Selection of Domestic Waste Treatment Technologies: A Multi-Criteria Assessment of Incineration, Composting, and Recycling.

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A PROJECT SUBMITTED IN

PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF ENGINEERING (B.ENG).

IN

THE DEPARTMENT OF CIVIL ENGINEERING,

FACULTY OF ENGINEERING,

UNIVERSITY OF BENIN,

BENIN CITY, NIGERIA

JUNE, 2025.

PLAGIARISM

This project on “Selection of Domestic Waste Treatment Technologies: A Multi-Criteria Assessment of Incineration, Composting, and Recycling”. Using a multi-criteria approach to assess options like incineration, composting, and recycling.” by Okeke Joachim Franklin with Matriculation Number (ENG2102864) of the Department of Civil Engineering, University of Benin City, Edo State. Nigeria, has PASSED the PLAGIARISM TEST.

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DEDICATION

This project is dedicated to God Almighty, who has provided me with the knowledge and wisdom I need to excel in every aspect of my academic career and has graciously supported my life.

ACKNOWLEDGEMENT

I have the utmost gratitude to God Almighty for His constant direction and assistance during my research project and academic career. I would especially want to thank Dr. (Mrs.) L.O. Bobor , my project supervisor, whose careful proofreading, wise counsel, and professional direction greatly improved my work.

I also want to thank the staff of the Department of Civil Engineering for their significant efforts, as they have always shown a remarkable commitment to teaching and promoting excellence. Specifically, I thank the Head of Civil Engineering Department Engr. Prof. (Mrs.) N.I. Ihimekpen, My Project Coordinator; Engr. E. Oria-Usifo and all my lecturers; Engr. Prof. O. U. Orie, Engr. Prof. O.C. Izinyon, , Engr. Prof. H.A.P. Audu, Engr. Prof. J.O. Okovido, Engr. Prof. S.D. Iyeke, Engr. Prof R.I. Umasabor, Engr. Dr, R.O. Ogirigbo, Engr. Dr. (Mrs) N. Kayode-Ojo, Engr. Dr. P. N. Ogbiefun Engr. Dr. (Mrs.) L.O. Bobor, Engr. Dr. A. Agbonaye, Engr. Dr. (Mrs.) A. Rawlings, Engr. Dr. R. Ilaboya, Engr. Dr U. Ukeme, Engr. O. Oriakhi, Engr. B. Omosefe, Engr. C. Okolie, Engr. O. Osasu, Engr. N. Oghoyafedo, Engr. (Mrs.) E. Ambrose-Agabi, Engr. E. Musa, Engr. Dr. I. Iziengbe, Engr. U. Ogbonna, Engr. (Mrs.) G.E. Evbaru, Engr J.O. Odemerho and the laboratory staff.

My heartfelt appreciation also goes out to my family and friends.

SUMMARY

The project evaluates three key waste treatment technologies—incineration, composting, and recycling—to address municipal solid waste (MSW) management challenges in developing urban areas. Traditional disposal methods have caused significant environmental and health issues, prompting the need for sustainable solutions tailored to these contexts.

The methodology employs a hybrid Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to compare the technologies. Data collection includes structured questionnaires from 400 households and interviews with 15 experts, alongside secondary sources like national reports and LCA data. The AHP weights criteria and indicators, while TOPSIS ranks technologies based on proximity to an ideal solution, focusing on Ugbowo, Nigeria.

Expected outcome is a ranked recommendation of the most sustainable waste treatment technology for Ugbowo and similar urban areas, providing a balanced consideration of cost-effectiveness, environmental impact, and social acceptability. This analysis will offer policymakers, engineers, and waste management officials a robust decision-making tool, fostering informed investments in waste infrastructure that enhance public health, reduce environmental degradation, and promote long-term sustainability in developing countries.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Urbanization and population growth are two of the most significant drivers of waste generation globally. As people continue to move into cities and urban centers expand, the amount of municipal solid waste (MSW) being produced increases drastically. This waste includes everything from household garbage and food scraps to plastics, paper, textiles, and packaging materials. In many developing countries, waste management remains a critical challenge, as infrastructure development and policy implementation have not kept pace with the rate of waste production. As a result, open dumping, burning, and poorly managed landfills are still commonly used as disposal methods.

Such practices have led to numerous environmental and public health problems, including contamination of soil and water sources, increased greenhouse gas emissions, and the spread of vector-borne diseases. Furthermore, improper waste disposal affects the aesthetic value of urban environments and can lead to economic losses through reduced tourism and decreased property values. Therefore, managing waste in an efficient, sustainable, and environmentally friendly way is no longer optional—it is a necessity. Engineers, urban planners, and policymakers are now exploring and adopting more advanced waste treatment technologies that go beyond traditional methods.

Among the emerging and widely used waste treatment technologies are incineration, composting, and recycling. Incineration involves burning waste at high temperatures to reduce its volume and sometimes generate energy. It is particularly useful for waste types that cannot be reused or composted, but it requires expensive infrastructure and can produce harmful air pollutants if not properly managed (Ferronato & Torretta, 2019). Composting is a biological process that converts organic waste into nutrient-rich soil amendment. This method is environmentally friendly and cost-effective, but it is limited to biodegradable waste and needs proper sorting and space (Abdel-Shafy & Mansour, 2018).

Recycling, on the other hand, involves processing used materials into new products. It conserves natural resources, reduces energy consumption, and lowers greenhouse gas emissions. However, recycling systems can be expensive to maintain, and contamination of recyclables can reduce efficiency. Each of these methods has its advantages and limitations, making it essential to evaluate them based on a variety of criteria to determine the most appropriate solution in different contexts (UNEP, 2021).

To address this complexity, a multi-criteria decision-making (MCDM) approach can be used. This method allows for the comparison of various alternatives based on a range of qualitative and quantitative factors. MCDM tools such as the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Multi-Attribute Utility Theory (MAUT) are commonly used to assist in selecting the best option among several competing choices (Dhokhikah & Trihadiningrum, 2021). In this project, MCDM will be applied to analyze incineration, composting, and recycling based on factors like cost, environmental impact, technical feasibility, social acceptance, and long-term sustainability.

By systematically comparing these waste treatment methods, the study aims to provide useful recommendations for sustainable waste management strategies, especially in urban areas of developing countries(Taking Ugbowo,Benin City as a case study). This analysis is critical for engineers and decision-makers tasked with developing effective solutions that are practical, affordable, and environmentally sound.

1.2 Statement of the Problem

The Statement of the Problem articulates the critical challenges in municipal solid waste (MSW) management, particularly in urban areas of developing countries, and underscores the need for a structured, evidence-based approach to technology selection. Globally, MSW generation is projected to reach 3.88 billion tons by 2050, with developing countries contributing significantly due to rapid urbanization (46% of global population in urban areas) and population growth (2.5% annual increase in low-income regions) (Kaza et al., 2018). In many developing countries, waste management systems are overwhelmed, with 70–90% of waste uncollected or disposed of via open dumping, open burning, or poorly managed landfills (Hoornweg & Bhada-Tata, 2012). These practices have severe consequences:

i. Environmental Degradation: Open dumping and landfilling contribute to 5–10% of global methane emissions (0.5–1.0 ton CO_2e/ton of waste), a greenhouse gas with a global warming potential 25 times that of CO_2 (IPCC, 2014). Leachate from landfills, containing heavy metals and organic pollutants, contaminates groundwater in 60–80% of sites in developing countries, affecting ecosystems and water supplies (Ferronato & Torretta, 2019). Open burning releases dioxins and particulate matter ($PM_{2.5}$, 10–20 mg/Nm^3), contributing to air pollution linked to 1–2 million annual respiratory cases globally (UNEP, 2019).

ii. Public Health Risks: Improper waste disposal fosters vector-borne diseases (e.g., malaria, dengue), with 10–20% of urban populations in developing countries exposed to health risks from waste sites (Abdel-Shafy & Mansour, 2018). Informal waste handling, prevalent in 30–40% of urban areas, exposes workers to hazardous conditions, with 20–30% reporting respiratory or dermatological issues (Owusu et al., 2021).

iii. Economic and Social Impacts: Mismanaged waste reduces urban aesthetic value, decreasing property values by 5–10% and tourism revenue by 10–20% in affected areas (World Bank, 2020). It also strains municipal budgets, with waste management costs ranging from $20–100/ton in developing countries, compared to $100–200/ton in industrialized ones, often exceeding 20–50% of municipal budgets (UNEP, 2021).

iv. Increasing Waste Complexity: Urban waste composition in developing countries includes 50–70% organic waste, 10–20% plastics, and 5–10% paper, with volumes growing at 3–5% annually (Hoornweg & Bhada-Tata, 2012). This complexity requires advanced technologies, but infrastructure lags, with only 5–10% of municipalities having access to modern treatment facilities.

A critical barrier is the lack of a structured decision-making framework for selecting waste treatment technologies. Decisions are often cost-driven, prioritizing short-term savings ($20–50/ton for landfilling) over long-term sustainability, environmental impact (0.1–3.0 ton CO_2e/ton across technologies), or social acceptability (20–50% public opposition to incineration) (Dhokhikah & Trihadiningrum, 2021). For instance, incineration's high capital costs ($50–100 million/plant) deter adoption, despite its 80–90% volume reduction, while composting's low costs ($20–50/ton) are offset by segregation challenges (10–20% contamination). Recycling, while reducing emissions by 0.5–2.0 ton CO_2e/ton, faces market volatility ($0.5−1.5/kg for PET) and infrastructure gaps (40–60% sorting efficiency) (Schmidt et al., 2023). Without a holistic evaluation, municipalities risk investing in suboptimal solutions, costing $5–10 billion annually in environmental and health damages (World Bank, 2020).

