Harnessing Untapped Resources for Sustainable Energy Production from Municipal Solid Waste in Recourse Challenged Economies: A Case Study of Rajshahi City Corporation, Bangladesh

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Abstract

The sustainable management of municipal solid waste is of utmost importance for cities in Bangladesh, including Rajshahi City, which faces unique challenges due to rapid urbanization, industrial growth, and population expansion. This study aimed to gain insights into waste generation patterns and characteristics in Rajshahi by analyzing factors like moisture content, bulk density, dry density, and calorific value of municipal solid waste at the Rajshahi landfill site. The objective was to identify the most feasible method for waste characterization and segregation. The research methodology utilized a comprehensive approach, incorporating field surveys, laboratory analyses, and statistical modeling to create an energy matrix and assess the potential for waste-to-energy production in Rajshahi City. This study aligns with several Sustainable Development Goals (SDGs) related to waste and energy management, including SDG 7: Affordable and Clean Energy - by exploring waste-to-energy options. SDG 11: Sustainable Cities and Communities - by addressing waste management challenges in a rapidly urbanizing area. SDG 12: Responsible Consumption and Production - by promoting sustainable waste management practices. SDG 13: Climate Action - by potentially reducing greenhouse gas emissions through efficient waste-to-energy conversion. Overall, this research contributes to Rajshahi City's efforts to achieve sustainable development while addressing its waste and energy needs by converting its 75.8% organic waste to electricity using an anaerobic digester.

Keywords: *Anaerobic, Rajshahi City Corporation, Municipal Solid Waste, Landfill*

Introduction

Bangladesh is home to a vast population of over 160 million individuals, and it's noteworthy that approximately 29.4% of this demographic is concentrated in urban areas (Barrientos, 2019). In the urban regions of Bangladesh, a daily solid waste output exceeds 25,000 tons, averaging about 0.465 kilograms per individual, as reported by Ahmed in 2019 (When the Garbage Piles Up, 2019). These solid waste materials in Bangladeshi cities originate from various sources, including residential zones, street cleaning efforts, commercial establishments, industrial complexes, healthcare facilities such as hospitals and clinics, as well as other diverse origins (Alamgir et al., 2003). This challenge is particularly pronounced in urban centers, including metropolitan cities, where rapid urbanization has led to an influx of the population, resulting in congestion and exerting immense pressure on all levels of infrastructure. Regrettably, this has culminated in a deterioration of sanitation standards, subsequently giving rise to adverse health consequences. In Bangladesh, the city of Rajshahi, a vital divisional center, faces significant challenges in managing solid waste. This study's results emphasize that, despite substantial financial investments in drainage and sanitation initiatives, the city has been unable to maintain a healthy environment due to ineffective waste management approaches. Consequently, waste materials are haphazardly disposed of on roads and in open spaces, precipitating substantial health hazards and contributing to the degradation of the living environment for approximately one million urban inhabitants. Municipal solid waste (MSW) management presents a formidable and pressing challenge for developing and underdeveloped nations. To provide a clear definition, "Municipal Solid Waste" (referred to as MSW) encompasses substances that are disposed of by households, businesses, or organizations when they are no longer needed by their owners (Vergara & Tchobanoglous, 2012). In stark contrast to their developed counterparts, which produce higher quantities of waste, these economically advanced countries boast efficient and well-funded waste management systems. In the context of countries like Bangladesh, classified as developing, the management of MSW becomes a formidable and costly issue, compounded by a general lack of public attention and commitment to waste disposal. The conundrum escalates with the simultaneous surge in population growth and urbanization, further exacerbating MSW generation, which, in turn, demands an expanding amount of land for disposal (Sharholy et al., 2007). This escalating MSW crisis portends grave environmental pollution and a multitude of hazards for the populace. It's essential to recognize that MSW management is not merely a technical dilemma; rather, it is a multifaceted issue influenced by various political, legal, environmental, and economic factors (Kum et al., 2005).

