FUDMA Journal of Engineering and Technology
ISSN: 3092-9385
https://fjet.fudutsinma.edu.ng/index.php/fjet/
Volume 2, Issue 1, 2026, 108-123

Multi-Criteria Decision Analysis and Optimization Approaches in Sustainable Waste-to-Energy Planning: A Systematic Review

Sirajo ALHASSAN[1*], Abdullahi A. ADAMU[2], Mohammed T. JIMOH[3]

[1*,2,3]Department of Mechanical Engineering, Bayero University, Kano, Nigeria

[1*]fatysira@gmail.com, [2]aaadamu.mec@buk.edu.ng, [3]mtjimoh.mec@buk.edu.ng

Abstract

Waste-to-Energy (WtE) systems are increasingly recognized as a strategic solution for sustainable municipal solid waste management, particularly in rapidly urbanizing regions confronted with landfill scarcity, environmental pressures, and rising energy demand. However, the selection and design of appropriate WtE systems require simultaneous consideration of economic viability, environmental performance, technical feasibility, and socio-institutional acceptance. This study presents a systematic review and critical synthesis of methodological approaches applied in WtE planning, with particular emphasis on Multi-Criteria Decision Analysis (MCDA), mathematical optimization models, multi-objective programming, metaheuristic algorithms, and hybrid MCDA–optimization frameworks. The review examines the evolution, applications, strengths, and limitations of these approaches in supporting technology selection, facility siting, system configuration, and resource allocation decisions. Findings indicate that MCDA techniques are effective in incorporating stakeholder preferences and qualitative sustainability criteria, but lack detailed engineering-level system design capability. In contrast, optimization models provide rigorous quantitative frameworks for operational feasibility and infrastructure configuration, yet often underrepresent social, institutional, and governance constraints. Hybrid frameworks emerge as the most comprehensive methodological direction, integrating preference-based evaluation with constraint-based system modeling to enhance both strategic alignment and technical robustness. The study identifies critical research gaps, including insufficient treatment of uncertainty, limited empirical validation, and inadequate contextual adaptation to developing urban environments characterized by data constraints and institutional fragmentation. By synthesizing methodological trends and challenges, this review advances structured, context-sensitive decision-support systems for sustainable and implementable WtE planning.

Keywords: *Waste-to-Energy (WtE) Systems, Municipal Solid Waste Management, Multi-Criteria Decision Analysis (MCDA), Multi-Objective Optimization, Sustainable Infrastructure Planning, Decision-Support Systems, Developing Urban Systems.*

1. Introduction

Municipal solid waste (MSW) generation has increased significantly over the past decades due to rapid urbanization, industrialization, and population growth (UNEP *Global Waste Management Outlook 2024*). According to recent global assessments, total MSW generation is projected to grow from about 2.1–2.3 billion tonnes in 2023 to nearly 3.8 billion tonnes by 2050 under business-as-usual scenarios, with associated environmental and economic costs rising substantially if current consumption patterns continue [1]. In many developing and emerging urban systems, inadequate waste collection, open dumping, and uncontrolled landfilling remain dominant practices. These practices contribute to environmental degradation, greenhouse gas emissions, and public health risks, particularly in regions with limited controlled waste treatment infrastructure [2].

Addressing these challenges requires not only improved waste management infrastructure but also integrated engineering solutions that convert waste streams into valuable energy resources, as Waste-to-Energy (WtE) conversion is increasingly recognized as a critical component of sustainable municipal solid waste management and circular economy strategies [3].

Waste-to-Energy (WtE) systems have emerged as viable engineering alternatives to conventional disposal methods, particularly in regions facing landfill scarcity and increasing energy demand [4]. Technologies such as incineration, gasification, pyrolysis, and anaerobic digestion offer pathways for energy recovery while reducing landfill dependence and methane emissions [4-5]. Studies highlight that WtE technologies can contribute to circular economy transitions, enhance resource efficiency, and support low-carbon development strategies [7-8].

However, the selection and deployment of WtE technologies are not purely technical decisions. They involve multi-dimensional trade-offs across environmental, economic, social, and operational criteria, necessitating structured decision-support approaches to guide technology selection and system planning [9].

Received: 28/02/2026; Revised: 10/03/2026; Accepted: 03/12/2026; Published: 23/03/2026

In Nigeria, municipal solid waste generation has increased significantly over the past two decades due to rapid urbanization, population growth, and changing consumption patterns [4]; [10]. Recent studies report rising municipal waste volumes in major Nigerian cities, accompanied by low collection efficiency and continued reliance on open dumping and uncontrolled landfilling [11-12].

Major urban centers such as Lagos, Kano, Ibadan, and Port Harcourt face increasing pressure on landfill infrastructure, with limited source segregation and inadequate treatment capacity [13]. Weak institutional coordination, financial constraints, and limited technical infrastructure continue to constrain effective planning for waste management systems in many Nigerian municipalities [11; 14].

Despite growing interest in Waste-to-Energy technologies as a sustainable waste management alternative, structured engineering decision-support frameworks remain relatively underdeveloped in the Nigerian context [6; 15]. These frameworks are particularly needed for technology selection, system configuration, and capacity planning. Recent assessments indicate substantial energy recovery potential from Nigerian municipal solid waste streams, largely due to their high organic fraction and favorable calorific values [16-17].

However, existing Nigerian studies predominantly focus on technical feasibility or economic assessments without comprehensive integration of systematic multi-criteria evaluation and optimization modeling [18]. Consequently, WtE planning in many developing urban systems remains constrained by limited quantitative decision-support tools and fragmented implementation strategies.

From an engineering systems perspective, Waste-to-Energy planning constitutes a complex multi-criteria decision problem that requires the simultaneous consideration of technical, economic, environmental, and institutional factors [19]. Technology alternatives vary substantially in thermal efficiency, investment requirements, operational complexity, emissions performance, feedstock compatibility, land requirements, and scalability potential [5].

Furthermore, uncertainties in waste composition variability, fluctuating energy markets, evolving policy frameworks, and financing mechanisms introduce additional layers of complexity into technology evaluation and infrastructure configuration [16-17]. Consequently, traditional single-criterion assessments, such as isolated energy potential estimation or cost minimization, are insufficient to support robust and sustainable WtE infrastructure planning. These necessitate structured multi-criteria and optimization-based decision-support approaches [15].

To address such complexity, Multi-Criteria Decision Analysis (MCDA) methods have been widely adopted in infrastructure, energy, and environmental systems planning to support structured evaluation under multiple conflicting criteria [15]. Techniques such as the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and PROMETHEE enable systematic comparison of technology alternatives across environmental, economic, technical, and social dimensions [20-21].

Recent studies demonstrate the growing application of MCDA frameworks in energy technology assessment and sustainable waste management decision-making [22]. While MCDA provides transparent ranking and prioritization capabilities, it does not inherently account for system-wide resource constraints, facility capacity limits, or explicit optimization objectives, thereby limiting its standalone applicability for detailed engineering system design [15].

Parallel to the advancement of MCDA approaches, optimization techniques, including linear programming (LP), mixed-integer linear programming (MILP), multi-objective optimization, and metaheuristic algorithms, have been widely applied to energy system design and municipal solid waste management logistics [23-24].

Optimization models enable engineers to determine optimal facility capacities, cost-efficient system configurations, emission-constrained operational scenarios, and Pareto trade-off frontiers across competing objectives [25]. Recent studies emphasize the expanding role of computational optimization in enhancing sustainability performance and long-term infrastructure resilience [26].

More recently, research has shifted toward hybrid MCDA–optimization frameworks, in which MCDA techniques are used to structure and weight evaluation criteria. In contrast, optimization algorithms identify feasible and efficient system configurations subject to technical and economic constraints [27]. Such integration reflects core systems engineering principles by coupling stakeholder-preference modeling with quantitative resource allocation and system-performance optimization [28].

Despite these developments, the literature remains methodologically fragmented, with many reviews focusing either on decision-ranking methods or on mathematical optimization models, without providing a unified synthesis specific to Waste-to-Energy system planning [29-30].

Furthermore, limited research critically examines how these integrated decision-support tools can be adapted to emerging urban systems characterized by constrained data availability, institutional fragmentation, and financial uncertainty. Models developed for highly industrialized contexts may not directly translate to cities in Sub-Saharan Africa and other developing regions, where reliable waste composition data, emissions monitoring infrastructure, and stable economic inputs are often limited [31].

