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A Circular Economy Approach to Addressing Waste Management Challenges in Tamale's Waste Management System

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Abstract: Ghana Tamale's current waste management system is overwhelmed by the growing waste crisis, necessitating the exploration of Waste-to-Energy technologies (WtE) as an innovative solution. This study explores challenges and opportunities for integrating WtE technologies into Tamale's existing waste management system. Qualitative research identified policy hurdles, financial constraints, social concerns, and institutional weaknesses as key barriers. Conversely, stakeholder collaboration, public education, and capacity building emerged as some success factors. A proposed implementation plan emphasizes feasibility studies, public engagement, public–private partnerships (PPPs), and technology selection based on waste composition. Additionally, a novel framework for WtE integration within a broader Integrated Solid Waste Management (ISWM) system is presented. This framework incorporates waste sorting, recycling, WtE alternatives, and responsible management of residuals. Validation by key stakeholders confirmed the framework's potential to improve waste management in Tamale. By overcoming identified challenges and implementing the proposed framework, Tamale can achieve environmental sustainability, energy generation, and progress towards UN SDGs 7, 11, and 12. This research offers valuable insights for policymakers and paves the way for a cleaner and more sustainable future for Tamale, potentially serving as a model for other developing cities.

Keywords: waste-to-energy; NVivo software (version 12.2); biomass; landfill; technologies; livelihoods

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1. Introduction

It is estimated that the municipal solid waste (MSW) generation rate in residential, commercial, and institutional areas will increase to 2.2 billion tons per year by 2025 worldwide [1,2]. MSW differs worldwide and is influenced by social, financial, cultural, psychological, educational, and technological factors [3,4]. Thus, the quantity and composition of MSW also vary according to the standard of living and the degree of urbanization [5,6].

The prevailing sanitation and integrated waste management plans in developing countries are often not comprehensive, which impairs the implementation of municipal waste management processes [7,8]. For the most part, municipalities lack systematic information and specialized technical staff, which forces them to manage and treat solid waste ineffectively [9–11]. Additionally, there are challenges in setting clear goals, actions, and procedures that ensure waste management objectives align with municipal realities [11]. There is also a lack of organizational resources and competitiveness [12,13], as well as efficient performance measurement systems [14,15]. Thus, the context in developing countries presents significant obstacles for integrated solid waste management (ISWM) [15].

The scenario above reveals in principle that the waste management frameworks used today are not effective and sustainable [16,17]. This highlights the urgent need for alternative solutions [18,19]. The growth of the Waste-to-Energy (WtE) sector offers a promising

alternative, but its development has faced significant challenges, such as inadequate funds, insufficient expertise, the lack of favorable national policies and legislation, as well as weak enforcement of existing regulations [20,21]. To overcome these barriers and solve numerous liabilities related to the environment, especially the mountains of MSW discarded daily, it is necessary to adapt strategies for the enhancement of social control of public policies, emphasizing strategic guidelines, institutional arrangements, legal aspects, and financing mechanisms [22,23]. The challenges of waste management in Ghana, including those in the Tamale Metropolis, align closely with findings from similar studies in other developing countries [24,25]. Despite this broader commonality, a unique issue in Tamale is the absence of an operational solid Waste-to-Energy plant. Consequently, mixed wastes are often disposed of indiscriminately—either dumped in open areas, burned, or transported to the decommissioned landfill for disposal [26,27]. In addition, the delays in the disbursement of funds to the Metropolitan Assemblies by the central government, coupled with low user-fee turnovers in the metropolis, make it difficult for waste management authorities and contractors to invest in new facilities and treatment technologies to support waste resources recovery and energy production [25,28]. These and several other factors have made the Tamale Metropolitan Assembly (TaMA) incapable of rendering effective waste management services in the metropolis [29,30]. To the best of the researchers' knowledge, although Tamale generates significant amounts of solid waste with considerable potential for energy production, no WtE plant has been established following the closure of the only landfill site in Gbalahi, a suburb of Tamale [31,32]. This inaction has left the city grappling with an escalating solid waste crisis [33,34].

While existing literature explores WtE technologies in Ghana, the focus has primarily been on documenting successful pilot trials or planned projects, with less attention given to integrating WtE into existing waste management systems. As a result, there is a gap in intellectual discourse on WtE in Ghana as a component of an integrated solid waste management system. Studies in the field very often overlook the design of frameworks that integrate WtE technologies into the current waste management systems, a critical gap, especially given the low success rate of WtE projects in developing countries [35,36]. Furthermore, while the National Solid Waste Management Strategy of Ghana (NSWMS) acknowledges the potential for energy recovery from waste, its exploration in both practice and academic research remains superficial [37]. As a result, inefficient and environmentally harmful practices such as the indiscriminate use of open dumps and burning continue to be the predominant methods for municipal solid waste disposal, exacerbating the depletion of natural resources and raising public health concerns [38,39]. Additionally, there is a growing disparity between the solid waste management capacity of the Tamale Metropolitan area and the rapid increase in waste generation, highlighting the limitations of the current disposal systems [24,40]. Given the extensive body of literature that underscores the benefits of innovative solutions like WtE technologies in simultaneously enhancing waste treatment and energy production, conducting a study to guide the integration of WtE into Tamale's existing waste management framework is essential [41,42].

Central to this study are two primary research questions: (1) What are the barriers hindering effective waste management and the adoption of WtE in Tamale's current solid waste management system? Additionally, the study aimed to address the question (2) What are the Critical Success Factors (CSFs) for the realization of an improved solid waste management system encompassing WtE in the Tamale metropolis?

These questions serve as the guiding framework for investigating and exploring various aspects of waste management in the Tamale metropolis. Through rigorous data collection and analysis using focus group discussions and in-depth interviews, this study aims to provide actionable insights informing the development of an effective waste management system incorporating viable Waste-to-Energy strategies. In addition to identifying barriers and critical success factors, this study aims to develop a novel framework offering a theoretical perspective and roadmap for the rollout of sustainable and improved solid waste management in Tamale. The framework seeks to address the challenges of solid waste

management in the Tamale metropolis by incorporating WtE into the existing system and integrating interdisciplinary perspectives and best practices. Finally, the insights gleaned from this study hold significant implications for policymakers and stakeholders in Tamale as they move forward with integrating WtE into the city's waste management system.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Tamale Metropolis, situated between latitude 9°16′ and 9°34′ N and longitudes 0°36′ and 0°57′ W. In 2017, the estimated population of the area was 485,000, with an annual growth rate of 3.5% [24]. The elevation is approximately 180 m above sea level, covering a total land area of 550 km^2. Notably, the metropolis has an urban population of 67.1%, making it the only predominantly urban district in the region (Figure 1). The population density is around 319 persons per square kilometer for the metropolis, significantly higher than the regional average density of 25.9 persons per square kilometer. Functioning as the capital and main commercial center for the Northern region of Ghana, the metropolis grapples with waste management challenges due to rapid socio-economic growth [38].

