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Optimizing Waste-to-Energy Feedstock Logistics in Ghana: An Operations and Circular Economy Framework

Joseph Ogudi and Marianna Kharlamova
Department of Environmental Safety and Product Quality Management, Institute of Environmental Engineering, RUDN University, 6 Miklukho-Maklaya St., 117198 Moscow Russian Federation
ogudjoseph33@gmail.com

Abstract

In Ghana, the municipal solid waste (MSW) management system faces increasing pressure due to rapid urbanization, infrastructure deficits and persistent operational inefficiencies. Although Waste-to-Energy (WtE) presents a viable roadmap for sustainable MSW management and renewable energy generation, inconsistent feedstock supply, weak collection logistics and limited coordination among stakeholders constrain its performance.With a focus on improving collection efficiency, resource recovery and institutional alignment, the study develops a conceptual operations-based framework for optimizing WtE feedstock logistics in Ghana. The paper identifies key gaps in MSW management in Ghana which include, collection inefficiencies, feedstock quality management and policy implementation through the structured synthesis of recent literature. The proposed framework integrates four interrelated components, namely, governance and policy alignment, MSW collection and transportation systems, resource recovery and feedstock management and stakeholder engagement, including the structured inclusion of the informal sector.This framework adopts a closed-loop perspective in which improvements in MSW collection and segregation directly enhance the reliability and quality of feedstock supplied to WtE facilities. A proof-of-concept application demonstrates the potential for increased collection coverage, improved logistics efficiency and enhanced energy recovery outcomes by using data from the Greater Accra region.The study contributes to the fields of industrial engineering and operations management and gives practical insight for policymakers who seek to transition from linear waste disposal systems to a circular resource recovery model.

Keywords
MSW Management, Waste-to-Energy, Informal Sector Integration, Circular Economy, Policy Framework

1.Introduction
The management of municipal solid waste (MSW) in Ghana represents a complex and escalating challenge, driven by rapid urbanization and inadequate infrastructure (Kusi-Appiah et al., 2025; Okuh, 2023). According to the World Bank report (2022), the average waste that was projected to be generated in that year was 2.24 billion tonnes, which is equivalent to about 0.79 kg per capita and is projected to reach 3.88 billion by 2050. Yakah et al. (2023) project that the waste generation in Ghana will rise by 123% to over 20,000 tonnes per day by 2030 (Yakah et al., 2023). Yakah et al. reported on average, every Ghanaian generates approximately 0.47kg of MSW per day, which is equivalent to over 14,000 tonnes of MSW per day in Ghana as of 2015. Based on this and the population statistics from the Ghana Statistical Service, the MSW generation projections were made from the year 2021 to 2030. **Figure 1** depicts the daily MSW generation in Ghana.