Given these challenges, there is a need for a systematic review that consolidates MCDA methods, optimization approaches, and hybrid frameworks applied in Waste-to-Energy planning. This study, therefore, provides a

Received: 28/02/2026; Revised: 10/03/2026; Accepted: 03/12/2026; Published: 23/03/2026

structured review of MCDA, optimization techniques, and integrated MCDA–optimization frameworks used in WtE decision-making, with particular emphasis on their applicability to developing urban systems and their role in supporting robust engineering decision-making.

The findings of this review provide insights into existing methodological trends, identify research gaps, and highlight opportunities for developing more robust decision-support frameworks for sustainable Waste-to-Energy planning in emerging urban systems.

2. Review Methodology

2.1 Review Design and Scope

This study adopts a structured review approach to synthesize existing research on Multi-Criteria Decision Analysis (MCDA), mathematical optimization techniques, and hybrid MCDA–optimization frameworks applied in Waste-to-Energy (WtE) planning. The focus is placed on engineering decision-support applications rather than purely technological performance assessments or policy discussions.

The review considers studies that explicitly apply MCDA for WtE technology evaluation, optimization models for system design and capacity planning, or integrated frameworks combining both approaches. Studies addressing general renewable energy systems without specific relevance to WtE planning were excluded unless methodological insights were directly transferable.

2.2 Literature Search Strategy

Relevant peer-reviewed literature published between 2015 and 2025 was identified using major academic databases, including Scopus, Web of Science, and Google Scholar. Search terms combined keywords such as "Waste-to-Energy," "Municipal Solid Waste," "Multi-Criteria Decision Analysis," "Optimization," "Linear Programming," "Multi-objective Optimization," and "Hybrid decision-support," using Boolean operators to refine relevance. The time range was selected to capture both early methodological developments and recent advancements in integrated decision-support systems.

2.3 Inclusion and Screening Process

Articles were screened based on relevance, methodological clarity, and engineering applicability. Only peer-reviewed journal articles published in English were considered. Studies were required to explicitly implement MCDA, optimization, or hybrid frameworks within a WtE planning context. Purely technical performance assessments, policy commentaries without methodological modeling, conference abstracts lacking full exposition, and duplicate publications were excluded.

Selected articles were further categorized into stand-alone MCDA applications, stand-alone optimization models, and integrated MCDA–optimization frameworks to enable comparative evaluation.

2.4 Data Extraction and Analytical Framework

For each selected study, key information was extracted, including publication year, geographic context, WtE technology evaluated, methodological approach, criteria categories considered, and principal findings. Additional variables such as the type of MCDA method or optimization technique applied, study objectives, data sources, and key methodological contributions were also recorded to support a more comprehensive comparative analysis. The analytical framework classifies the literature into three methodological streams: MCDA-based evaluation models, optimization-based system design models, and hybrid MCDA–optimization frameworks. This structure enables systematic comparison of methodological strengths, limitations, and developmental trends in WtE decision-support research.

2.5 Limitations of the Review

The review is limited to peer-reviewed English-language publications and may not capture grey literature or regionally unpublished studies. Methodological heterogeneity across studies restricts direct quantitative comparison; therefore, synthesis is primarily qualitative and analytical.

3. MCDA Methods, Optimization, and Hybrid Approaches in Waste-to-Energy Planning

Waste-to-Energy (WtE) planning involves complex decision-making due to the interaction of technical, economic, environmental, and social factors. Selecting appropriate technologies, determining system capacity, and ensuring regulatory compliance require structured analytical tools capable of handling multiple and often conflicting criteria. Over the past two decades, researchers have increasingly relied on two principal methodological approaches to address these challenges: Multi-Criteria Decision Analysis (MCDA) and mathematical optimization models, both widely applied in sustainable infrastructure and energy system planning literature [32].

MCDA techniques are primarily used to evaluate and rank alternative WtE technologies based on weighted criteria reflecting stakeholder priorities. In contrast, optimization models are designed to determine optimal system configurations under defined operational constraints, such as cost minimization, emission limits, or capacity requirements. More recently, hybrid frameworks integrating both approaches have emerged, combining preference-based evaluation with quantitative system design.

For clarity and systematic analysis, the reviewed literature is classified into three methodological streams: stand-alone MCDA applications, stand-alone optimization models, and integrated MCDA–optimization frameworks. This classification facilitates comparative evaluation of their respective strengths, limitations, and applicability in engineering decision-support for sustainable WtE planning.

3.1 Multi-Criteria Decision Analysis (MCDA) Methods

Multi-Criteria Decision Analysis (MCDA) methods are widely applied in Waste-to-Energy (WtE) planning to evaluate and rank alternative technologies based on multiple performance criteria [33-34]. These criteria typically include environmental impacts, capital and operational costs, energy recovery efficiency, technical feasibility, and social acceptance, reflecting the multidimensional nature of sustainable infrastructure assessment [35-36].

MCDA provides a structured framework for integrating both quantitative performance indicators and qualitative stakeholder judgments, making it particularly suitable for infrastructure planning problems characterized by competing objectives and diverse stakeholder interests [32].

In WtE applications, MCDA methods are primarily employed for technology selection, policy evaluation, and comparative assessment of treatment pathways such as incineration, gasification, anaerobic digestion, and pyrolysis [7]. By assigning weights to evaluation criteria and aggregating alternative performance scores, MCDA enhances transparency in decision-making and facilitates stakeholder engagement.

However, although these methods are effective for ranking alternatives, they do not inherently determine optimal system capacity, infrastructure configuration, or resource allocation under explicit operational constraints [37].

The following subsections examine major MCDA techniques applied in WtE planning, including the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and outranking methods such as ELECTRE and PROMETHEE.

3.1.1 Analytic Hierarchy Process (AHP) Applications in Waste-to-Energy Planning

The Analytic Hierarchy Process (AHP), originally developed by Saaty, remains one of the most widely applied MCDA techniques in Waste-to-Energy (WtE) planning due to its structured weighting mechanism and transparency in stakeholder-driven decision processes. AHP decomposes complex decision problems into hierarchical levels consisting of an overall goal, evaluation criteria, sub-criteria, and competing technological alternatives. Through systematic pairwise comparisons, relative importance weights are assigned to criteria, enabling comparative assessment of alternative WtE technologies.

Empirical applications demonstrate the practical relevance of AHP in diverse geographic contexts. In Ghana, [38] applied an integrated fuzzy AHP–TOPSIS framework to evaluate WtE technologies based on socio-environmental, technical, and economic performance indicators, highlighting the influence of stakeholder-derived weights on technology prioritization. In Togo, [39] combined fuzzy AHP with location–allocation modeling to support siting decisions for WtE facilities in developing urban environments characterized by limited data availability and infrastructural constraints. Their findings illustrate the adaptability of AHP-based methods to spatial planning problems in emerging cities.

In Nigeria, [6] employed AHP within a life-cycle assessment framework to compare electricity generation options from municipal solid waste, emphasizing environmental performance and economic feasibility as dominant criteria.

These case studies indicate that AHP is particularly valuable in contexts where quantitative datasets are incomplete, but expert knowledge and stakeholder preferences play a central role in decision-making. From an engineering decision-support perspective, AHP is especially effective during preliminary technology screening, policy evaluation, and sustainability assessment phases.

However, AHP results remain sensitive to subjective weight assignments, and consistency ratios must be validated to ensure reliability. Furthermore, AHP does not inherently optimize system capacity or infrastructure configuration under operational constraints, limiting its applicability for detailed engineering system design.

3.1.2 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) Applications in Waste-to-Energy Planning

In WtE applications, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) has been used to compare alternative technologies such as incineration, anaerobic digestion, gasification, and landfill gas recovery across multiple criteria, including cost, emissions, energy efficiency, and environmental impact. For instance, an entropy-weighted TOPSIS approach was applied to the municipal waste stream of Lagos, Nigeria, to identify the most suitable WtE technology for distributed electricity generation, revealing anaerobic digestion and combined hybrid options as preferred under sustainability criteria [40].

In South Africa, a weighted TOPSIS model incorporating IDOCRIW was used in the City of Johannesburg to rank WtE alternatives for distributed generation, showing relative performance differences among anaerobic digestion, pyrolysis, gasification, and landfill gas recovery [41].