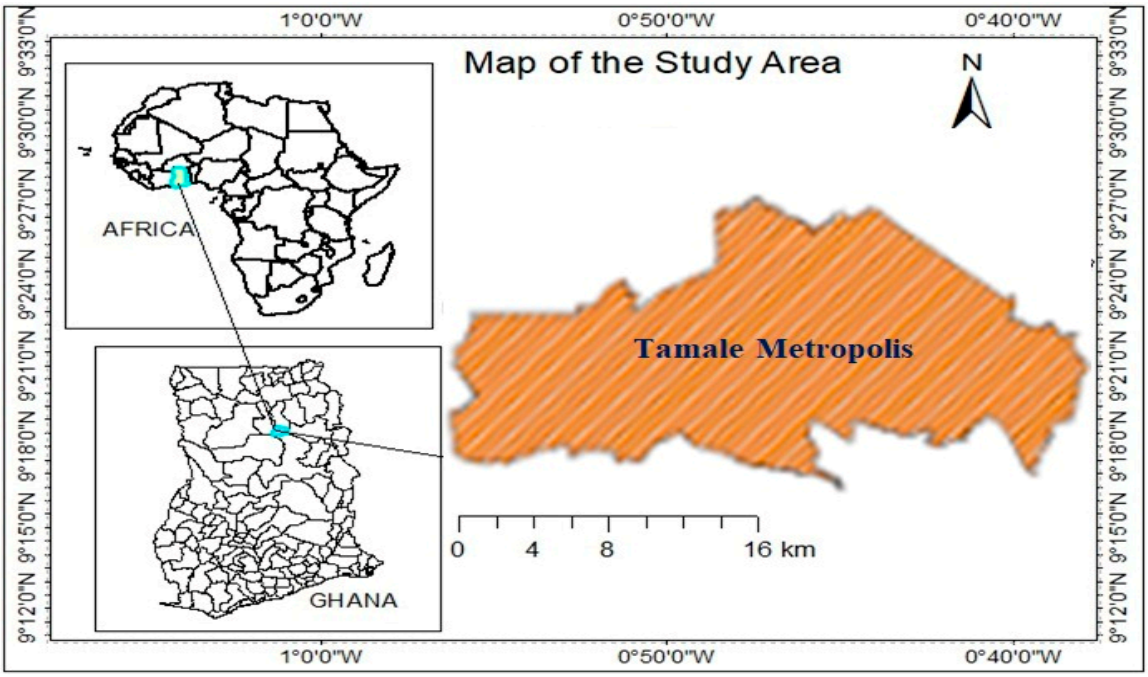

Figure 1. Location map of Tamale in the Northern Region of Ghana (Source; Author's construct).

The current MSW management in the Tamale metropolis is characterized by several challenges. Indiscriminate disposal, insufficient waste collection and transportation, and open dumping are the predominant practices, with the majority of waste being openly dumped without any pre-treatment [24]. Additionally, the waste management bodies in Tamale collect only 7.5 tons of MSW per day, leaving a backlog of 142.5 tons per day [43]. There is minimal provision of MSW disposal infrastructure and communal collection containers [44]. Furthermore, a major challenge to effective MSW disposal in Ghana and other developing countries is the non-segregation of wastes at the various generation sources and throughout the waste management chain [45–47].

As an illustration, In Tamale, mixed MSW is often stored in single bins, improperly disposed of (e.g., burned, buried, or dumped in bushes), or collected through door-to-door services and communal containers before being openly dumped at an unregulated landfill site [24,48]. This system has detrimental environmental and public health consequences, including pollution of natural resources, ecological damage, and long-term health complica-

tions [49–51]. While informal material recovery by scavengers and metal waste merchants partially mitigates the impact and provides livelihoods [52], there is no formal waste recovery or recycling system in place. As in many developing countries, informal recovery diverts some materials from the municipal waste stream [2,53]. Therefore, implementing formal waste segregation, recovery, and recycling programs could significantly reduce the amount of MSW requiring disposal, thereby mitigating the adverse effects of current practices. Given these challenges, Tamale urgently needs to expand and invest in innovative waste management strategies, such as WtE technologies.

2.2. Qualitative Survey

We gathered data from a variety of participants in the waste management sector using a variety of techniques, including focus groups, in-depth interviews, observation, and site visits, to understand the barriers and critical success factors associated with integrating Waste-to-Energy into municipal solid waste management (MSWM) in the Tamale metropolitan area and to avoid bias. Stakeholders were selected according to recommendations from the literature [3,54]. All participants in the study were over 18 years of age. The study selected participants from various entities such as the Tamale Metropolitan Assembly's Department of Waste and Sanitation, Zoomlion Ghana Ltd., (Tamale, Ghana) the Environmental Protection Agency (EPA), and research institutions.

Between January 2024 and February 2024, the principal investigator conducted 10 face-to-face, semi-structured interviews and focus group discussions with managers, researchers, administrators, and other staff members from organizations involved in environmental and MSWM in Tamale (refer to Table 1). The selection of these ten interviewees was based on the principle of thematic saturation, as outlined by [55], who suggest that saturation in qualitative studies is typically reached with six to twelve participants. This sample size was considered adequate to capture a comprehensive range of perspectives and facilitate a thorough analysis of the data.

Table 1. Stakeholder Composition for In-Depth Interviews on Waste Management Challenges in Tamale.

Group	Number
Zoomlion Ghana limited	2
Tamale Metropolitan Assembly	3
Community leaders	2
Environmental Protection Agency	2
Institute of Local Governance	1
Total	10

Interview durations varied from 20 to 40 min per person, with scheduling tailored to accommodate the technical and cultural backgrounds of the interviewees. Upon agreeing to participate, potential interviewees were contacted by the principal investigator to schedule an appointment. Nonprobability sampling was employed for participant selection, utilizing a technique where the primary researcher extended an invitation, which included the research instruments, to two initial potential participants from different sectors (academia, industry, community, etc.). This was followed by employing a Snowball sampling technique [55,56], where each participant was encouraged to recommend others from related fields who might be interested in participating. Each focus group comprised no more than fifteen participants, with sessions lasting between 60 and 90 min. The research team for each session included the researcher, a moderator, a note-taker, an audio recorder, and an organizer. Audio recordings of the focus group discussions were made for subsequent review. During these sessions, the moderator played a crucial role in maintaining the focus of the discussion, ensuring active participation from all attendees, and prompting participants to elaborate on their responses.

The audio files generated from the 10 face-to-face semi-structured interviews and two focus group discussions were transcribed by the researcher onto a word processor and later uploaded and analyzed for thematic content using NVivo software (Version 12.2) [57]. Analysis was undertaken immediately to prevent bias or loss of nuance that might arise from translated terms or expressions. Salient quotes were captured for use in publication. The principal investigator also visited the Gbalahi landfill site in the study area to view and take photos of its state and condition (see in Supplementary Files as Figure S1).

The analytical framework for this study was built upon factors or aspects identified in the literature on solid waste management, drawing from sources such as [58], and a cross-national study by [59] that specifically examined developing countries. Thematic aspects of the framework include technical, institutional, socio-political, and financial matters.

2.2.1. Methodology Rationale and Trade-Offs

As outlined in the preceding section, this study employed semi-structured interviews and focus group discussions to delve into the complexities of MSWM within Tamale. The choice of these qualitative methodologies was driven by several factors. Firstly, they allow for an in-depth exploration of perceptions and experiences, providing nuanced insights that are essential for understanding the multifaceted issues in MSWM. Secondly, the flexibility of these methods facilitates adaptive questioning based on participant responses, which is crucial for uncovering new and complex topics. Lastly, focus groups offer a dynamic interaction platform where participants can engage in discussions, providing a richer array of community perspectives and fostering a comprehensive understanding through collective dialogue. However, these methodologies also involve inherent trade-offs. The use of nonprobability sampling, specifically the snowball sampling technique, while effective in accessing a specialized population, may introduce selection bias. This bias stems from relying on the networks of initial participants, which could limit the diversity of perspectives gathered. Additionally, while the rich, contextual insights gained from these qualitative methods are invaluable, they may not be as easily generalizable to other settings or populations, a limitation that we acknowledged in favor of detailed local understanding.