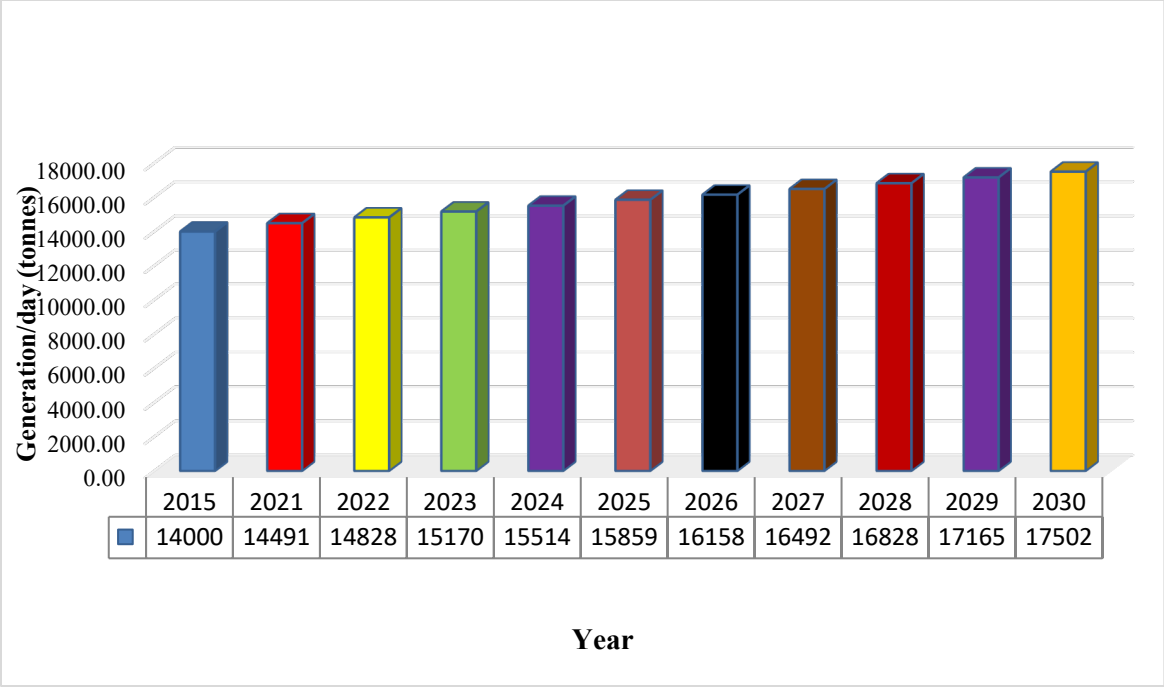

Figure 1. MSW Generation in Ghana per day (Yakah et al., 2023)

The current MSW management system, marked by both coverage and collection rates below 100% and significant environmental pollution, is unsustainable (Adedara et al., 2023). This crisis necessitates a paradigm shift from mere disposal to resource recovery.

Waste-to-Energy (WtE) technologies offer a promising avenue for such a shift; these technologies are capable of reducing landfill use, generating renewable energy, and advancing a circular economy (Adedara et al., 2023). In a study conducted on the potentials of Ghana's MSW, it was found that the MSW could generate up to 13,002 GWh of electricity annually, representing a substantial portion of its renewable energy targets (Darmey et al., 2023). However, the viability of WtE is critically dependent on a reliable supply of high-quality feedstock, which is currently thwarted by inefficiencies in collection and sorting logistics (Khan et al., 2022). **Figure 2** illustrates the MSW collection rate in the regional capital of Ghana, Accra. The figure shows that the year 2006 had the highest collection rate with 93%, and the lowest was 79.9% in 2005 and 2010.

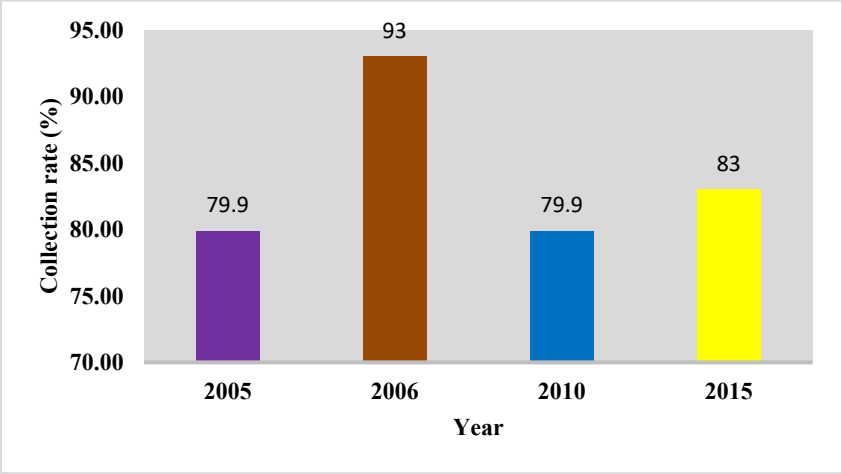

Figure 2. The MSW Collection rate in Accra for selected years (Adedara et al., 2023)

While previous studies have explored Ghana's Waste-to-Energy (WtE) potential and broader municipal solid waste (MSW) management challenges, less attention has been given to operational inefficiencies that constrain reliable feedstock supply. Most studies often treat MSW generation, collection and energy recovery as separate domains, which result in fragmented approaches that fail to address the interconnection within the system. Low collection coverage, poor MSW segregation, inconsistent transportation systems and weak coordination among stakeholders have been the persistent challenges that continue to thwart the viability of WtE initiatives.

In addition, despite the role of the informal sector an integral part of MSW management in Ghana, it remains insufficiently integrated into formal MSW management frameworks. Policy implementation gaps and institutional misalignments continue to serve as barriers to effective coordination required for efficient MSW logistics and resource recovery at the same time. These gaps expose a lack of an interconnected, operations-oriented framework that systematically links MSW collection processes with WtE feedstock requirements.

1.1 Research Objective

This study therefore seeks to address these limitations by developing a conceptual framework that integrates MSW collection logistics, resource recovery processes, governance structures and stakeholder engagement into a singular system. The objective is to develop a closed-loop framework in which improvements in MSW collection and segregation directly enhance the reliability and quality of feedstock supplied to WtE facilities. This will improve the overall MSW management system efficiency and then support the transition toward a circular economy in Ghana.

2.Literature Review

2.1 Current State of MSW Management in Ghana

Across the literature, Ghana's MSW system is consistently described as unsustainable, characterized by rapid population growth, infrastructure deficits, and pervasive data gaps. As noted by multiple studies, there is a rise in waste generation, from current levels of 14,000 tonnes/day to a projected 20,392 tonnes/day by 2030, representing a 123% increase (Darmey et al., 2023; Yakah et al., 2023). This surge is strongly linked to urbanization and expanding built-up areas, as noted by Adu et al. (Adu et al., 2025).