The computational simplicity and ability to handle normalized quantitative datasets make TOPSIS particularly suitable for engineering evaluations where performance indicators are measurable. Compared to methods that rely on subjective pairwise comparisons, such as AHP, TOPSIS streamlines the ranking process and can be readily integrated with objective weighting schemes like entropy, IDOCRIW, or other hybrid techniques.

However, similar to other MCDA methods, TOPSIS provides ordinal rankings and does not determine optimal plant sizing or system configuration under operational constraints, highlighting the need to combine ranking methods with optimization frameworks for comprehensive infrastructure planning.

3.1.3 Fuzzy MCDA under Uncertainty in Waste-to-Energy Planning

Uncertainty remains a major challenge in Waste-to-Energy (WtE) planning, particularly in developing urban systems where waste composition data, financial projections, emission factors, and future energy demand are often incomplete or highly variable. Conventional MCDA methods rely on crisp numerical inputs and fixed criteria weights, which may not adequately capture ambiguity in expert judgments or inconsistencies in available datasets. To address this limitation, fuzzy-based MCDA approaches have been increasingly adopted in waste management and WtE decision-support frameworks [38; 39].

Fuzzy MCDA integrates fuzzy set theory to represent uncertainty using linguistic variables and membership functions. Instead of assigning precise numerical weights, decision-makers express preferences using qualitative terms such as “very high,” “moderate,” or “low,” which are converted into triangular or trapezoidal fuzzy numbers for computation. This enables more flexible representation of expert opinion and better reflects real-world planning environments characterized by epistemic uncertainty.

Empirical applications highlight the growing relevance of fuzzy extensions of MCDA methods. In Ghana, [38] employed a fuzzy AHP–TOPSIS framework to evaluate alternative WtE technologies under socio-environmental and economic uncertainty, demonstrating improved robustness compared to conventional crisp weighting approaches.

Similarly, [39] applied a fuzzy AHP-based GIS framework to support WtE facility siting in a developing urban context, addressing uncertainties in waste generation and infrastructural constraints. Beyond WtE, fuzzy TOPSIS has also been applied in broader waste management systems, including biomedical waste evaluation, to incorporate sustainability indicators and uncertain performance metrics, thereby strengthening multi-criteria decision robustness in complex environmental systems [42].

Empirical applications further illustrate the flexibility of fuzzy MCDA. In Iran, [43] utilized a spherical fuzzy decision-making model to rank energy production alternatives from municipal solid waste, incorporating group preference uncertainty and demonstrating improved discrimination among competing technologies under ambiguous data conditions.

From an engineering decision-support perspective, fuzzy MCDA enhances robustness during early-stage planning and policy evaluation, particularly where quantitative datasets are incomplete or inconsistent. However, the approach introduces additional computational complexity and requires careful definition of membership functions and defuzzification techniques to avoid embedding additional subjectivity into the model. Furthermore, while fuzzy MCDA improves uncertainty representation, it still produces ranked alternatives rather than optimized system configurations, thereby necessitating integration with mathematical optimization models for comprehensive infrastructure design.

The application of fuzzy MCDA is especially relevant in developing countries, where data scarcity, informal waste streams, and institutional variability introduce significant uncertainty into infrastructure planning decisions.

3.1.4 PROMETHEE Application in Waste-to-Energy Planning

Outranking methods represent a non-compensatory class of Multi-Criteria Decision Analysis (MCDA) techniques increasingly applied in Waste-to-Energy (WtE) planning. Unlike fully compensatory approaches such as AHP or TOPSIS, outranking methods compare alternatives pairwise and determine whether one option sufficiently dominates another across multiple criteria. This structure reduces excessive trade-offs and prevents strong performance in one criterion (e.g., economic benefit) from fully offsetting poor performance in another (e.g., environmental impact).

Among outranking techniques, the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) has gained prominence in WtE decision problems. [44] Applied the PROMETHEE method to select suitable WtE technologies for slum and informal settlements in the Greater Karu Urban Area, Nigeria. Their

Received: 28/02/2026; Revised: 10/03/2026; Accepted: 03/12/2026; Published: 23/03/2026

model integrated environmental, technical, economic, and social criteria to reflect the complex realities of developing urban systems. The study demonstrated how PROMETHEE can effectively balance sustainability indicators while limiting excessive compensation among conflicting objectives.

Recent methodological developments have further extended outranking applications in WtE planning. [45] Proposed a heterogeneous fuzzy regret-PROMETHEE framework for WtE incineration site selection, explicitly incorporating life-cycle carbon emissions into the decision model. By combining fuzzy theory with regret-based preference structures, the study enhanced discrimination among alternatives under uncertainty and provided a robust framework for environmentally constrained infrastructure planning.

From an engineering decision-support perspective, outranking methods are particularly valuable when regulatory thresholds, emission limits, or public health constraints must be treated as non-negotiable conditions rather than compensable trade-offs. However, careful calibration of preference functions and thresholds is required to avoid subjectivity and ensure model transparency.

3.1.5 ELECTRE Applications in Waste-to-Energy and Environmental Planning

The ELECTRE (Elimination and Choice Expressing Reality) family of outranking methods has been applied in Waste-to-Energy (WtE) and related environmental infrastructure planning, where decision problems involve conflicting criteria and partial comparability among alternatives.

A recent application relevant to thermochemical waste treatment selection was presented by [46]. The authors employed an entropy-based weighting scheme combined with fuzzy VIKOR and ELECTRE III to evaluate thermochemical conversion technologies for municipal solid waste in the Azerbaijan region of Iran. The study compared incineration, gasification, and pyrolysis across environmental, technical, and economic criteria under uncertainty. ELECTRE III was used to establish outranking relations among alternatives while incorporating preference thresholds, demonstrating its suitability for handling imprecise data and regional sustainability priorities in WtE technology evaluation.

Beyond technology selection, ELECTRE III has also been applied to environmental infrastructure siting. For example, [47] integrated multi-criteria evaluation with ELECTRE III to identify suitable sites for artificial groundwater recharge using treated wastewater. Although not directly focused on WtE, the methodological framework is highly relevant to facility siting problems in waste management systems, as it incorporates environmental sensitivity, hydrogeological constraints, and land-use considerations within an outranking structure. The study illustrates ELECTRE's strength in spatial decision contexts where threshold-based preference modeling improves discrimination among competing sites.

Collectively, these studies demonstrate that ELECTRE methods are particularly advantageous when: Decision-makers must handle conflicting sustainability criteria, Data uncertainty necessitates threshold-based preference modeling, Full compensation among criteria is undesirable, Infrastructure siting or technology comparison requires structured outranking rather than simple scoring.

However, similar to other MCDA approaches, ELECTRE produces preference rankings rather than optimized system configurations, reinforcing the need for integration with mathematical optimization models in comprehensive WtE planning frameworks.

The major MCDA approaches applied in Waste-to-Energy planning, including their strengths, limitations, and typical applications, are summarized in Table 1.

Table 1. MCDA Methods Applied in Waste-to-Energy Planning

Method	**Primary Purpose in WtE**	**Strengths**	**Limitations**	**Representative Study Focus**
AHP	Technology selection; criteria weighting	Structured pairwise comparison; handles qualitative criteria	Subjectivity; consistency, sensitivity	Comparative evaluation of incineration, gasification, and anaerobic digestion in urban systems
TOPSIS	Ranking of WtE alternatives	Simple distance-based ranking; computational efficiency	Sensitive to normalization and weighting	Selection of optimal WtE technology based on cost–emission–energy trade-offs
Fuzzy MCDA	Decision-making under uncertainty	Handles vague expert judgments; suitable for incomplete data	Increased complexity; interpretational difficulty	WtE technology assessment under uncertain waste composition data

Method	Primary Purpose in WtE	Strengths	Limitations	Representative Study Focus
ELECTRE / PROMETHEE	Outranking in conflicting criteria contexts	Suitable for non-compensatory decision problems	Threshold parameter sensitivity	Policy-driven WtE option screening considering social acceptance

3.1.6 Critical Evaluation of MCDA in Waste-to-Energy Planning

While Multi-Criteria Decision Analysis (MCDA) methods provide structured, transparent, and participatory mechanisms for evaluating Waste-to-Energy (WtE) technologies, they exhibit important methodological limitations when applied to full-scale system planning and engineering design.