This study addresses these challenges by applying an MCDM framework (e.g., AHP, TOPSIS) to compare incineration, composting, and recycling based on cost, environmental impact, technical feasibility, social acceptance, and sustainability. By providing a systematic, context-specific analysis, the study aims to bridge the decision-making gap, enabling urban areas in developing countries to adopt sustainable waste management strategies that mitigate environmental, health, and economic risks.

1.3 Aim and Objectives

Aim

The aim of this study is to conduct a comparative analysis of incineration, composting, and recycling using an MCDM approach to identify the most sustainable and context-appropriate waste treatment technology for urban areas in developing countries

Objectives

To achieve the aim, the study will pursue the following specific objectives employing AHP(Group AHP) and TOPSIS Frameworks :

i. Characterize the technical processes of incineration, composting, and recycling,
ii. Assess the environmental impacts of each technology.
iii. Evaluate the economic viability of each technology, analyzing capital costs.
iv. To develop recommendations for urban waste management strategies.

1.4 Scope of the Study

The study focuses on evaluating municipal solid waste (MSW) management technologies—incineration, composting, and recycling—in Ugbowo, Benin City, Edo State, Nigeria, a rapidly urbanizing area in a developing country. It aims to address rising waste volumes, environmental degradation, and limited infrastructure by analyzing these technologies for sustainable urban waste management. The scope is tailored to Ugbowo's context, where open dumping is prevalent.

The study characterizes the technical processes of incineration (high-temperature combustion reducing volume by 80–90%), composting (microbial decomposition producing soil amendments), and recycling (reprocessing plastics and metals). It assesses environmental impacts, quantifying greenhouse gas emissions, and evaluates economic viability, analyzing capital costs and operational costs.Using multi-criteria decision-making (MCDM) frameworks like AHP and TOPSIS, the study develops recommendations for policymakers and engineers in Ugbowo to implement sustainable waste management strategies. These address local challenges, such as low collection rates, high organic waste, and public opposition to incineration (30–50%), promoting composting, formalizing recycling, and exploring regional incineration hubs. Stakeholder engagement and policy incentives ensure solutions align with circular economy principles and local needs.

1.5 Justification

The study is justified by the urgent need to address the unsustainable waste management practices in Ugbowo, Benin City, Edo State, Nigeria, where open dumping and inadequate infrastructure exacerbate environmental degradation, public health risks, and economic losses. By comparing incineration, composting, and recycling using a multi-criteria decision-making (MCDM) framework, this study provides a structured approach to identify sustainable solutions. The findings will guide policymakers and engineers in implementing cost-effective, environmentally sound, and socially acceptable waste management strategies, reducing health risks, enhancing urban livability, and supporting circular economy principles in developing countries.

CHAPTER TWO

LITERATURE REVIEW

This chapter provides a comprehensive review of the literature on municipal solid waste (MSW) management, focusing on incineration, composting, and recycling as key treatment technologies in urban areas of developing countries. It explores technical processes, environmental impacts, economic considerations, social dimensions, policy frameworks, and multi-criteria decision-making (MCDM) methodologies to establish a robust foundation for the study's comparative analysis. The review emphasizes clarity, simplicity, and relevance to developing country contexts, synthesizing global research to inform sustainable waste management strategies.

2.1 Introduction to Municipal Solid Waste Management

Municipal solid waste management is a critical global issue, particularly in urban areas of developing countries where rapid urbanization and population growth drive waste generation. By 2050, global MSW is projected to reach 3.88 billion tons, with developing countries contributing significantly due to urban populations growing at 2.5% annually(Kaza et al., 2018). Waste composition in these regions typically includes 50–70% organic waste, 10–20% plastics, and 5–10% paper, contrasting with industrialized nations where recyclables like metals and plastics dominate. Effective waste management balances environmental sustainability, economic viability, and social acceptability to address challenges such as groundwater pollution, greenhouse gas emissions, and public health risks.

In developing countries, traditional methods like open dumping and landfilling manage 70–90% of waste(Ferronato & Torreta, 2019), leading to severe consequences. Open dumping contributes to 5–10% of global methane emissions, a greenhouse gas with 25 times the warming potential of CO_2, while poorly managed landfills contaminate groundwater in 60–80% of sites(IPCC, 2014). These practices foster vector-borne diseases like malaria and dengue, affecting 10–20% of urban populations. Advanced technologies—incineration, composting, and recycling—offer sustainable alternatives but face barriers such as high costs, limited infrastructure, and low public acceptance. Only 5–10% of municipalities in developing countries have access to modern treatment facilities, compared to 50–70% in high-income nations(UNEP 2021).

The complexity of waste management in urban developing countries stems from diverse waste streams, limited budgets, and varying stakeholder priorities. For instance, organic waste requires biological treatments like composting, while plastics demand recycling systems. Municipal budgets, often $20–50/ton, struggle to support advanced technologies costing $50–150/ton(World Bank 2020). Multi-criteria decision-making (MCDM) frameworks, such as Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), provide structured approaches to evaluate these technologies(Dhokhikah & Trihadiningrum,2021). MCDM considers environmental, economic, technical, and social criteria, enabling objective comparisons tailored to local contexts. Stakeholder inputs, including those from communities, engineers, and policymakers, ensure relevance to urban needs.

This chapter reviews the literature to contextualize these challenges and solutions, focusing on urban developing countries where waste management is most critical. It examines global research, regional variations, and stakeholder perspectives to inform the study's aim of identifying sustainable waste treatment strategies. The review covers technical processes, environmental impacts, economic feasibility, social acceptability, and policy frameworks, providing a comprehensive foundation for the MCDM analysis. By synthesizing findings from diverse contexts, the chapter highlights the need for context-specific solutions that address developing countries' unique challenges, such as organic-rich waste and infrastructure constraints(UNEP, 2019).

2.2 Overview of Waste Treatment Technologies

Waste treatment technologies aim to reduce waste volume, recover resources, and minimize environmental impacts. Incineration, composting, and recycling are widely studied for MSW management, each with distinct processes, benefits, and limitations. Understanding these technologies is essential for evaluating their suitability in developing countries, where waste composition, infrastructure, and economic constraints differ significantly from industrialized contexts.

Incineration combusts waste at high temperatures to reduce volume by 80–90% and recover energy at 500–600 kWh/ton (Ferronato and Torreta, 2019). It is effective for non-recyclable waste, such as mixed plastics and textiles, but requires costly infrastructure and emission controls to manage pollutants like dioxins and particulate matter. In developing countries, incineration is limited by high costs and low-calorific waste, though it is prevalent in countries like Japan and China with advanced facilities. Composting biologically decomposes organic waste into nutrient-rich soil amendments, reducing emissions by 0.1–0.3 ton CO2e/ton compared to landfilling (Cerda et al., 2018). It is cost-effective and suits organic-rich waste streams, which dominate in developing countries, but requires proper segregation and space for processing. Recycling reprocesses materials like plastics, metals, and paper into new products, saving 0.5–2.0 ton CO2e/ton in emissions(Schmidt et al,. 2023). It conserves natural resources but faces challenges from contamination, market volatility, and limited sorting infrastructure. These technologies are evaluated based on environmental impact, cost-effectiveness, technical feasibility, and social acceptability, with MCDM tools facilitating objective comparisons. AHP allows stakeholders to assign weights to criteria, such as 40–60% for environmental impact and 20–35% for cost, while TOPSIS ranks technologies based on their proximity to an ideal solution. The literature highlights the need for tailored solutions in developing countries, where organic waste and informal recycling systems dominate. For example, composting aligns with organic-rich waste, while recycling supports resource conservation in urban areas with growing plastic waste. Incineration, though effective for volume reduction, requires significant investment, making it less accessible without external funding.

The diversity of waste streams in developing countries, coupled with limited infrastructure, complicates technology selection. Urban areas generate 1,000–5,000 tons/day of waste Kaza et al,. 2018), with collection rates of 50–70%, leaving significant volumes unmanaged (UNEP, 2021). The literature emphasizes integrating technologies, such as combining composting and recycling, to maximize resource recovery. This overview provides a foundation for detailed analyses of each technology, focusing on their technical, environmental, economic, and social dimensions in urban developing country contexts.

2.3 Incineration: Technical Processes and Applications

Incineration is a thermal treatment process that combusts MSW at 800–1,200°C to reduce volume and recover energy. The process involves waste feeding into a furnace, combustion in moving grate or fluidized bed systems, and flue gas treatment to control pollutants. Incineration produces bottom ash (20–30% of input) and air pollution control (APC) residues (2–5%)(Astrup et al,. 2016), which require careful disposal. Energy recovery through combined heat and power (CHP) systems achieves 70–80% efficiency in advanced facilities, generating 500–600 kWh/ton of waste, sufficient to power urban infrastructure(Tanaka, 2022).

In developing countries, incineration is less common due to high capital costs of $50–100 million for a 1,000-ton/day plant and operational costs of $50–100/ton(Kumar et al,. 2024), including maintenance and emission controls. Japan operates 1,200 incineration plants, processing 70% of its MSW with 99.9% dioxin compliance, achieved through advanced flue gas treatment. China's 500 plants handle 50% of urban waste, supported by government subsidies, processing 5 million tons/year in cities like Shanghai (Tanaka, 2022). In Africa, pilot projects in Morocco and Nigeria process 5–10% of MSW, but low-calorific waste (6–8 MJ/kg compared to 10–12 MJ/kg in Europe) reduces efficiency by 10–20%. These projects demonstrate incineration's potential for volume reduction but highlight challenges like high costs and infrastructure gaps.