MSW collection and coverage rates remain below 100%, with significant spatial inconsistencies and chronic accumulation of uncollected waste reported by Adedara et al. (Adedara et al., 2023). The studies collectively identify weak collection logistics, lack of segregation of heterogeneous waste streams in developing countries, and severe data scarcity across municipalities.

Importantly, while many authors highlight WtE as a promising intervention, they also emphasize that poor feedstock quality, inconsistent supply, and inadequate operational data undermine its viability. A recurring theme across the literature is that data deficits, not just infrastructure, represent a core barrier to evidence-based planning and MSW optimization in Ghana.

Below is **Figure 3**, which is an illustration of MSW composition in Ghana (Yakah et al., 2023). It clearly shows that the organic waste fraction (61%) is almost two-thirds of the total MSW composition in Ghana, and this is good for biological conversion for energy recovery. The second largest fraction is the plastic (14%), and paper (5%), textiles (2%), rubber & leather (1%), and miscellaneous (5%) are all good for thermochemical energy conversion. This demonstrates that, by any assessment of the MSW composition in Ghana, there is potential for energy recovery

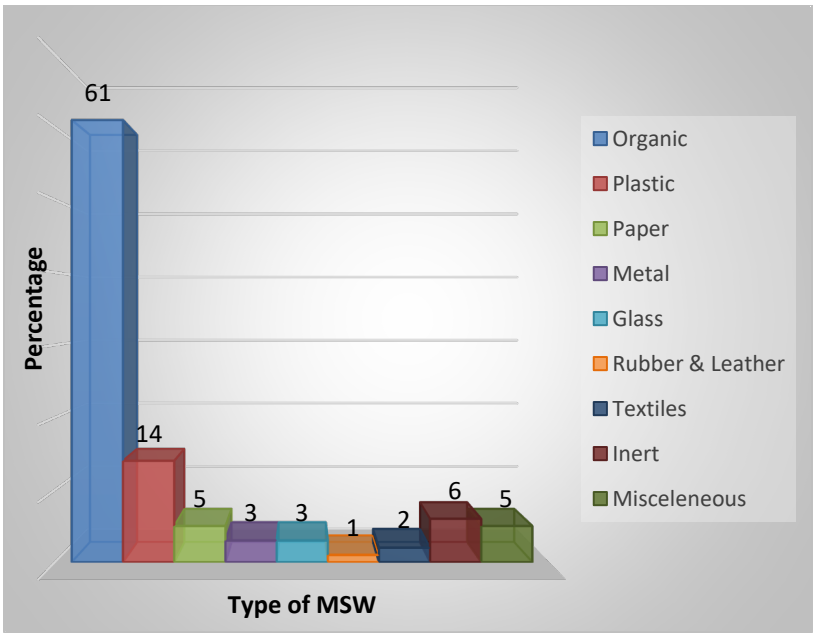

Figure 3. MSW composition in Ghana (Yakah et al., 2023)

2.2 Waste-to-Energy Technologies and Feedstock Considerations

Ghana's MSW composition of 61% organic matter, 14% plastics, and others suggests high potential for biological conversion (e.g., anaerobic digestion) while also supporting thermochemical options such as incineration, gasification, and pyrolysis (Darmey et al., 2023). Darmey et al. estimate that Ghana could generate 13,002 GWh of electricity annually through optimized WtE deployment (Darmey et al., 2023).

However, several authors (Darmey et al., Yakah et al., Li et al.) identify persistent barriers: limited techno-economic analyses tailored to Ghana, insufficient performance data from existing small-scale plants, social and regulatory hurdles, and lack of high-resolution data for plant siting or feedstock forecasting (Darmey et al., 2023; Li et al., 2025; Yakah et al., 2023).

As illustrated in **Figure 4,** the diversity of WtE technologies offers multiple pathways; however, the optimal choice for Ghana depends heavily on the waste composition shown in **Figure 3** and quality, reliable feedstock. **Figure 4** depicts the two main pathways of WtE technologies with MSW as the feedstock