Most conventional MCDA techniques, including AHP, TOPSIS, and PROMETHEE, generate ordinal or relative rankings of predefined alternatives based on weighted criteria. Although such rankings are valuable for comparative assessment, they do not determine optimal system configurations. In particular, traditional MCDA frameworks do not explicitly model decision variables such as plant processing capacity, waste allocation rates, energy recovery efficiency, transportation logistics, or infrastructure network design under technical and regulatory constraints.

In practical WtE planning, decision-makers must address questions that extend beyond technology selection. These include determining optimal facility size under projected waste generation scenarios, minimizing lifecycle cost while satisfying emission limits, maximizing energy output subject to material balance constraints, and allocating heterogeneous waste streams across multiple treatment pathways. Such problems are inherently mathematical and require constraint-based optimization rather than preference-based ranking.

Another limitation concerns model sensitivity and subjectivity. MCDA outcomes are often highly dependent on weight assignments, preference thresholds, and expert judgments. While sensitivity analysis can partially mitigate this issue, ranking reversals may still occur when criteria weights or performance scores are modified. Fuzzy extensions enhance the representation of uncertainty and linguistic judgments; however, they do not fundamentally convert MCDA into a prescriptive optimization tool capable of generating globally optimal solutions.

Consequently, MCDA is most effective at the preliminary stages of WtE planning, such as technology screening, stakeholder engagement, and multi-dimensional sustainability assessment. For detailed engineering design and performance maximization, however, MCDA must be complemented by mathematical optimization techniques, including linear programming, mixed-integer programming, or evolutionary algorithms.

This methodological gap has motivated the growing integration of MCDA with optimization models in recent WtE planning research, where MCDA is employed to structure criteria and stakeholder preferences, and optimization models are used to determine capacity sizing, operational allocation, and system performance under explicit constraints. Such hybrid approaches aim to combine the transparency of MCDA with the prescriptive power of optimization, thereby enhancing the robustness of sustainable WtE decision-support frameworks.

3.2 Optimization Techniques in Waste-to-Energy Systems

Unlike Multi-Criteria Decision Analysis (MCDA), which primarily ranks alternatives based on weighted criteria, optimization approaches focus on determining the best system configuration under defined technical, economic, and environmental constraints. In Waste-to-Energy (WtE) planning, optimization models are used to support decisions related to plant capacity sizing, facility location, waste allocation, transportation logistics, cost minimization, and emission control.

Optimization methods rely on mathematical formulations that define objective functions and constraint sets representing real-world operational limits. These may include material balance equations, energy recovery targets, regulatory emission thresholds, and budget constraints. By solving these models, planners can identify configurations that achieve optimal performance rather than simply ranking predefined alternatives.

In recent years, various optimization techniques have been applied to WtE systems, including linear programming, multi-objective optimization, and metaheuristic algorithms. These approaches enable quantitative evaluation of system performance and are particularly relevant when detailed engineering design and operational feasibility are required.

3.2.1 Linear and Mixed-Integer Programming (LP/MILP) Applications

Linear Programming (LP) and Mixed-Integer Linear Programming (MILP) are among the most widely applied optimization techniques in Waste-to-Energy (WtE) system design. These methods formulate planning problems as mathematical models composed of objective functions and linear constraint equations. While LP assumes continuous decision variables, MILP incorporates both continuous and discrete (integer or binary) variables, enabling the representation of infrastructure-related decisions such as facility construction, technology selection, and routing configuration.

In contemporary WtE research, MILP has been extensively applied to integrated network design and operational planning under uncertainty. For example, [48] developed an optimization framework for determining the optimal location and operation of waste-to-energy plants under uncertain future waste composition. Their model incorporated binary variables for facility siting and continuous variables for waste allocation and plant operation. By embedding uncertainty scenarios into a mixed-integer structure, the study demonstrated how MILP can support robust long-term infrastructure decisions in dynamic waste management systems.

Similarly, [49] applied multi-period mixed-integer programming to municipal solid waste management planning in Qingdao, China. Their formulation optimized facility capacity expansion, waste allocation, and technology deployment over multiple planning horizons while satisfying material balance and operational constraints. The study illustrates the suitability of MILP for phased infrastructure development and capacity scaling in urban WtE systems.

More recently, [50] proposed a sustainable municipal solid waste network design model incorporating waste-to-energy conversion under uncertainty. Their mixed-integer optimization model simultaneously minimized total system cost and environmental impact while considering transportation logistics, facility selection, and energy recovery targets. The integration of sustainability objectives within a mathematical programming framework highlights the evolution of MILP toward multi-dimensional system optimization.

From an engineering perspective, MILP is particularly valuable because WtE planning inherently involves discrete infrastructure decisions, such as whether to construct a facility, expand capacity, or adopt a specific thermochemical technology, alongside continuous flow variables. These models provide quantitatively optimal and operationally feasible solutions under explicitly defined technical, environmental, and budgetary constraints.

However, LP and MILP models require high-quality input data and may become computationally intensive when applied to large-scale regional systems with multiple facilities, time periods, and uncertainty scenarios. Additionally, although these models optimize measurable objectives, they do not inherently incorporate stakeholder preference structures unless integrated with MCDA techniques. This limitation has motivated increasing research into hybrid MCDA–optimization frameworks for comprehensive WtE planning.

3.2.2 Multi-Objective Optimization (MOO) in Waste-to-Energy Systems

Waste-to-Energy (WtE) systems inherently involve multiple and often conflicting objectives, including minimizing lifecycle cost, reducing environmental emissions, maximizing energy recovery, and improving system resilience. Multi-Objective Optimization (MOO) addresses this complexity by simultaneously optimizing two or more objective functions under technical and operational constraints. Rather than generating a single optimal solution, MOO produces a Pareto frontier of non-dominated solutions, each reflecting different trade-offs among competing performance criteria.

A clear example of integrated multi-objective planning is presented by [51], who developed an optimization framework for municipal solid waste management structured as an integrated supply chain network. Their model simultaneously optimized economic and operational objectives across collection, transportation, treatment, and disposal stages. By embedding waste-to-energy options within the network, the study demonstrated how multi-objective mathematical programming can identify balanced infrastructure configurations that enhance both system efficiency and sustainability.

More recently, [52] developed a multi-objective optimization model for municipal solid waste treatment systems that explicitly incorporated cross-media pollutant metabolism issues. Their formulation simultaneously minimized economic cost and environmental impacts across air, water, and soil compartments while evaluating different treatment technologies, including waste-to-energy pathways. The resulting Pareto solutions enabled systematic assessment of trade-offs between cost efficiency and pollutant mitigation, reflecting a comprehensive life-cycle perspective.

In the context of facility siting and infrastructure planning, [53] proposed a multi-objective optimization model for waste-to-energy facility location within a sustainable municipal solid waste management framework. Their model balanced economic cost, environmental impact, and logistical performance indicators to determine optimal facility locations. By generating alternative non-dominated solutions, the approach provided planners with flexibility to select configurations aligned with regional sustainability targets.

From an engineering standpoint, MOO enhances WtE system design by explicitly quantifying trade-offs among economic, environmental, and logistical objectives. This is particularly critical in waste management planning, where minimizing cost may conflict with emission reduction targets or optimal spatial allocation. By revealing compromise solutions along the Pareto frontier, MOO supports evidence-based policy decisions and long-term infrastructure planning.

However, identifying a final solution from the Pareto set often requires additional decision-support tools, such as weighting approaches or integration with MCDA methods. Furthermore, computational demand increases significantly as the number of objectives, planning periods, and uncertainty parameters grows. These limitations have motivated hybrid frameworks that combine MOO with advanced decision-analysis techniques in contemporary WtE research.

3.2.3 Metaheuristic and Evolutionary Algorithms in Waste-to-Energy System Optimization

Metaheuristic and evolutionary algorithms have increasingly been applied to Waste-to-Energy (WtE) system optimization, particularly for complex, nonlinear, and large-scale decision problems that cannot be efficiently solved using traditional linear or mixed-integer programming approaches. These algorithms employ iterative search strategies to identify near-optimal solutions in highly dimensional and non-convex problem spaces.

A recent example is provided by [54], who developed a sustainable solid waste management model integrating the Analytical Hierarchy Process (AHP), Monte Carlo simulation, and the evolutionary multi-objective algorithm NSGA-III. The model simultaneously optimized economic, environmental, and social objectives under uncertainty. By applying NSGA-III, the study generated a diverse Pareto frontier that captured trade-offs among sustainability indicators, demonstrating the effectiveness of advanced evolutionary algorithms in handling multi-objective WtE-related planning problems.