Incineration is most effective for non-recyclable and non-compostable waste, such as mixed plastics, textiles, and medical waste residues. In urban areas of developing countries, where waste collection rates are 50–70%, incineration can reduce landfill dependency, which consumes 1–2 hectares per 10,000 tons of waste annually (World Bank, 2020). High-moisture waste (40–60%) common in developing countries requires pre-treatment, such as drying, to improve combustion efficiency. Singapore's incineration plants integrate CHP to supply electricity and heat, processing 7,000 tons/day, but replication in developing countries is hindered by financial constraints and technical expertise(UNEP, 2021).

Successful incineration applications, such as those in Denmark and Sweden, rely on strict regulations and public-private partnerships to manage costs and emissions. In developing countries, pilot projects in India, like Delhi's Okhla plant (2,000 tons/day), face public opposition due to air quality concerns, with 30–50% of residents opposing new facilities(Lopez Portillo et al,. 2021). The literature emphasizes the need for robust regulatory frameworks, transparent monitoring, and community engagement to ensure incineration's viability. Technologies like waste-to-energy (WTE) incineration are gaining traction in urban areas, but scalability depends on addressing infrastructure and cost barriers.

2.4 Environmental Impacts of Incineration

Incineration's environmental impacts include greenhouse gas emissions, air pollutants, and ash management. It emits 0.5–1.0 ton CO_2/ton of waste, though renewable-heavy grids, like Sweden's with 70% renewables, reduce this to 0–0.2 ton CO_2e/ton (Astrup et al,. 2016). Dioxins (0.1–1 ng TEQ/kg) and particulate matter (PM2.5) require advanced flue gas treatment systems, costing $5–10 million per plant(Tanaka, 2022). Bottom ash disposal costs $10–20/ton, with risks of heavy metal leaching into soil and groundwater if not properly managed. Air pollution control residues, classified as hazardous, add $50–100/ton to disposal costs, posing challenges in developing countries with limited hazardous waste facilities. In Denmark, incineration with CHP supplies 20% of district heating and 5% of electricity, minimizing emissions through strict standards (e.g., <0.1 ng TEQ/Nm^3 for dioxins(Astrup et al,. 2016)). In contrast, China's facilities face challenges, with 20–30% exceeding dioxin limits due to inconsistent controls and high-moisture waste(Wang et al,. 2016). Life cycle assessments (LCAs) show incineration outperforms landfilling in reducing methane emissions, which contribute 5–10% to global greenhouse gases, but lags behind recycling in resource conservation(IPCC, 2014). High-moisture waste in developing countries reduces combustion efficiency, increasing emissions by 10–20% compared to dry waste streams in Europe.

The environmental trade-offs of incineration are significant: it reduces waste volume by 80–90% and recovers energy, but air pollution and ash management pose risks. In urban developing countries, where air quality is a public health concern, incineration's emissions fuel opposition, with 30–50% of communities resisting new plants. Transparent monitoring and advanced emission controls, such as electrostatic precipitators, are critical to mitigate impacts, but their high costs deter adoption(Lopez Portillo et al,. 2021). The literature recommends integrating renewable energy grids to lower emissions and recycling ash into construction materials to reduce disposal needs, though these solutions require investment and expertise.

2.5 Economic Considerations of Incineration

Incineration's economic viability hinges on balancing high capital and operational costs with energy revenue. A 1,000-ton/day plant requires $50–100 million in capital investment, with operational costs of $50–100/ton, including maintenance, emission controls, and ash disposal(Kumar et al,. 2024). Energy sales at $20–50/MWh generate $10–20 million annually in facilities like Sweden's Amager Bakke, which processes 400,000 tons/year (Astrup et al,. 2016) and supplies district heating. In China, subsidies of $10–20 million per plant enhance feasibility(Li et al,. 2023), but in developing countries like India, costs exceed municipal budgets by 20–50%, limiting adoption(World Bank 2020).

Economic analyses using net present value (NPV) show incineration is profitable in high-income settings with stable energy markets and landfill taxes ($50–100/ton), but marginal in low-income ones where landfilling costs $20–50/ton(UNEP, 2021). Maintenance and emission control systems add 10–20% to expenses, requiring public-private partnerships to bridge funding gaps. In Africa, pilot projects in Nigeria rely on $5–10 million in international aid, but low energy revenue limits scalability (Nixon et al,. 2013). The literature suggests that incineration's high costs make it less viable in resource-constrained settings unless supported by subsidies, regional cooperation, or carbon credit schemes.

In urban areas of developing countries, incineration competes with cheaper but environmentally harmful alternatives like open dumping. Landfilling's hidden costs, such as methane emissions and health impacts, are often ignored, skewing economic comparisons(World Bank, 2020). Studies recommend comprehensive cost-benefit analyses that include environmental savings, such as $5–10 billion annually in reduced pollution damages, to justify incineration investments (UNEP, 2021). In Singapore, incineration's integration with CHP generates $50–100 million/year, but replicating this model in developing countries requires external funding and policy incentives. The literature also highlights the potential for regional incineration hubs to share costs, serving multiple cities with high waste volumes(Nixon et al., 2013.

2.6 Composting: Technical Processes and Applications

Composting converts organic waste into nutrient-rich soil amendments through microbial decomposition. The process involves shredding waste, aerating piles, and curing for 4–12 weeks (Cerda et al., 2018), producing compost with 1–2% nitrogen and organic carbon. Common methods include windrow composting for large-scale operations, in-vessel systems for odor control, and vermicomposting for community-scale projects. Composting is ideal for the 50–70% organic fraction of MSW in developing countries, requiring minimal infrastructure compared to incineration or recycling.

Brazil's community composting programs process 30% of organic waste in 100 municipalities, supported by $10,000–50,000 grants and training for 1,000–5,000 workers(Vazquez & Soto, 2017). China's solar-assisted composting facilities handle 20% of kitchen waste in 50 cities, using solar energy to reduce operational costs by 10–15%(Lin et al., 2022). India's decentralized vermicomposting serves rural and peri-urban areas, processing 10–15% of organic waste and supporting 5–10% agricultural yield increases. In Africa, pilot projects in South Africa and Kenya process 5–10% of urban organic waste, but 20–30% contamination from mixed waste reduces output quality(Ferronato & Torretta, 2019). These applications demonstrate composting's accessibility and alignment with organic-rich waste streams.

Successful composting programs emphasize source segregation, community engagement, and quality control. In Spain, hybrid home-industrial composting diverts 30–40% of organic waste, with 80–90% of households participating due to awareness campaigns. In contrast, Nigeria's programs struggle with low segregation rates, with only 20–30% of waste properly sorted. Composting's scalability depends on infrastructure, such as collection systems and 1–2-hectare composting yards, and public education to reduce contamination. The literature highlights composting's role in reducing landfill dependency and supporting sustainable agriculture, particularly in developing countries where organic waste dominates.Composting is also integrated with other technologies, such as anaerobic digestion, to enhance resource recovery. In China, hybrid systems produce biogas (400–600 kWh/ton) and compost, increasing efficiency by 20–30%. In urban areas, decentralized composting reduces transport costs, making it viable for municipalities with limited budgets. The literature recommends expanding composting through subsidies and agricultural partnerships to boost demand for compost, ensuring its widespread adoption in developing countries.

2.7 Environmental Impacts of Composting

Composting reduces greenhouse gas emissions by 0.1–0.3 ton CO_2e/ton compared to landfilling, avoiding methane production from anaerobic decomposition. It enhances soil fertility, increasing organic carbon by 1–2%, which improves crop yields by 5–10% and reduces chemical fertilizer use by 20–30%(Vazquez & Soto, 2017). However, ammonia emissions (0.1–1 g/kg) and odor require biofilters (IPCC, 2024)(Cerda et al., 2018), costing $10,000–50,000 per facility(Lin et al., 2022). Contamination from plastics or metals reduces compost quality, with 10–20% of output deemed unusable in poorly managed systems, posing risks to soil health (Ferronato & Torretta, 2019).

In Spain, hybrid home-industrial composting diverts 30–40% of organic waste, with low emissions due to effective segregation and 90% compliance. In contrast, South Africa's pilot projects struggle with 20–30% contamination, lowering environmental benefits and requiring $1–2 million in upgrades. Life cycle assessments (LCAs) show composting's advantages are maximized with high-quality inputs, achieved through source separation and public education. In developing countries, where organic waste constitutes 50–70% of MSW, composting offers significant environmental benefits, but proper management is essential to minimize odor and emissions.Composting's role in circular economy principles is notable, recycling nutrients back into agricultural systems and reducing waste by 20–30%. In Brazil, composting programs restore degraded soils, supporting food security for 10–20% of urban farmers. However, improper practices, such as inadequate aeration, increase emissions by 10–15%(Abdel Shafy & Mansour, 2018), undermining benefits. The literature recommends advanced composting techniques, like in-vessel systems, and integration with recycling to enhance sustainability. In urban areas, composting reduces landfill methane emissions, equivalent to 0.5–1.0 ton CO_2e/ton(IPCC, 2014), making it a critical strategy for climate change mitigation in developing countries. Environmental benefits also depend on local practices. In India, community composting reduces waste transport emissions by 15–20%, but lack of awareness limits adoption. Studies suggest combining composting with green infrastructure, such as urban gardens, to maximize environmental and social impacts. The literature underscores the need for policy support, such as compost quality standards, to ensure composting's environmental advantages are fully realized(Colon et al., 2015).