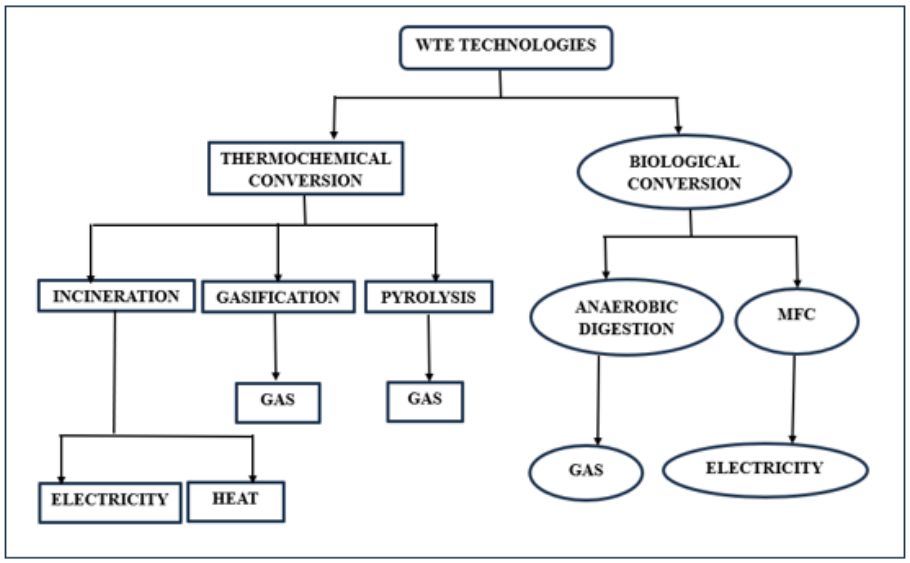

Figure 4. A flowchart of WtE technologies and their end products (Yakah et al., 2023)

2.3 Policy Landscape in Ghana

According to Badasu et al., Ghana's environmental sanitation policies are comprehensive on paper (Badasu et al., 2025), highlighting the following: sustainable funding; the polluter-pays principle; standard-setting; research and monitoring.

However, there are still implementation gaps because of:

- Inadequate enforcement
- Insufficient funds
- Digital systems' unclear technical requirements
- Lack of mechanisms for data governance

Ghana lacks the particular regulatory framework that is required to operationalize socio-economic system or guarantee constant WtE feedstock quality, despite the existence of policy underpinnings, according to this report.

Figure 5 is the legal and institutional framework of MSW in Ghana. The figure demonstrates that 'policy & planning' and 'regulation & facilitation' happen at the national level, coordination at the regional level, and implementation at the district level.

