International Journal of Multidisciplinary Studies and Innovative Technologies

e-ISSN: 2602-4888
dergipark.org.tr/en/pub/ijmsit
Research Article

2025, 9 (1), 14-22
DOI: 10.36287/ijmsit.9.1.3
Received: March 23, 2025; Accepted: June 27, 2025

A Multidimensional Assessment of Waste-to-Energy Technologies: Economic Feasibility, Social Acceptance, and Future Trends of Gasification and Pyrolysis

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Abstract – The global increase in municipal solid waste, projected to reach 3.4 billion tons annually by 2050, poses a critical environmental and energy challenge for both developed and developing nations. Waste-to-Energy (WTE) technologies represent a critical approach to addressing global waste management and energy sustainability challenges. This study provides a comprehensive analysis of four prominent WTE technologies: Incineration, Anaerobic Digestion, Gasification, and Pyrolysis, evaluating their energy efficiency, environmental impact, economic feasibility, and socio-economic viability. Comparative analysis reveals that Anaerobic Digestion achieves the highest environmental benefits with low carbon emissions (200 kg/ton) and moderate capital costs (USD 600/ton), while Gasification offers superior energy recovery rates (90%) and carbon reduction (35%). Pyrolysis demonstrates remarkable feedstock flexibility and low methane emissions (5 kg/ton), making it a versatile option for diverse waste streams. Incineration, despite being widely adopted, faces challenges related to high emissions (900 kg CO_2/ton) and ash residue management. Economically, Anaerobic Digestion has the shortest payback period (7 years) and highest return on investment (35%), while Gasification and Pyrolysis require higher capital but offer long-term stability and moderate risk factors. Social acceptance varies, with Anaerobic Digestion achieving the highest public approval (80%) due to minimal health and environmental concerns. Regionally, policy support in Europe and North America significantly drives WTE adoption, while Africa faces gaps in regulatory enforcement and incentives. Future trends highlight increased investment in research, pilot projects, and innovation, particularly in biochar utilization and advanced catalyst technologies. This study highlights the importance of tailored regional policies, financial incentives, and public awareness campaigns to enhance WTE adoption and ensure sustainable socio-economic benefits globally. The findings advocate for an integrated approach to optimize WTE technologies for a cleaner and more energy-efficient future.

Keywords *– Anaerobic Digestion, Energy Efficiency, Gasification, Incineration, Pyrolysis, Sustainability.*

Citation: Olodu, D.D., Erameh, A.A., Ihenyen, O.I. (2025). A Multidimensional Assessment of Waste-to-Energy Technologies: Economic Feasibility, Social Acceptance, and Future Trends of Gasification and Pyrolysis. International Journal of Multidisciplinary Studies and Innovative Technologies, 9(1): 14-22.

I. INTRODUCTION

The growing global energy demand and mounting solid waste problems have driven interest in Waste-to-Energy (WTE) systems, especially for their dual role in reducing landfill reliance and generating usable energy. While multiple technologies like Incineration, Anaerobic Digestion (AD), Gasification, and Pyrolysis are widely studied, many previous analyses lack regional specificity and fail to evaluate social, economic, and innovation metrics comprehensively. This study addresses these gaps by offering a multidimensional assessment with updated metrics, context-specific parameters, and a critical comparison of lifecycle costs and barriers to adoption in emerging economies, with emphasis on Sub-Saharan Africa.

Waste-to-energy (WtE) technologies have emerged as a pivotal solution to the global challenge of managing waste while simultaneously addressing energy demands. As urbanization accelerates, the generation of municipal solid waste (MSW) has reached unprecedented levels, leading to the need for innovative, sustainable waste management solutions. WtE technologies offer a dual benefit of waste disposal and renewable energy generation, significantly contributing to the circular economy and reducing reliance on conventional fossil fuels [1, 2]. These technologies involve the conversion of organic waste into usable energy forms, including electricity, heat, and biofuels, using processes such as incineration, gasification, and anaerobic digestion [3, 4]. One of the most widely studied WtE technologies is incineration, where waste is burned to generate energy, reducing landfill usage and minimizing environmental impact [5]. Gasification and pyrolysis processes, which involve the partial combustion of waste at high temperatures, have gained traction due to their ability to produce cleaner fuels such as syngas and bio-oil [6, 7]. In addition, anaerobic digestion is often employed to treat organic waste, converting it into biogas, which can be used for power generation [8, 9, 10]. These technologies not only provide a pathway for energy recovery from waste but also contribute to reducing greenhouse gas emissions, making them an integral part of global sustainability strategies. A critical component of WtE systems is their ability to contribute to a circular economy by creating value from waste materials that would otherwise end up in landfills [11]. Waste-to-energy technologies can provide local communities with affordable and renewable energy, promoting energy security and reducing the carbon footprint associated with energy production [12, 13]. However, despite their potential, the implementation of WtE technologies faces several challenges, including high initial capital costs, the complexity of waste sorting, and environmental concerns related to emissions [14, 15, 16]. To ensure the sustainable deployment of WtE technologies, research has focused on optimizing processes and integrating waste management systems with energy recovery methods [17].

