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WASTE-TO-ENERGY CONVERSION FOR SUSTAINABLE ELECTRICITY GENERATION IN LAGOS, NIGERIA: A THERMODYNAMIC AND ENVIRONMENTAL ANALYSIS

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ABSTRACT
Rapid urbanization and increasing municipal solid waste generation in Lagos, Nigeria, have intensified environmental challenges and energy deficits. This study investigates the potential of waste-to-energy (WtE) conversion as a sustainable pathway for electricity generation, using thermodynamic and environmental analysis frameworks. The research evaluates key WtE technologies—incineration, anaerobic digestion, gasification, and pyrolysis—based on their energy efficiency, calorific value of local waste streams, and greenhouse gas emission profiles. Primary and secondary data on waste composition, generation rates, and energy demand in Lagos were integrated into thermodynamic models to estimate power generation potential and system performance.Results indicate that Lagos generates over 13,000 tonnes of municipal solid waste daily, with a significant organic fraction suitable for energy recovery. Thermodynamic analysis reveals that incineration and gasification offer the highest energy yields, with potential electricity generation ranging between 400–600 MW, depending on system efficiency and feedstock variability. Environmental assessment shows that WtE technologies can significantly reduce landfill dependency, methane emissions, and public health risks when properly managed. However, challenges such as high capital costs, technological limitations, and policy gaps remain critical barriers. The study concludes that integrating WtE into Lagos' energy mix can enhance sustainable electricity supply, improve waste management, and support climate change mitigation goals. Policy recommendations emphasize investment in modern WtE infrastructure, regulatory frameworks, and public-private partnerships.
Keywords*: Waste-to-Energy (WtE), Sustainable-Electricity-Generation, Municipal Solid-Waste, Thermodynamic Analysis, Lagos Nigeria.*

1.0 INTRODUCTION

Urban centers in developing countries face dual challenges of energy shortages and inefficient waste management. Lagos, Nigeria commercial hub with over 20 million residents, generates enormous quantities of waste daily; Lagos State Waste Authority Reports (2024-2025).

Waste-to-Energy (WTE) technologies provide an integrated solution by converting municipal solid waste into usable energy while reducing environmental hazards. Globally, WTE contributes to renewable energy portfolios and supports circular economy models; World Bank (2024). This study explores the feasibility of WTE systems in Lagos through thermodynamic and environmental perspectives. Lagos faces severe waste management challenges: Daily waste generation exceeds 13,000 tones Lagos State Waste Management Authority Reports (2024-2025), Only a fraction is properly collected and recycled Environews Nigeria (2024) and open dumping and burning lead to pollution and health risks.

Simultaneously, Nigeria experiences persistent electricity deficits. The absence of integrated waste-to-energy systems results in: Loss of potential energy resources, Increased greenhouse gas emissions and Landfill overflow and environmental degradation.

The study adopts an integrated waste-to-energy framework: Waste - Generation ⟶ Collection ⟶ Segregation

⟶ Conversion ⟶ Energy Output ⟶Environmental Impact.

The Key Components includes (i) Input: Municipal Solid Waste (organic + inorganic) fractions.(ii) Conversion Technologies: Incineration, Anaerobic digestion, Gasification and (iii) Outputs: Electricity, heat, emissions residues.

Nigeria's electricity generation capacity is insufficient relative to the country's population and industrial needs. Frequent power outages force households and businesses to rely on diesel and petrol generators, environmental pollution.

The Key challenges include; Insufficient generation capacity, Aging power infrastructure, Transmission losses and Over dependence on fossil fuels. These problems highlight the need for alternative and renewable energy sources. (1) Anaerobic Digestion: Anaerobic Digestion is a biological process in which microorganisms breakdown organic waste in the absence of oxygen to produce biogas. Biogas consist mainly of: Methane (CH_4) and Carbon dioxide (CO_2).

The methane can be used to generate electricity using gas turbines or generators. Advantages include: Suitable for organic waste, Produces renewable biogas and Reduces methane emissions from landfill. (2) Incineration: Incineration involves the combustion of waste materials at high temperatures. The heat generated during combustion is used to produce steam which drives turbines to generate electricity. Benefits include; Significant volume reduction of waste, High energy recovery potential and Reduced landfill dependency. However, emission must be carefully controlled using pollution-controlled systems. (3) Gasification: Gasification is a thermochemical process that converts waste materials into synthetic gas (syngas) at high temperatures with limited oxygen. Syngas mainly contains: Carbon monoxide (CO) and Hydrogen. This gas can be used to generate electricity or produce other fuels. Gasification offers higher efficiency and lower emission compared to conventional incineration. (4) Municipal Solid Waste (Msw) Generation: Nigeria produces millions of tons of Municipal Solid Waste annually. Major cities such as Lagos the study area, Abuja, Enugu, Port Harcourt, Anambra generate large volumes of organic waste, plastic, paper and other materials.