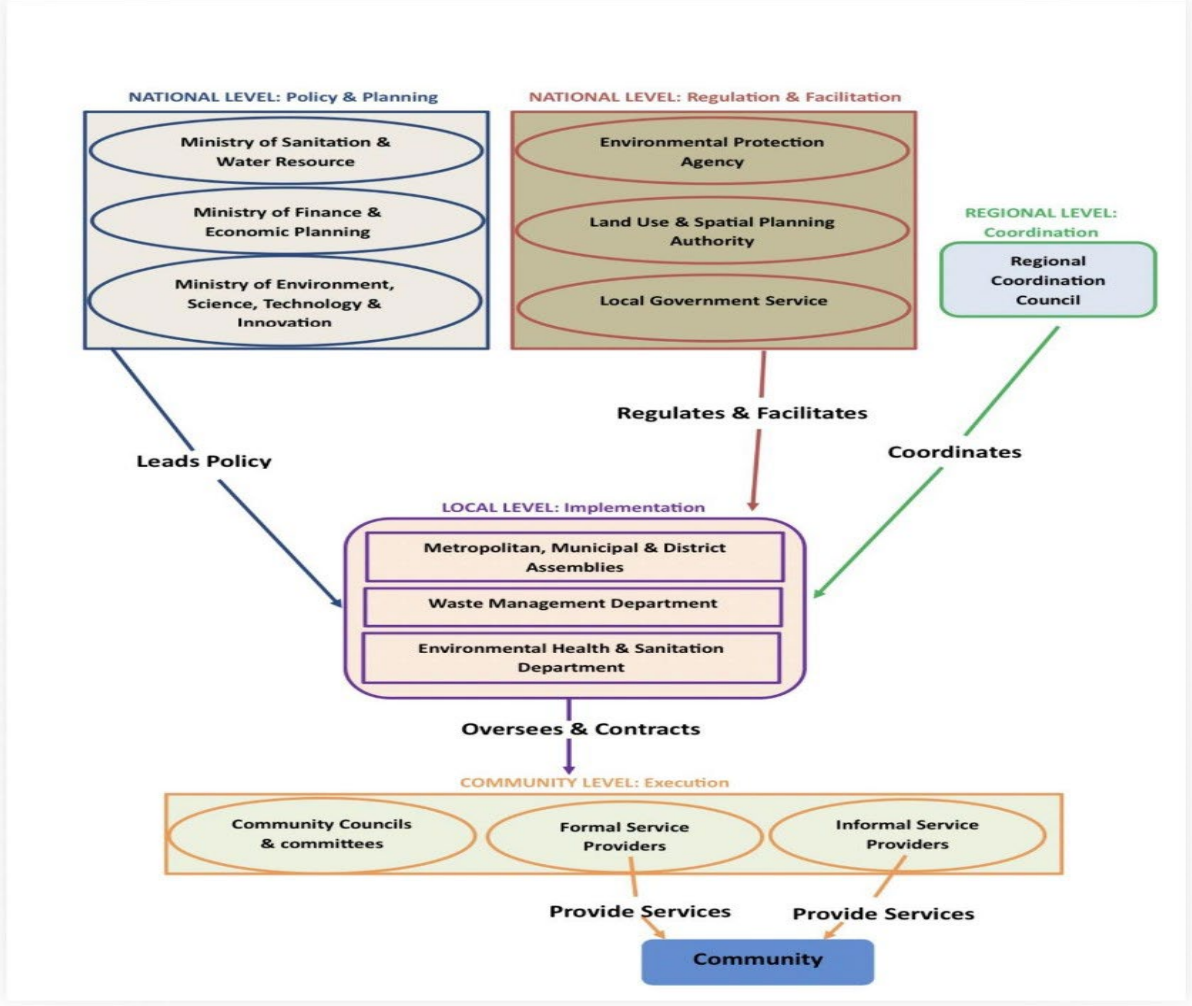

Figure 5. Legal and Institutional Framework of Ghana

The execution takes place at the community level. Policy flows downward from the national apex body, the Ministry of Sanitation & Water Resources (MSWR), and other key ministries to the local implementers, Metropolitan, Municipal, and District Assemblies (MMDAs). Regulation and facilitation are provided by national agencies, the Environmental Protection Agency, the Land Use & Spatial Planning Authority, and the Local Government Services (EPA, LUSPA, and LGS) to the MMDAs. Coordination at the regional level is handled by the Regional Coordination Council (RCC). Implementation is the core responsibility of the MMDAs and their technical departments, the Waste Management Department/Environmental Health & Sanitation Department (WMD/EHSD) at the local level. Execution of services is carried out at the community level by various formal and informal providers, overseen by the MMDAs.

3. Framework Development Methodology

This study employs a conceptual framework development methodology, widely used in engineering, environmental systems, and socio-technical research to integrate knowledge from multiple domains into a structured model. Following guidance from Jabareen, Miles et al., and MacInnis, conceptual frameworks are suited to contexts with limited empirical data, emerging technologies, and complex multi-stakeholder environments (Jabareen, 2009; MacInnis, 2011; Miles et al., 2014).

This method is appropriate given Ghana's MSW data deficits and the need to synthesize technological, logistical, and policy components.

3.1 Phase 1 & 2: Problem Contextualization & Literature Synthesis

A systematic literature search and review were conducted to identify relevant peer-reviewed articles published between 2020 and 2025. The key databases included were Google Scholar and Dimensions, which were searched using a combination of search terms such as "MSW management", "solid waste Ghana", "WtE logistics" and "MSW optimization".

The literature was screened against predefined criteria to ensure relevance and rigor. The inclusion criteria were:

- Peer-reviewed journals, official government and organization reports, and reviews that were published in English.
- Focus on municipal solid waste (MSW), Waste-to-Energy (WtE), or relevant policy frameworks.
- Specific relevance to waste management challenges in developing countries.
- Peer-reviewed journal articles that were considered foundational work even though dated before the year 2020.

Studies were excluded if they:

- Lacked methodological clarity or were purely opinion pieces.
- The studies were technical papers with no direct applications to MSW management.
- They were published in other languages except English.
- Lacked full access to the paper.
- Dated from before the year 2020, unless considered a foundational work.

The initial search yielded over 272 articles. After applying the inclusion and exclusion criteria, 29 peer-reviewed papers were selected for in-depth thematic analysis. Through this screening process, a final set of 15 peer-reviewed papers were selected for an in-depth thematic analysis. The synthesis focused on identifying Waste-to-Energy, logistical, and policy gaps in Ghana's MSW management system.

3.2 Phase 3: Identification of Core Components & Interactions

Insights from the synthesis phase were used to derive key components of the framework through:

- Policy and governance structure
- MSW collection and transport system
- MSW resource recovery processes
- Stakeholder roles: both formal and informal

3.3 Phase 4: System Integration (Framework Design)

The final step was synthesizing components into a closed-loop architecture. This involved:

- Linking MSW to WtE
- Coordination of logistics for smooth operational performance
- Consistent supply and feedstock quality to WtE facilities.
- Institutional alignment for effective performance

This multi-layered design reflects best practices in smart-city system integration and circular economy modelling. **Figure 6** below illustrates the phases.