Moreover, qualitative methods such as those employed are resource-intensive, requiring considerable time and effort in planning, execution, and analysis. This includes preparing participants, ensuring effective moderation during discussions, and meticulous transcription and analysis of the discussions. The methodological design, participant selection, and discussion structuring were specifically tailored to the unique environmental and regulatory frameworks of Tamale. This approach not only ensures the relevance and applicability of the findings to MSWM practices in Tamale but also provides a template for other cities or regions with similar urban and developmental profiles.

2.2.2. Stakeholder Roles, Conflicts, and Synergies in Waste Management in Tamale

To effectively implement WtE initiatives in Tamale, understanding the roles, conflicts, and synergies among various stakeholders considered for their perspectives in this study is crucial, as each stakeholder group brings unique contributions, challenges, and collaborative potential to the WtE landscape, as detailed below:

Zoomlion Ghana Limited: As a major waste management operator, Zoomlion is integral to the operational aspects of WtE initiatives. Their role primarily involves the execution of waste collection and processing, which is critical for the success of these projects. However, conflicts can arise from their commercial priorities, which may occasionally clash with environmental and community goals. Despite this, Zoomlion's capacity for large-scale operations creates synergies in implementing efficient waste management solutions.

TaMA: TaMA is responsible for regulatory oversight and policy facilitation within the metropolitan area. They play a synergistic role by establishing a conducive regulatory environment that supports WtE initiatives. TaMA's contributions are essential in the areas of licensing, policy enforcement, and stakeholder coordination. However, they sometimes

face conflicts stemming from budgetary constraints and varying public opinions, which can influence the pace and scope of project implementation.

Community Leaders: Community leaders act as liaisons between the WtE initiatives and the local populace, ensuring that projects align with the community's needs and values. Their role is crucial in mobilizing local support and facilitating grassroots engagement. By fostering trust and cooperation, community leaders enhance the social acceptability and success of WtE projects, although they must navigate the diverse expectations and reservations of the community members.

Environmental Protection Agency (EPA): The EPA ensures that WtE projects comply with environmental standards, protecting ecological integrity and public health. Their role can lead to conflicts with other stakeholders when environmental regulations limit operational efficiencies or economic goals. Nonetheless, the EPA's strict compliance requirements are vital for ensuring the long-term sustainability of WtE initiatives, thereby contributing to their overall success.

Institute of Local Governance: This academic and policy-oriented body provides research-based insights and governance frameworks for WtE initiatives. While their involvement typically does not directly conflict with other stakeholders, the Institute significantly contributes by enhancing the governance, transparency, and effectiveness of WtE projects through informed policy recommendations and scholarly input.

3. Results and Discussions

3.1. Content Analysis

The following analysis includes findings from in-depth interviews and focus group discussions. The results present the most frequently cited issues.

3.1.1. Structure of Waste Management in Tamale Metropolis

The waste management system in Tamale involves multiple stakeholders and a complex structure aimed at addressing the city's waste disposal needs. This structure includes government bodies, private-sector partnerships, and community involvement. To address questions regarding the structure of waste management in the Tamale metropolis, participants had the following to say:

> *"The Metropolitan Waste Management Department (MWMD) in Tamale is legally tasked with managing the cleanliness of public spaces, including drains, streets, and markets, and maintaining sanitary facilities. Our operations involve treating and disposing of all waste forms, largely facilitated through partnerships with private entities like Zoomlion GH Ltd., savannah waste management service, sewage system ltd and other private waste service providers who are mostly unregistered. Challenges persist in the system, characterized by a lack of waste bins, inconsistent waste collection schedules, inadequate segregation practices, and logistical constraints."* —Local Government Officer, MWMD 2 (In-depth Interview).

> *"Zoomlion Ghana Limited's involvement has bolstered the waste management capacity within Tamale, providing additional equipment, vehicles, and labor. This enhancement has increased service coverage to approximately 70% of the Metropolis, improving the cleanliness of main streets, lorry parks, and enabling gutter dredging alongside selective door-to-door services."* —Zoomlion Gh Ltd. Staff, Z1 (in-depth interview).

> *"In Tamale, the waste management structure and waste collection vary significantly across different residential classes. To illustrate, Savannah Waste Management Service, a subsidiary of the Jospong Group, provides solid waste sanitation services on behalf of Zoomlion Gh Ltd. in the metropolis. High-class areas benefit from regular door-to-door service, contributing to their cleanliness through this service provider. Middle-class areas also have access to these services upon request, but most residents prefer communal containers, which can become overcrowded. In low-class neighborhoods, which are fraught with irregular layouts and crowded public places such as markets, communal containers*

are mostly utilized. However, they are often insufficient as they frequently overflow. It is critical to mention that the irregular layout of these areas complicates regular waste collection. Additionally, through the partnership with the Jospong Group's subsidiary, all sludge and wastewater are collected and treated by Sewage System Ltd. The form of treatment entails converting fecal sludge into compost." —Local government staff, MWMD 1 (In-depth Interview).

The structure of waste management in Tamale, as detailed in the in-depth interviews, incorporates a multi-stakeholder approach. This system includes government bodies, private sector partnerships, and community involvement, each playing a distinct role in the handling and disposal of waste. The Metropolitan Waste Management Department (MWMD) coordinates the overall management efforts, while private companies like Zoomlion GH Ltd., Savannah Waste Management Service, Sewage System Ltd., and other private waste service providers are engaged in operational activities. This collaborative framework is designed to tackle the city's growing waste management demands. Also, interviewees reported inconsistent waste collection services in Tamale. According to them, the municipal waste management trucks are deployed intermittently without a predictable schedule, which exacerbates the accumulation of waste. This irregularity in service delivery, coupled with poor neighborhood planning—especially in low-income settlements—hampers the efficiency of waste management in the city.

3.1.2. Waste Management System and Waste-to-Energy in Tamale

Stakeholders collectively recognize the potential benefits of Tamale's emerging Waste-to-Energy facility, though they also identify key areas needing enhancement to maximize its impact.

A local government staff member discussed the limitations of the new 1000-metric-ton Wastewater Treatment Plant at Gbalahi, stating,

"While the plant marks a significant step forward in our sanitation efforts, it currently only converts fecal waste into compost and does not address solid waste treatment. Moreover, it does not yet have the capability to convert waste into energy, which is a critical function for truly advancing our waste management goals" (Local Government Staff, ID LGS1, focus group discussion).

An environmental protection officer emphasized the importance of expanding the scope of the plant:

"The waste-to-energy operations by Zoomlion Ghana Limited effectively manage sludge water disposal and provide an energy solution. However, to fully harness the benefits and minimize environmental impacts, it's crucial to broaden these solutions to also tackle the growing solid waste issues in our municipality, ensuring compliance with environmental standards throughout" (Environmental Protection Officer, ID EPO2, in-depth interview).

A Zoomlion employee shared their firsthand experience with the plant's operations:

"Working at Zoomlion, I see the effectiveness of our waste management practices daily. It's rewarding to contribute to a project that not only mitigates waste in Tamale but also has the potential to generate energy" (Zoomlion Gh Ltd. staff, ID Z3, in-depth interview).

An academic perspective highlighted the broader implications of integrating this technology with existing systems:

"The new plant represents a crucial development. Integrating it with our current waste management system could significantly reduce health issues stemming from improper waste disposal. It's essential to expand this initiative to encompass municipal solid waste too" (Academia, ID A3, in-depth interview).

Overall, there is a consensus among stakeholders about the positive contributions of the waste treatment plant towards improving waste management and energy production in Tamale. However, a critical limitation is its current inability to treat solid waste or fully convert waste to energy, underscoring an urgent need for system enhancements to address these challenges effectively.