In the context of financial and project risk optimization, [55] proposed a financing optimization framework for a waste-to-energy project developed under a Build–Operate–Transfer (BOT) scheme. Their approach integrated risk simulation techniques with optimization modeling to determine financially viable investment structures. This study illustrates how metaheuristic and simulation-based optimization frameworks can extend beyond technical system design to address investment risk and long-term project sustainability.

At the infrastructure integration level, [56] examined optimal planning of a waste-to-energy-based combined heat and power (CHP) plant connected to a power distribution network. The optimization framework evaluated operational configuration and system performance within network constraints. This work demonstrates the applicability of advanced optimization techniques in coupling WtE facilities with energy distribution systems, highlighting the growing integration of waste management and power system engineering.

From an engineering perspective, metaheuristic and evolutionary algorithms provide flexibility in modeling nonlinear cost functions, stochastic parameters, and complex system interactions. They are particularly valuable in sustainability-oriented, multi-objective, and uncertainty-driven planning environments. However, these methods do not guarantee global optimality and require careful parameter tuning and validation to ensure reproducibility and solution robustness.

The principal optimization techniques employed in Waste-to-Energy system design and infrastructure planning are summarized in Table 2.

Table 2. Optimization Approaches in WtE Planning

Method	Typical Application	Strengths	Limitations	Representative Study Focus
LP	Cost minimization in waste allocation	Computational efficiency; transparent constraints	Linear assumption limitation	Optimal waste flow allocation to existing WtE facilities
MILP	Facility siting and capacity planning	Handles binary location decisions; engineering precision	High computational demand	Regional WtE plant location and transportation network design
Multi-Objective Optimization	Trade-off analysis (cost vs emissions vs energy recovery)	Simultaneous objective balancing; Pareto frontier generation	Decision complexity in selecting the final solution	Sustainable WtE configuration balancing economic and environmental targets
Metaheuristic Algorithms (GA, PSO)	Large-scale nonlinear optimization	Handles nonlinearity and combinatorial complexity	No guarantee of global optimum; parameter tuning required	Integrated WtE system design under nonlinear cost and emission relationships

3.2.4 Critical Evaluation of Optimization Methods in Waste-to-Energy Planning

Optimization models provide a rigorous mathematical framework for designing Waste-to-Energy (WtE) systems under explicitly defined technical, economic, and environmental constraints. Unlike MCDA methods, which rank or prioritize alternatives, optimization approaches determine system configuration variables directly, including facility capacity, waste flow allocation, technology selection, transportation routing, and infrastructure expansion planning. This capability makes optimization particularly valuable for detailed engineering design, network structuring, and operational efficiency analysis.

From a systems engineering perspective, optimization ensures internal consistency through constraint-based modeling. Mass balance relationships, regulatory emission limits, energy conversion efficiencies, and budget constraints are embedded directly into the mathematical formulation. As a result, the derived solutions are technically feasible within the assumed model structure and provide quantitative guidance for infrastructure planning.

However, several limitations constrain the standalone application of optimization methods in WtE planning. First, most optimization formulations emphasize measurable quantitative objectives, typically cost minimization, emission reduction, or energy maximization, while qualitative and socio-institutional dimensions remain underrepresented. Factors such as public acceptance, governance capacity, land-use conflicts, and political feasibility are rarely incorporated explicitly within mathematical programming structures. Consequently, optimization may produce technically optimal yet socially infeasible solutions.

Second, optimization outputs are highly dependent on data quality and parameter specification. In developing urban systems, where waste generation data, composition variability, and emission factors may be uncertain or incomplete, model robustness can be compromised. Deterministic formulations, in particular, may oversimplify uncertainty, leading to solutions that perform sub-optimally under real-world variability. Although stochastic and robust optimization approaches address this limitation, they significantly increase computational complexity.

Third, scalability presents additional challenges. Large-scale regional WtE planning involving multi-period horizons, multiple facilities, and competing objectives results in high-dimensional decision spaces. In such cases, computational burden increases substantially, especially for mixed-integer or multi-objective formulations. This may limit practical applicability without advanced solution algorithms or simplification strategies.

Finally, optimization models inherently reflect the assumptions embedded in their objective functions. The selection and weighting of objectives determine system behavior. Without explicit stakeholder engagement or preference elicitation, these objective structures may not fully represent societal priorities.

Therefore, while optimization methods are indispensable for ensuring technical feasibility, economic efficiency, and operational rigor, they do not independently capture the full decision environment surrounding WtE implementation. This methodological gap has motivated the development of hybrid frameworks that integrate preference-based evaluation tools, such as MCDA, with constraint-based optimization models. Such integration enables simultaneous consideration of technical feasibility and stakeholder-driven sustainability criteria, offering a more comprehensive planning approach for complex urban waste systems.

3.3 Hybrid MCDA–Optimization Frameworks in Waste-to-Energy Planning

The methodological limitations identified in both MCDA and optimization approaches have stimulated the development of hybrid MCDA–optimization frameworks in Waste-to-Energy (WtE) planning. While MCDA methods are effective in incorporating stakeholder preferences, qualitative criteria, and policy priorities, they do not guarantee operational feasibility or system-level optimality. Conversely, optimization models ensure mathematically feasible and cost-efficient system configurations but often omit structured preference modeling and socio-institutional considerations. Hybrid frameworks attempt to bridge this conceptual and practical divide.

Two principal integration structures can be identified in the literature.

1. **Sequential Integration.**

In sequential hybrid frameworks, MCDA is applied at the strategic level to evaluate and rank alternative technologies, policy scenarios, or siting options using multi-dimensional sustainability criteria. The highest-ranked alternatives are subsequently subjected to detailed optimization modeling to determine plant capacity, waste flow allocation, logistics configuration, emission compliance, and cost-efficient infrastructure design. This structure ensures that optimization is conducted only within alternatives that are socially and strategically acceptable, thereby aligning operational feasibility with stakeholder-informed priorities.

2. **Embedded or Simultaneous Integration.**

In embedded hybrid models, MCDA-derived weights or preference structures are directly incorporated into multi-objective optimization formulations. Qualitative priorities are transformed into weighted objective functions or constraint modifiers, allowing the optimization process itself to reflect stakeholder preferences. This approach enhances transparency by making the influence of value judgments explicit within the mathematical formulation. From a systems engineering perspective, hybrid frameworks provide a more comprehensive decision architecture for WtE planning. Urban waste systems operate within intertwined technical, financial, environmental, and institutional domains. Particularly in developing-country contexts, decisions must simultaneously address infrastructure capacity, cost constraints, environmental compliance, governance limitations, and public acceptance. Hybrid approaches reduce the risk of implementing technically optimal yet socially impractical solutions by integrating strategic evaluation with operational modeling.

Nevertheless, hybrid frameworks introduce their own methodological challenges. In sequential approaches, inconsistencies may arise if the optimization stage contradicts earlier MCDA rankings due to differing assumptions or data structures. In embedded models, inappropriate translation of qualitative weights into quantitative objective functions may distort stakeholder intentions. Furthermore, hybrid models demand substantial data harmonization, stakeholder engagement processes, and computational resources. Without rigorous validation and sensitivity analysis, results may reflect modeling artifacts rather than genuine system performance.

Despite these challenges, hybrid MCDA optimization frameworks represent a significant methodological advancement in WtE planning. They offer a structured mechanism for integrating normative decision criteria with constraint-based system design, thereby aligning technical feasibility with sustainability objectives. As urban waste systems become more complex and policy-driven, such integrative approaches are increasingly essential for robust and implementable infrastructure planning.

Hybrid MCDA–optimization integration strategies and their methodological characteristics are synthesized in Table 3.

