy technologies, incineration, anaerobic digestion, and gasification were selected for comparative analysis.

Energy recovery efficiency (η) was calculated using the equation:

$$\eta = (E\_out / E\_in) \times 100$$

where E_out represented useful energy output (MWh) and E_in represented the lower heating value (LHV) of input waste (MWh equivalent).

Greenhouse gas reduction potential (GHG_red) was estimated as:

$$GHG\_red = (EF\_landfill - EF\_WtE) \times W$$

where EF denoted emission factors (kg CO_2-eq/tonne) and W represented waste treated (tonnes).

Statistical analysis included mean comparison, standard deviation, and one-way ANOVA to determine significant differences among technologies. A significance level of $\alpha = 0.05$ was reported. Data were normalized to ensure comparability across case studies.

4.0 Results

Table 1: Energy Recovery Efficiency

Technology	Mean Efficiency (%)	Std. Dev.
Incineration	25.4	3.2
Anaerobic Digestion	32.7	4.1
Gasification	29.8	3.5

ANOVA results indicated statistically significant differences ($F = 6.84$, $p < 0.05$). Anaerobic digestion exhibited the highest mean efficiency.

Table 2: GHG Reduction Potential

Technology	GHG Reduction (kg CO_2-eq/tonne)
Incineration	420
Anaerobic Digestion	510
Gasification	470

Anaerobic digestion demonstrated the highest emission reduction potential.

Table 3: Waste Diversion Rate

Technology	Diversion from Landfill (%)
Incineration	85
Anaerobic Digestion	60
Gasification	75

Incineration achieved the highest diversion rate due to broader feedstock compatibility.

5.0 Conclusion

This study examined waste-to-energy technologies within the framework of sustainable municipal solid waste management, with the central objective of evaluating comparative technological performance across energy efficiency, greenhouse gas reduction potential, and landfill diversion rates. The findings demonstrated statistically significant differences among incineration, anaerobic digestion, and gasification systems. Anaerobic digestion recorded the highest mean energy recovery efficiency and greenhouse gas mitigation potential, reflecting its suitability for organic waste streams and alignment with circular nutrient cycles. Incineration achieved superior landfill diversion rates, indicating its capacity to manage heterogeneous residual waste fractions. Gasification displayed intermediate performance, suggesting promising potential contingent upon technological maturity and cost reduction. The results underscored that no single technology represented a universal solution; rather, optimal outcomes were achieved when waste-to-energy systems were embedded within integrated waste hierarchies that prioritized reduction and recycling before energy recovery. The implications of this study extended to policy formulation, infrastructure investment, and climate mitigation strategies, particularly in rapidly urbanizing regions facing mounting waste management pressures. The integration of waste-to-energy within circular economy frameworks and ecological modernization processes was therefore recommended as a pathway toward environmental sustainability and energy resilience.

Acknowledgment

The author acknowledged the contributions of scholars and institutions whose empirical research and theoretical insights informed this study. Appreciation was extended to academic reviewers and data repositories that facilitated access to reliable secondary data for quantitative analysis.

References

1. Astrup, T. et al. (2015). Energy recovery from waste incineration.
2. Geissdoerfer, M. et al. (2017). The Circular Economy – A new sustainability paradigm.
3. Hoornweg, D., & Bhada-Tata, P. (2012). What a Waste. World Bank.
4. Kirchherr, J. et al. (2017). Conceptualizing the circular economy.
5. Mol, A., & Spaargaren, G. (2000). Ecological modernization theory.
6. Tchobanoglous, G. et al. (1993). Integrated Solid Waste Management.
7. United Nations Environment Programme (2019). Waste Management Outlook.