3.1.3. Challenges of the Waste Management System in Tamale

Policy Perspectives

The absence of clear and consistent government policies regarding WtE technologies presents a significant hurdle to their adoption in Tamale, Ghana. Both employees at Zoomlion Gh. Ltd. and officials from the Waste Department of the TaMA stress the importance of supportive regulations and policy coherence at both national and sub-national levels. These measures are vital for encouraging investment and facilitating the effective implementation of WtE projects. Without such policies, private sector involvement and investment in WtE initiatives are discouraged, and local authorities face difficulties navigating the regulatory landscape and accessing resources for project success. Consequently, the fragmented policy framework obstructs the sustainable integration of WtE technologies into Tamale's waste management infrastructure, hindering progress toward environmental sustainability and energy security goals.

> *"There is a need for clear government policies supporting the adoption of WtE technologies. Without supportive regulations, it's challenging to incentivize investment in these initiatives."* Zoomlion staff—ID Z4 (focus group).

> *"Policy coherence between national and local levels is crucial. Local authorities need guidance and support from the central government to effectively implement WtE projects."* Local government staff—ID LG2 (in-depth interview).

While the dominant narrative suggests a lack of effective policy, a minority of interviewees presented a different viewpoint. Three local government representatives (15%) in a focus group expressed the belief that existing policies are sufficient. For example,

> *"Policy is not the problem."* Local government staff—ID LG5 (focus group).

> *"We at Zoomlion Gh. Ltd. have recently commissioned a €20-million wastewater treatment plant at Gbalahi, a suburb of Tamale. This feat was achieved with funding from the Hungarian Government. Therefore, with the right funding and willpower from the Ghanaian government, we should be able to smoothly integrate WtE into the existing solid waste management system to address issues of solid waste"* Zoomlion Gh Ltd. staff—ID Z3 (in-depth interview).

Financial Implications

Amidst considerable financial hurdles linked to municipal solid waste management in the Tamale Metropolis, Ghana, both Zoomlion Staff and TaMA Waste Department Officials emphasize the urgent need for sufficient financing and thorough cost-effectiveness assessments to support the implementation and long-term viability of WtE initiatives. The paucity of accessible financial incentives and investment mechanisms hampers private sector engagement in the sector, while the absence of comprehensive economic feasibility studies poses risks to the financial sustainability of WtE projects. Therefore, without addressing these financial obstacles, the realization of WtE as an effective waste management solution in Tamale remains uncertain, undermining efforts toward environmental preservation and energy generation objectives.

> *"Securing adequate financing for WtE projects is a major challenge. Financial incentives and investment mechanisms are needed to attract private capital into the sector."* Zoomlion Gh Ltd. Staff-ID Z1 (in-depth interview).

> *"WtE plants require a high initial investment, coupled with ongoing maintenance and operation costs. Economic viability studies are therefore crucial to assess their long-term*

financial sustainability and ensure value for money. Unlike the Gbalahi landfill site in Tamale, which fell short of expectations, WtE plants, when properly assessed and managed, can deliver a more sustainable waste management solution." Local Government Staff-ID LG3 (Focus group).

"While WtE offers potential advantages, the high upfront costs and ongoing expenses raise concerns about affordability, especially considering Tamale's limited resources. Exploring alternative, potentially less expensive waste management solutions that are more readily adaptable to our local context might be a more prudent approach in the short term." —Community Representative—ID CR2 (Focus Group Discussion).

However, it is important to acknowledge a minority (10%) viewpoint within the focus group discussions. Some participants expressed concerns that the social burden of WtE projects might outweigh the potential financial benefits.

"While WtE offers potential benefits, we shouldn't rush into significant debt for these projects. A thorough cost analysis is crucial, but the long-term social implications on the community need careful consideration." —Community Representative—ID CR8 (Focus group discussion).

Socio-Political Dynamics

Participants, comprising private waste service providers, waste researchers (experts), local assembly staff, Zoomlion Gh Ltd. staff, and others, emphasize the significance of social acceptance, public awareness campaigns, community engagement, political will, and stakeholder involvement in the success of WtE initiatives. Failure to address misconceptions and concerns and secure public support through effective communication strategies may result in resistance from communities and obstacles in project implementation. Furthermore, the lack of political dedication and inclusive decision-making processes may impede the prioritization and advancement of sustainable waste management solutions, hindering progress towards environmental sustainability and energy generation objectives in Tamale.

"Political will and stakeholder engagement are key determinants of WtE success. Decision-makers must prioritize sustainable waste management solutions and involve relevant stakeholders in the decision-making process." Waste Researcher—ID WR 1 (in-depth interview).

"The acceptance of WtE technologies by society is crucial. It requires public awareness initiatives and community engagement endeavors to tackle misunderstandings and apprehensions among local residents" Private Waste Service Provider—ID PWS 3 (in-depth interview).

Although a majority of participants (80%) agree with the need for stakeholder engagement and political will, not everyone (20%) agrees that the level of public engagement is necessary. Some participants expressed concerns that extensive public discussions could delay project implementation and potentially lead to misinformation campaigns.

"While public awareness is important, shouldn't the focus be on technical expertise and ensuring the proper functioning of the plant? Extensive community engagement can be time-consuming and potentially delay progress."— Community representative—ID CR10 (in-depth interview).

"There's a fear that community concerns might be used to stall the project altogether. While some engagement is necessary, the final decisions should be left to the experts."— Local Government Staff—ID LG4 (in-depth interview).

Additionally, a minority group (15%) represented by waste pickers voiced apprehension about the potential impact of WtE on their livelihoods in focus group discussions. They expressed concerns that WtE plants could reduce the amount of recyclable materials available for collection, impacting their income.

> *"We support sustainable waste management, but WtE shouldn't come at the expense of our livelihoods. We need assurances that WtE won't significantly reduce the amount of recyclable materials available for collection."*— Private Waste Service Provider—ID PWS 1 (Focus group discussion).

These quotes from minority viewpoints (15%) in the focus group discussion highlight contrasting perspectives on the importance of social engagement. They raise concerns about potential delays and the impact on waste pickers' livelihoods, suggesting a need to balance public participation with project efficiency and social responsibility.

Institutional Framework

The majority of participants (70%) stress the importance of efficient collaboration between public and private entities and highlight the need to enhance institutional capacity for the successful implementation of WtE initiatives. Without strong partnerships between the public and private sectors, the effective operation and maintenance of WtE facilities may be compromised. Similarly, the absence of institutional capacity and trained personnel could hinder the planning, execution, and management of WtE projects. Therefore, addressing these institutional challenges is crucial to fully harnessing the potential of WtE as a sustainable waste management solution in Tamale.

> *"Building institutional capacity is crucial for successful WtE implementation. Training and skill development programs are necessary for waste management personnel."* Local Government Staff—ID LG 1 (focus group discussion).

> *"Public-private partnerships (PPPs) are not just essential, they offer the most promising path forward for WtE in Tamale. By leveraging the expertise of the private sector alongside public resources, we can ensure efficient operation and maintenance of WtE facilities, while mitigating financial risks for the government. PPPs can also foster innovation and technology transfer, leading to a more sustainable WtE solution for the city"* Zoomlion Gh. Staff—ID Z2 (in-depth interview).

While many stakeholders emphasized collaboration, a researcher expressed reservations about private sector involvement in WtE projects.

> *"I understand the potential benefits of PPPs, but concerns exist about potential profit motives overriding environmental considerations. Local businesses should be given a fair chance to participate in WtE initiatives, ensuring transparency and community benefit."*— Waste researcher—ID WR1 (In-depth interview).