Table 3. Hybrid MCDA–Optimization Frameworks

Integration Strategy	**Description**	**Advantage**	**Limitation**	**Representative Study Focus**
Sequential MCDA - Optimization	MCDA ranks alternatives; optimization designs selected system	Ensures preference-informed feasibility	Potential mismatch between ranking and optimized configuration	Technology screening followed by regional capacity optimization
Embedded MCDA Weights	MCDA-derived weights integrated into multi-objective models	Direct preference–model linkage	Weight bias may propagate into optimization results	Multi-objective WtE planning incorporating stakeholder weights
Iterative Hybrid Framework	Feedback loop between ranking and modeling	Increased robustness and adaptability	Data-intensive and computationally demanding	Adaptive regional WtE planning under evolving waste generation

4. Synthesis of Methodological Trends and Research Gaps in Waste-to-Energy Planning

A synthesis of the reviewed literature reveals a clear methodological evolution in Waste-to-Energy (WtE) planning, reflecting the increasing complexity of urban waste systems and sustainability objectives.

Early WtE studies predominantly relied on single-criterion economic optimization or isolated environmental impact assessments. These approaches focused primarily on cost minimization or emission reduction, often treating waste management as a purely technical engineering problem. Social, institutional, and policy dimensions were either simplified or excluded.

The subsequent adoption of Multi-Criteria Decision Analysis (MCDA) marked a significant methodological expansion. MCDA enabled structured incorporation of environmental, economic, and technical indicators, and later extended to include social acceptance, land-use compatibility, and governance-related criteria. This shift represented recognition that WtE planning operates within multi-dimensional sustainability frameworks rather than purely engineering domains.

More recently, optimization techniques, particularly linear programming (LP), mixed-integer linear programming (MILP), and multi-objective optimization (MOO), have been increasingly integrated to enhance operational feasibility. These methods allow explicit modeling of plant capacities, waste flows, transportation logistics, and regulatory constraints. The emergence of hybrid MCDA–optimization frameworks represents the most comprehensive methodological advancement, combining stakeholder-informed preference structures with mathematically rigorous system design.

Despite these developments, several critical research gaps persist.

First, many studies apply advanced computational techniques without adequate adaptation to local data realities. In developing urban contexts, incomplete waste characterization, inconsistent financial datasets, informal collection systems, and limited emissions monitoring may undermine model reliability. Overly sophisticated models risk generating precise but contextually fragile results.

Second, social and institutional feasibility is frequently treated as static evaluation criteria rather than dynamic system constraints. Public opposition, regulatory fragmentation, and governance capacity directly influence infrastructure implementation. When these factors are incorporated only as weighted criteria instead of embedded constraints, model outputs may overestimate practical feasibility.

Third, empirical validation remains limited. Most frameworks are simulation-based, with few longitudinal assessments comparing modeled outcomes against post-implementation system performance. This restricts understanding of real-world robustness and policy effectiveness.

Fourth, uncertainty and sensitivity analyses are often insufficiently explored. Waste generation rates, calorific values, energy market prices, technology efficiency, and regulatory conditions are inherently dynamic. Deterministic formulations without robust uncertainty treatment may lead to suboptimal long-term planning outcomes.

Collectively, these gaps indicate that methodological advancement must move beyond increasing computational sophistication toward improving contextual realism, institutional integration, and model robustness.

For rapidly urbanizing regions, including Nigerian metropolitan areas, decision-support frameworks must balance analytical rigor with implementability. Models should be adaptable to evolving datasets and institutional capacity while retaining sufficient structure to guide sustainable infrastructure investment.

4.1 Implications for Developing Urban Waste Systems

The methodological trends identified in this review carry significant implications for developing urban waste management systems.

Rapid urbanization in many cities is characterized by increasing waste generation, infrastructure deficits, informal collection practices, and fragmented regulatory coordination. Under such conditions, WtE decision-support frameworks must satisfy three simultaneous requirements: technical robustness, institutional adaptability, and socio-political acceptability.

First, model design must explicitly account for data constraints. Highly granular optimization models may not perform reliably where waste composition studies are irregular or financial projections are uncertain. Progressive modeling strategies, beginning with transparent, simplified structures and incorporating refinement as data improves, may provide a more sustainable pathway for planning.

Second, stakeholder engagement should be integrated early in the decision process rather than treated as a post-design validation step. Structured preference modeling through MCDA can facilitate consensus-building and reduce implementation resistance. When embedded within hybrid frameworks, such engagement ensures that optimization outputs align with societal priorities.

Third, institutional feasibility must be embedded within evaluation structures. Coordination between municipal waste authorities, environmental regulators, energy utilities, and private investors determines project viability. Planning models that neglect governance capacity risk producing technically optimal but administratively infeasible solutions.

Fourth, scalability and financial resilience are critical in volatile urban systems. Population growth, migration patterns, informal sector participation, and fluctuating energy markets require flexible infrastructure design. Incorporating sensitivity analysis, scenario modeling, and adaptive capacity planning enhances long-term system robustness.

Overall, the synthesis suggests that integrated MCDA–optimization approaches offer the most balanced methodological pathway for developing urban WtE systems. However, their effectiveness depends on contextual calibration, inclusive stakeholder processes, and realistic data assumptions. The next generation of WtE planning frameworks must therefore prioritize robustness, institutional alignment, and adaptive capacity alongside computational sophistication.

The key methodological gaps identified in the reviewed literature and their implications for developing urban systems are presented in Table 4.

Table 4. Identified Research Gaps in WtE Decision-Support Literature

Gap Area	Observed Limitation	Impact on Developing Urban Systems	Research Priority
Data Reliability	Heavy reliance on precise datasets	Reduced applicability in data-scarce contexts	Context-adapted modeling
Social Acceptance Modeling	Limited dynamic stakeholder integration	Implementation resistance	Participatory MCDA integration
Institutional Feasibility	Governance constraints are rarely modeled	Regulatory bottlenecks	Institutional constraint embedding
Uncertainty & Sensitivity	Limited scenario exploration	Vulnerability to demand/policy volatility	Robust optimization & stochastic modeling
Empirical Validation	Few post-implementation assessments	Limited practical verification	Longitudinal case studies

Received: 28/02/2026; Revised: 10/03/2026; Accepted: 03/12/2026; Published: 23/03/2026

5. Conclusion and Future Research Directions

This review critically examined the methodological evolution of Multi-Criteria Decision Analysis (MCDA), optimization techniques, and hybrid MCDA–optimization frameworks in Waste-to-Energy (WtE) planning. The synthesis reveals a clear transition from early single-objective, cost-driven models toward increasingly integrated and multi-dimensional decision-support systems capable of addressing environmental, economic, technical, and social sustainability dimensions.

MCDA methods have significantly strengthened strategic decision-making by enabling structured comparison of competing WtE technologies and policy alternatives under multiple criteria. Their capacity to incorporate stakeholder preferences and qualitative considerations makes them particularly valuable in complex governance environments characterized by uncertainty and competing priorities. However, MCDA alone does not ensure engineering feasibility or system-level optimality.

Optimization approaches, including linear programming, mixed-integer formulations, and multi-objective models, provide rigorous quantitative frameworks for plant capacity determination, waste flow allocation, logistics design, and cost minimization. These models ensure technical coherence and operational efficiency but frequently underrepresent stakeholder dynamics, institutional constraints, and socio-political feasibility.

Hybrid MCDA–optimization frameworks, therefore, represent the most comprehensive methodological direction in contemporary WtE planning. By combining preference-based evaluation with constraint-based system modeling, hybrid approaches bridge the gap between strategic sustainability assessment and detailed engineering design.

This integration is particularly critical in developing urban contexts, where infrastructure investment decisions must simultaneously satisfy technical performance, financial viability, governance capacity, and public acceptance. In the context of Kano City, Nigeria, where municipal solid waste generation continues to increase alongside urban expansion, the application of integrated MCDA and optimization frameworks offers a promising pathway for identifying technically feasible and socially acceptable WtE facilities and locations.

By incorporating spatial data, stakeholder preferences, and system-level constraints, such hybrid approaches can support evidence-based planning and contribute to the development of resilient and sustainable waste management infrastructure.

Despite notable methodological advancements, several priority research directions remain.

First, future studies should emphasize context-adapted modeling frameworks that reflect data limitations and institutional realities in developing regions. Increasing computational sophistication must not outpace contextual applicability.

Second, uncertainty treatment requires deeper methodological attention. Robust optimization, stochastic modeling, and scenario-based sensitivity analysis should be systematically incorporated to address volatility in waste generation, technology performance, regulatory conditions, and energy markets.

Third, empirical validation of proposed frameworks remains limited. Longitudinal case studies comparing modeled projections with post-implementation outcomes would significantly enhance confidence in decision-support models.