Table 1: Typical Lagos State Waste Composition

S/N	Waste Type	Percentage
1	Organic Waste	50-60%
2	Plastics	10-15%
3	Paper	10-12%
4	Metals	5-8%
5	Others	10-15%

The high organic content makes Nigerian waste particularly suitable for energy recovery through biological and thermochemical process. Waste-to-energy technologies (Wte) convert waste materials into usable energy through several processes. Recent studies highlight: Lagos generates over 5.46 million tonnes annually; Lagos State Waste Management Authority Report (2024-2025), Waste composition includes organic matter, plastics, paper and metals; Umar, Y (2024) and Anaerobic digestion produces higher energy efficiency and lower emissions than other methods; Nubi, O. (2022). Other findings: WTE plants can convert 2,250 tonnes/day into 60-175MW;

Environews Nigeria (2024), Organic waste dominates Lagos MSW (approximately 50-55%); Olagunju et al. (2025), Waste mismanagement leads to pollution and disease risks; Olamiyi and Ajayi (2024) and Methane emissions from dumpsites are significant; Riman et al. (2022).
This study is based on:

(i) Thermodynamic Theory:

- <u>First Law:</u> Energy conservation in conversion systems.

Q_{in} = Wout + Qloss

- <u>Second Law:</u> Efficiency limitations due to entropy.

$\eta = \frac{Wout}{Qin} < 1$ or $\eta = \frac{Wout}{Qin}$ X 100

(ii) ENERGY CONVERSION MODELS

(a) Incineration:

$E = m \times CV \times \eta$ Where; m= mass of waste (tonnes)
CV = Calorific Value (Mj/kg)
η = efficiency.

(b) Anaerobic Digestion:

$CH_4 = VS \times Y_{CH_4}$

Energy balance: E output = $\eta \times$ E input

(iii) Environmental System Theory

- Interaction between waste systems and ecological systems.
- Life Cycle Assessment (LCA) for emissions evaluation.
- Revolution Pathways

(iv) Circular Economy Theory: Waste is treated as: Resource input→ energy recovery → reuse loop.

(i) Thermodynamic Theory: Thermodynamic theory is a branch of physics that deals with energy, heat, work, and their transformations in physical systems. It explains how energy moves and changes form, especially in systems like engines, refrigerators, chemical reactions, and even living organisms.

The Core Concepts: 1. System and Surroundings System: The part of the universe being studied (e.g., gas in a cylinder). Surroundings: Everything outside the system. 2. State Variables

Properties that describe a system; Temperature (T), Pressure (P), Volume (V) and Internal energy (U). Laws of Thermodynamics : (i) Zeroth Law (Thermal Equilibrium): If two systems are each in thermal equilibrium with a third system, they are in equilibrium with each other. This defines temperature. First Law (Energy Conservation): Energy cannot be created or destroyed, only transformed. $\Delta U = Q - W$, ΔU: Change in Internal energy, Q: Heat added to System, W: Work done by the system, Second Law (Entropy), Heat flows naturally from hot to cold, not the reverse. Introduces entropy (S) → a measure of disorder. In any natural process, total entropy increases. Third Law: As temperature approaches absolute zero: Entropy approaches a constant minimum value. The Key Ideas are Heat and Work: Heat (Q): Energy transfer due to temperature difference and Work (W): Energy transfer by force (e.g., piston movement) . The Processes: Isothermal (constant temperature), Adiabatic (no heat exchange), Isobaric (constant pressure), Isochoric (constant volume), Entropy and Irreversibility, Real processes are irreversible and Systems tend toward maximum entropy
Applications: Engines (cars, power plants), Refrigerators and air conditioners, Chemical reactions and biological systems (metabolism).

(ii) Energy Conversion Models: An energy conversion model describes how energy is transformed from one form to another within a system, often with attention to efficiency, losses, and useful output. These models are central in fields like thermodynamics, engineering, environmental science, and energy planning.