Additionally, the minority group (30%) voiced concerns about potential knowledge gaps within the local government when entering into PPPs with private waste management companies.

> *"Collaboration is crucial, but capacity building within the government sector is essential. We need to ensure local authorities have the necessary expertise to effectively negotiate and manage PPP agreements related to WtE projects."*— Environmental Protection Agency—ID EPA 2 (In-depth interview).

These quotes from the focus group discussion and in-depth interviews highlight contrasting perspectives on institutional collaboration. They raise concerns about potential profit motives and knowledge gaps within the government, suggesting a need for a balanced approach that emphasizes transparency, local participation, and capacity building.

Technical Considerations

In terms of the technical aspects involved in implementing WtE projects in the Tamale Metropolis, Ghana, a significant majority emphasizes the importance of conducting feasibility assessments, embracing technological advancements, and promoting ongoing research and innovation to optimize WtE processes. Factors such as waste composition, available technology, and infrastructure significantly impact the feasibility and success of WtE initiatives. Without comprehensive feasibility studies and advancements in technology to

improve efficiency and environmental sustainability, the execution of WtE projects may encounter technical obstacles and fail to realize their potential benefits. Addressing these technical considerations is vital to ensure the effective integration of WtE technologies into the waste management framework in Tamale, thereby contributing to sustainable development and resource utilization in the region.

> *"Thorough feasibility studies are crucial, but we should also consider adaptable technologies that can accommodate the evolving nature of our waste stream. Tamale's waste composition may change over time, and we need WtE solutions that can adapt to maintain efficiency and environmental benefits."*— Environmental Protection Agency—ID EPA3 (in-depth interview).

> *"Technological advancements play a vital role in optimizing WtE processes. Continuous research and innovation are necessary to improve efficiency and environmental sustainability."* Waste researcher—ID WR 3 (in-depth interviews).

While the focus on technical considerations was widely shared, some dissenting voices emerged within the focus groups.

> *"The focus on high-tech solutions may not be the most practical approach for Tamale. Simpler, low-maintenance WtE technologies might be more suitable for our context, considering limited resources and technical expertise."*— Local Government staff—LG2 (Focus group discussion).

Additionally, an environmental expert (10%) expressed concerns about the potential limitations of current WtE technologies.

> *"While advancements are promising, WtE still carries inherent environmental risks. We need to prioritize stricter emissions regulations and ongoing monitoring to ensure WtE projects in Tamale are truly sustainable and don't create new environmental burdens."*— Environmental Protection Agency Representative—ID EPA 2 (In-depth interview).

These quotes from participants in the study highlight contrasting perspectives on the technical aspects of WtE implementation. They raise concerns about the suitability of complex technologies and the potential environmental impact, suggesting a need to consider simpler solutions and prioritize robust environmental safeguards.

Further Analysis

The integration of WtE technologies into Tamale's existing waste management system encounters numerous challenges, as uncovered by the qualitative survey findings presented in this study. The results demonstrate a consensus on major challenges and opportunities, as well as intriguing divergent perspectives.

- Policy and Financial Hurdles:

A consensus among stakeholders emphasizes the critical necessity for supportive government policies and clear regulations to incentivize investment in WtE projects, a finding reflected in the literature [60,61]. Participants underscored the importance of conducting financial feasibility studies to ensure long-term economic viability; a sentiment echoed in the literature [32,62,63]. Similarly, Ref. [64] reported similar findings, highlighting that, like many cities in developing countries, the majority of MSWM budgets are allocated to collection and disposal rather than supporting innovative waste minimization efforts.

Moreover, a significant majority of stakeholders identify financial hurdles as a major barrier to implementing WtE initiatives. Concerns primarily revolve around the substantial upfront costs, operational and maintenance expenses, and the lack of readily available financing mechanisms to support these projects. Additionally, limited access to financial incentives and investment options discourages private sector participation, while the absence of comprehensive economic feasibility studies raises doubts about long-term financial sustainability. This uncertainty surrounding the viability of WtE as a solution

could potentially hinder progress toward environmental and energy goals in Tamale. Moving forward, it is imperative to explore WtE alternatives that are potentially less expensive for waste management, alongside conducting thorough examinations of WtE's financial feasibility and social impact. This aligns with findings from the literature [17,65,66], where finance emerges as one of the primary barriers to developing a WtE system in developing nations.

Conversely, a minority viewpoint (23%) in this study suggests that existing policies might be sufficient. This underscores a potential gap in understanding and/or the need for more targeted policy interventions [67–71].

- Social and Political Considerations:

The research underscores the importance of public awareness campaigns, community engagement, and stakeholder involvement for successful WtE implementation, Refs. [5,72] found similar outcomes in their study on sustainable cities as options for improving solid waste management in Nairobi city. Notably, some concerns were raised about potential delays in WtE projects due to extensive public engagements; this is not different from the account in the literature by [73–75]. Additionally, waste pickers expressed apprehension about the impact of WtE on their livelihoods, a concern that resonates with earlier research by [76], where he explored the link between waste governance structures and livelihood options for urban waste pickers. These contrasting viewpoints suggest a need for a balanced approach that prioritizes transparency, community education, and social impact assessments alongside project efficiency [77].

- Institutional Collaboration and Capacity Building:

Stakeholders in the study widely recognize the value of PPPs for tapping into expertise and reducing financial risks, a sentiment supported by existing literature [35,78,79]. However, concerns have arisen regarding the possibility of profit motives overshadowing environmental concerns, echoing findings in the literature [5,67,80]. Also, a critical challenge lies in the observed knowledge gaps and know-how within the local government and waste industry in Tamale. This is highlighted by the limited experience in both entering Public–Private Partnership (PPP) agreements and managing Waste-to-Energy plants. This situation underscores the need for robust PPP frameworks that prioritize transparency, local participation, and capacity-building initiatives.

- Technical Considerations and Innovation:

The importance of conducting feasibility studies, embracing technological advancements, and promoting ongoing research for efficient and environmentally sustainable WtE processes was dominant under the technical and innovation theme, echoing findings in the literature [81–83]. However, dissenting voices advocated for simpler, low-maintenance technologies suitable for Tamale's context and emphasized the need for stricter environmental regulations to mitigate potential risks. Even though the perspectives are not so contrasting, the findings highlight the importance of considering both technical efficiency and environmental safeguards when selecting and implementing WtE technologies, as echoed in the literature [84,85]. Overall, the integration of WtE technologies in Tamale's waste management system requires addressing policy perspectives, financial implications, socio-political dynamics, institutional framework, and technical considerations. By overcoming these challenges, Tamale can harness the potential of WtE technologies to achieve environmental sustainability, energy generation, and waste management objectives.

3.1.4. Barriers, Success Factors, and Practical Implementation of WtE in the Existing System of Solid Waste Management in Tamale

Leveraging insights from focus group discussions, in-depth interviews, and literature, this section outlines a framework for effective WtE integration within Tamale's MSW management system. While WtE holds promise, successful implementation hinges on careful consideration of three crucial elements: stakeholders, barriers, and success factors, as detailed in Figure 2.