Literature Review

In the broader context of Bangladesh, rapid urbanization is occurring at a substantial rate of approximately 6% per annum, with a notable concentration in six major cities, including Rajshahi, as emphasized by Habib et al. in 2021 (Habib et al., 2021). This urban growth trend has inevitably led to a significant increase in the generation of municipal solid waste (MSW). Rajshahi, strategically situated along the banks of the Padma River, holds a prominent status as one of Bangladesh's major divisional towns (B. K. Das et al., 2014). Geographically, the city spans a latitude from 24.05' to 25.14' north and a longitude from 88.09' to 89.25' east, covering an area of 96.96 square kilometers. The city corporation was officially established in 1987, as indicated in Halder et al.'s 2014 study. It's worth noting that Rajshahi is home to a population of 0.85 million residents. Within the administrative boundaries of the Rajshahi City Corporation (RCC), the residents collectively generate a substantial daily volume of 400 tons of waste. However, it's important to highlight that door-to-door waste collection services are available in less than 50% of the city's wards, as reported by Halder et al. in 2014 (Halder et al., 2014). A comprehensive analysis of the situation reveals that solid waste generated by households makes up a substantial portion, contributing to about 77.18 percent of the total Municipal Solid Waste (MSW) generated in RCC, as reported by Habib et al. in 2021 (Habib et al., 2021).

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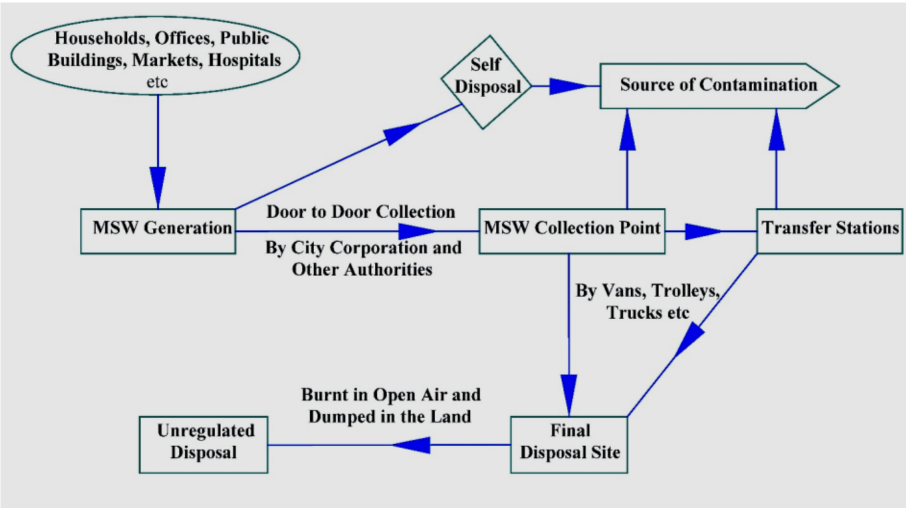
The Figure 1 represents the Current Municipal Solid Waste Management in Rajshahi City Corporation. This flow chart was developed after interviewing the waste management authorities of RCC.

Figure 1: *Current Municipal Solid Waste Management in Rajshahi City Corporation developed based on information from RCC waste management authorities.*