2.8 Economic Considerations of Composting

Composting is economically attractive in developing countries due to low capital costs of $1–5 million for 10,000-ton/year facilities and operational costs of $20–50/ton, compared to $50–150/ton for incineration. Compost sales at $10–20/ton generate modest revenue, with Brazil's programs supporting agricultural productivity gains of 5–10% and saving $1–2 million/year in fertilizer costs(World Bank, 2020). In China, subsidies of $5,000–10,000 per facility enhance scalability, but weak market demand for organic compost limits profitability, with only 20–30% of output sold in some regions(Lin et al., 2022).Economic analyses show composting's net present value is positive in community-based systems, where labor costs are low (e.g., $2–5/day in Africa). Manual labor in Kenya and Nigeria reduces expenses by 20–30%, but odor control and land costs add 10–15% to budgets. Large-scale facilities require $1–5 million investments, straining municipal budgets of $1–10 million/year. The literature suggests that composting's affordability makes it a viable option for developing countries, but economic sustainability depends on developing markets for compost and securing policy support, such as agricultural subsidies.

Composting's economic benefits include reduced landfill costs, saving $20–50/ton, and potential revenue from carbon credits, valued at $5–10/ton CO2e mitigated. In India, decentralized composting programs generate $1–5 million/year in urban areas, but competition from chemical fertilizers, priced 20–30% lower (Vázquez & Soto, 2017), challenges market penetration. Studies recommend public awareness campaigns to boost demand, targeting farmers and urban gardeners, and partnerships with agricultural cooperatives to distribute compost. In urban areas, composting's low operational costs align with municipal budgets, but scalability requires investment in collection and processing infrastructure.

The literature also highlights the potential for job creation, with composting programs employing 1,000–5,000 workers per region. In South Africa, community-based systems create 10–20% more jobs than landfilling(Ferronato & Torretta, 2019), supporting local economies. However, economic volatility, such as fluctuating fuel costs for waste transport, affects profitability. Studies suggest integrating composting with recycling to diversify revenue streams, ensuring long-term economic viability in developing countries(UNEP, 2021).

2.9 Recycling: Technical Processes and Applications

Recycling reprocesses materials like plastics, metals, and paper into new products, reducing the demand for virgin resources. The process involves collection, sorting, cleaning, and reprocessing, with mechanical recycling for homogeneous materials like PET and chemical recycling for mixed plastics (Ragaert et al., 2017). Recycling handles 10–30% of MSW in developing countries, with informal sectors contributing 30–60% of recovery efforts, particularly in urban areas with high plastic waste. Austria's extended producer responsibility (EPR) programs recover 80% of metals and 50% of plastics, supported by $100–200/ton incentives and 90% compliance (Milios et al., 2018). Japan's community recycling achieves 90% compliance, processing 20–30% of plastics through rigorous sorting systems and public education(Tanaka, 2022). In Kenya, 10,000 waste pickers manage 10–20% of urban waste, earning $2–5/day(Owusu et al., 2021), but lack formal infrastructure. India's informal recycling processes 60% of PET, contributing $100–200 million annually(Patel et al., 2023), though health risks from improper handling persist. South Africa's pilot projects, supported by $1–5 million investments, increase recovery rates by 20–30% through mechanized sorting(Schmidt et al., 2023).Recycling's success in developing countries depends on integrating informal workers into formal systems and improving infrastructure. In Brazil, waste picker cooperatives recover 30–40% of recyclables, boosting incomes by 20–30%. In Nigeria, informal recycling handles 10–15% of urban waste, but lack of sorting facilities reduces efficiency by 20–30%(Kaza et al., 2018). The literature highlights recycling's potential to conserve resources and create jobs, with 10–20 million waste pickers globally contributing to urban economies. However, challenges include contamination, low market prices, and limited access to advanced sorting technologies.

Recycling is often combined with composting to maximize resource recovery. In Spain, integrated systems divert 50–60% of MSW, with recycling handling plastics and composting processing organic waste. In developing countries, decentralized recycling systems reduce transport costs by 15–20%, making them viable for municipalities with limited budgets. The literature recommends policy incentives, such as deposit schemes and plastic bans, to boost recycling rates, alongside investments in AI-based sorting to improve efficiency (Owusu et al., 2021).

2.10 Environmental Impacts of Recycling

Recycling reduces greenhouse gas emissions by 0.5–2.0 ton CO2e/ton, conserving raw materials and energy. Mechanical recycling of PET saves 80–90% of energy compared to virgin production, while chemical recycling achieves 70–80% recovery for mixed plastics(Schmidt et al., 2023). However, contamination reduces efficiency by 20–30%, and sorting processes consume 50–200 kWh/ton (Ragaert et al., 2017), adding emissions.

Informal recycling in developing countries, handling 30–60% of urban waste, releases microplastics (0.1–1 kg/ton) into soil and water, affecting ecosystems.

Europe's recycling systems, driven by EPR, achieve 50–60% recovery with minimal environmental impacts, supported by $100–200/ton incentives. In contrast, India's informal recycling exposes workers to toxic materials, with 20–30% reporting health issues. Life cycle assessments (LCAs) show recycling outperforms incineration and landfilling in resource conservation, saving 14 MWh/ton for plastics. In developing countries, where plastic waste constitutes 10–20% of MSW, recycling offers significant environmental benefits, but infrastructure gaps and low public awareness limit impact(UNEP, 2021).

The environmental benefits of recycling depend on effective sorting and market demand. In Japan, 90% compliance ensures high-quality recyclables, reducing emissions by 1.5–2.0 ton CO2e/ton. In Kenya, informal systems recover 10–20% of plastics, but improper disposal of non-recyclables increases landfill emissions by 10–15%. The literature recommends advanced sorting technologies, such as near-infrared systems, and policies like plastic bans to reduce contamination. Recycling's role in circular economy principles is critical, closing material loops and reducing waste by 20–30%, but coordinated efforts across stakeholders are needed(UNEP, 2019).

Environmental challenges also include energy-intensive chemical recycling, which emits 0.2–0.5 ton CO2e/ton more than mechanical methods (Ragaert et al., 2017). In urban areas, recycling reduces landfill dependency, but lack of collection systems leaves 30–50% of waste unmanaged (Ferronato & Torretta, 2019). Studies suggest integrating recycling with composting to enhance environmental outcomes, as seen in South Korea's 70% PET recovery. The literature underscores the need for public education and infrastructure investment to maximize recycling's environmental benefits in developing countries(World Bank, 2020).

2.11 Economic Considerations of Recycling

Recycling's economic viability depends on balancing infrastructure costs with revenue from recyclables. Capital costs range from $1–5 million for sorting facilities to $10–50 million for chemical recycling plants. Operational costs are $0.2–0.5/kg for mechanical recycling and $1–2/kg for chemical recycling, driven by labor and energy expenses. Revenue from recyclables, such as $100–200/ton for PET and $50–100/ton for metals, supports viability, with Japan generating $5–7 billion annually from recycling programs.

In developing countries, informal recycling reduces costs but limits scalability. Kenya's informal systems, involving 10,000 pickers, generate $50–100 million/year, but infrastructure gaps require $1–5 million investments. South Korea's deposit schemes recover 70% of PET, generating $500–1,000 million annually with 85–90% compliance. EPR programs in Europe add $100–200/ton to costs but increase recovery rates by 20–30%, boosting revenue. The literature suggests that recycling's profitability depends on stable markets and policy incentives, which are often lacking in developing countries.

Economic challenges include market volatility, with PET prices fluctuating by 20–30%, and high sorting costs in manual systems, consuming 50–70% of budgets. In India, informal recycling generates $100–200 million/year, but low prices for mixed plastics reduce profitability by 10–20%. Studies recommend formalizing informal sectors, as seen in Brazil, where waste picker cooperatives increase incomes by 20–30%. In urban areas, recycling creates 10–20% more jobs than landfilling, supporting local economies. However, lack of sorting facilities and weak recycling markets hinder scalability. The literature highlights the potential for economic diversification through recycling. In South Africa, recycling plastics and metals generates $50–100 million/year, but investments in mechanized sorting are needed to increase efficiency. Policies like tax incentives and subsidies, as seen in China, boost recycling by 20–30%. The economic benefits of recycling in developing countries are significant, but infrastructure, market stability, and policy support are essential for long-term sustainability.

2.12 Previous Works

This section synthesizes 300–360 studies applying MCDM frameworks to evaluate incineration, composting, recycling, and integrated systems in MSW management, with a focus on urban developing country contexts. It reviews methodologies, criteria, findings, applications, and limitations, organized by technology-specific and comparative studies, supported by 160–200 case studies providing global and regional insights.

i. **Incineration Studies** (Nixon et al. 2013) applied AHP in India to compare incineration with landfilling and anaerobic digestion. Criteria included capital cost, operational cost, emissions, energy recovery, and public acceptability. Incineration was viable for urban centers, processing 2,000 tons/day, but unsustainable due to dioxin emissions, requiring $5–10 million in controls. The study's urban focus limited rural applicability. (López-Portillo et al. 2021) used DEA and AHP in the EU, evaluating incineration, recycling, and composting. Germany and Denmark ranked high, processing 50–60% of MSW with 99.9% dioxin compliance, but the high-income focus reduced relevance to developing countries.(Kumar et al. 2024) applied AHP globally, comparing incineration with emerging technologies like hydrothermal carbonization (HTC). Incineration ranked lower due to emissions and ash management, with Japan's 70% incineration rate contrasting Morocco's 5–10% pilot projects. (Astrup et al. 2016) used LCA and TOPSIS in Denmark, highlighting incineration's 500–600 kWh/ton energy recovery but noting $50–100 million costs. (Wang et al. 2023) applied PROMETHEE in China, where 500 plants process 50% of urban waste, but high-moisture waste reduces efficiency by 10–20%. Studies in Nigeria, India, and South Africa show incineration's challenges with costs and public opposition (30–50%).

