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Waste-to-Energy Potential in Medan City, Indonesia: Challenges and Opportunities for Sustainable Urban Development

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ABSTRACT
Medan City, Indonesia, faces significant challenges in managing its municipal solid waste (MSW), with approximately 628,749 tons generated annually. The current waste management system primarily relies on landfills, which are unsustainable and contribute to environmental pollution. This study explores the potential of waste-to-energy (WtE) technologies as a solution to Medan's waste management challenges and a means to contribute to renewable energy production. The theoretical energy potential of Medan's MSW is estimated to be 1,747,000 MWh per year, based on its calorific value. However, the implementation of WtE technologies, such as incineration, anaerobic digestion, and gasification, faces technical, economic, environmental, social, and policy challenges. These include infrastructure gaps, high costs, emission concerns, public opposition, and regulatory barriers. Overcoming these challenges requires a multi-stakeholder approach, including partnerships with the private sector and international organizations, integration with local energy and waste management policies, and public education campaigns. By leveraging existing case studies and best practices, Medan can develop a comprehensive WtE strategy that addresses its waste management needs while contributing to renewable energy goals.

Keywords: waste-to-energy; Medan city; solid waste management; sustainability; renewable energy.

HIGHLIGHTS
- Medan generates approximately 628,749 tons of solid waste annually.
- Current waste management in Medan primarily relies on insufficient landfills.
- Medan waste has a theoretical annual energy potential of 1, 747, 000 MWh.
- Waste-to-energy technologies face technical, economic, environmental, social, and policy challenges.
- Overcoming challenges requires a multi-stakeholder approach, policy frameworks, and public awareness.
- Medan can enhance waste management practices and contribute to renewable energy goals.

INTRODUCTION
Waste management in Medan City, Indonesia, presents a complex challenge that is exacerbated by rapid urbanization and population growth. The city generates approximately 628,749.22 tons of solid waste annually, highlighting the urgent need for effective waste management strategies [1]. The current waste management system relies primarily on standard disposal methods, which include transferring waste from temporary shelters to landfills. This approach is insufficient to address the growing waste problem because it does not incorporate waste reduction, recycling, or recovery practices [2].

The inefficiency of waste collection and management systems in Medan significantly contributes to urban pollution and public health risks. An integrated and sustainable solid waste management system is essential to mitigate these issues [3]. The lack of resources and training for waste management personnel further complicates the situation, particularly in healthcare settings, where medical waste is generated. Approximately 376,089 kg of medical waste is produced annually in Medan, indicating the pressing need for improved management practices in this sector [4].

The Deli River, which flows through Medan, has been severely affected by improper waste disposal practices, with significant pollution resulting from both organic and inorganic wastes [5,6]. This situation underscores the need for comprehensive waste management policies that not only address waste collection and disposal but also promote sustainable practices such as recycling and waste reduction [7]. The involvement of the private sector in waste management has been shown to enhance efficiency and effectiveness, suggesting that partnerships could be a viable solution for Medan [8].

Waste-to-energy (WtE) initiatives have gained traction globally as a sustainable solution to the increasing challenges of municipal solid waste (MSW) management. These initiatives convert non-recyclable waste into usable energy, primarily in the form of electricity or heat, thereby reducing the volume of waste sent to landfills and mitigating greenhouse gas emissions associated with waste decomposition [9,10]. The WtE process not only addresses waste disposal issues but also contributes to energy production, which is particularly crucial in regions facing energy shortages [11,12].

In Southeast Asia, including Indonesia, WtE technologies such as incineration and anaerobic digestion are being explored to effectively manage the growing waste problem [12]. Medan City, one of Indonesia's largest urban centers, generates a significant amount of waste, making it a prime candidate for implementing WtE solutions. The city currently faces challenges related to waste collection and disposal, with a substantial portion of its waste ending up in landfills and exacerbating environmental pollution [1,2]. By adopting WtE technologies, Medan could not only reduce landfill dependency but also harness energy from its waste, thereby contributing to local energy needs and promoting sustainability [13].

The exploration of WtE potential in Medan City presents a critical opportunity to address the dual challenges of waste management and energy production. Medan, a rapidly urbanizing city in Indonesia, has faced significant waste management issues, primarily because of its reliance on open dumping practices since 1993, which has led to severe environmental and public health concerns, including deteriorating air quality and increased respiratory illnesses among residents [14]. The city's waste generation is substantial, with a notable composition of recyclable materials, indicating the potential of WtE initiatives to convert waste into valuable energy resources [15,16].