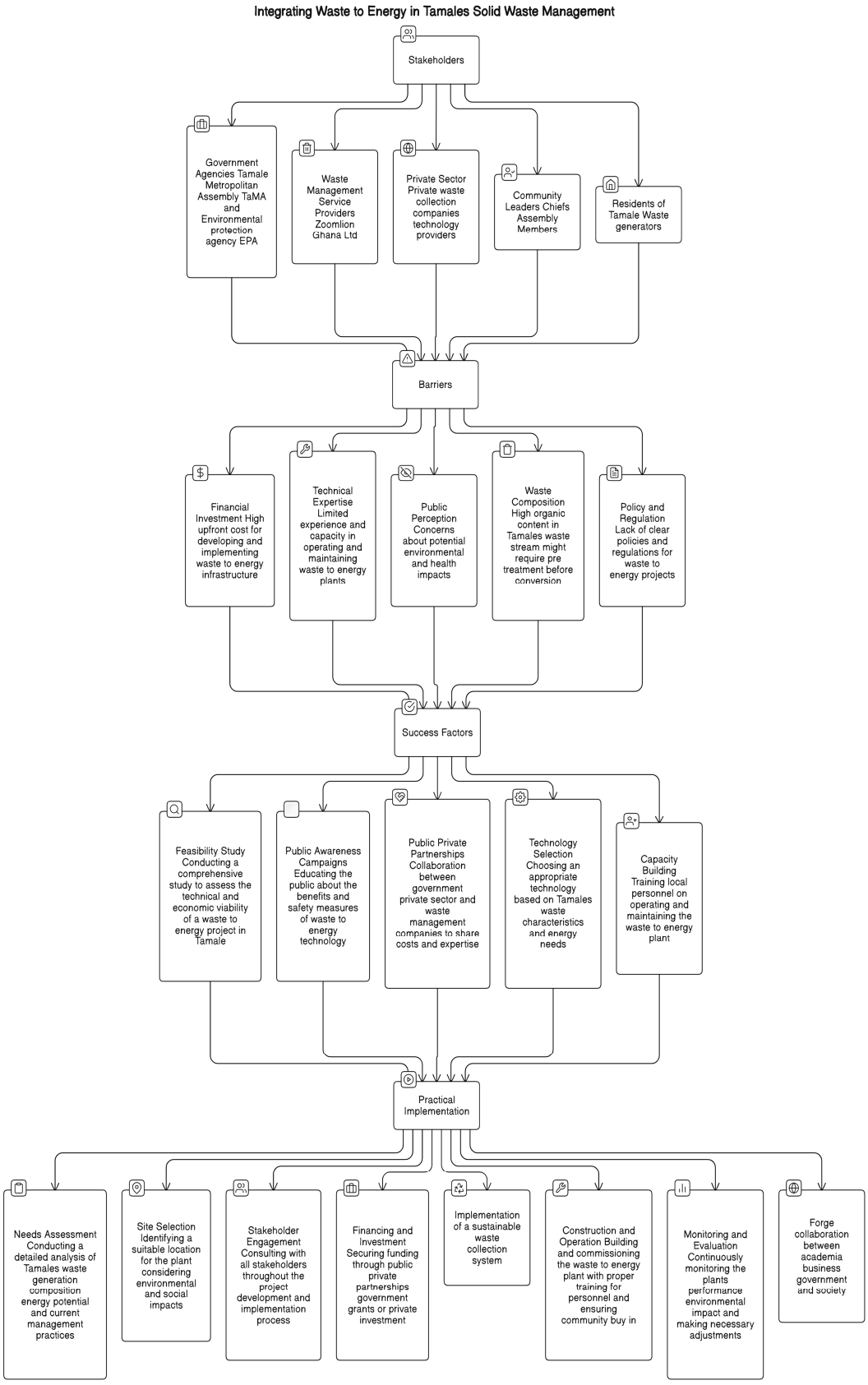

Figure 2. Barriers, success factors, and practical implementation of WtE in the existing system of solid waste management in Tamale.

The framework begins with a cluster of stakeholders whose active participation is essential for the successful implementation of a WtE project. The stakeholder group includes government agencies, particularly the TaMA and the Environmental Protection Agency (EPA), which play crucial roles in creating a supportive policy framework and ensuring environmental compliance. Private sector entities and waste management service providers, such as Zoomlion Ghana Ltd. and Sama Sama, contribute by leveraging their existing infrastructure and expertise for efficient waste collection, technology, and delivery to the proposed WtE facility. Community leaders, such as chiefs and assembly members, serve as vital bridges between a WtE project and residents, fostering public acceptance and facilitating smooth project execution. Finally, residents of Tamale, as waste generators, play crucial roles in waste segregation and responsible disposal practices. Engaging them through educational campaigns and promoting community ownership of the project are essential steps.

The key barriers hindering a successful WtE implementation in Tamale include the following: Firstly, the high initial investment required for infrastructure development poses a significant hurdle. PPPs can play a crucial role in mitigating this challenge by sharing costs and leveraging private sector expertise. Secondly, the limited technical expertise in operating and maintaining WtE plants presents another barrier, which can be addressed through capacity-building programs. Public perception is also a critical barrier, with concerns about potential air and water pollution needing proactive addressing. Comprehensive environmental impact assessments and transparent communication strategies are essential to ensure public safety and garner community support. Furthermore, Tamale's waste stream, characterized by its high organic content, may require pre-treatment processes before conversion to energy. Careful technology selection and feasibility studies are necessary to address this challenge by identifying WtE technologies suitable for the specific waste composition. Lastly, the lack of clear policies and regulations surrounding WtE projects is a major hurdle. Collaborative efforts between government agencies and industry stakeholders can help develop a regulatory framework to incentivize WtE development and ensure responsible operation.

Drawing insights from focus group discussions, in-depth interviews, and existing literature, the following success factors are compiled for the effective implementation of WtE in Tamale (See Figure 2). Firstly, conducting a comprehensive feasibility study is vital to assess the technical and economic viability of a WtE plant in the local context. Secondly, public awareness campaigns are necessary to educate residents about the benefits of WtE technology, including waste reduction, energy generation, and environmental conservation practices. Thirdly, public–private partnerships that leverage government resources, private sector expertise, and community participation are crucial for ensuring the long-term sustainability of the project. Additionally, selecting the most appropriate technology based on Tamale's specific waste composition and energy needs is essential. Finally, capacity building through training programs for local personnel ensures the efficient operation and maintenance of the WtE plant.

Lastly, moving from planning to action requires a well-defined implementation plan. This can be found in the fourth cluster of Figure 2. Firstly, a comprehensive assessment will be carried out to detail Tamale's waste generation, composition, energy potential, and current management practices. These data will inform the selection of the most suitable technology. Identifying a suitable site for the plant that minimizes environmental and social impacts is crucial. Stakeholder engagement throughout the process fosters trust, addresses concerns, and ensures community buy-in. Financing and investment strategies, as key implementation activities, will involve a combination of public-private partnerships, government grants, or private investments. A sustainable waste collection system is essential to ensure a consistent supply of waste to the WtE plant. Construction and operation of the plant require careful planning, adherence to safety standards, and comprehensive training for personnel. Lastly, monitoring and evaluation will be carried

out to assess the plant's performance and environmental impact and make necessary adjustments for sustained success.

3.1.5. Models for Waste-to-Energy Systems in Developing Countries

Tamale, Ghana, could potentially learn from several successful WtE systems implemented in other developing countries, which optimize waste management and generate electricity:

Phuket, Thailand: Phuket has implemented a WtE system where municipal solid waste is converted into electricity via an incineration plant. The facility has a capacity of 9.5 MW and processes about 600 tons of waste per day. The electricity produced is sold to the national grid, creating a revenue stream for the local government [86].

Lahore, Pakistan: Lahore features a WtE plant with a capacity of 12 MW, processing approximately 3000 tons of waste daily [87]. This project represents a public–private partnership, showcasing the potential for collaboration in WtE initiatives.