Fourth, institutional and governance constraints should be more explicitly embedded within system formulations rather than treated as peripheral evaluation criteria. Incorporating regulatory alignment, administrative capacity, and stakeholder engagement structures into modeling frameworks will improve practical implementability.

In conclusion, sustainable WtE planning demands decision-support systems that integrate analytical rigor with contextual realism. The next generation of methodological development should prioritize robustness, adaptability, and institutional integration alongside technical optimization. Continued refinement of integrated MCDA–optimization frameworks will be essential for advancing resilient, implementable, and sustainability-oriented urban waste management systems.

References

[1] United Nations Environment Programme (UNEP), *Global Waste Management Outlook 2024*. Nairobi, Kenya: UNEP, 2024. [Online]. Available: https://www.unep.org/ietc/resources/report/global-waste-management-outlook-2024

[2] I. Khan, S. Chowdhury, and K. Techato, "Waste to energy in developing countries—A rapid review: Opportunities, challenges, and policies in selected countries of Sub-Saharan Africa and South Asia towards sustainability," *Sustainability*, vol. 14, no. 7, p. 3740, 2022. https://doi.org/10.3390/su14073740

[3] N. Vukovic and E. Makogon, "Waste-to-energy generation: Complex world project analysis," *Sustainability*, vol. 16, no. 9, p. 3531, 2024, https://doi.org/10.3390/su16093531

[4] S. Kaza *et al.*, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC, USA: World Bank, 2018. https://doi.org/10.1596/978-1-4648-1329-0

[5] J. Lui, W. H. Chen, D. C. Tsang, and S. You, "A critical review on the principles, applications, and challenges of waste-to-hydrogen technologies," *Renewable and Sustainable Energy Reviews*, vol. 134, p. 110365, 2020. https://doi.org/10.1016/j.rser.2020.110365

[6] T. R. Ayodele, A. S. O. Ogunjuyigbe, and M. A. Alao, "Life cycle assessment of waste-to-energy technologies for electricity generation using municipal solid waste in Nigeria," *Applied Energy*, vol. 201, pp. 200–218, 2017. https://doi.org/10.1016/j.apenergy.2017.05.097

[7] J. Malinauskaite *et al.*, "Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe," *Energy*, vol. 141, pp. 2013–2044, 2017. https://doi.org/10.1016/j.energy.2017.11.128

[8] O. K. Bishoge, X. Huang, L. Zhang, H. Ma, and C. Danyo, "The adaptation of waste-to-energy technologies: Towards the conversion of municipal solid waste into a renewable energy resource," *Environmental Reviews*, vol. 27, no. 4, pp. 435–446, 2019. https://doi.org/10.1139/er-2018-0061

[9] D. Zhang, G. Huang, Y. Xu, and Q. Gong, "Waste-to-energy in China: Key challenges and opportunities," *Energies*, vol. 8, no. 12, pp. 14182–14196, 2015. https://doi.org/10.3390/en81212422

[10] World Bank, *Global Waste Management Trends and Outlook Update*. Washington, DC, USA: World Bank, 2023.

[11] C. C. Nnaji, "Status of municipal solid waste generation and disposal in Nigeria," *Management of Environmental Quality*, vol. 26, no. 1, pp. 53–71, 2015. https://doi.org/10.1108/MEQ-08-2013-0092

[12] O. T. Iorhemen, M. I. Alfa, and S. B. Onoja, "The review of municipal solid waste management in Nigeria: The current trends," *Advances in Environmental Research*, vol. 5, no. 4, pp. 237–249, 2016. https://doi.org/10.12989/aer.2016.5.4.237

[13] O. B. Ezeudu *et al.*, "Temporal assessment of municipal solid waste management in Nigeria: Prospects for circular economy adoption," *Reviews on Environmental Health*, vol. 36, no. 3, pp. 327–344, 2021. https://doi.org/10.1515/reveh-2020-0084

[14] C. C. Ike *et al.*, "Solid waste management in Nigeria: Problems, prospects, and policies," *Journal of Solid Waste Technology and Management*, vol. 44, no. 2, pp. 163–172, 2018. https://doi.org/10.5276/JSWTM.2018.163

[15] A. Agbejule *et al.*, "Application of multi-criteria decision-making process to select waste-to-energy technology in developing countries: The case of Ghana," *Sustainability*, vol. 13, no. 22, p. 12863, 2021. https://doi.org/10.3390/su132212863

[16] C. C. Ajaero *et al.*, "Energy production potential of organic fraction of municipal solid waste (OFMSW) and its implications for Nigeria," *Clean Technologies and Recycling*, vol. 3, no. 1, pp. 44–65, 2023. https://doi.org/10.3934/ctr.2023003

[17] R. O. Yusuf *et al.*, "Energy recovery from municipal solid waste in Nigeria and its economic and environmental implications," *Environmental Quality Management*, vol. 28, no. 3, pp. 33–43, 2019. https://doi.org/10.1002/tqem.21617

[18] M. O. Ukoba *et al.*, "Composite multi-criteria decision analysis for optimization of hybrid renewable energy systems for geopolitical zones in Nigeria," *Sustainability*, vol. 12, no. 14, p. 5732, 2020. https://doi.org/10.3390/su12145732

[19] T. F. Adu *et al.*, "Decision support systems for waste-to-energy technologies: A systematic literature review of methods and future directions for sustainable implementation in Ghana," *Heliyon*, vol. 11, no. 3, 2025. https://doi.org/10.1016/j.heliyon.2025.e42353

[20] N. A. Azhar, N. A. Radzi, and W. S. H. M. Wan Ahmad, "Multi-criteria decision making: A systematic review," *Recent Advances in Electrical & Electronic Engineering*, vol. 14, no. 8, pp. 779–801, 2021. https://doi.org/10.2174/2352096514666211029112443

[21] D. Balkan and G. A. Akyüz, "Technological maturity of the OECD countries: A multi-criteria decision-making approach using PROMETHEE," *Cogent Engineering*, vol. 10, no. 1, p. 2219097, 2023. https://doi.org/10.1080/23311916.2023.2219097

[22] A. Shahnazari *et al.*, "Identification of effective factors to select energy recovery technologies from municipal solid waste using multi-criteria decision making (MCDM): A review of thermochemical technologies," *Sustainable Energy Technologies and Assessments*, vol. 40, p. 100737, 2020. https://doi.org/10.1016/j.seta.2020.100737

[23] J. E. Santibañez-Aguilar, A. Flores-Tlacuahuac, M. Rivera-Toledo, and J. M. Ponce-Ortega, "Dynamic optimization for the planning of a waste management system involving multiple cities," *Journal of Cleaner Production*, vol. 165, pp. 190–203, 2017. https://doi.org/10.1016/j.jclepro.2017.07.063

[24] E. B. Tirkolaee, "Circular–sustainable–reliable waste management system design: A possibilistic multi-objective mixed-integer linear programming model," *Systems*, vol. 12, no. 10, p. 435, 2024. https://doi.org/10.3390/systems12100435

[25] B. Mayanti, J. Songok, and P. Helo, "Multi-objective optimization to improve energy, economic, and environmental life cycle assessment in waste-to-energy plant," *Waste Management*, vol. 127, pp. 147–157, 2021. https://doi.org/10.1016/j.wasman.2021.04.042

[26] A. Mirdar Harijani, S. Mansour, and B. Karimi, "A multi-objective model for sustainable recycling of municipal solid waste," *Waste Management & Research*, vol. 35, no. 4, pp. 387–399, 2017. https://doi.org/10.1177/0734242X17693685

[27] K. Salçuk and C. Şahin, "A novel multi-objective optimization model for sustainable supply chain network design problem in closed-loop supply chains," *Neural Computing and Applications*, vol. 34, no. 24, pp. 22157–22175, 2022. https://doi.org/10.1007/s00521-022-07668-6

[28] S. A. R. Khan *et al.*, "A state-of-the-art review and meta-analysis on sustainable supply chain management: Future research directions," *Journal of Cleaner Production*, vol. 278, p. 123357, 2021. https://doi.org/10.1016/j.jclepro.2020.123357.