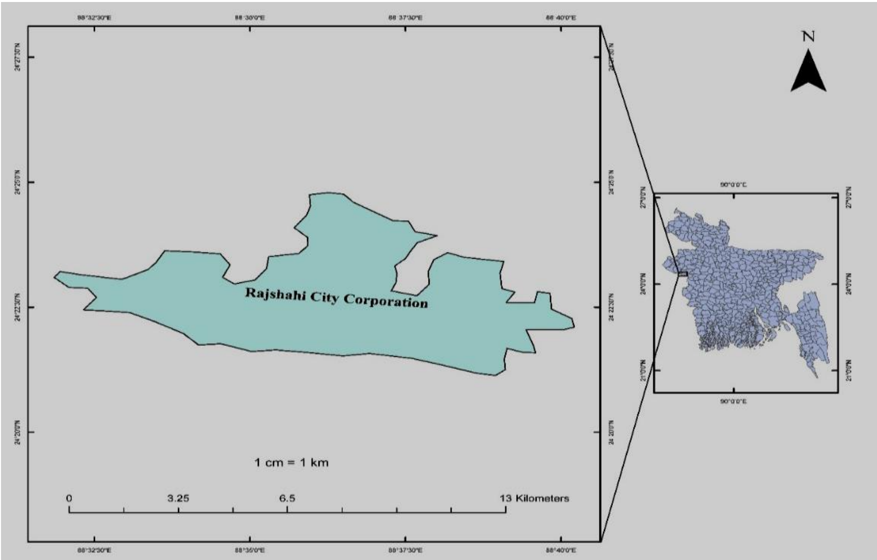
The waste management system consists of 35 secondary collection points and a single final disposal site situated in Nowdapara, as delineated by Islam in 2016. Unfortunately, due to inadequate waste disposal practices, the environmental conditions are deteriorating, giving rise to safety concerns.The solid waste in Rajshahi predominantly consists of a significant organic content, ranging from 60% to 70%, while its proportion of combustible materials is relatively low. Those waste materials that go uncollected find their way into open spaces, streets, and drainage systems, resulting in blockages and causing significant environmental degradation and health hazards. At present, the collected waste is primarily disposed of in a low-lying area located approximately 3 kilometers away from the corporation area. In Rajshahi, waste items with market value undergo reclamation and salvaging processes to facilitate recycling. It is of utmost importance that unmanaged solid waste be systematically gathered and effectively managed, and authorities should prioritize this aspect to enhance the city's overall health and livability (Rahman, 2013). Bari, Hassan, and Haque (Hamidul Bari et al., 2012) conducted a study that delved into the traditional recycling practices of solid waste within Rajshahi municipality. They engaged in a questionnaire survey, revealing their findings related to various recycling establishments during the period spanning April 2010 to January 2011. Their investigation identified a total of 140 recycling shops, predominantly clustered in the vicinity of the Stadium market in Rajshahi. Approximately 1906 individuals actively participated in recycling activities throughout the city, managing an estimated 28.13 tons of recycled solid waste in Rajshahi on a daily basis. This recycled segment accounted for 8.25% of the total daily waste generation, a substantial 54.6% of the overall recyclable waste, and an impressive 68.29% of readily recyclable materials. The primary materials subjected to recycling were iron, glass, plastic, and paper. Interestingly, only five factories were engaged in the initial processing of recyclable waste materials. This recycling process effectively entailed the collection and processing of secondary materials, followed by the manufacturing of products containing recycled content. Furthermore, it completed the cycle by promoting the purchase of recycled products, thereby establishing a sustainable and self-perpetuating loop. This comprehensive approach not only ensured the success of recycling but also yielded a multitude of benefits encompassing financial, environmental, and social dimensions. Waste-to-energy technology offers a promising solution to solid waste disposal by simultaneously improving environmental quality and generating clean energy. The challenges of managing municipal solid waste (MSW) and meeting the demand for alternative energy sources are widespread in developing countries. There is potential for establishing a 5-10 MW power plant based on the quality and quantity of solid waste in the Rajshahi City Corporation (RCC). Effective waste management practices and the implementation of regulations are vital for a more robust system. Inadequate waste management poses health hazards and environmental risks, emphasizing the importance of understanding local waste generation and environmental factors in designing appropriate waste management systems. Current research indicates that modern MSW management has minimal adverse effects on human health and the environment when compared to the risks of unmanaged waste. It is recommended that efforts be made to reduce MSW generation, with continued vigilance and understanding among government, regulators, the waste management industry, and the public to foster better control of this essential industry. Further studies are encouraged to enhance our understanding of the health and environmental effects of solid waste management (Rahman and Jakia, 2015).