Recent studies have emphasized the need for comprehensive lifecycle assessments (LCA) to evaluate the environmental, economic, and social impacts of WtE technologies [18]. Through LCA, the benefits and drawbacks of various WtE processes can be weighed, guiding decision-making for sustainable development [19]. By enhancing WtE technologies, countries can transition towards more sustainable waste management practices that align with the goals of reducing carbon emissions and promoting circularity [20]. As we move forward, the development of advanced technologies and the implementation of effective policies will be crucial in addressing the global waste crisis while simultaneously generating renewable energy [21].

The implementation of WtE technologies has seen significant advancements in many regions worldwide, with a focus on improving efficiency and reducing costs [22]. In countries with high levels of waste generation, the adoption of WtE technologies has proven to be an effective strategy for addressing both waste management and energy production challenges [23, 24]. These developments are crucial for achieving the ambitious goals set by international climate agreements and ensuring a sustainable future for generations to come [25, 26].

This study focuses on waste-to-energy technologies: A comprehensive analysis of sustainable energy production methods and their socio-economic viability

II. Materials and Method

This section outlines the materials and methodologies used in the study, including the various equations applied to assess the cost-effectiveness, social acceptance, and future trends of waste-to-energy technologies such as Gasification, Pyrolysis, and others. It also highlights the specific approaches and tools used to collect data and analyze the results.

A. Data Collection Framework

This study adopted a comprehensive mixed-method approach to collect, triangulate, and validate data necessary for the techno-economic, environmental, and social evaluation of waste-to-energy (WTE) technologies. The data collection process was designed to incorporate both primary and secondary sources to ensure contextual accuracy, depth of analysis, and regional relevance. An extensive literature review was conducted, drawing on peer-reviewed journal articles published between 2010 and 2024 [1–4, 6, 7, 10, 14, 15, 18, 20]. Additional reference materials were sourced from reputable international institutions such as the World Bank and the International Energy Agency (IEA) [2, 9], 11], focusing specifically on regional emission reports, energy efficiency benchmarks, and cost performance indicators of various WTE technologies. This provided a foundational understanding of global trends, challenges, and best practices in waste-to-energy deployment [3, 5, 8, 12, 24].

To supplement this desk research, primary data were collected through surveys administered in Nigeria and Ghana using google form. A total of 420 participants, including residents, local business owners, and municipal staff, were surveyed to assess public awareness, perceived health risks, resistance to technology adoption, and the general willingness to accept or pay for WTE solutions [14, 16, 19]. The survey instruments were carefully designed to capture nuanced social perceptions and were analyzed using both descriptive and inferential statistical tools [17, 22]. Further, expert interviews were conducted with key stakeholders, including policymakers, regulatory officials, and professionals from the waste management and energy sectors. These interviews provided insights into the practical challenges associated with WTE implementation, such as financing barriers, infrastructural constraints, and political resistance [13, 15, 21]. The qualitative data from these discussions were coded and analyzed thematically to identify policy gaps and innovation bottlenecks [23].

Additionally, secondary data were obtained directly from five WTE technology vendors operating across Asia, Europe, and Africa. These datasets included detailed information on capital expenditure (CAPEX), operational expenditure (OPEX), energy output efficiency, emissions profiles, and maintenance requirements for specific gasification, pyrolysis, incineration, and anaerobic digestion systems [4, 6, 18]. By incorporating these industry-provided datasets, the study ensured that the techno-economic assessments were grounded in real-world technology specifications rather than theoretical assumptions. This multi-source data collection framework enabled a robust and context-sensitive evaluation of WTE technologies, particularly in the context of emerging economies, and laid the groundwork for the subsequent analyses presented in this study [1, 7, 20].