1. Basic Concept: Energy cannot be created or destroyed (First Law of Thermodynamics), only converted. A general energy conversion system can be expressed as: Energy Input → Conversion Process → Useful Output →Losses. 2. General Mathematical Model; Efficiency is the key metric: $\eta = \frac{\text{Useful Energy Output}}{\text{Total Energy Input}}$ Where: η = efficiency (0–1 or %), Losses often occur as heat, sound, or friction. 3. Types of Energy Conversion Models: a. Thermodynamic Models Based on laws of thermodynamics: First Law → Energy balance, Second Law (Second Law of Thermodynamics) → limits efficiency due to entropy, Example (heat engine): $Q_{in} = W_{out} + Q_{loss}$ b. Mechanical–Electrical Conversion Used in generators and turbines: for example: Hydropower system $P = pghQ\eta$ Where; p = power output, *p*= fluid density, g = gravity, h = head and Q= flow rate.

c. Chemical–Thermal–Electrical Models: This is Common in waste-to-energy or fossil fuel plants: 1. Chemical energy → combustion, 2. Thermal energy → steam, 3. Mechanical → turbine and 4. Electrical → generator. d. Renewable Energy Models: This includes Solar: radiation → via PV cells, Wind: kinetic → mechanical → electrical and Biomass: chemical → thermal → electrical. For example; Waste-to-Energy Model (Relevant to Nigeria) For municipal solid waste: $E = M \times CV \times \eta$ Where; E = energy generated, M = mass of waste, CV = calorific value and η = conversion efficiency This is widely used in studies of cities like Lagos for sustainable electricity generation.

5. The Key Factors Affecting Conversion: Technology efficiency, Environmental conditions, Material properties, System design and Energy losses (heat, friction). The Applications: Power plants (thermal, hydro, solar), Waste-to-energy systems, Smart grids, Industrial energy systems and Urban sustainability planning.

(iii) Environmental System Theory

Environmental System Theory is a framework used to understand how different components of the environment interact as a system. It draws heavily from the Systems Ecology and Environmental Science, emphasizing that natural and human systems are interconnected and function as a whole. The Core Idea of Environmental System Theory views the environment as a complex system made up of interacting parts—such as air, water, land, organisms, and human activities. These parts are linked through flows of energy and matter. The Key Components are: 1. System Elements: Biotic components: living organisms (plants, animals, humans) and Abiotic components: non-living elements (soil, water, climate). 2. Inputs and Outputs: Inputs: solar energy, rainfall, nutrients and Outputs: heat, waste materials, emissions

3. Processes include: Interactions such as photosynthesis, nutrient cycling, energy transfer and Feedback Mechanisms. This includes Positive feedback: amplifies changes (e.g., deforestation increasing erosion) and Negative feedback: stabilizes systems (e.g., predator-prey balance)

Types of Environmental Systems include: 1. Open Systems: Exchange both energy and matter with surroundings. Example: a river system, 2. Closed Systems: Exchange energy but not matter. Example: Earth (approximately). 3. Isolated Systems: Exchange neither energy nor matter (rare in reality). Key Concepts includes: Equilibrium: balance within the system, Resilience: ability to recover from disturbances, Sustainability: long-term maintenance of system functions and Carrying capacity: maximum population an environment can support. The Applications: Environmental System Theory is used in Urban planning (e.g., waste management systems in Lagos), Climate change analysis, Ecosystem conservation and Sustainable development policies. For example, in Lagos, waste generation, flooding, and energy demand can be analyzed as interconnected systems rather than separate problems. Simple Illustration are shown below:

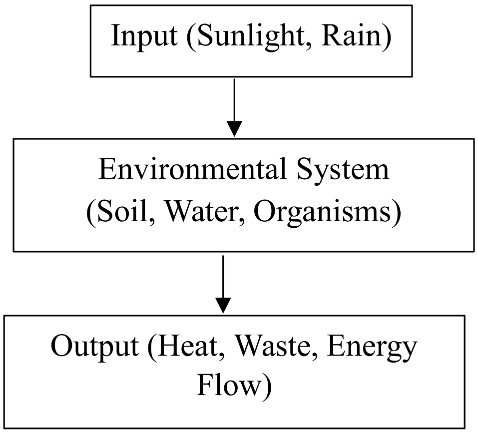

Fig 1: Showing Simple Application of Environmental System Theory.

(iv) Circular Economy Theory :

What is Circular Economy Theory? Circular economy theory is based on designing systems where materials, products, and resources are kept in use for as long as possible through reuse, repair, remanufacturing, and recycling. The goal is to create a closed-loop system that minimizes environmental impact while maximizing resource efficiency. The Key Principles include: 1. Design out waste and pollution: Products are designed from the beginning to reduce waste generation and environmental harm. 2. Keep products and materials in use through strategies like reuse, recycling, refurbishment, and sharing systems. 3. Regenerate natural systems: Instead of depleting resources, circular systems restore ecosystems (e.g., composting organic waste). The Core Concepts: (i) Closed-loop systems: Materials are continuously cycled without becoming waste . Industrial symbiosis: Waste from one process becomes input for another Product life extension: Designing durable and repairable goods Resource efficiency: Maximizing output with minimal input, Linear vs Circular Economy, Linear Economy Circular Economy, Take → Make → Dispose Reduce → Reuse → Recycle, High waste generation Minimal waste, Resource depletion - Resource regeneration and Short product life Extended product life. The applications include: Waste management (e.g., waste-to-energy systems in Lagos), Sustainable manufacturing, Urban planning and housing and Agriculture (nutrient recycling, composting).