Research Methodology

The comprehensive survey phase involved the meticulous selection of 150 households, each chosen from the 30 wards of RCC, with five households representing each ward. The deliberate intention was to encompass a broad spectrum of household types found within RCC, thus facilitating a comprehensive assessment of RCC's overall waste generation rate. The data collection was done from March – June 2023. Figure 2 shows the map of the RCC waste management area.

In addition, a comprehensive evaluation of the chemical makeup of the gathered municipal solid waste (MSW) was carried out by experts at the Bangladesh Council of Scientific and Industrial Research, and this assessment was conducted in dry conditions. To obtain a more in-depth insight into the composition of MSW in RCC, additional analyses were performed on MSW samples collected from twenty different households, with a specific emphasis on wet conditions. The data collected from the survey involving 150 households formed the foundational information for both estimating the calorific value of MSW and evaluating the potential for generating electrical energy from it.

Figure 2: Map of Study Area



The initial step in determining the calorific value of MSW involved the application of Dulong's formula (Khurmi et al., 2016), as presented in equation 1 below. In this equation, C, H, O, and S denote the weight percentages of carbon, hydrogen, oxygen, and sulfur present in the gathered municipal solid waste (MSW). The elemental weight percentages of MSW were determined using an extensive elemental analysis performed at the Bangladesh Council of Scientific and Industrial Research (BCSIR). As a result of this analysis, approximately 70% of the overall heat energy was converted into steam energy (Themelis & Kim, 2002). Subsequently, the calculation of net electrical power output was derived using the subsequent equation (2), where, EP = Electrical power = Steam power/11,395 (kWh/kg), SA = Station service allowance = 0.06 $*$ EP (Halder et al., 2014).

$$\textit{Heating Value} = 33800C + 144000\,(H - O/8) + 927S \quad (1)$$

$$\textit{Net Electrical Power} = EP - SA \quad (2)$$

Result and Discussions

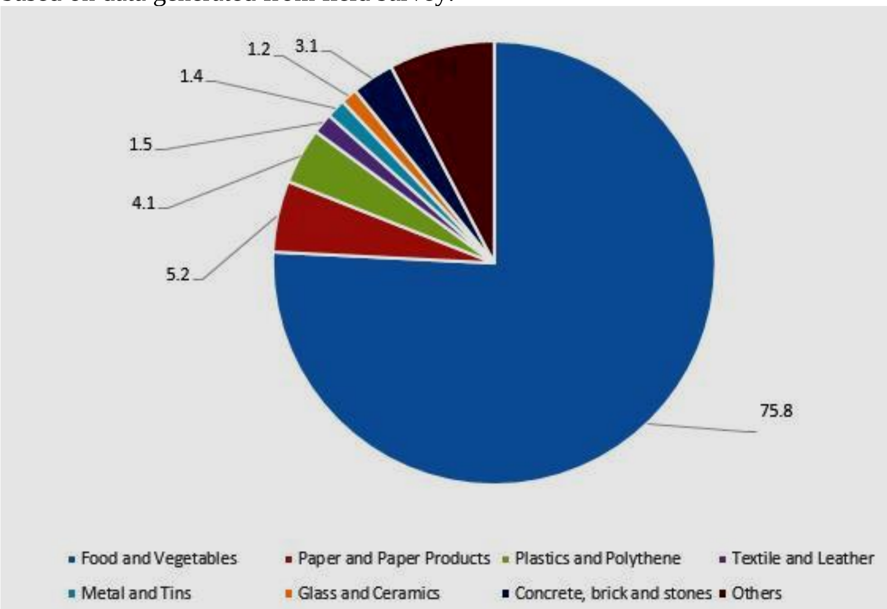
A survey encompassing one hundred and fifty households of various types aimed to provide an encompassing understanding of Municipal Solid Waste (MSW) generation patterns across RCC. The selection of households included a diverse range, from regular residences to larger student housing. This survey illuminated the noticeable variations in MSW generation, influenced by factors such as dietary habits, income levels, and educational attainment, among others.
The survey of 150 households involved a total of 2,316 residents, leading to a combined waste generation of 998.67 kilograms. This computation resulted in an average daily waste production of approximately 0.46 kilograms per individual, a finding consistent with previous research. Based on data provided by the Rajshahi City Corporation, the city's population is estimated to be around 0.85 million (Islam et al., 2020). As a result, the anticipated total daily waste generation in RCC is assessed at approximately 359.12 tons, a figure that closely aligns with previous research findings (Hamidul Bari et al., 2012, Halder et al., 2014, Habib et al., 2021). Both the overall estimated daily waste generation and the per capita waste production are in line with results from earlier studies. This research suggests that, in line with previous studies, the per capita waste generation remains consistent. However, the slightly higher daily municipal solid waste (MSW) output can be linked to the growing population in RCC. Therefore, it is a reasonable inference that the chosen households collectively provide a varied representation of household types in Rajshahi City Corporation.