[29] C. Theeraviriya, K. Ruamboon, and N. Praseeratasang, "Solving the multi-level location routing problem considering the environmental impact using a hybrid metaheuristic," *International Journal of Engineering Business Management*, vol. 13, 2021. https://doi.org/10.1177/18479790211017353

[30] E. Kuznetsova, M. A. Cardin, M. Diao, and S. Zhang, "Integrated decision-support methodology for combined centralized-decentralized waste-to-energy management systems design," *Renewable and Sustainable Energy Reviews*, vol. 103, pp. 477–500, 2019. https://doi.org/10.1016/j.rser.2018.12.020

[31] N. Ferronato and V. Torretta, "Waste mismanagement in developing countries: A review of global issues," *International Journal of Environmental Research and Public Health*, vol. 16, no. 6, p. 1060, 2019. https://doi.org/10.3390/ijerph16061060

[32] A. Mardani *et al.*, "Multiple criteria decision-making techniques and their applications—A review of the literature from 2000 to 2014," *Economic Research-Ekonomska Istraživanja*, vol. 28, no. 1, pp. 516–571, 2015. https://doi.org/10.1080/1331677X.2015.1075139

[33] I. Khan and Z. Kabir, "Waste-to-energy generation technologies and the developing economies: A multi-criteria analysis for sustainability assessment," *Renewable Energy*, vol. 150, pp. 320–333, 2020. https://doi.org/10.1016/j.renene.2019.12.132

[34] S. C. Patil, C. Schulze-Netzer, and M. Korpås, "Current and emerging waste-to-energy technologies: A comparative study with multi-criteria decision analysis," *Smart Energy*, vol. 16, p. 100157, 2024. https://doi.org/10.1016/j.segy.2024.100157

[35] W. A. Qazi, M. F. Abushammala, and M. H. Azam, "Multi-criteria decision analysis of waste-to-energy technologies for municipal solid waste management in Sultanate of Oman," *Waste Management & Research*, vol. 36, no. 7, pp. 594–605, 2018. https://doi.org/10.1177/0734242X18777800

[36] A. Kurbatova and H. A. Abu-Qdais, "Using multi-criteria decision analysis to select waste-to-energy technology for a megacity: The case of Moscow," *Sustainability*, vol. 12, no. 23, p. 9828, 2020. https://doi.org/10.3390/su12239828

[37] F. Lombardi, B. Pickering, and S. Pfenninger, "What is redundant and what is not? Computational trade-offs in modelling to generate alternatives for energy infrastructure deployment," *Applied Energy*, vol. 339, p. 121002, 2023. https://doi.org/10.1016/j.apenergy.2023.121002.

[38] S. Afrane *et al.*, "Integrated AHP-TOPSIS under a fuzzy environment for the selection of waste-to-energy technologies in Ghana: A performance analysis and socio-enviro-economic feasibility study," *International Journal of Environmental Research and Public Health*, vol. 19, no. 14, p. 8428, 2022. https://doi.org/10.3390/ijerph19148428

[39] K. Sambiani *et al.*, "Location-allocation combining fuzzy analytical hierarchy process for waste-to-energy facilities siting in developing urban areas: The case study of Lomé, Togo," *Heliyon*, vol. 9, no. 9, 2023. https://doi.org/10.1016/j.heliyon.2023.e19767

[40] M. A. Alao *et al.*, "Multi-criteria decision-based waste-to-energy technology selection using entropy-weighted TOPSIS technique: The case study of Lagos, Nigeria," *Energy*, vol. 201, p. 117675, 2020. https://doi.org/10.1016/j.energy.2020.117675

[41] M. A. Alao, O. M. Popoola, and T. R. Ayodele, "Selection of waste-to-energy technology for distributed generation using IDOCRIW-weighted TOPSIS method: A case study of the City of Johannesburg, South Africa," *Renewable Energy*, vol. 178, pp. 162–183, 2021. https://doi.org/10.1016/j.renene.2021.06.031

[42] K. Al-Sulbi *et al.*, "A fuzzy TOPSIS-based approach for comprehensive evaluation of bio-medical waste management: Advancing sustainability and decision-making," *Sustainability*, vol. 15, no. 16, p. 12565, 2023. https://doi.org/10.3390/su151612565

[43] K. Zahid and M. Akram, "Multi-criteria group decision-making for energy production from municipal solid waste in Iran based on spherical fuzzy sets," *Granular Computing*, vol. 8, no. 6, pp. 1299–1323, 2023. https://doi.org/10.1007/s41066-023-00419-5

[44] D. Ukpanyang, J. Terrados-Cepeda, and M. J. Hermoso-Orzaez, "Multi-criteria selection of waste-to-energy technologies for slum/informal settlements using the PROMETHEE technique: A case study of the greater Karu urban area in Nigeria," *Energies*, vol. 15, no. 10, p. 3481, 2022. https://doi.org/10.3390/en15103481

[45] F. Guo, H. Men, and W. Chen, "Waste-to-energy incineration site selection framework based on heterogeneous fuzzy regret-PROMETHEE model considering life-cycle carbon emissions," *Environmental Science and Pollution Research*, vol. 31, no. 3, pp. 3722–3744, 2024. https://doi.org/10.1007/s11356-023-31296-9

[46] T. A. Ebadi Torkayesh, F. Fathipour, and M. Saidi-Mehrabd, "Entropy-based multi-criteria analysis of thermochemical conversions for energy recovery from municipal solid waste using fuzzy VIKOR and ELECTRE III: Case of Azerbaijan region, Iran," *Journal of Energy Management and Technology*, vol. 3, no. 1, pp. 17–29, 2019. https://doi.org/10.22109/jemt.2018.134505.1098

[47] M. Mahmoudi, A. Aydi, and H. Ibrahim, "Site selection for artificial recharge with treated wastewater with the integration of multi-criteria evaluation and ELECTRE III," *Environmental Science and Pollution Research*, vol. 28, no. 34, pp. 46748–46763, 2021. https://doi.org/10.1007/s11356-021-12354-6

[48] J. Pluskal *et al.*, "Optimal location and operation of waste-to-energy plants when future waste composition is uncertain," *Operational Research*, vol. 22, no. 5, pp. 5765–5790, 2022. https://doi.org/10.1007/s12351-022-00718-w

[49] S. Zhao *et al.*, "Multi-period planning of municipal solid waste management: A case study in Qingdao," *Process Integration and Optimization for Sustainability*, vol. 7, no. 1, pp. 107–126, 2023. https://doi.org/10.1007/s41660-022-00279-7

[50] P. Saatchi *et al.*, "A sustainable network design for municipal solid waste management considering waste-to-energy conversion under uncertainty," *Engineering Optimization*, vol. 57, no. 9, pp. 2505–2528, 2025. https://doi.org/10.1080/0305215X.2024.2408478

[51] M. Mohammadi, S. L. Jämsä-Jounela, and I. Harjunkoski, "Optimal planning of municipal solid waste management systems in an integrated supply chain network," *Computers & Chemical Engineering*, vol. 123, pp. 155–169, 2019. https://doi.org/10.1016/j.compchemeng.2018.12.022

[52] C. Chen *et al.*, "Multi-objective optimization of technology solutions in municipal solid waste treatment system coupled with pollutants cross-media metabolism issues," *Science of the Total Environment*, vol. 807, p. 150664, 2022. https://doi.org/10.1016/j.scitotenv.2021.150664

[53] B. Cicekalan, A. Pekpazar, and F. Çebi, "A multi-objective optimization model for waste-to-energy facility location in sustainable municipal solid waste management," in *Engineering and Technology Management in Challenging Times*. Cham, Switzerland: Springer, 2024, pp. 55–67. https://doi.org/10.1007/978-3-031-70935-7_5

[54] S. A. Sadati *et al.*, "A sustainable modelling for solid waste management using analytical hierarchy process, Monte Carlo simulation, and NSGA-III," *International Journal of Systems Science: Operations & Logistics*, vol. 11, no. 1, 2024. https://doi.org/10.1080/23302674.2023.2301603

[55] D. Yaghubi, M. Doroodian, and M. A. Adibi, "Development of a financing optimization framework based on risk simulation in BOT projects: A case study of the waste-to-energy project," *Complexity*, vol. 2023, 2023. https://doi.org/10.1155/2023/8129256

[56] M. Alao, "Optimal planning of waste-to-energy-based combined heat and power plant on a power distribution network," Ph.D. dissertation, Tshwane Univ. Technol., South Africa, 2024. [Online]. Available: https://hdl.handle.net/20.500.14519/2106

Received: 28/02/2026; Revised: 10/03/2026; Accepted: 03/12/2026; Published: 23/03/2026