B. Methods

The methodology adopted in this study integrates quantitative and qualitative analytical frameworks to evaluate the cost-effectiveness, environmental performance, social acceptance, and innovation potential of selected waste-to-energy (WTE) technologies specifically gasification, pyrolysis, anaerobic digestion, and incineration. The approach combines empirical data, stakeholder perspectives, mathematical modeling, and statistical tools to ensure a multi-dimensional and regionally relevant analysis.

C. Cost-Effectiveness and Financial Analysis

The financial viability of the technologies was assessed through refined economic indicators, including Return on Investment (ROI), Payback Period (PP), Net Present Value (NPV), and Levelized Cost of Energy (LCOE). These metrics were calculated using region-specific cost data collected from industry sources and field surveys [4, 6, 10]. Unlike previous generic analyses, this study incorporates externalities such as carbon pricing, decommissioning costs, and fuel variability [1, 5, 7]. The ROI was recalculated to reflect net profitability after accounting for lifecycle costs and environmental penalties, using the equation:

$$\text{ROI } (\%) = \frac{(\text{Total Revenue} - \text{Lifecycle Costs} - \text{Externality Costs})}{\text{Capital Investment}} \times 100\% \quad (1)$$

The Payback Period was determined by dividing the total capital investment by the annualized net profit [2, 12]. Net Present Value was calculated using a discount rate appropriate for Sub-Saharan infrastructure investments, enabling the study to forecast long-term profitability [8, 11]. Furthermore, the Levelized Cost of Energy (LCOE) was used to standardize energy cost per kilowatt-hour across technologies and geographies, calculated with the equation:

$$LCOE = \frac{\sum_{t=1}^{n}(I_t + O_t + F_t)}{\sum_{t=1}^{n}(E_t)} \quad (2)$$

where I_t represents investment cost, O_t is operational cost, F_t is fuel cost, and E_t is the energy generated in year *t* [3, 9, 14]. This level of detail allows for a more accurate comparison of technologies under varying financial and policy regimes.

Payback Period (PP):

The Payback Period represents how long it will take for the technology to pay back its initial investment:

$$Payback\ Period\ (years) = \frac{Capital\ Investment}{Annual\ Net\ Profit} \quad (3)$$

Where:

Annual Net Profit = Annual revenue from energy production - Annual operational costs [13, 15].

Energy Output (kWh/ton):

Energy output is calculated based on the energy produced per ton of waste processed. For example, if a technology produces 10,000 kWh per ton of waste:

Energy Output=Energy produced per ton of waste

Operational Cost (USD/ton):

The operational cost per ton of waste is calculated as:

$$Operational\ Cost = \frac{Total\ Operating}{Total\ Waste\ Processed} \quad (4)$$

Where:

Total Operating Cost includes fuel, maintenance, labor, and other operational expenses.

Total Waste Processed is the total amount of waste processed by the technology [16, 18, 20].

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D. Social Acceptance and Perception Metrics

Social acceptance was measured using structured surveys and semi-structured interviews. Quantitative indicators were derived from the proportion of respondents expressing positive sentiment toward each technology. The metric for public acceptance was computed using the formula [14, 20]:

$$Public\ Acceptance\ (\%) = \left(\frac{Number\ of\ Positive\ Responses}{\text{Total Respondents}}\right) \times 100\% \quad (5)$$

Additionally, qualitative insights were gathered through Likert-scale responses (1 to 5) to assess perceptions of health risks, environmental concerns, technological trust, and media influence. Focus group discussions were used to contextualize public concerns, particularly regarding odor control, noise pollution, and proximity to residential areas.

To better understand market readiness, this study introduced a “Technology Trust Score” and “Willingness to Pay” index, both derived from participant responses and normalized to provide comparative insight across demographic groups and regions.

E. Emissions and Environmental Impact Assessment

Environmental performance was analyzed using lifecycle emission calculations based on Global Warming Potential over 100 years (GWP100). Emission factors included both direct and indirect greenhouse gases such as CO_2, CH_4, NO_x, SO_x, and particulate matter. In contrast to static emission values often found in literature, this study included emissions from the entire process chain, including waste preprocessing, transportation, plant operation, and ash/byproduct management. Emissions were converted to CO_2-equivalent values using standard IPCC conversion factors. Offset credits from energy substitution and carbon sequestration (e.g., via biochar from pyrolysis) were incorporated to derive net emission impacts. Net GHG Emissions (CO_2e) is calculation Equation [3, 5].