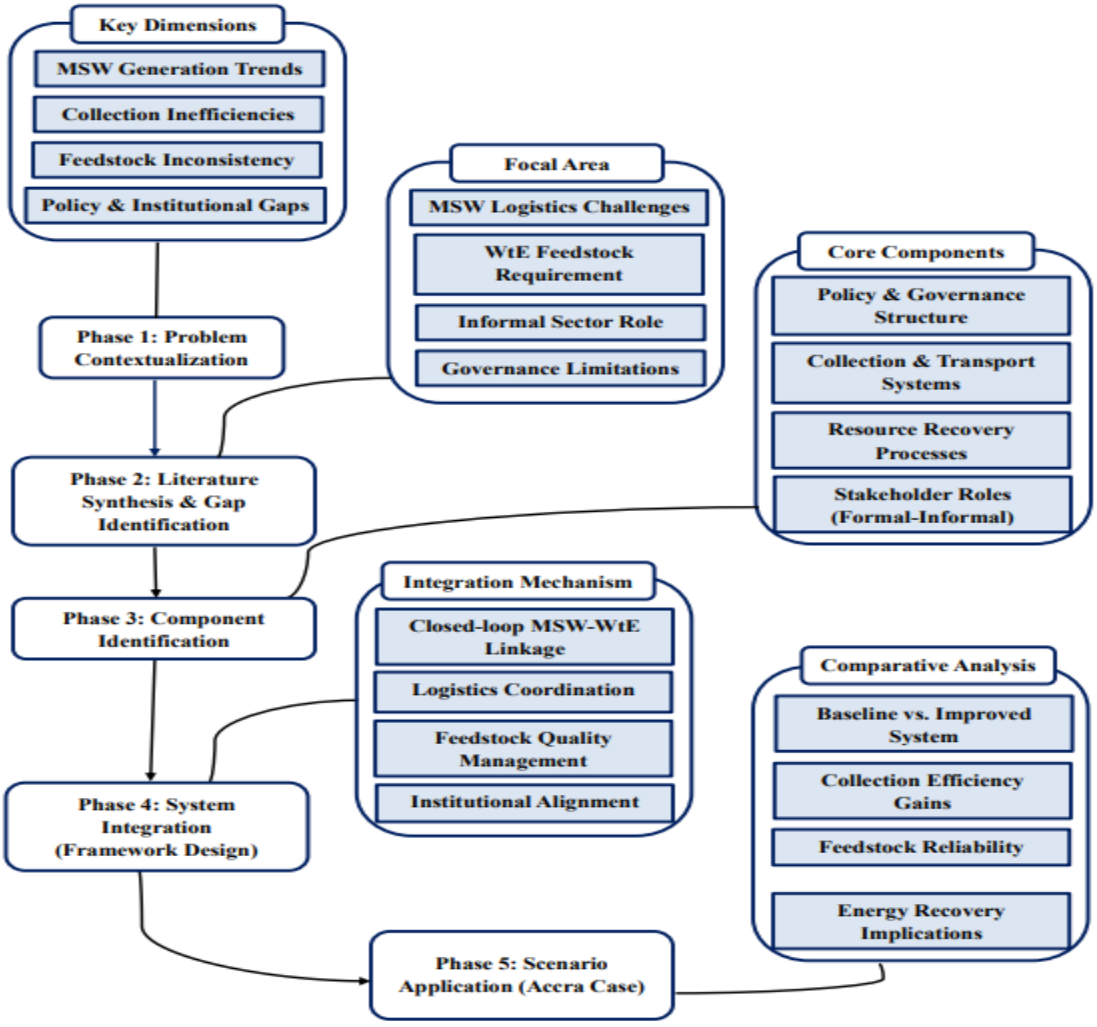

Figure 6. Methodological Framework for Developing a Waste-to-Energy Feedstock Logistics System (authors)

4. Integrated Framework for Waste-To-Energy Feedstock Optimization

4.1 Overview of the Integrated Framework

The development of a comprehensive framework that links MSW generation, collection and processing systems to the efficiency of WtE operations is the central contribution of this study. This framework emphasizes coordinated logistics, structured data practices and institutional alignment as key drivers of improved feedstock supply.

The framework is designed to address inconsistent MSW collection, poor feedstock quality and weak coordination among stakeholders, as these are persistent challenges in MSW management in Ghana. The study therefore proposes a closed-loop system in which improvements in MSW collection and sorting directly enhance the reliability of feedstock supplied to WtE facilities. This will help to increase the operational efficiency when implemented.

This system acknowledges that sustainable MSW management in developing countries does not only rely on infrastructure, but also on governance effectiveness, stakeholder participation and practical operational improvements.

4.2 Structure of the Framework and Functional Layers

There are four interrelated layers that this proposed framework operates, collectively supporting efficient feedstock logistics and circular resource flows.