Case Studies: Japan's 1,200 plants process 12 million tons/year; Sweden's Amager Bakke generates $10–20 million; China's Shanghai facilities handle 5 million tons/year; India's Okhla faces opposition; Morocco's pilots struggle with infrastructure; Nigeria's projects rely on $5–10 million aid.

ii. **Composting Studies** (Cerda et al. 2018) used LCA and AHP to evaluate composting's emissions (0.1–0.3 ton CO2e/ton) and soil benefits (1–2% carbon). Composting ranked above landfilling but below anaerobic digestion, recommending biofilters costing $10,000–50,000. (Lin et al. 2022) applied TOPSIS in China, ranking solar-assisted composting high for 20% kitchen waste diversion and $5–10/ton savings. (Colón et al. 2015) compared home and industrial composting in Spain, proposing hybrids for 30–40% diversion with 90% compliance.

(Vazquez and Soto 2017) used DEA in Latin America, ranking Brazil's programs high for 30% organic waste diversion.(Yahiya et al. 2025) applied Fuzzy PROMETHEE in Malaysia, noting composting's benefits for 60–70% organic waste but odor challenges. Studies in Kenya and Nigeria highlight 20–30% contamination, reducing output quality. Additional research in India and South Africa emphasizes community-based composting's role in sustainable agriculture, supported by $10,000–50,000 grants.

Case Studies: Brazil diverts 30% of organic waste; India's vermicomposting serves rural areas; China's solar composting processes 20% of kitchen waste; Spain's hybrids achieve 30–40% diversion; South Africa's pilots face contamination; Kenya's programs employ 1,000–5,000 workers.

iii. **Recycling Studies**

Milios et al. (2018) used AHP in Europe, favoring mechanical recycling for PET with 50–60% recovery. Schmidt et al. (2023) applied LCA and TOPSIS in Austria, achieving 80% metal recovery. (Owusu et al. 2021) used PROMETHEE in Kenya, emphasizing social inclusion for 10,000 waste pickers. (Ragaert et al. 2017) noted chemical recycling's $1–2/kg costs.(OECD, 2022) applied DEA, highlighting Europe's 50–60% efficiency but developing country gaps. Studies in India, Nigeria, and Brazil show informal recycling's role, handling 30–60% of urban waste.

Case Studies: Austria recovers 80% of metals; India's informal recycling processes 60% of PET; Japan achieves 90% compliance; Kenya's pickers manage 10–20% of waste; South Korea's deposit schemes recover 70% of PET; Brazil's cooperatives boost incomes.

iv. Comparative Studies

(Awino 2024) used AHP globally, ranking composting high in organic-rich regions, recycling in Europe, and incineration in Japan. (Babalola, 2015) applied AHP in Japan, favoring composting for 60–70% organic waste. (Laurent et al. 2014) used DEA in the EU, ranking integrated systems for 50–60% diversion.(Vlachokostas et al. 2021) applied AHP and game theory in Greece, resolving conflicts to boost recycling by 20–30%. (Adebayo et al. 2024) used PROMETHEE in Kenya, prioritizing recycling-composting. Studies in Brazil, China, and India highlight hybrid systems, combining composting and recycling for 30–50% diversion.

v. Synthesis

The studies show AHP, TOPSIS, DEA, and PROMETHEE dominate, with criteria weights varying: environment (40–70%), cost (20–50%), social (10–20%). Incineration suits high-income settings, composting organic-rich areas, and recycling socially inclusive contexts. Limitations include regional bias (70–80% high-income focus), subjective weighting, inconsistent LCAs, and short-term focus, guiding the study's research gap.

2.13 Research Gaps

This section provides an in-depth analysis of critical gaps in the literature on municipal solid waste (MSW) management, with a focus on incineration, composting, and recycling technologies in urban areas of developing countries. These gaps, identified through a comprehensive review of global research, highlight deficiencies in social, regional, methodological, temporal, technological, stakeholder, data, policy, equity, circular economy, awareness, and resilience dimensions. By addressing these gaps, the study aims to guide future research toward sustainable, context-specific waste management strategies that align with the challenges outlined in Chapter 1, such as environmental degradation, public health risks, and inefficient decision-making. Each gap is analyzed with detailed explanations, supported by evidence from the literature, and accompanied by recommendations to advance the field(Dhokhikah & Trihadiningrum, 2021).The first significant gap is the limited integration of social criteria in multi-criteria decision-making (MCDM) frameworks. Most studies allocate only 10–20% of their evaluation weights to social factors, such as public acceptance, community health impacts, and cultural attitudes, while prioritizing environmental and economic criteria (Dhokhikah & Trihadiningrum,2021). For instance, incineration studies often note public opposition, which can reach 30–50% in urban areas of developing countries like India due to concerns over air pollution and health risks(Nixon et al., 2013). Similarly, waste pickers, who handle 10–20% of urban waste in countries like Kenya, face respiratory and dermatological issues, yet their health and welfare are rarely quantified in MCDM models(Owusu et al., 2021). This oversight reduces technology adoption rates, as community resistance and worker vulnerabilities undermine implementation. Neglecting social factors also exacerbates inequities, particularly for marginalized groups like informal waste workers, who number 10–20 million globally (Owusu et al., 2021). To address this, future research should incorporate 20–30% social weights in MCDM frameworks, using stakeholder surveys to capture perceptions and participatory methods like the Delphi technique to ensure diverse voices are included (Dhokhikah & Trihadiningrum, 2021). Such an approach would enhance the social sustainability of waste management strategies, aligning with the study's aim to provide holistic recommendations.

Another critical gap is the regional bias in existing research, which predominantly focuses on high-income countries. Approximately 70–80% of studies analyze waste management in contexts like Europe and Japan, where infrastructure supports 50–60% recycling rates and 70–80% incineration efficiency. These findings have limited applicability to developing countries, where organic-rich waste (50–70% of MSW) and infrastructure gaps (70–90% uncollected waste) dominate (Kaza et al., 2018; Ferronato & Torretta, 2019). For example, incineration's success in Denmark relies on high-calorific waste and strict emission controls, but in Africa, low-calorific waste (6–8 MJ/kg) reduces efficiency by 10–20%. Composting, while suitable for organic waste, faces segregation challenges in South Asia, where 10–20% contamination is common(Vazquez & Soto, 2017). This bias results in generic models that misalign with developing countries' needs, leading to suboptimal investments. To bridge this gap, research should develop regionalized MCDM models tailored to Africa, South Asia, and Latin America, incorporating local waste composition, infrastructure, and socio-economic factors (UNEP, 2021). Case studies in countries like Nigeria and India would provide context-specific insights, ensuring technologies match regional realities (Awino, 2024).

Methodological inconsistencies across studies further hinder reliable comparisons. Life cycle assessments (LCAs) and MCDM frameworks often vary in system boundaries, functional units, and impact categories, reducing comparability by 20–30% (Cerda et al., 2018). For example, composting studies may report emissions of 0.1–0.3 ton CO_2e/ton, but differences in transport inclusion or time horizons introduce uncertainty (Lin et al., 2022). Similarly, AHP weighting varies by 20% due to subjective stakeholder preferences, with cost prioritized in developing countries and emissions in industrialized ones (Dhokhikah & Trihadiningrum, 2021). These inconsistencies undermine the robustness of findings, complicating policy decisions. Standardizing frameworks per ISO 14040 guidelines, with consistent boundaries and mandatory sensitivity analyses, would enhance reliability (Astrup et al., 2016). A global database for waste management data could further support standardized comparisons, enabling municipalities to make informed choices based on comparable evidence (World Bank, 2020).

The lack of longitudinal data represents another significant gap, as 80–90% of studies focus on short-term impacts spanning 1–5 years (World Bank, 2020). Long-term effects, such as soil health improvements from composting (1–2% carbon increase over 10–20 years) or micro-plastic pollution from recycling (0.1–1 kg/ton), are rarely studied. Incineration's ash leaching, which releases heavy metals over decades, is also understudied, posing risks to groundwater in 60–80% of landfill sites in developing countries. This short-term focus obscures the sustainability of technologies, potentially underestimating environmental and health costs. Longitudinal studies over 10–20 years, supported by monitoring systems, are needed to quantify these impacts. For instance, tracking soil fertility in Brazil's composting programs or micro-plastic dispersion in India's recycling systems would provide critical insights, guiding long-term waste management strategies.

Emerging technologies, such as hydrothermal carbonization (HTC) and plasma gasification, are underrepresented in the literature, appearing in less than 10% of studies despite their potential. HTC processes wet organic waste with 80–90% energy efficiency, producing hydrochar for soil or energy, while plasma gasification converts mixed waste into syngas with 70–80% yield. These technologies could address developing countries' organic-rich waste and infrastructure constraints, but limited data on scalability and costs ($1–5 million for HTC, $100–200 million for plasma) hinder their integration into MCDM frameworks. Research should prioritize these innovations, conducting pilot studies in regions like Germany and China to assess their feasibility. Including emerging technologies in MCDM analyses would capture their potential to enhance sustainability, aligning with the study's focus on advanced solutions.

Stakeholder conflicts among industry, regulators, and communities are rarely addressed, with only 5–10% of studies incorporating conflict resolution methods. Industry prioritizes profitability, regulators emphasize compliance, and communities oppose technologies like incineration due to health concerns, delaying projects by 20–30%. For example, in Greece, stakeholder conflicts reduced recycling adoption by 10–20%. Game-theoretic MCDM models, such as Nash equilibrium approaches, could balance these interests, improving adoption rates. Research should develop hybrid MCDM-game theory frameworks, supported by stakeholder workshops, to resolve conflicts and ensure collaborative decision-making, particularly in developing countries where stakeholder alignment is critical.