Calorific Potential and Prospects for Electrical Power Generation

Following the extensive survey involving 150 households, a carefully selected subset of 20 families was chosen to act as representatives of various household categories prevalent in RCC. Figure 3 illustrates the physicial composition of collected waste from those households.

The main objective was to explore the physical composition of their MSW, providing valuable insights into the patterns of waste generation. A notable finding was the substantial proportion of solid waste, averaging about 75.80%, that originated from food and vegetable sources. The percentage closely aligns with the findings of a literature review undertaken by Alamgir et al. (Alamgir et al., 2007), in which they reported that about 71.1% of Rajshahi City Corporation's (RCC) overall municipal solid waste (MSW) could be traced back to food and vegetables. Likewise, the research conducted by Haldar et al. in 2014 demonstrated that food and vegetables made up an average of 73.19% of RCC's total MSW, thus supporting the conclusions of the current study.

Figure 3: Physical composition of MSW in RCC collected from twenty households based on data generated from field survey.



In order to obtain a comprehensive understanding of waste generation, the average waste production observed within twenty families was utilized as a reference point. This assessment entailed the determination of the weight percentages of MSWs in their moist state, followed by the subsequent process of blending and desiccating these materials. Upon completion of the drying procedure, various components of solid waste were segregated, and their individual weights were meticulously documented. The analysis of weight disparities allowed for the determination of moisture contents for distinct waste categories and, subsequently, the overall moisture content. Notably, food and vegetable waste exhibited the highest moisture content, registering at 64.8%. The cumulative moisture content of MSW in RCC was calculated at 50.90%. These results are in concordance with other research findings extracted from literature reviews, notably the study conducted by Hossain et al. in 2014 (Zakir Hossain et al., 2014), which estimated the moisture content of MSW to fall within the range of 45% to 50%. Two additional investigations carried out in 2013 and 2014 provided further validation for these outcomes, reporting an average moisture content of approximately 50% in RCC's MSW, thereby reinforcing the findings of the present study (Zakir Hossain et al., 2014, Rahman, 2013).

Understanding the chemical makeup of Municipal Solid Waste (MSW) holds significant importance when it comes to implementing effective waste management strategies. To decipher the chemical composition of MSW, a thorough testing process was carried. This elemental composition analysis involved conducting five repetitions, from which data pertaining to the presence of carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) was generated. Accompanying this discussion, these mean values serve as the fundamental dataset for the subsequent analyses within this research. It becomes evident that the predominant element within RCC's MSW is oxygen, accounting for an average of 40.76%. This oxygen content exceeds the levels observed in previous studies, with RCC's MSW containing 40.76%, marking a noteworthy increase in comparison to earlier findings (Habib et al., 2021). Table 1 shows the moisture contents of municipal solid waste components collected from twenty families.