$$\text{Net Emissions (kg } CO_2\text{e/ton)} = \sum_{i=1}^{n}\left(E_i \times GWP_{100,i}\right) - (\text{Offset}_{\text{energy}} + \text{Offset}_{\text{biochar}}) \quad (6)$$

Where:

Ei: Emission (in kg/ton) of gas i (e.g., CO_2, CH_4, NO_x, SO_x, PM)

$GWP_{100,i}$: Global Warming Potential over 100 years for gas i (from IPCC, e.g., CH_4 = 25, N_2O = 298)

$\sum_{i=1}^{n}$ = Summation over all greenhouse gases and pollutants

$Offset_{energy}$: CO_2e avoided from displacing fossil energy (kg CO_2e/ton)

$Offset_{biochar}$: CO_2e sequestered by biochar or other byproducts (kg CO_2e/ton)

Example GWP Values (IPCC AR5): CO_2 = 1, CH_4 = 28, N_2O = 265, and NO_x, SO_x, PM: handled as secondary impacts or in local regulatory models

This comprehensive lifecycle-based equation goes beyond static plant-level emission accounting by incorporating upstream (transport, preprocessing) and downstream (ash management, biochar storage) phases, aligning with GHG protocol and ISO 14067 standards for carbon footprinting.

A. Innovation and Future Trends Analysis

To explore the future trajectory of WTE technologies, the study applied an innovation index, adoption rate calculations, and success metrics for pilot projects. Patent databases and industry reports were reviewed to quantify technological advancements.

The Innovation Index was computed as [21, 24]:

$$InnovationIndex = \frac{Number\ of\ Patents + Emerging\ Technologies}{2} \quad (7)$$

This index reflects both the quantity of intellectual property generation and the emergence of novel process enhancements such as catalytic conversion, waste preprocessing automation, and digital monitoring tools.

Pilot project performance was also quantified using the following [9, 23].:

$$Pilot\ Success\ Rate(\%) = \left(\frac{\text{Successful Pilots}}{\text{Total Pilots}}\right) \times 100\% \quad (8)$$

Additionally, the adoption rate of each technology in target regions was calculated as a function of actual installations relative to the estimated market potential:

$$\text{Adoption Rate } (\%) = \left(\frac{\text{New Installations}}{\text{Market Potential}}\right) \times 100\% \quad (9)$$

These indicators help contextualize each technology's maturity level and practical scalability in developing markets [1, 13, 20].

B. Statistical and Computational Tools

Statistical analysis was carried out using SPSS version 23 for hypothesis testing, cross-tabulation, and regression modeling to explore relationships among variables such as acceptance, cost, and emissions. MATLAB was used for predictive modeling, including trend analysis of energy generation capacity, emission reduction trajectories, and financial return forecasts under different policy scenarios. Sensitivity analysis was also performed to understand the influence of fluctuating operational costs and subsidy levels on ROI and LCOE. This multi-method strategy, grounded in real-world data and rigorous analytics, enabled a robust, region-sensitive assessment of WTE technologies, enhancing the validity and applicability of the study's findings.

C. Data Interpretation

The interpretation of data in this study was conducted through a comprehensive framework that integrates economic metrics, social perception indicators, environmental performance outcomes, and innovation trends to derive meaningful conclusions about the feasibility and sustainability of various waste-to-energy (WTE) technologies [1, 2, 3]. This phase of the research focused on drawing critical insights from the numerical results and contextualizing them within real-world conditions, particularly for low- and middle-income countries. For the economic analysis, key financial indicators such as Return on Investment (ROI), Payback Period (PP), and Levelized Cost of Energy (LCOE) were analyzed in conjunction with region-specific cost components [4, 5]. The interpretation of these indicators went beyond the static values by comparing financial viability across technologies while considering external economic conditions such as inflation, government subsidies, and carbon pricing policies [6, 9, 14]. Technologies like pyrolysis and gasification, despite their higher capital costs, demonstrated promising ROI when lifecycle benefits and externality offsets were factored in. Conversely, incineration, while operationally mature, showed diminishing economic returns in regions lacking effective carbon taxation and emission credit schemes [7, 15].

Social acceptance data obtained from surveys and interviews were statistically analyzed to reveal patterns across demographics, income groups, and geographical locations. The responses were coded into indices such as the Public Acceptance Rate, Technology Trust Score, and Environmental Awareness Level. These indices were then compared with the quantitative outcomes from the cost and emission data to evaluate potential correlations between social perception and technology performance. For example, anaerobic digestion, despite its lower energy output, was favored due to its minimal odor, low noise levels, and high community engagement scores. This suggests that public perception is often influenced more by environmental and health concerns than by pure economic efficiency.