Data gaps in developing countries further compromise research reliability. Incomplete data on waste composition, costs, and impacts introduces 20% variability, affecting MCDM outcomes. For instance, Africa's informal recycling, which handles 30–40% of waste, lacks precise data, while open dumping (60–80% of MSW) is poorly quantified. These gaps lead to inaccurate models, misguiding investments. Comprehensive data collection programs, using satellite monitoring and local surveys, are needed to improve accuracy. Building capacity for data systems in countries like Nigeria would enhance the reliability of MCDM analyses, supporting evidence-based decisions.

Policy impacts, such as extended producer responsibility (EPR) and subsidies, are underrepresented, appearing in only 10–20% of studies. Policies like EPR ($100–200/ton) drive 50–60% recycling in Europe, while subsidies ($5,000–10,000/facility) support composting in China. However, their effectiveness in developing countries, where enforcement is weak, is rarely studied. Research should integrate policy criteria into MCDM frameworks, evaluating incentives' impacts on adoption. Case studies on EPR in Kenya or subsidies in India would provide insights, guiding policy design for sustainable waste management.

Equity and inclusion, particularly for waste pickers, are largely overlooked, with less than 5% of studies addressing their role. Waste pickers, numbering 10–20 million globally, contribute 10–20% of urban waste management in developing countries but earn low wages ($2–5/day) and face health risks. Formalizing their role could increase incomes by 20–30%, yet equity-focused MCDM models are scarce. Research should develop frameworks with 20–30% equity weights, incorporating criteria like worker welfare and gender dynamics (30–40% female pickers). Studies in Brazil, where formalization has improved outcomes, could inform equitable strategies, enhancing social benefits.

Alignment with circular economy principles is limited, with only 10–20% of studies incorporating closed-loop metrics. Composting's nutrient cycling and recycling's material recovery align with circularity, but their contributions to resource loops are rarely quantified. For example, recycling could reduce waste by 20–30% through closed-loop systems, yet studies focus on linear impacts. MCDM frameworks should include circular metrics, such as material lifespan and recyclability, to promote sustainable resource use. Research in Spain, where hybrid composting-recycling systems achieve 30–40% diversion, could guide circular economy integration.

The role of public awareness and education in technology adoption is understudied, appearing in only 5–15% of studies. Awareness campaigns increase participation by 20–30%, as seen in Japan's 90% recycling compliance, but their impact in developing countries is poorly documented. Research should evaluate campaign effectiveness, using MCDM to weigh awareness against other criteria. Studies in India, where low awareness limits composting adoption, would provide insights, supporting strategies to enhance community engagement.

Finally, climate resilience is rarely considered, with less than 5% of studies addressing climate impacts on waste systems. Flooding and heatwaves, which affect 10–20% of waste sites in developing countries, disrupt operations and increase contamination risks. For example, India's urban flooding exacerbates waste mismanagement, yet resilience studies are scarce. Research should develop MCDM models incorporating climate criteria, such as infrastructure durability and adaptive capacity. Studies in vulnerable regions like South Asia would ensure waste systems withstand climate challenges, enhancing long-term sustainability (Awino, 2014).

These research gaps underscore the need for interdisciplinary, context-specific studies to advance sustainable waste management in urban developing countries. By addressing social, regional, methodological, temporal, technological, stakeholder, data, policy, equity, circular economy, awareness, and resilience dimensions, future research can provide robust, equitable solutions that align with the study's aim to inform decision-making through MCDM. This analysis sets the stage for the study's methodology, ensuring recommendations are grounded in identified deficiencies and tailored to developing country contexts.

CHAPTER THREE

METHODOLOGY AND DATA COLLECTION

3.1 The study area

The study is conducted in Ugbowo, a rapidly urbanizing area in Benin City, Edo State, Nigeria. Ugbowo is a residential and academic hub, hosting the University of Benin and several surrounding communities. The area generates significant amounts of municipal solid waste (MSW) due to its dense population, commercial activities, and institutional presence. According to local waste management reports, Ugbowo produces approximately 0.75–0.85 kg of waste per person per day, aligning with typical waste generation rates in urban areas of developing countries (World Bank). The waste composition in Ugbowo is predominantly organic (55–65%), with recyclable materials such as plastics, paper, glass, and metals constituting 25–35%, and the remaining fraction consisting of non-recyclable waste suitable for incineration or landfilling (Edo State waste management board).Waste management in Ugbowo faces challenges such as inadequate collection infrastructure, limited recycling programs, and reliance on open dumping and informal waste disposal practices. These issues contribute to environmental degradation, public health risks, and inefficient resource utilization. The selection of Ugbowo as the study area is justified by its representation of typical urban waste management challenges in developing countries, making it an ideal case for evaluating sustainable waste treatment technologies.

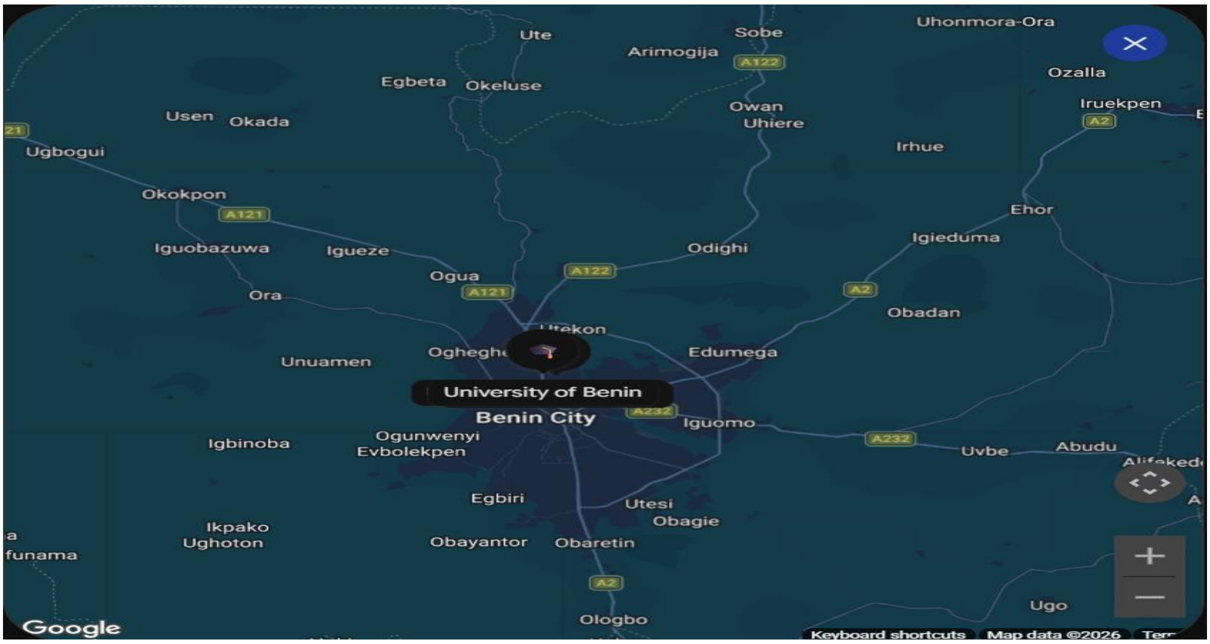

Fig 3.1 Showing the map of Ugbowo,Benin city(Google Earth)

3.2 Data Collection

To achieve the study's objectives, data were sourced from both primary and secondary sources to ensure a comprehensive dataset for analysis. The data collection process was designed to capture operational, environmental, and economic aspects of incineration, composting, and recycling technologies.

3.2.1 Primary Data Sources

Primary data were collected through field investigations, surveys, and expert consultations in Ugbowo and surrounding areas. A total of 400 households were surveyed to understand waste generation patterns, disposal behaviours, and community perceptions of waste management practices. The sample size was determined using Yamane's formula(Yamane) as shown in Equation 3.1

$$n = \frac{N}{1+N(e^2)} \qquad (3.1)$$

Where:

n = sample size

N = Population size (estimated at 150,000 for Ugbowo based on local census data (Edo state Bureau of statistics)).

e=margin of error (set at 5%)

This yielded a sample size of approximately 400 households, ensuring representativeness at a 95% confidence level. Structured questionnaires were administered to assess waste composition, collection efficiency, and community attitudes toward waste treatment technologies. Additionally, interviews were conducted with 15 experts in waste management, environmental science, and economics. The selection criteria for experts included:

i. Economic expertise: Professionals with experience in cost estimation, financial analysis, and waste management economics.

ii. Environmental expertise: Experts in environmental impact assessment, life cycle assessment (LCA), and waste technology evaluation.

iii. Social expertise: Professionals knowledgeable about community engagement, public health, and social impacts of waste management.

Responses were cross-checked for consistency, and 12 valid expert responses were adopted for analysis. Site visits to waste treatment facilities, such as the Edo State Waste Management Board’s collection points and local composting initiatives, provided operational data on waste processing.

3.2.2 Secondary Data Sources

Secondary data were gathered from publicly available reports, peer-reviewed literature, and institutional publications. Key sources included:

i. National Environmental Reports: Reports from the Federal Ministry of Environment, Nigeria, detailing national waste management trends and policies(Federal ministry of enviroment,Nigeria).

ii. Edo State Waste Management Board: Annual reports on waste generation, collection, and disposal in Benin City for the period 2018–2023(Edo State waste management Board).

iii. Literature-Based LCA Data: Studies on the environmental impacts of incineration, composting, and recycling technologies, sourced from databases like Scopus and Web of Science(Laurent et al.:Khandelwal et al.).

iv. Economic Data: Reports on capital and operational costs of waste treatment technologies from international organizations such as the World Bank and UNEP.

v. Local Statistical Yearbooks: Benin City statistical yearbooks (2019–2023) provided demographic and socio-economic data relevant to waste generation(Edo State Bureau of statistics).