Table 1: Moisture contents of municipal solid waste components collected from twenty families

MSW Composition	Weight before dry, kg	Weight after dry, kg	Weight Percentage (dry), %	Moisture content (%)
Food and Vegetables	51.85	18.25	26.3	64.8
Paper and Paper Products	3.58	3.29	4.74	8.1
Polythene	2.89	2.11	3.04	26.98
Textile and Leather	2.72	2.14	3.07	21.69
Metal and Tins	0.82	0.8	1.15	2.44
Glass and Ceramics	0.32	0.31	0.44	3.13
Concrete, Brick and Stones	1.85	1.82	2.62	1.62
Others	7.24	7.22	10,40	0,28
Total	71.27	35.94		50.9

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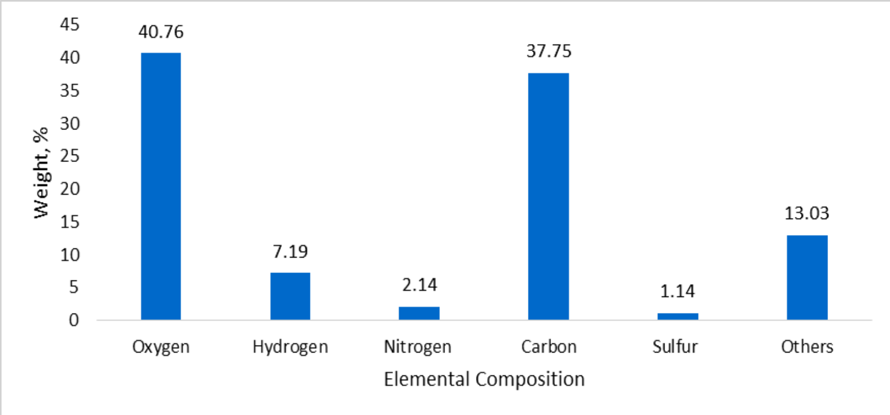
Figure 4: Weight percentages of different elements present in municipal solid waste



Upon determining the chemical composition of municipal solid waste (MSW), we utilized Dulong's formula, as represented by Equation (1) using the data from figure 4 to calculate its calorific value, resulting in a determined value of 15.88 MJ/kg. This calorific value aligns with findings from previous studies on MSW in RCC (Islam et al., 2001). Calorific values were observed to vary within a range of 10 to 17 MJ/kg, influenced by variations in composition and moisture content. Furthermore, based on the total heat energy, calculations were performed to determine both steam energy and net electrical energy. The overall potential power output derived from MSW was calculated to be 0.917 kWh/kg. Considering a daily estimated waste generation of 359.12 tons and an observed moisture content of 50.90% in MSW, the daily quantity of dry waste was determined to be 176.32 tons. Consequently, the energy potential originating from MSW in RCC amounts to 5.98 MW, closely aligning with findings from prior research studies. Thus, empirical equations suggest that approximately 156.86 MWh of electrical energy can be generated daily from the MSW generated in RCC.

Table 2: Treatment techniques for municipal solid waste in RCC

Technique of Treatment	Category of Solid Waste	Percentage of Solid Waste
Anaerobic Digestion/ Composting	Vegetable and Food	75.8
Recycling	Paper, Plastic, Textile, Glass	13.4
Landfilling	Non-biodegradable	10.8