Addis Ababa, Ethiopia: The Reppie Project in Addis Ababa marks one of Africa's first WtE facilities, with a capacity of 50 MW and processing around 1400 tons of waste per day [88]. The project exemplifies effective governmental and private-sector cooperation.

Other African Initiatives

Kenya: The Gorge Farm Anaerobic Digestion Power Plant in Naivasha, Kenya, processes vegetable and flower waste to generate 2.4 MW of power [89].

South Africa: The Bronkhorstspruit Biogas Plant, operated by Bio2Watt Ltd., is the continent's first industrial-scale WtE facility, producing biogas from organic waste to generate electricity. Additionally, a state-of-the-art biogas plant is planned for 2025 to serve Cape Town [90].

Zimbabwe: Plans are underway for the Bulawayo Waste-to-Energy power plant to convert solid waste into biodiesel and biogas for electricity generation [91].

Ghana's Emerging Projects: A notable project in Gyankobaa, Ghana, is the Hybrid-PV-Biogas-Pyrolysis plant, the first in the nation, which aims to convert 12 tons of waste daily into bio-fertilizer and energy [92]. This medium-scale power plant will combine solar energy, biogas, and pyrolysis of plastic waste to generate electricity.

These examples illustrate diverse approaches in the deployment of WtE technologies that efficiently manage waste while producing energy, offering valuable lessons for implementing similar systems in Tamale, Ghana.

3.1.6. Transition to an Integrated Sustainable Waste Management Framework That Integrates WtE System in Tamale

The block diagram below illustrates an integrated waste management system encompassing WtE plants. This comprehensive waste management framework tailored for Tamale seamlessly integrates WtE technologies, heralding a new era of sustainability and circularity in waste management practices. At its core, the system addresses the multifaceted challenges posed by MSW generation from both commercial and residential sources. The schematic diagram begins with the meticulous collection and transportation of MSW to a centralized sorting facility. Here, manual and automated sorting techniques are employed to segregate recyclable materials, effectively minimizing waste and maximizing resource recovery.

A pivotal aspect of the system lies in its treatment of mixed waste streams, a common challenge in the prevailing solid waste management system in Tamale. Following the sorting processes, non-recyclable materials are directed towards a specialized material recovery chamber for pre-processing of non-recyclables towards WtE plant utility. Organic waste, a significant fraction of MSW, is channeled to the anaerobic digestion plant, yielding biogas for energy production and compost for soil enrichment. This dual benefit not only reduces the carbon footprint but also fosters sustainable agricultural practices, promoting soil fertility and crop productivity.

Meanwhile, other non-recyclable materials from the material recovery chamber, together with residual waste unsuitable for conventional recycling or composting, find their way to a landfill plant equipped with gas capture and scrubber capabilities. Here, energy is harnessed through methane production for the generation of heat and electricity while mitigating environmental impacts. Notably, stringent measures are implemented to minimize emissions, ensuring that odor, NOx, and other pollutants are kept at minimal levels.

The energy and resources harvested through these processes form the cornerstone of a circular economy paradigm. Recycled materials are seamlessly reintegrated into the consumption and production cycle, reducing reliance on virgin resources and mitigating environmental degradation. Clean energy derived from biogas and landfill WtE processes meets both the WtE plants' energy requirement and the city's energy needs sustainably, fostering resilience and independence. Furthermore, the production of compost enriches soil fertility, fostering sustainable agricultural practices and reducing dependence on chemical fertilizers. By championing a circular economy, the framework not only addresses the immediate challenges posed by MSW but also paves the way for long-term environmental sustainability and economic resilience in Tamale.

In essence, this waste management framework represents a paradigm shift towards holistic and sustainable practices, embodying the principles of circularity, resource efficiency, and environmental stewardship. By harnessing the potential of WtE technologies and embracing innovative solutions, Tamale is poised to lead the way toward a greener, cleaner, and more prosperous future.

4. Validation of Proposed Framework

Considering that the best practice for managing solid waste involves an ISWM system and recognizing that TaMA is solely responsible for managing MSW in Ghana, it was essential to involve staff from TaMA, EPA, which is responsible for environmental regulation within the country, and Zoomlion Ghana Limited which is a waste service provider with extensive expertise in the field of waste in Ghana in validating the developed framework. Their participation allowed for confirmation or challenge of the framework's findings. By selecting representatives from waste management regulators, service providers, and the government sector, the validation process aimed to assess the framework's theoretical standpoint for the concept of MSW management integrated with Waste-to-Energy for adoption in Tamale against the practical considerations of these key stakeholders. Answers to the framework validation questions are presented in Table 2. A consensus emerged among participants regarding the framework's logical structure, its effectiveness in addressing WtE and MSW management issues, its adequacy, and its feasibility.

This framework can assist waste management decision-makers in taking the guesswork out of decisions for waste management planning in the metropolis, as the framework incorporates a better picture of how a waste management system encompassing WtE works and how that could improve the solid waste issues of Tamale. Thus, the application of this framework has the potential to increase the level of decision-makers' awareness of the challenges of prevailing MSWM and possibly lead to the effective take-off of WtE technologies in Tamale.

The participants from EPA, Zoomlion Gh. Ltd., and TaMA were in agreement that the WtE framework is highly important for effective MSW management. They found the framework easy to comprehend, with a clear structure that focuses on actionable points. The framework was also well-received as an adequate aid for MSW management decision-making, providing a logical and comprehensive approach. They particularly emphasized the potential for reducing reliance on landfills and promoting waste diversion through the effective implementation of WtE technologies.

Table 2. Stakeholder Perspectives on the Waste-to-Energy Framework's Applicability and Effectiveness—Framework validation.

Question	**Responses**		
	EPA	**Zoomlion Gh. Ltd.**	**TaMA**
How important are all the elements of waste-to-energy in the framework to effective MSW management?	Crucial. All elements in the framework are essential for a comprehensive MSW management.	Highly important. The framework provides a roadmap for integrating WtE seamlessly into existing system.	Essential. WtE can address waste challenges, but a holistic approach as this is needed for long-term success.
How easy is it to understand the framework?	The framework is well structured and easy to follow.	Easy to understand and focus on key action points.	The framework is straightforward.
To what extent will you say this framework is adequate for effective MSW management decision-making?	A well-developed framework. It provides a strong starting point for informed decision-making.	Valuable tool. The framework helps assess the feasibility and optimize WtE integration for Tamale's specific needs.	The framework offers an innovative approach to effective MSW management.
To what extent is this framework logical?	Logical and well-organized. The framework builds on a sequential process, ensuring a comprehensive approach.	Logical	Makes good sense. Framework aligns with best practices for sustainable waste management.
Do the elements suggested in the framework address MSW siege in the metropolis?	The framework, if implemented effectively, can significantly reduce reliance on landfills and promote waste diversion through WtE.	By addressing waste composition and optimizing WtE technology, the framework tackles MSW challenges.	The framework offers a strategic approach to tackling the waste crisis in Tamale.
How transferrable is this framework to other jurisdictions with similar challenges as Tamale?	The framework can be adapted to other cities with similar waste composition and development level. However, local context needs to be considered.	We see potential for adaptation of this framework in other cities with similar waste management needs.	The framework can be a valuable blueprint for other cities facing similar waste issues, with necessary adjustments for local specifics.
What do you consider as the strengths and weaknesses of the framework?	Strengths: Holistic approach, focus on public engagement, and emphasis on financial sustainability. Weaknesses: None	Strengths: Clear focus on WtE integration. Weakness: Financial projections might need collaboration with relevant stakeholders.	Strengths: Addresses long-term waste management needs. Weakness: None
What can be added to and/or removed from the framework?	Add or remove nothing	Nothing	Remove nothing

Furthermore, the respondents acknowledged the transferability of the framework to other cities facing similar waste challenges, with necessary modifications to suit local contexts. They highlighted the strengths of the framework, such as its holistic approach, public engagement focus, and financial sustainability considerations. There were no significant weaknesses noted, though some suggested that financial projections might require further collaboration.