The integration of WtE technologies could significantly mitigate the adverse effects of waste accumulation, while simultaneously contributing to energy sustainability. However, the implementation of such systems is fraught with challenges including inadequate infrastructure, lack of public awareness, and insufficient governmental support [17]. For instance, existing waste management practices in Medan are characterized by a lack of effective separation at the source, which complicates recycling and energy recovery processes [18]. Furthermore, a city's spatial planning and governance structures may not currently support the necessary investments in WtE technologies, highlighting the need for a comprehensive strategic approach that encompasses both technological and policy dimensions [19,20].

Opportunities for enhancing WtE potential in Medan also lie in community engagement and education. Initiatives such as waste banks have begun to foster community participation in waste sorting and management, which is essential for the success of WtE projects (Auliani et al., 2023; Khair et al., 2019). Additionally, leveraging advancements in information technology can improve waste monitoring and management systems, thereby enhancing operational efficiency and stakeholder involvement [1]. As Medan City continues to evolve, the exploration of WtE potential not only aligns with global sustainability goals but also addresses local environmental and energy challenges, paving the way for a more resilient urban future.

Medan City represents a critical case study because of its rapid urbanization rates and the local government's recent initiative to explore renewable energy sources, making it a prime candidate for WtE technologies. While previous studies have investigated the theoretical potential of WtE in Indonesia, this study aims to specifically analyze the technical, economic, and policy barriers to implementing such technologies in Medan City.

This study contributes to the development of sustainable waste management policies in Medan by providing insights into the potential of WtE technologies and identifying challenges and opportunities associated with their implementation. By addressing the waste management crisis through innovative solutions, Medan can enhance its urban resilience and support Indonesia's renewable energy goals.

METHODS

1. Research Design

A qualitative research design was adopted, using a systematic literature review. This approach facilitates a thorough synthesis of the existing knowledge on waste-to-energy technologies and their relevance to Medan City.

2. Data Collection

Data for this study were collected from diverse sources to ensure a comprehensive analysis.

- Peer-reviewed Articles: Academic research on waste management and WtE technologies.
- Government Reports: Publications from Indonesian authorities, including the Ministry of Environment and Forestry and Medan's municipal agencies.
- Case Studies: Documented examples of WtE projects in Southeast Asia and other comparable urban contexts.
- Policy Documents: National and local policies addressing waste management and renewable energy.
- Municipal Waste Statistics: Data on waste generation, composition, and disposal practices in Medan City.

RESULTS AND DISCUSSION

1. Current Waste Management in Medan

Medan generates a substantial amount of waste, with estimates indicating that approximately 5,616 m^3 of waste is produced daily, translating to approximately 2,000 tons [21]. This high volume of waste is driven by rapid urbanization, population growth, and increasing consumption patterns. The National Waste Management Information System indicates that the total waste generated in Medan is approximately 628,749 tons annually [1]. The sheer volume of waste poses significant challenges to its effective management and disposal, particularly given the limited capacity of existing landfills.

The composition of waste in Medan reflects typical urban waste characteristics with a significant proportion of organic materials. While specific data on Medan's waste composition are limited, studies from similar urban contexts suggest that organic waste, plastics, and paper constitute the majority of the waste stream. For instance, in other urban areas, organic waste accounts for approximately 50-60% of total waste, followed by plastics (20-30%) and paper (10-15%) [22]. In Medan, the waste composition is likely to be similar, with the notable presence of food waste, plastics, and other recyclables, which highlights the potential for implementing effective recycling and composting programs.

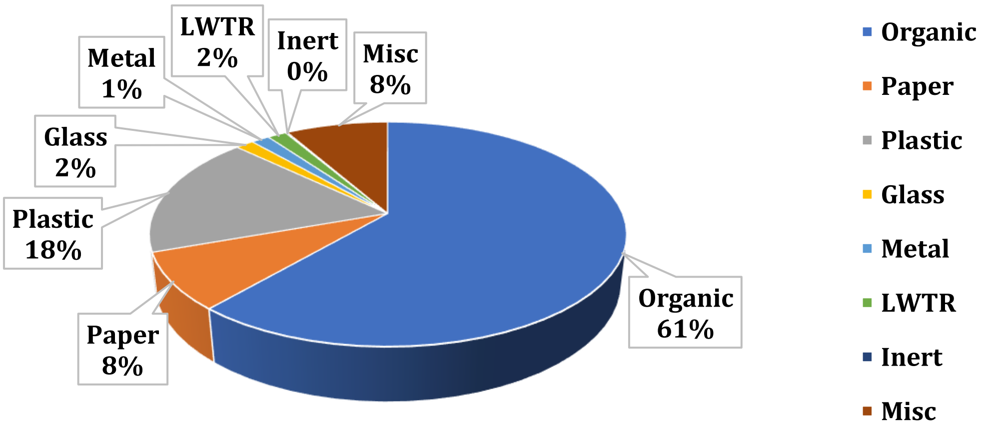

FIGURE 1: Waste composition of Medan City [23].