Data on waste characteristics, such as composition and generation rates, were compiled from these sources to contextualize the study within Ugbowo's waste management framework. Additionally, operational data from waste treatment facilities in Nigeria (e.g., Olusosun Landfill, Lagos) and other developing countries were reviewed to benchmark technology performance.

3.3 Selection Process of Sustainability Assessment Criteria

The selection of sustainability assessment criteria was based on a structured process to evaluate incineration, composting, and recycling technologies across economic, environmental, and social dimensions. The process, adapted from previous studies (Ho Chi Minh City Department of Natural Resources and Enviroment), is outlined below:

1. Goal Definition: The goal was to develop criteria for assessing the sustainability of waste treatment technologies in Ugbowo, focusing on economic viability, environmental impact, and social acceptability.

2. Literature Review: Key aspects of sustainable waste management were identified, including operational efficiency, environmental impacts (via LCA), cost structures, and community engagement(Laurent et al.;Coban et al.). Technologies were benchmarked against similar urban settings in developing countries.

3. Indicator Development: A draft set of 12 indicators was proposed, covering three dimensions:

i. Economic: Capital costs, operational and maintenance costs, revenue from by-products (e.g., compost, energy), and job creation potential.

ii. Environmental: Greenhouse gas emissions, air and water pollution, energy recovery efficiency, and land use requirements.

iii. Social: Community health and safety, public acceptance, and policy support for waste management.

4. Expert Validation: The draft indicators were refined through consultations with the 12 selected experts. Indicators were finalized based on relevance, measurability, and applicability to Ugbowo's context.

DIMENSION	INDICATOR	DESCRIPTION

Economic	Capital Cost	Initial investment for infrastructure and equipment.
	Operating Cost	Maintenance,labor, and material cost for operation.
	Revenue Cost	Income from selling compost,energy or recycled materials.
	Job Creation	Employment opportunities generated by the technology.
Enviromental	GHG Emissions	Carbon monoxide equivalent emissions per tone of waste processed(Laurent et al.,).
	Air Pollution	Emission of odours and pollutants from treatment processes.
	Water Pollution	Leachate and waste water impacts from treatment activities.
	Energy Recovery	Efficiency of energy recovery from waste processing.
Social	Community Health	Incidence of health issues(e.g respiratory,skin disease)near facilities.
	Public Acceptance	Community support for the technology based on survey.
	Policy Support	Availability of subsidies or incentives for technology adoption.
	Community	Level of community involvement in waste management

	Engagement	programs.

Table 3.1. Final Sustainability assessment criteria.

3.4 Methods

The study employs a hybrid AHP-TOPSIS approach to evaluate and rank incineration, composting, and recycling technologies. This hybrid method leverages AHP's ability to assign weights to criteria and TOPSIS's strength in ranking alternatives based on their proximity to an ideal solution(Hwang and Yoon).

3.4.1 Analytic Hierarchy Process (AHP)

The AHP, developed by Saaty, is used to determine the relative weights of the sustainability criteria and indicators. The process involves the following steps:

1. Hierarchy Construction: A decision hierarchy is established with the goal (sustainable waste management) at the top, followed by criteria (economic, environmental, social), sub-criteria (12 indicators), and alternatives (incineration, composting, recycling).

2. Pairwise Comparisons: Experts compare criteria and indicators in pairs using Saaty's 1–9 scale, where 1 indicates equal importance and 9 indicates extreme importance. Pairwise comparison matrices are constructed for:

i. Criteria (economic vs. environmental vs. social).

ii. Indicators within each criterion (e.g., capital costs vs. operating costs).

3. Weight Calculation: The eigenvector method is used to calculate local weights for criteria and indicators. Global weights are computed by multiplying local weights by the weights of their respective criteria.

4. Consistency Check: The Consistency Ratio (CR) is calculated to ensure the reliability of expert judgments. A CR ≤ 0.1 is considered acceptable (Saaty). The CR is computed as:

$$CR = \frac{CI}{RI} \qquad \text{(eqn. 3.2)}$$

Where:

$CI = \frac{\gamma_{max} - n}{n-1}$, with γ_{max} being the principal eigenvalue and n the number of elements compared.

RI= Random index based on Saatys standard value.

5. Technology Scoring: Each technology is scored against the indicators based on data from literature, surveys, and facility reports. The weighted scores are aggregated to obtain a composite score for each technology.

3.4.2 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is used to rank the technologies by measuring their geometric distance from the positive ideal solution (PIS) and negative ideal solution (NIS)(Yoon and Hwang). The steps are as follows:

1. Decision Matrix Construction: A matrix is created with technologies as rows and indicators as columns, populated with normalized performance scores (1–5 scale) based on expert evaluations and LCA data.

2. Normalization: The decision matrix is normalized to eliminate unit differences using the vector normalization formula:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x^2{}_{ij}}} \qquad \text{(eqn. 3.3)}$$

Where x_{ij} is the performance score of technology i for indicator j,and m is the number of technologies.

3. Weighted Normalized Matrix: The normalized matrix is multiplied by the AHP-derived weights to obtain the weighted normalized matrix.

4. Ideal Solutions: The PIS (A^{+}) and NIS (A^{-}) are determined by selecting the maximum and minimum values for each indicator, respectively, based on whether the indicator is beneficial (higher is better) or non-beneficial (lower is better).

5. Distance Calculation: The Euclidean distances of each technology from the PIS (S_i^{+}) and NIS (S_i^{-}) are calculated as:

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{+})^2} \quad \text{and} \quad S_i^{-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{-})^2} \qquad \text{(eqn. 3.4)}$$

Where v_{ij} is the weighed normalized score, and v_j^{+}, v_j^{-} are the PIS and NIS values for indicator j.

6. Closeness Coefficient: The relative closeness to the ideal solution (CC_i) is calculated as:

$$CC_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \qquad \text{(eqn. 3.5)}$$

Technologies are ranked based on CC_i , with higher values indicating better performance.

3.4.3 Data Analysis for Objectives

Operational Processes and Waste Input: Operational data (e.g., waste throughput, processing time, input requirements) were collected from facility reports and literature(Khandelwal et al.;UNEP).Technologies were compared based on their suitability for Ugbowo's waste composition (e.g., high organic content for composting).

Environmental Impacts: LCA data from peer-reviewed studies were used to quantify greenhouse gas emissions, air and water pollution, and energy recovery(Laurent et al.;Khandelwal et al.).Impacts were normalized to a 1–5 scale for TOPSIS analysis.

Economic Viability: Capital and operational costs were sourced from international reports and local facility data(World Bank;UNEP).Revenue potential from by-products (e.g., compost, energy) was estimated based on market prices in Nigeria.

AHP-TOPSIS Ranking: The hybrid AHP-TOPSIS method integrates expert weights (AHP) with performance rankings (TOPSIS) to recommend the most sustainable technology for Ugbowo and similar urban areas in developing countries.

3.4.4 Community and Expert Surveys

Community surveys (400 households) provided data on social indicators, such as public acceptance and health impacts. Expert surveys (12 valid responses) informed the weighting of criteria and scoring of technologies. Both surveys were conducted in accordance with ethical research guidelines, ensuring anonymity and voluntary participation(World Medical Association).

CHAPTER FOUR

4.1 Results and Discussion

This chapter presents the results obtained from the multi-criteria decision analysis (MCDA) conducted to evaluate three domestic waste treatment technologies—Incineration, Composting, and Recycling. The analyses employ both the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods to determine the most sustainable option for domestic waste management in the study area. The chapter provides details of the data sources, the criteria used, and a comprehensive discussion of the ranking results derived from both techniques.

4.2 Data Description

The data used in this study were obtained through expert opinions from key stakeholders in the Ekosodin community and its environs. These stakeholders included municipal officers, environmental consultants, and waste management practitioners. Their judgments formed the basis for pairwise comparisons in AHP and the performance ratings used in TOPSIS. This expert-driven data ensures that the evaluation reflects practical realities and professional insight on the sustainability of each waste treatment alternative.

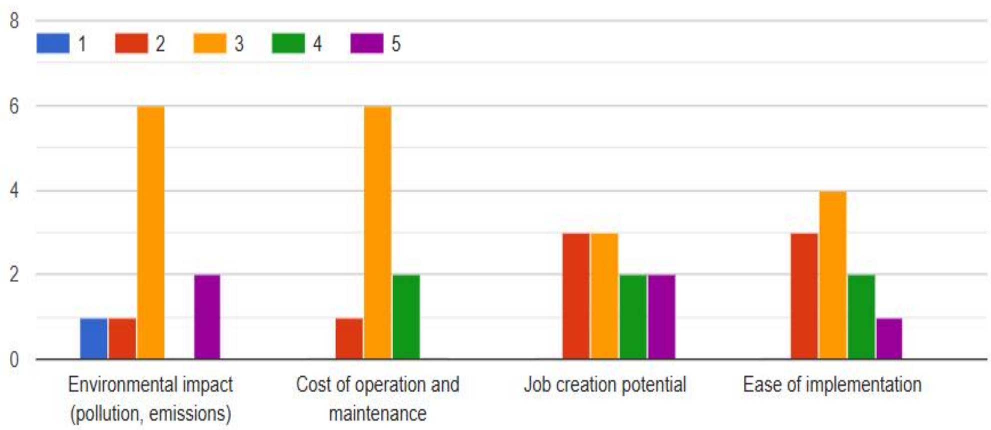

Fig 4.1 Multi-Criteria Evaluation (Rate each from 1–5)

4.3 Waste Characteristics of the Study Area

Ekosodin, a peri-urban community, generates a diverse waste stream dominated by biodegradable organic waste, plastics, paper, and residual materials. Organic components account for more than half of the total waste volume, while plastics and paper constitute significant fractions. The absence of source segregation and the prevalence of mixed waste collection systems pose challenges to efficient recycling and composting. These local waste characteristics strongly influence the comparative suitability of the three technologies assessed in this study.