The consensus was that the framework is robust and well-equipped to address the MSW crisis in Tamale and that it can also serve as a valuable guide for other cities with similar waste management goals.

4.1. Benefits of the Proposed New Waste System Centered on Waste-to-Energy

The proposed new waste management system centered on WtE technology (see Figure 3 offers numerous benefits for Tamale. Firstly, it provides a sustainable solution to the city's growing waste problem by diverting waste from landfills and reducing the environmental impact of waste disposal. WtE plants can process non-recyclable waste, which would otherwise end up in landfills, and convert it into valuable energy resources. Secondly, WtE technology can generate renewable energy in the form of electricity and heat, contributing to Tamale's energy security and reducing its reliance on fossil fuels. This can lead to lower energy costs for residents and businesses, as well as a reduction in greenhouse gas emissions, mitigating the city's contribution to climate change.

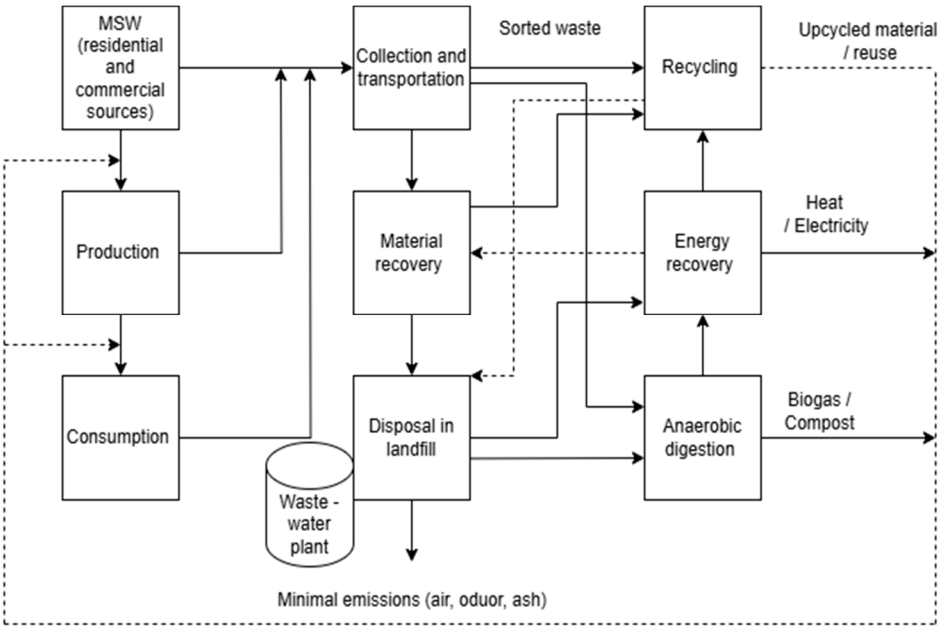

Figure 3. Roadmap for WtE-focused IWMS for Tamale.

Thirdly, the implementation of a WtE plant can create jobs and stimulate economic growth in Tamale. The construction and operation of the plant require skilled labor, providing employment opportunities for local residents. Additionally, the sale of electricity and heat generated from the plant can generate revenue for the city. Fourthly, WtE technology can improve public health by reducing the amount of waste disposed of in open dumps and landfills. This can minimize the risk of disease transmission and create a cleaner and healthier environment for residents. Finally, the adoption of WtE technology can enhance Tamale's reputation as a sustainable and forward-thinking city. It can attract investment, promote tourism, and contribute to the overall well-being of the community. By embracing WtE as a central component of its waste management strategy, Tamale can pave the way for a more sustainable and prosperous future.

4.2. Generalizability of Study Findings to Other Urban Areas in Developing Countries

The application of the insights from this study, which focused on integrating WtE technology within Tamale's MSWM system, to other urban areas requires careful consideration of several contextual factors. This section outlines the conditions under which our findings and recommendations may be applicable to other urban settings in developing countries, providing a guide for assessing the potential for similar implementations elsewhere.

4.2.1. Urban and Institutional Contexts

Our findings are likely applicable to urban areas facing similar challenges in waste management infrastructure, particularly in cities undergoing rapid urbanization without corresponding advancements in MSWM capabilities. The generalization is also contingent upon the presence of underdeveloped or loosely enforced policy frameworks similar to those observed in Tamale.

4.2.2. Public Perception and Cultural Factors

The effectiveness of our recommendations depends significantly on local cultural attitudes towards waste management. Cities with cultural dynamics comparable to Tamale, where waste segregation practices are minimal and public awareness is lacking, may find these insights particularly relevant.

4.2.3. Economic Conditions

The strategies we propose, particularly those emphasizing PPPs for financial and operational enhancement, are predicated on the presence of economic environments that support such collaborations. Urban areas that already have PPP frameworks in place or are evaluating PPPs as a feasible method to improve municipal solid waste management are likely to observe comparable advantages.

4.2.4. Environmental Priorities

Cities that prioritize environmental sustainability and are aligned with global sustainability goals, such as SDGs 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production), are more likely to benefit from the application of the research findings.

4.2.5. Technological Suitability

The choice of specific WtE technologies should be adapted based on local waste composition and the technological infrastructure available. Our implementation strategies are particularly pertinent to regions that can either adopt similar technologies or adapt them to local conditions. Through this analysis, our research extends its reach, offering a scalable model for enhancing MSWM practices across diverse urban landscapes in the developing world.

5. Conclusions

This comprehensive study delved into the imperative task of integrating WtE technology within Tamale's existing MSWM system [93]. By meticulously examining potential barriers, delineating success factors, and formulating a pragmatic implementation plan, this research furnishes invaluable insights for guiding future endeavors and policy formulations. Using focus group discussions and in-depth interviews, the study unearthed five pivotal barriers impeding WtE integration in Tamale, including unclear policy frameworks, financial constraints, institutional inefficiencies, negative public perceptions, and a deficient waste segregation culture. To surmount these hurdles, it advocates for the development of comprehensive policies, exploring PPPs to alleviate financial constraints, and augmenting institutional capacities. Furthermore, it underscores the importance of public awareness campaigns and fostering responsible waste disposal practices to assuage public concerns and garner community support.

Conversely, the research proposed key implementation strategies essential for the successful rollout of WtE technology in Tamale. These encompass conducting thorough feasibility studies, embarking on robust public awareness campaigns, fostering PPPs to leverage resources and expertise, selecting suitable WtE technology tailored to Tamale's waste composition, and investing in capacity building through training programs. This research not only provided valuable insights but also guided the development of a novel framework for MSW management with viable WtE alternatives. If adopted by the Tamale Metropolitan Assembly, this framework has the potential to significantly accelerate progress towards achieving SDGs 7, 11, and 12 and can pave the way for tangible progress towards a cleaner, more sustainable future for Tamale and serve as a beacon for sustainable waste management practices in other developing regions.

Further, the insights gleaned from this study hold significant implications for policymakers and stakeholders in Tamale as they contemplate the integration of WtE into the city's waste management system. By adeptly addressing the identified barriers and leveraging the outlined success factors, Tamale stands poised to realize substantial advancements toward a sustainable future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/world5030034/s1, Figure S1: Gbalahi landfill site.

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