Proposed Waste to Energy Conversion Technology

Anaerobic digestion presents an alternative waste decomposition process that functions in an oxygen-deprived environment, yielding biogas as a renewable energy source. This method is particularly effective for managing solid waste with high moisture content, such as food and vegetable waste. Biogas, predominantly composed of CH_4, serves a multitude of purposes, including cooking, power generation, and utilization in engines. A study conducted by Rao and Singh in 2004 featured a 100-day digestion process (RAO, 2004), resulting in an energy output of 12,528 kJ/kg of volatile solids, boasting an 84.51% conversion efficiency and CH_4 content ranging from 62% to 72%. It is noteworthy that biogas can be upgraded to Biomethane with a CH_4 content exceeding 90%, significantly enhancing its versatility. It's crucial to note that 1 Nm^3 of Biomethane, containing 97% CH_4, yields an energy potential of 9.67 kWh, whereas biogas with a 60% CH_4 content offers a reduced energy potential of just 6.0 kWh (Kapoor et al., 2019). There are various physiochemical and biological methods available for improving biogas quality, with the primary hurdle being the elimination of impurities such as hydrogen sulfide (H_2S) and CO_2 from the biogas. Among the various waste treatment methods discussed earlier, each approach presents distinct technological challenges. Landfilling, although common, is no longer a feasible choice due to land scarcity. Incineration, commonly employed in Waste-to-Energy (WTE) plants, faces challenges related to flue gas treatment, carbon dioxide capture, storage, alongside concerns about high carbon emissions and the release of harmful flue gases. Pyrolysis, another prevalent method for WTE conversion, necessitates small particle sizes for fluidized bed reactors and grapples with issues related to technology maturation. However, it is not suitable for processing plastic and rubber waste. Gasification encounters difficulties in tar removal and costly pretreatment processes (Md. Sohel Rana, 2016).

So, anaerobic digestion is more preferable 75.8% of waste is organic and the waste as a high moisture content of more than 50%. It is environmentally sustainable and helps to tackle the energy crisis.

Table 3: Recovery potential of energy from anaerobic digestion

Total MSW Generation in RCC	359.12 tons/day
Food and Vegetables	272 tons/day
Total Biogas Generation	40,800 m3
Compost Fertilizer	68 tons/day

Anaerobic digestion of 1 ton of MSW has the potential to yield 150 cubic meters of biogas. Anaerobic digestion can yield 250 tons of compost fertilizer from 1000 tons of municipal solid waste (MSW) (Md. Sohel Rana, 2016). Given that a substantial portion of the waste (75.80%) is biodegradable, anaerobic digestion (AD) emerges as an appealing process for harnessing energy. AD has the dual benefit of producing electricity and reducing the amount of waste going to landfills. It also yields digestate, comprising harmless liquid and solid residues. The biogas generated through AD can be used for power generation, while digestate can be further processed into compost, thereby reducing its environmental impact. The diagram in the document outlines the proposed waste management process in RCC. Waste that cannot be recycled or is not biodegradable is recommended for incineration or landfill disposal. Recyclable materials, such as metals, should undergo additional processing, while plastics, paper, and paper products can be reduced through pyrolysis, offering a valuable source of energy. Table 3 provides insights into the energy recovery potential of anaerobic digestion, showing that approximately 40,800 m3 of biogas can be generated daily from MSW in RCC, with various potential applications, including cooking. Moreover, about 68 tons of compost fertilizer can be produced daily from MSW, potentially resulting in savings of around BDT 0.39 million from the sale of compost (Das et al., 2019). Table 4 shows the potential electricity production from an anaerobic digester yearly.

Table 4: Electricity production from anaerobic bio-digester plant.

Electricity generation from 1 ton of organic waste (Hadid & Omer, 2017, Zhang et al, 2012)	0.992 MWh
Organic Waste	272 tons/day
Operating days in a year	365
Operating hours in a year	7446
Waste capacity per year	99280 tons
Plant Capacity Factor (Hadid & Omer, 2017, Renewable Energy Cost Analysis-Biomass for Power Generation, n.d.)	85%
Facility annual throughput per year	(99280*85%)
Electricity Generation Efficiency (Hadid & Omer, 2017, Renewable Power Generation Costs in 2014, 2015)	36%
Electricity Production per Year	(84388*0.992*0.36) = 30137 MWh

Implying Circular Economy principles in Municipal Solid Waste Management in resource-constrained economies