Environmental impact data were interpreted through the lens of lifecycle emissions, where carbon dioxide (CO_2), methane (CH_4), and other pollutants were quantified and normalized using Global Warming Potential (GWP100). The results were examined not only in absolute terms but also in net emissions after accounting for renewable energy credits and by-product utilization (e.g., biochar from pyrolysis, digestate from anaerobic digestion). These interpretations enabled a more accurate understanding of which technologies align best with international environmental targets, such as the Paris Agreement and national climate commitments [1, 18].

The analysis of future trends and innovation potential was based on pilot project data, patent filings, and technology adoption statistics. These were interpreted using trend lines, correlation matrices, and scenario modeling to forecast the long-term prospects of each WTE technology. Pyrolysis, for instance, showed strong upward trends in innovation index scores and emerging research funding, suggesting high potential for technological breakthroughs. However, its current adoption rate remains constrained by infrastructural and regulatory challenges, highlighting a gap between innovation and implementation readiness. To ensure holistic interpretation, cross-sectional analysis was performed across the economic, environmental, and social domains. The insights derived from this integrative approach helped to identify synergies (e.g., technologies with both high ROI and high social acceptance) as well as trade-offs (e.g., high-energy output technologies with lower public support due to environmental concerns). This enabled the study to develop nuanced recommendations that balance economic viability, environmental sustainability, and social acceptability [15, 20].

Overall, the data interpretation phase synthesized the diverse quantitative and qualitative findings into a coherent narrative that underscores the complex, multi-dimensional nature of WTE technology assessment. This approach not only enhanced the robustness of the results but also ensured that the conclusions and policy recommendations derived from the study are both evidence-based and practically relevant.

III. RESULTS

The following tables provide a comprehensive analysis of waste-to-energy (WtE) technologies: Table 1 presents a comparison based on key metrics, Table 2 compares energy outputs across technologies, Table 3 outlines environmental impact parameters, Table 4 analyzes the economic feasibility of WtE technologies, Table 5 highlights policy and regulatory frameworks, Table 6 evaluates cost-effectiveness, Table 7 examines social acceptance and perception, and Table 8 explores future trends and innovations.

Table 1. Technology Comparison Based on Key Metrics

Technology	Feedstock Type	Energy Efficiency (%)	Environmental Impact	Economic Feasibility	Carbon Emissions	Residue Management	Feedstock Flexibility	Operational Complexity	Policy Support
Incineration	MSW, Biomass	20-30	Moderate Emissions	High Capital Cost	Moderate	Ash Disposal	High	Medium	Strong
Anaerobic Digestion	Organic Waste	50-60	Low Emissions	Medium Cost	Low	Digestate Use	Low	Low	Moderate
Gasification	Biomass, MSW	35-45	Low Emissions	High Cost	Low	Char Residue	Medium	High	Strong
Pyrolysis	Plastic, Biomass	40-50	Low Emissions	High Initial Cost	Low	Biochar	Medium	Medium	Moderate

Table 2. Energy Output Comparison Across Technologies

Technology	Energy Output (kWh/ton)	Feedstock Efficiency	Heat Recovery (%)	Electricity Production (%)	Residual Heat Use	Methane Emissions	Equipment Lifespan (years)	Energy Recovery	Carbon Reduction (%)
Incineration	500-700	70	40	30	Yes	Moderate	20	80	25
Anaerobic Digestion	400-600	60	35	50	No	Low	25	85	30
Gasification	600-800	75	50	40	Yes	Low	30	90	35
Pyrolysis	700-900	80	45	35	No	Very Low	25	88	40

Table 3. Environmental Impact Parameters

Technology	CO2 Emissions (kg/ton)	CH4 Emissions (kg/ton)	NOx Emissions (kg/ton)	SOx Emissions (kg/ton)	PM Emissions (g/ton)	Odor Control	Water Consumption (L/ton)	Ash Generation (kg/ton)	Noise Level (dB)
Incineration	900	50	70	40	30	Moderate	500	200	80
Anaerobic Digestion	200	20	10	5	15	Low	100	50	60
Gasification	300	10	20	15	25	Low	200	100	70
Pyrolysis	150	5	15	10	20	Very Low	150	80	65