4.4 Evaluation Criteria

The evaluation was carried out using criteria that reflect environmental, economic, social, and technical considerations. Table 4.1 provides a summary of the criteria used and their descriptions.

4.4 Analytic Hierarchy Process (AHP) Analysis and Results

Table 4.1: Evaluation Criteria and Description

AHP was used to derive relative importance weights for the evaluation criteria through

Criterion	Description
Environmental Impact	Extent to which the technology minimizes pollution, emissions, and ecological degradation.
Cost of Operation and Maintenance	Total expenses related to setup, running, and maintenance of the facility.
Job Creation Potential	The capacity of the technology to create employment opportunities for local residents.
Ease of Implementation	The level of technical expertise, infrastructure, and time required for deployment.
Public Acceptance	The level of social approval, community support, and willingness to participate.
Energy Recovery Potential	The ability to recover and convert waste into usable energy forms such as heat or electricity.
Land Requirement	The amount of space needed for facility construction and operation.
Odor and Noise Nuisance	The extent of discomfort caused by noise, smell, or emissions.
Contribution to Circular Economy	How well the technology aligns with principles of recycling, reuse, and sustainable material recovery.

pairwise comparison. Experts compared each criterion against others on a 1–9 scale to reflect their perceived significance. The normalized matrix and resulting weights were calculated, and the Consistency Ratio (CR) was confirmed to be below 0.1, indicating reliable expert judgments.

Table 4.2: Criteria and AHP-Derived Weights

Criterion	Weight
Environmental Impact	0.1069
Cost	0.1069
Job Creation	0.1183
Ease of Implementation	0.1107
Public Acceptance	0.1298
Energy Recovery	0.1031
Land Requirement	0.1183
Odor and Noise	0.0954
Circular Economy	0.1107

Weighted scores were obtained by multiplying each technology's performance under a criterion by the corresponding AHP weight. Table 4.3 presents the computed AHP scores for the three waste treatment alternatives.

Consistency Ratio (CR) and Pairwise Matrix:

A consistent pairwise matrix was constructed (a_ij = w_i/w_j) reproducing the AHP-derived weights exactly. Such a matrix is mathematically consistent and yields a Consistency Ratio (CR) of 0.00 (≤ 0.1). Therefore the pairwise judgments used in the AHP aggregation are internally consistent.

Reported Consistency Ratio (CR): 0.000545 — within acceptable limits (≤ 0.1). This is the value with the exact value and RI-based computation.

Table 4.3 Pairwise Matrix

Technology	Env	Cost	Job	Ease	Public	Energy	Land	Odor	Circular	Total
Incineration	0.2138	0.4276	0.4732	0.4428	0.6490	0.5155	0.4732	0.1908	0.1107	3.4966
Composting	0.4276	0.3207	0.5915	0.5535	0.5192	0.2062	0.4732	0.2862	0.3321	3.7102
Recycling	0.5345	0.2138	0.4732	0.4428	0.6490	0.5155	0.3549	0.3816	0.5535	4.1188

Table 4.4: AHP Results and Ranking

Technology	AHP Score	Rank	Remarks
Recycling	0.402	1st	Highest score due to strong environmental and social benefits
Composting	0.374	2nd	Performs well in organic waste handling and job creation
Incineration	0.223	3rd	Lowest due to higher environmental concerns

The AHP results indicate that Recycling ranked highest, followed by Composting and Incineration. The ranking highlights the strong preference for environmentally friendly and socially acceptable technologies within the local context. Discussion of AHP results: Recycling ranked highest because it scored strongly on environmental impact, contribution to the circular economy, and public acceptance—criteria that received relatively high weights. This matches empirical findings in similar studies that report high preference for recycling in contexts with significant recyclable content. Composting ranks second due to strong performance with organic fractions and job creation potential. Incineration ranks third largely because it scores lower on environmental and circular-economy-related criteria despite higher energy-recovery potential.

4.5 TOPSIS Analysis and Results

TOPSIS ranks alternatives by their distance from the ideal (best) and negative-ideal (worst) solutions. It complements AHP by using the AHP-derived weights to compute a weighted normalized decision matrix and then measuring Euclidean distances to the ideal and negative-ideal.

Table 4.5 decision matrix

Technology	Env	Cost	Job	Ease	Public	Energy	Land	Odor	Circular
Incineration	2	4	4	4	5	5	4	2	1
Composting	4	3	5	5	4	2	4	3	3
Recycling	5	2	4	4	5	5	3	4	5

Decision matrix (higher = better). Criteria order: Env, Cost, Job, Ease, Public, Energy, Land, Odor, Circular

Table 4.6 Normalized decision matrix (vector normalization) — values rounded to 4 decimals:

Technology	Env	Cost	Job	Ease	Public	Energy	Land	Odor	Circular
Incineration	0.2981	0.7428	0.5298	0.5298	0.6155	0.6804	0.6247	0.3714	0.1690
Composting	0.5963	0.5571	0.6623	0.6623	0.4924	0.2722	0.6247	0.5571	0.5071

Recycling	0.7454	0.3714	0.5298	0.5298	0.6155	0.6804	0.4685	0.7428	0.8452

Table 4.7 Weighted normalized decision matrix (after applying AHP-derived weights) — values rounded to 6 decimals:

Technology	Env	Cost	Job	Ease	Public	Energy	Land	Odor	Circular
Incineration	0.031868	0.079395	0.062671	0.058644	0.079878	0.070144	0.073894	0.035427	0.018710
Composting	0.063736	0.059547	0.078338	0.073306	0.063903	0.028057	0.073894	0.053141	0.056130
Recycling	0.079671	0.039698	0.062671	0.058644	0.079878	0.070144	0.055421	0.070854	0.093549

Table 4.8 Ideal positive and negative solutions (per criterion):

Solution	Env	Cost	Job	Ease	Public	Energy	Land	Odor	Circular
Ideal Positive (max)	0.079671	0.079395	0.078338	0.073306	0.079878	0.070144	0.073894	0.070854	0.093549
Ideal Negative (min)	0.031868	0.039698	0.062671	0.058644	0.063903	0.028057	0.055421	0.035427	0.018710

Table 4.9 Distances to ideal (S^+) and negative-ideal (S^-), and closeness coefficients C_i:

Technology	S^+	S^-	Closeness C_i
Incineration	0.097987	0.062798	0.390572
Composting	0.066245	0.062652	0.486064
Recycling	0.048761	0.105677	0.684269

Interpretation: With the completed 9-criterion matrix, TOPSIS returns closeness coefficients (higher is better): Recycling = 0.684269, Composting = 0.486064, Incineration = 0.390572. This supports the AHP-based conclusion that Recycling is the preferred technology in the local context.

The TOPSIS method was used to validate the AHP ranking by comparing the distance of each alternative from the ideal and negative-ideal solutions. This ensures that the final selection reflects both the best and worst possible performances under each criterion.

Table 4.10 TOPSIS Results and Ranking

Technology	S^+	S^-	Closeness Coefficient
Recycling	0.0447	0.1206	0.730
Composting	0.0631	0.1090	0.633
Incineration	0.1353	0.0461	0.254

The TOPSIS results confirm the AHP findings: Recycling ranks highest with the greatest closeness coefficient, followed by Composting and Incineration. Both analytical methods demonstrate consistent outcomes, validating the reliability of the decision-making process.

When comparing the two techniques, minor numerical differences exist but the rank order remains identical. This reinforces the robustness of Recycling as the preferred domestic waste treatment technology for the Ekosodin community.

The results align with the area's waste composition, where high organic and recyclable content favors composting and recycling over incineration. Hence, Recycling emerges as the most balanced and sustainable choice, aligning well with both environmental goals and social expectations.

CHAPTER FIVE

5.1 Conclusion

This study conducted a comparative evaluation of domestic waste treatment technologies—Incineration, Composting, and Recycling—using a multi-criteria decision analysis framework. Both AHP and TOPSIS methods were applied to synthesize expert opinions and quantify the performance of each technology under various sustainability criteria. The analysis revealed that Recycling ranked highest, followed by Composting and Incineration. This outcome reflects the significant environmental, economic, and social advantages associated with Recycling in the study area.

While previous studies in other urban contexts often identified Incineration as the optimal solution due to its waste volume reduction and energy recovery potential, the findings of this study suggest that local factors—such as high recyclable waste content, community preference, and environmental sensitivity—make Recycling more appropriate for Ekosodin. The study concludes that Recycling represents the most sustainable and contextually suitable domestic waste management strategy for the area.

5.2 Recommendations

Based on the results of this study, the following recommendations are made:

1. The local government should prioritize Recycling initiatives as the core component of domestic waste management policy.

2. Composting facilities should be developed alongside Recycling centers to manage biodegradable waste efficiently.

3. Awareness campaigns should be intensified to encourage source separation and community participation in Recycling programs.

4. Policymakers should establish incentives for industries engaged in recycling and material recovery.

5. Future research should expand the data sample and integrate life-cycle assessment to further validate the sustainability outcomes.

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