The waste collection system in Medan is primarily managed by the Medan City Environmental Agency, which is responsible for coordinating waste collection from households and businesses. In practice, the collection is handled by a sub-district. They had trucks provided by the Environmental Agency. However, current collection methods face several challenges, including inadequate coverage, insufficient resources, and lack of public participation in waste segregation practices. Reports indicate that not all waste generated is effectively transported from temporary shelters to final disposal sites, leading to significant amounts of waste remaining uncollected in households and at illegal dumping sites [1,21].

Moreover, reliance on landfills as the primary disposal method exacerbates the challenges faced by waste management systems. Existing landfills are nearing capacity, and the environmental impacts of landfilling, such as leachate and methane emissions, pose additional concerns [1]. Inefficiencies in waste collection systems are further compounded by a lack of community awareness regarding proper waste disposal practices, which can lead to increased littering and pollution [17].

Existing landfill-based approaches to waste disposal in Medan City, as in many urban areas worldwide, face several limitations that hinder effective waste management and pose significant environmental and public health risks.

- *Environmental Pollution*

One of the most critical limitations of landfill-based approaches is their potential for causing environmental pollution, particularly through leachate generation. Leachate, a toxic liquid formed when rainwater percolates through waste, can contaminate groundwater and surface water resources. Studies have shown that leachate from landfills can contain harmful substances, including heavy metals and organic pollutants, which pose risks to human health and ecosystems [24,25]. In Medan, where waste management practices are still developing, the risk of leachate contamination is of particular concern because of inadequate landfill management and monitoring [26].

- *Greenhouse Gas Emissions*

Landfills are significant sources of greenhouse gas emissions, particularly methane, which is produced during the anaerobic decomposition of organic waste [27,28]. Methane is a potent greenhouse gas with a global warming potential that is many times greater than that of carbon dioxide. The release of methane from landfills contributes to climate change and poses challenges to urban sustainability. In Medan, the lack of effective methane capture and utilization systems exacerbates this issue, highlighting the need for alternative waste management strategies to minimize emissions [28,29].

- *Landfill Capacity and Space Constraints*

The reliance on landfills for waste disposal is becoming increasingly unsustainable owing to the limited available space. Many landfills in urban areas, including Medan, are reaching their capacity limits, leading to the urgent need for new disposal sites [27,30] The search for suitable landfill locations often encounters public opposition due to concerns about environmental impacts and property values, creating a significant barrier to expanding landfill capacity [31,32].

This situation necessitates a shift towards more sustainable waste management practices that reduce reliance on landfills.

- *Inefficient Resource Recovery*

Landfill-based approaches typically result in the loss of valuable resources, which can be recovered through recycling and composting. The high volume of organic waste and recyclables in the waste stream presents opportunities for resource recovery, which is often overlooked in traditional landfill operations[33,34]. In Medan, the lack of effective waste segregation and recovery programs means that a significant portion of recyclable materials and organic waste is disposed of in landfills, leading to missed economic and environmental benefits [33,35].

- *Public Health Risks*

Landfills can pose direct public health risks owing to the potential for odor, pest infestations, and the spread of disease. Poorly managed landfills can attract rodents and other pests that carry diseases that affect local communities. In Medan, where waste management practices are still evolving, the public health implications of landfill operations are a pressing concern that must be addressed through improved waste management strategies [25,30].

2. Waste-to-Energy Potential

Estimating the recoverable energy from municipal solid waste (MSW) in Medan City involves analyzing the calorific value of the waste generated and the total volume of waste available for energy recovery. Given that Medan produces approximately 628,749 tons of waste annually, understanding the composition and energy potential of this waste is critical for assessing the feasibility of WtE technologies in the city.

The energy potential of MSW is influenced by several factors, including its calorific value, moisture content, and physical and chemical composition [36]. The calorific value, which represents the amount of energy released during waste combustion, varies significantly depending on the organic and inorganic components of the waste. Typically, organic waste, such as food scraps and yard waste, has a higher calorific value than inorganic materials such as plastics and metals [37].