4.2.1 Policy and Governance Layer

The institutional foundation for the entire system is provided by this layer. National and local authorities establish regulations, standards and strategic priorities that guide MSW management practices. Key functions under this layer include:

- Defining MSW collection and sorting standards
- Establishing regulatory frameworks for WtE operations.
- Creating incentives for improved MSW segregation and recovery.
- Ensuring coordination between national agencies and local authorities.

Accountability, consistency and long-term sustainability of the system require effective governance.

4.2.2 MSW Collection and Logistics Layer

This layer deals with the physical movement of MSW from generation points to processing facilities. It entails:

- Improved collection coverage across peri-urban and urban areas.
- Efficient route planning based on the population density and amount of MSW generation patterns.
- It helps reduce uncollected MSW through better service distribution.
- It also strengthens transportation and transfer systems.

This layer directly solves the issue of inconsistent feedstock supply to WtE facilities through optimized collection and transportation processes.

4.2.3 Resource Recovery and Feedstock Management Layer

MSW is sorted, aggregated and prepared for energy conversion at this layer. The effectiveness of this layer is dependent on the following:

- Improved segregation of MSW streams at source and collection points.
- Standardized feedstock quality for WtE processes.
- Development of material recovery systems to separate recyclables.
- Coordination between collection systems and WtE facilities.

For feedstock management that can enhance both the quantity and quality of materials available for energy recovery, there is a need for a structured approach.

4.2.4 Stakeholder Engagement and Implementation Layer

This layer connects local authorities, private MSW operators, communities and the informal sector within the system. Its primary aims include:

- It facilitates coordination between formal and informal MSW actors.
- It promotes community participation in MSW segregation.
- It supports operational decision-making at the district level.
- Transparency and accountability in service delivery is enhanced here.

This layer ensures that the system is inclusive, adaptable and responsive to local authorities.

4.3 Integration of the Informal Sector

The structured inclusion of the informal MSW sector which plays a vital role in MSW collection and material recovery in Ghana is the key innovation of this framework. The framework recognizes the informal actors as essential contributors to the system’s efficiency.

The integration is achieved through the following:

- Formal recognition of informal collectors at the district level.
- Consistent MSW collection and sorting through incentive-based mechanisms to encourage them.
- To reduce overlap and improve coverage, there should be designated collection zones.
- There should be partnerships between formal operators and informal MSW collectors.

This approach will help to enhance collection efficiency, improve feedstock availability and promotes socio-economic inclusion. This will strengthen the overall resilience of the MSW management systems.

4.4 Proof-of-Concept Scenarios: Application to Accra

A proof-of-concept scenario is applied to Greater Accra region using existing literature to demonstrate the practical implications of the framework. In light of the existing dearth of empirical pilot data, we use published data from Yakah et al. and Adedara et al. to illustrate the framework's potential impact through a proof-of-concept scenario validation applied to Greater Accra (Adedara et al., 2023; Yakah et al., 2023).

4.4.1 Baseline Situation (Present Situation):

- The amount of waste generated each day is about 3,000 tonnes.
- The collection rate is about 80% (Adedara et al., 2023).
- High variability in feedstock supply
-

4.4.2 Scenario for Framework Implementation (Projected):

- Collection coverage increases to approximately 90% due to improved coordination.
- Inefficiencies in MSW transportation is reduced due to enhanced logistics.
- Structured inclusion of informal sectors contributes to significant recovery rates.
- WtE plant performance improved due to feedstock supply consistency.

4.4.3 Impact of Energy Recovery:

Waste-to-Energy facilities can operate more efficiently, potentially increasing overall energy generation and then by reducing over reliance on landfill disposal when there is more reliable and higher-quality feedstock.
Feedstock reliability can be assessed using indicators such as collection coverage rates, material recovery levels and consistency in daily waste supply volumes.

4.5 Contribution to Theory and Practice

In terms of theoretical contributions, this framework advances the understanding of MSW management system in developing countries' contexts by:

- Demonstrating the significance of integrating logistical, institutional and social dimensions.
- The introduction of a closed-loop association between MSW collection efficiency and energy recovery.
- Highlighting the essential role that the informal sector plays in the integration in circular economy systems.

In the case of practical contributions or from a practical perspective, the framework provides:

- A scalable roadmap for districts in Ghana to improve MSW collection and feedstock management.
- A policy guidance for aligning governance structures with operational needs.
- An inclusive MSW management pathway that incorporates informal actors.
- A foundation for improving the financial and operational viability of WtE projects.