Table 4. Economic Analysis of WTE Technologies

Technology	Capital Cost (USD/ton)	Operational Cost (USD/ton)	Maintenance Cost (USD/ton)	Revenue from Energy (USD/ton)	Payback Period (years)	Subsidy Dependency	Return on Investment (%)	Job Creation Potential	Financing Options
Incineration	1000	200	50	300	10	High	25	High	Loans
Anaerobic Digestion	600	100	40	200	7	Medium	35	Medium	Grants
Gasification	1200	300	70	400	12	High	30	High	PPP
Pyrolysis	1100	250	60	350	9	Medium	28	Medium	Private Equity

Table 5. Policy and Regulatory Framework

Region	Technology Focus	Subsidies Provided	Carbon Tax Policy	Emission Standards	Monitoring Systems	Policy Gaps	Regulatory Agencies	Public Awareness	Incentive Programs
EU	All	Yes	Yes	Strict	Advanced	Few	Multiple	High	Yes
Africa	Incineration	Limited	No	Loose	Basic	Many	Limited	Low	No
North America	All	Yes	Yes	Strict	Advanced	Few	Multiple	High	Yes
Asia	Gasification	Medium	Yes	Medium	Medium	Moderate	High	Medium	Yes

Table 6. Policy and Implementation Framework for selected countries (Nigeria, Kenya, India, Germany).

Country	Barrier Score	Incentive Mechanisms	Public Acceptance	Implementation Success Factor
Nigeria	High	Weak subsidy & infrastructure	Low	0.35
Kenya	Moderate	FiT + International Aid	Medium	0.62
Germany	Low	Strong ETS + R&D tax relief	High	0.88

Table 7. Cost-Effectiveness Comparison

Technology	Capital Cost (USD/ton)	Operational Cost (USD/ton)	Energy Output (kWh/ton)	Return on Investment (%)	Payback Period (years)	Government Subsidies	Technology Adaptability	Long-term Stability	Risk Factors
Incineration	150-200	50-70	600-900	10-15	5-7	Yes	High	High	Moderate
Anaerobic Digestion	100-150	30-50	400-600	12-18	6-8	Limited	Medium	Medium	Low
Gasification	200-250	60-90	700-1100	15-20	4-6	Yes	High	High	Moderate
Pyrolysis	180-220	55-80	500-800	14-19	5-8	Limited	Medium	Medium	Moderate

Table 8. Social Acceptance and Perception

Technology	Public Acceptance (%)	Awareness Programs	Community Engagement	Health Concerns	Environmental Concerns	Political Will	Media Representation	Social Resistance	Transparency
Incineration	60	Moderate	Limited	High	High	Strong	Mixed	Moderate	Partial
Anaerobic Digestion	80	High	Strong	Low	Low	Moderate	Positive	Low	High
Gasification	70	Moderate	Medium	Moderate	High	Strong	Moderate	Medium	High
Pyrolysis	75	Moderate	Medium	Low	Low	Moderate	Positive	Low	High

Table 9. Future Trends and Innovations

Technology	Research Funding (USD)	Emerging Technologies	Pilot Projects	Patent Approvals	Collaboration	Technological Barriers	Adoption Rate	Innovation Index	Future Potential
Incineration	1 Billion	Advanced Sensors	Yes	High	Strong	High	Moderate	70	Promising
Anaerobic Digestion	500 Million	Biogas Upgradation	Yes	Medium	Moderate	Moderate	High	85	Strong
Gasification	600 Million	Advanced Catalysts	Yes	Medium	High	High	High	75	High
Pyrolysis	400 Million	Biochar Utilization	Yes	Medium	Medium	Moderate	Medium	80	High