In cities like Ibadan and Lagos: Helps manage solid waste challenges, supports waste-to-energy initiatives, Encourages informal recycling sectors and Reduces environmental pollution and flooding caused by waste.

The Key Scholars & Foundations are: Ellen MacArthur Foundation – global leader in circular economy research and advocacy Walter R. Stahel – introduced the idea of a "performance economy" Kenneth E. Boulding – early thinker on closed economic systems

2.0MATERIALS AND METHODS

2.1 Description of Study Area

The study area is Lagos State. Lagos State is located in the South-Western part of Nigeria between Latitude 6^0 23'N - 6^0 41'N and Longitude 2^0 42'E - 3^0 42'E. It is the most urbanized and densely populated state in Nigeria, with an estimated population exceeding 20 million people. The Key Characteristics Of Study Area – Lagos: High urban density (Greater than 6,000 people/ {km}^{2} in core areas), Rapid industrialization (Apapa, Ikeja, Lekki corridors), Coastal geography (Lagoon + Atlantic Coast), Limited Land availability for Land fill expansion and High municipal solid waste (MSW) generation.

The Waste Generation Profile Of Lagos: Estimated daily Municipal Solid Waste (MSW): 13,000 – 15,000 tonnes/ day, Annual MSW: Approximately 5 – 6 million tonnes/year and Composition of MSW which includes; Organic waste: 50 – 55%, Plastics: 10 – 15%, Paper: 7 – 10%, Metals and glass: 5 – 8% and Others: 10 – 15%.

Fig 1: Map of Lagos State, Nigeria.

2.2 Data Acquisition

2.2a Primary Data (Conceptual/Field-Based Inputs): Where applicable, the following are required for empirical validation: Waste sampling from collection trucks and dumpsites, Moisture content analysis of MSW, Calorific value (CV) laboratory testing and Composition sorting (organic, plastics, paper, metals, glass). 2.2b Secondary Data Sources: The study relies heavily on validated secondary datasets: Lagos Waste Management Authority (LAWMA) reports (2020–2025), World Bank urban solid waste datasets, UNEP Global Waste Management Outlook, Peer-reviewed journals (Scopus-indexed articles), Satellite-derived urban land-use data and Population and density data from Nigerian Bureau of Statistics (NBS). 2.2c Software and Tools: ArcGIS / QGIS → spatial waste mapping, Excel / MATLAB / Python → energy modeling and simulation, SPSS / R → statistical analysis and AutoCAD / GIS plugins → conceptual layout of WtE facilities.

2.3 Data Processing

2.3a Waste Generation / Composition Data in Nigeria: Data obtained from municipal waste management reports and population estimates. The study assumes: Average waste generation per person: 0.65 kg/day and Population considered: 200 million people

Total waste generated per day:

W = P X G Where: W = Total waste generated, P = Population and G = Waste generation rate.

2.3b Energy Potential Estimation

The energy content of municipal waste is calculated using the Lower Heating Value (LHV): E = W X LHV Where: E = Energy potential, W = Waste mass, LHV = Lower Heating Value (Typical LHV ranges between 7–12 MJ/kg).

2.3c Electricity Generation Estimation: Electricity generation is estimated using conversion efficiency: P = η X E Where; P = Electrical power output, η= System efficiency (**20–30%**)

3.0 RESULTS AND DISCUSSION

Using the estimated waste generation data, Nigeria could generate substantial energy from municipal waste. Estimated results suggest: Total waste generation: 130,000 tons/day and Potential energy output: Several gigawatts of electricity. This would significantly supplement Nigeria's natural electricity supply. The Environmental Benefits: Reduce landfill waste by up to 80%, Lower methane emissions, Improve urban sanitation and Reduce reliance on fossil fuels. The Economic Benefits: Employment opportunities, Investment in renewable energy infrastructure and Revenue from electricity generation. The Challenges of Waste-To-Energy Implementation: Despite its benefits, several barriers exist: High initial capital costs, Lack of technical expertise, Weak waste collection systems and Policy and regulatory limitations. Addressing these challenges requires strong government support and international collaboration.

4.0 CONCLUSION

Waste-to-Energy technology offers a sustainable pathway to address Nigeria's waste management and electricity challenges simultaneously. By converting municipal solid waste into electricity, Nigeria can reduce environmental pollution while improving energy supply. Thermodynamic analysis indicates that significant electricity could be generated from the country's waste resources. With appropriate policy framework and investment, Waste-to-Energy systems can become an important component of Nigeria's sustainable energy future.

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