5. Discussion

This paper set out to address a critical gap in Ghana's MSW management landscape, namely the absence of an integrated, data-informed planning capable of improving feedstock logistics for Waste-to-Energy (WtE) facilities. Drawing on a multidisciplinary literature base, the paper proposes a novel, closed-loop socio-economic framework that optimizes WtE feedstock logistics and formally integrate informal waste collectors, which creates a financially inclusive circular economy model. The following discussion synthesizes the study's major insights in relation to the research questions and situates the proposed framework within broader sustainability and circular economy goals.

5.1 Interpretation of Key Findings in Relation to the Research Questions (RQ)

The literature consistently portrays Ghana's MSW sector as strained by rapidly increasing waste generation, insufficient collection coverage (less than 100%), and significant spatial inequalities as observed by Yakah et al., Darmey et al., and Adedara et al. (Adedara et al., 2023; Darmey et al., 2023; Yakah et al., 2023). A recurring challenge identified by multiple authors is the chronic lack of reliable, granular waste data, which weakens planning, infrastructure investment, and operational decision-making (Kusi-Appiah et al., 2025; Okuh, 2023; Yakah et al., 2023). The sector's systemic challenges, long-standing infrastructure deficits, informal sector fragmentation and limited monitoring capacity further underscore the importance of transitioning from linear disposal practices toward resource recovery pathways.

A critical finding, though often underexplored in the literature, is the pivotal role of Ghana's informal waste sector, including waste pickers and aggregators. A review of the literature used in this study reveals a significant gap regarding structured models for their integration into MSW management models. However, their exclusion from earlier proposed frameworks would represent a major operational and social oversight, as they form the backbone of recycling in many developing countries (Kala et al., 2022). Therefore, the framework must explicitly incorporate this sector. This could allow them to report on waste types and quantities, receive optimized collection schedules for specific zones, and be connected directly to WtE plants or formal recycling channels. By formalizing their role, the framework can enhance

their livelihoods, improve the traceability of recyclables, and ensure a more inclusive and resilient waste management ecosystem, aligning with calls for co-production in urban services (Ezeudu et al., 2021).

While Ghana has a robust sanitation policy landscape on paper (Badasu et al., 2025), gaps remain in technical standards, data governance mechanisms and digital infrastructure regulations. According to studies, the success of efficient MSW management partly depends on policy and public engagement (Yeboaa et al., 2025). The findings highlight that policy must evolve beyond waste collection mandates to include:

- Clear Public-Private Partnership frameworks for financing MSW models
- Regulatory guidelines for WtE plant emissions and feedstock specifications

The integrated policy layer in the proposed framework therefore plays a central enabling role, aligning governance structures with socio-economic capabilities.

5.4 Limitations and Directions for Future Research

This work is conceptual and therefore requires future empirical validation. Real-world pilot testing is essential to:

- Identify behavioral and institutional factors affecting adoption.
- Conduct detailed techno-economic analyses of system deployment.

Despite these limitations, the framework offers a rigorous foundation upon which further applied research and policy experimentation can be built.

6. Conclusion

Lack of a coordinated and efficient framework for ensuring reliable feedstock supply to WtE facilities in Ghana are addressed in this study. These were critical challenges in Ghana's MSW management system. The study highlights the significance of logistics optimization, governance alignment and stakeholder integration in improving overall system performance. This is achieved through shifting the focus from technology-driven solutions to an operations and system perspective.

Sustainable WtE development does not depend solely on technological capacity but also on the efficiency of upstream MSW collection, transportation and material recovery processes as demonstrated by the proposed framework. The study shows how improvements in MSW collection and segregation can directly enhance feedstock reliability, operational efficiency and energy recovery outcomes by structuring these components into a closed-loop system.

One of the key contributions of this study is the explicit integration of the informal sector into the MSW management system in Ghana. The paper found that recognizing informal actors as essential contributors to the collection and recovery processes of MSW provides both operational benefits and socio-economic value by strengthening system resilience and inclusivity.

Demonstrating potential improvements in collection coverage, logistics efficiency and WtE performance, the proof-of-concept application to the Greater Accra region illustrates the practical relevance of this framework. Even though the study is conceptual and requires empirical validation, it provides a strong foundation for future applied research, pilot implementations and policy development. For a successful implementation and operationalization of this proposed framework, it is recommended that the Ministry of Sanitation should engage **ZOOMLION** Ghana to pilot this proposed framework in a medium city like Ho or Sunyani. **ZOOMLION** Ghana is a "giant" in Africa when it comes to MSW management, so therefore a key stakeholder in MSW management in the Africa continent.

Overall, this study adds to the existing knowledge in industrial engineering and operations management literature by presenting a scalable, context-sensitive framework for MSW supply chain optimization in developing countries. This framework provides a practical roadmap for moving from the linear to circular economy model that supports sustainable energy generation and improved urban environmental management.

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