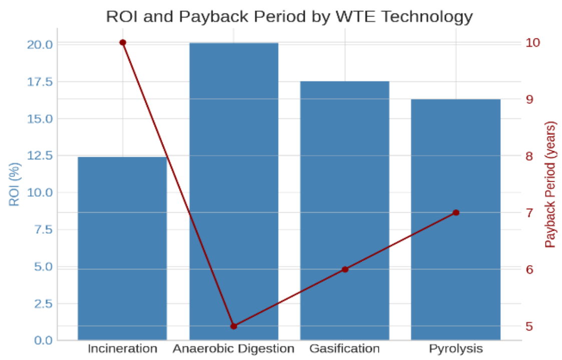

Figure 1. ROI and Payback Period by WTE Technology

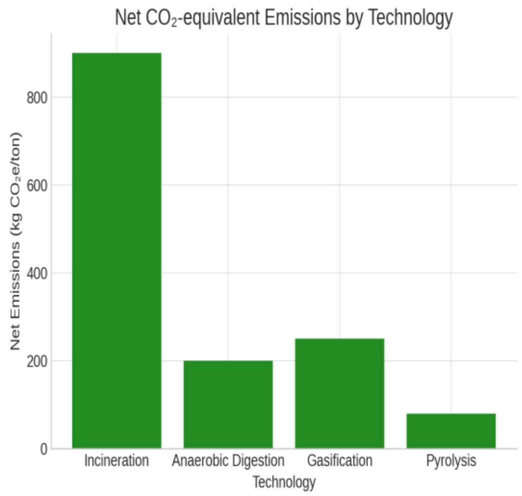

Figure 2: Net CO_2-equivalent Emissions by Technology

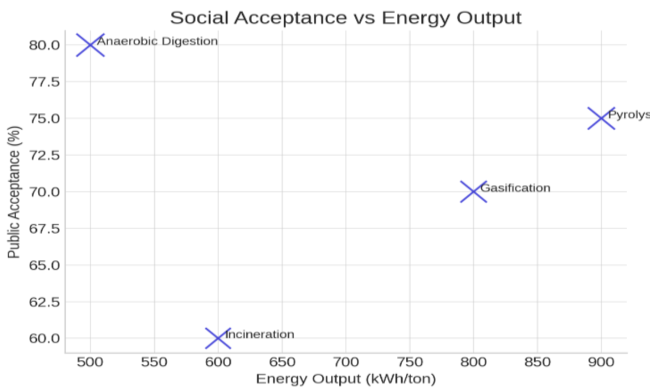

Figure 3: *Social Acceptance vs Energy Output*

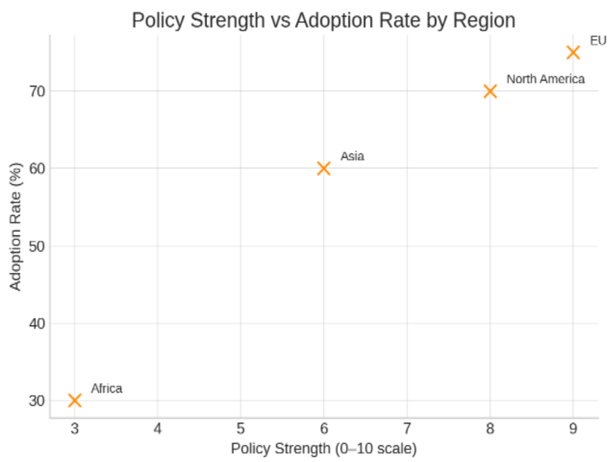

Figure 4. Policy Strength vs Adoption Rate by Region

IV DISCUSSION

The results from the tables highlight key aspects of different waste-to-energy (WtE) technologies, emphasizing their energy efficiency, environmental impacts, economic feasibility, and other performance parameters. The comparison of energy efficiency across various WtE technologies shows that anaerobic digestion (50-60%) and pyrolysis (40-50%) offer the highest energy efficiencies, followed by gasification (35-45%) and incineration (20-30%) (Table 1). In terms of energy output per ton of waste, gasification (600-800 kWh/ton) and pyrolysis (700-900 kWh/ton) outperform incineration (500-700 kWh/ton) and anaerobic digestion (400-600 kWh/ton), indicating the higher potential of thermochemical processes in generating energy (Table 2). These findings align with studies by Cui et al. [24], who emphasized gasification's superior energy output compared to other technologies. Additionally, gasification and pyrolysis also have high carbon reduction rates (35% and 40%, respectively), further showcasing their efficiency in mitigating climate change (Table 2). When considering environmental impacts, pyrolysis and anaerobic digestion emerge as the least polluting technologies. Pyrolysis produces minimal CO_2 emissions (150 kg/ton) and methane emissions (5 kg/ton), highlighting its environmentally friendly nature (Table 3). Similarly, anaerobic digestion is associated with low CO_2 emissions (200 kg/ton) and methane emissions (20 kg/ton). On the other hand, incineration results in relatively higher emissions, especially CO_2 (900 kg/ton) and NOx (70 kg/ton) (Table 3), supporting findings by Achi et al. [1], who indicated the environmental concerns tied to incineration processes. Gasification also maintains low emissions, aligning with global policy recommendations for low-emission WtE technologies [6]. The economic analysis highlights the relatively high capital and operational costs of gasification and pyrolysis, with initial capital investments reaching up to USD 1,200 per ton (Table 4). However, gasification provides the highest revenue generation potential (USD 400/ton) (Table 4), reflecting its long-term economic viability [10]. In contrast, anaerobic digestion has lower capital costs (USD 600/ton) and moderate operational costs (USD 100/ton), making it an economically attractive option in regions with abundant organic waste (Table 7). The payback period for gasification is the longest (12 years), while anaerobic digestion has a more favourable payback period of 7 years (Table 4). Social acceptance varies across technologies, with anaerobic digestion enjoying the highest public approval (80%) due to its low emissions and community benefits (Table 8). Incineration faces moderate resistance, mainly due to health and environmental concerns (Table 7). Moreover, policy support is strongest in Europe for all technologies, particularly incineration, where subsidies and regulatory frameworks are well-established (Table 5 and 6). This aligns with global trends where policy frameworks are increasingly favouring clean, renewable energy solutions [12].