For instance, studies have indicated that the calorific value of MSW can range from 8 to 15 MJ/kg depending on its composition [38]. In Medan, where organic waste constitutes a significant portion of the waste stream, the calorific value may be at the higher end of the spectrum. Assuming an average calorific value of 10 MJ/kg for the waste generated in Medan. The total energy recoverable was 1,747,000 MWh per year.

3. Challenges and Considerations

Although the theoretical energy potential from Medan's MSW is substantial, several challenges must be addressed to realize this potential.

- Moisture Content: The moisture content of the MSW can significantly affect its calorific value. High moisture levels reduce the energy yield during combustion [39]. It is essential to assess the moisture content of the waste in Medan to refine energy recovery estimates.

- Waste Composition: The physical and chemical composition of the waste influences both the calorific value and efficiency of energy recovery technologies. A detailed characterization of Medan waste is necessary to optimize the selection of appropriate WtE technologies such as incineration or gasification [40,41].

- Technology Selection: Different WtE technologies have varying efficiencies and emission profiles. Technologies such as gasification and anaerobic digestion may offer cleaner alternatives to traditional incineration; however, they require specific waste characteristics for effective operation [37,38].

- Public Acceptance and Policy Framework: The successful implementation of WtE technologies in Medan depends on public acceptance and a supportive policy framework that encourages investment in renewable energy and waste management solutions [7,42].

A comparison of viable waste-to-energy (WtE) technologies, such as incineration, anaerobic digestion, and gasification, is essential to understand their potential roles in sustainable waste management, particularly in urban settings such as Medan City. Each technology has distinct advantages and challenges that can inform decision-making regarding waste management strategies.

TABLE 1: Waste to Energy technologies comparison.

Aspect	Incineration	Anaerobic Digestion	Gasification
Description	A thermal treatment process that combusts waste at high temperatures, reducing it to ash, flue gas, and heat.	Biological process that breaks down organic waste in the absence of oxygen, producing biogas and digestate.	Thermal process converting organic materials into syngas at high temperatures with limited oxygen.
Key Product/Output	Electricity (via heat energy).	Biogas (methane) and digestate (fertilizer).	Syngas (hydrogen and carbon monoxide) for energy or chemical feedstock.

Aspect	Incineration	Anaerobic Digestion	Gasification
Advantages	Volume Reduction: Reduces waste volume by up to 90% [43].	Energy Generation: Produces renewable biogas for energy [44].	High Efficiency: Converts diverse waste types into energy efficiently (Bučinskas et al., 2018).
	Energy Recovery: Generates substantial energy [45].	Nutrient Recovery: Digestate as fertilizer [44].	Lower Emissions: Produces fewer emissions than incineration (Bučinskas et al., 2018).
	Reduced Landfill Dependency: Alleviates landfill pressure [46].	Lower Emissions: Reduces methane emissions compared to landfills [44].	Resource Recovery: Recovers recyclable materials like metals [47].
Challenges	Emissions: Produces harmful pollutants [48].	Feedstock Limitations: Efficiency depends on waste quality [44].	Complex Technology: Requires advanced systems, increasing costs [47].
	Public Opposition: Concerns about air quality [45].	Infrastructure Needs: Requires dedicated facilities [44].	Feedstock Variability: Affects process efficiency [47].
	High Costs: Significant investment required [45].	Public Awareness: Limited acceptance and understanding [44].	Limited Adoption: Less commonly used [47].

3.1 Challenges in Implementation

The implementation of waste-to-energy (WTE) technologies, such as incineration, anaerobic digestion, and gasification, faces multiple challenges in urban settings such as Medan City. These challenges span technical, economic, environmental, social, and policy domains.

- Technical challenges include infrastructure gaps, because many cities lack adequate facilities for waste sorting, processing, and energy recovery [49]. Additionally, waste quality issues, such as high moisture content and contamination with non-combustibles, reduce the calorific value and energy recovery potential, complicating effective WtE implementation [50].

- Economic challenges involve high initial investments for constructing WtE facilities and acquiring technology, which are often difficult in regions with limited budgets [51]. Furthermore, high operational and maintenance costs require significant revenue from energy sales and waste processing fees to ensure financial viability [52].

- Environmental challenges include emission concerns, particularly with incineration, despite modern pollution controls and issues related to ash disposal, which require careful management to avoid contamination [53].