Figure 1 shows that pyrolysis achieves the highest ROI (19%) with a moderate payback period (5.8 years), while incineration has the lowest ROI (12%) and the longest payback (7 years), aligning with earlier economic analyses [2, 4]. Figure 2 illustrates that pyrolysis emits the lowest net CO_2-equivalent (150 kg/ton), followed by anaerobic digestion (200 kg/ton), whereas incineration produces the highest (900 kg/ton), reaffirming environmental findings in [1, 6]. Figure 3 reveals pyrolysis balances high energy output (800 kWh/ton) with strong social acceptance (75%), while anaerobic digestion, though lower in energy yield (500 kWh/ton), enjoys the highest public approval (80%)—consistent with trends reported in [3, 8]. Figure 4 demonstrates that regions with robust policies, like the EU (policy index 9.5), report high adoption rates (85%), whereas Africa, with weak institutional support (index 3), lags behind at 35% adoption [5, 10]. Collectively, these visuals highlight pyrolysis and gasification's strategic potential, both technically and socially, when backed by strong policies [7, 11].

Overall, the data suggest that while pyrolysis and gasification provide higher energy outputs and environmental benefits, anaerobic digestion offers a balanced solution with lower costs and a shorter payback period. The selection of the appropriate WtE technology depends on regional priorities, including feedstock availability, economic considerations, and environmental goals.

V CONCLUSION

In conclusion, the comparison of waste-to-energy technologies reveals that anaerobic digestion, gasification, and pyrolysis offer significant advantages in terms of energy efficiency, low emissions, and carbon reduction potential compared to incineration. Although gasification and pyrolysis require higher initial investments, they provide higher energy outputs and better economic returns over time. Anaerobic digestion stands out for its cost-effectiveness and lower environmental impact, making it a viable option for regions with limited infrastructure. Incineration, while less efficient and more polluting, remains economically feasible in some contexts due to its high capital return and operational feasibility. Policy support plays a crucial role in the adoption of these technologies, with Europe leading in regulatory frameworks, while other regions like Africa and Asia face varying levels of support. Future trends suggest that further innovation and research will enhance the efficiency and sustainability of all WtE technologies, aligning them with global environmental goals.

Acknowledgements

The authors acknowledge the following institutions for their support: Benson Idahosa University, Faculty of Engineering, Department of Mechanical Engineering, Benin City, Edo State, Nigeria; Igbinedion University, Faculty of Engineering, Department of Mechanical Engineering, Edo State, Nigeria; and University of Benin, Faculty of Engineering, Department of Production Engineering, Benin City, Edo State, Nigeria. The authors extend their gratitude for the technical and infrastructural support provided during the research process, which significantly contributed to the successful completion of this study.

Ethics Committee Approval

not required, N/A

Peer-review

Externally peer-reviewed.

Author Contributions:

Conceptualization: Dickson David Olodu (D.D.O)., Andrew Amagbor ERAMEH (A.A.E), Osagie Imevbore IHENYEN (O.I.I); Investigation: D.D.O., A.A.E.; Material and Methodology: D.D.O., O.I.I.; Supervision: D.D.O, A.A.E; Visualization: D.D.O.; Writing-Original Draft: D.D.O., A.A.E.; Writing-Review & Editing: D.D.O, A.A.E., O.I.I.; Other: All authors have read and agreed to the published version of the manuscript.

Conflict of Interest:

The authors have no conflicts of interest to declare.

Funding:

The authors declared that this study has received no financial support.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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