- Social challenges highlight the difficulty of gaining public acceptance, as communities often fear the health risks and environmental impacts associated with WtE plants [54]. Transparent communication and education campaigns such as waste reduction and renewable energy generation [48].

- Policy challenges include regulatory barriers, where unclear or restrictive frameworks hinder WtE development, and a lack of financial incentives such as subsidies or tax breaks, which are critical for attracting investments [49]. Addressing these challenges through coordinated efforts in infrastructure development, public engagement, and supportive policy environments can enhance the feasibility and acceptance of WtE technologies in Medan and elsewhere.

3.2 Opportunities for Development

The implementation of WtE technologies in Medan presents several opportunities for development that can enhance waste management practices and contribute to sustainable urban growth.

Leveraging existing case studies and best practices in Indonesia and Southeast Asia

Leveraging Existing Case Studies and Best Practices Indonesia and Southeast Asia, several successful case studies can serve as models for implementing WtE technologies in Medan. For instance, the implementation of WtE facilities in cities such as Jakarta and Surabaya has demonstrated the feasibility of converting municipal solid waste (MSW) into energy while addressing waste management challenges [36]. By analyzing these case studies, Medan can identify best practices, such as effective waste segregation, community engagement strategies, and operational efficiencies that can be adapted to local contexts. Additionally, the experiences of other Southeast Asian countries, such as Malaysia and Thailand, in developing WtE projects can provide valuable insights into overcoming common challenges, such as public opposition and regulatory hurdles [55]. These examples highlight the importance of tailored approaches that consider the local waste characteristics, community needs, and environmental regulations.

Potential partnerships with the private sector and international organizations

Potential Partnerships with Private Sectors and International Organizations Establishing partnerships with private sector entities and international organizations can significantly enhance the development and implementation of WtE technologies in Medan. Private companies often possess the technical expertise and financial resources necessary to invest in WtE infrastructure, whereas international organizations can provide funding, technical assistance, and capacity-building support [56]. Collaboration with private sector stakeholders can facilitate the adoption of innovative technologies, such as anaerobic digestion and gasification, which may not be readily available locally [57]. Furthermore, partnerships with international organizations can help Medan access best practices and lessons learned from successful WtE projects globally, fostering knowledge transfer and capacity building [58]

Integration with local energy and waste management policies

The integration of local energy and waste management policies with WtE technologies is essential to create a supportive environment for their implementation. The local government of Medan can develop policies that promote the use of WtE as a viable solution for waste management while aligning with broader energy and environmental goals [59]. For example, incorporating WtE into a city's renewable energy targets can enhance the attractiveness of such projects to investors and stakeholders [60]. Additionally, establishing clear regulatory frameworks that incentivize WtE development, such as feed-in tariffs for energy generated from waste, can stimulate investment and innovation in the sector [61]. Moreover, aligning WtE initiatives with existing waste management strategies, such as recycling and composting programs, can create a comprehensive approach to waste management that maximizes resource recovery and minimizes the environmental impact [62]. This integrated approach can enhance the overall efficiency and effectiveness of the waste management systems in Medan.

CONCLUSION

The implementation of waste-to-energy (WtE) technologies in Medan City offers a promising avenue for tackling waste management challenges while contributing to renewable energy production. This study highlights the potential of a city to integrate WtE technology into its waste management framework. Medan generates approximately 628,749 tons of solid waste annually, predominantly managed through landfills, which face sustainability and capacity issues. With a theoretical energy potential of 1,747,000 MWh annually derived from the calorific value of its waste, the city has a significant opportunity to address both waste disposal and energy needs. Technologies, such as incineration, anaerobic digestion, and gasification, have unique benefits and challenges. However, its implementation is hindered by infrastructure gaps, high costs, environmental and public concerns, and regulatory barriers. Overcoming these challenges requires multi-stakeholder collaboration and alignment with local and national policies.

Several recommendations have been proposed to advance the adoption of WtEs. First, detailed waste characterization studies should guide accurate energy potential assessments and appropriate technology selection. A comprehensive WtE strategy that integrates broad waste management and renewable energy policies is essential for sustainable development. Public education campaigns can address concerns and build community support, while public-private partnerships can bring in necessary expertise and resources. Capacity-building and pilot projects will further refine and demonstrate the feasibility of WtE solutions in the Medan context. By addressing these challenges and seizing available opportunities, Medan can enhance its waste management practices, contribute to renewable energy goals, and position itself as a leader in sustainable urban development.

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