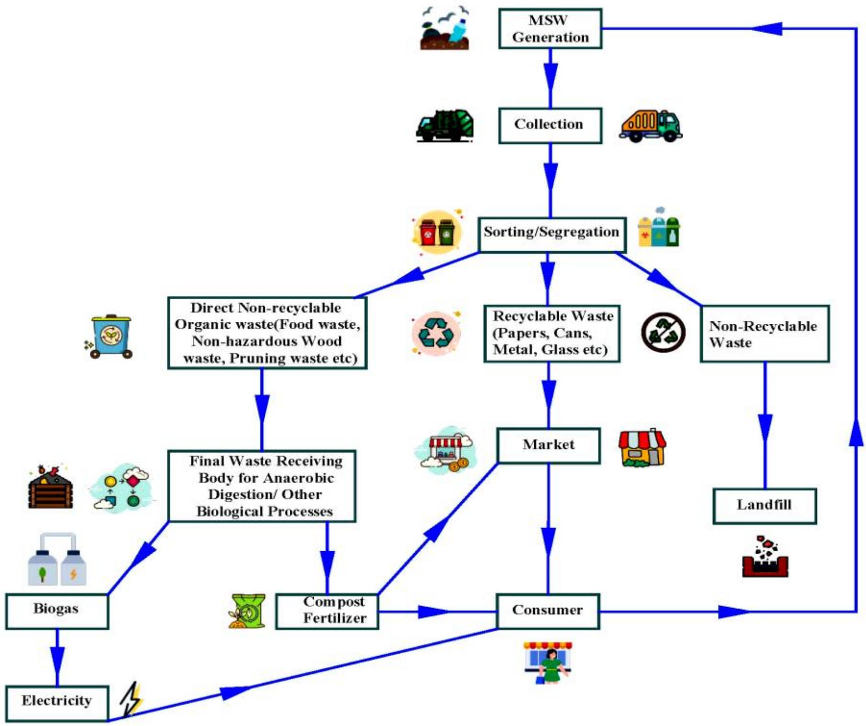
Today, waste recovery has evolved to a degree where it facilitates the production of electricity for residential purposes. With the scarcity of natural resources, the existing landfills are poised to become a valuable reservoir of raw materials for various processing industries. This is because it is anticipated that only 30% of the waste deposited in landfills over several years will naturally decompose (Geby Otivriyanti et al., 2023). Table 5 shows the key concepts of Circular Economy in managing MSW. The circular economy plays a vital role in the management of municipal solid waste (MSW) through several key aspects (Fan et al., 2020, Henrieta Pavolová et al., 2020, Tsai et al., 2020, Malinauskaite et al., 2017, Allevi et al., 2021). Figure 5 shows the conceptual model of circularity in handling the wastes in RCC.

Table 5: Key concepts of Circular Economy in managing MSW

Key Aspects	
Waste Reduction and Prevention	The circular economy encourages waste reduction and prevention strategies by promoting the concept of designing products and packaging with longevity and reusability in mind. This reduces the generation of MSW at the source
Reuse and Repair	In a circular economy, there is an emphasis on reusing and repairing products whenever possible. This approach extends the lifespan of items, reducing the need for disposal and lessening the burden on MSW

	management systems
Recycling and Material Recovery	Circular economy principles promote efficient recycling and material recovery processes. This includes sorting, processing, and reusing materials from MSW to create new products, reducing the demand for virgin resources
Resource Efficiency	The circular economy aims to maximize the use of resources within the economy. In the context of MSW, this involves extracting the maximum value from waste materials by recycling, upcycling, or converting them into valuable resources
Closing Material Loops	The circular economy seeks to close material loops by ensuring that materials are continuously reused and recycled within the economy, reducing the need for landfilling or incineration

Figure 5: Suggested strategy for Municipal Solid Waste Management in RCC applying Circular Economy concepts



Conclusion

This research involved the collection of waste data within RCC, resulting in an average daily waste generation of 0.46 kg per person. Based on this metric, the total daily waste production in the city corporation was approximated to be 359.12 tons. The Municipal Solid Waste (MSW) exhibited a calorific value of 15.88 MJ/kg, translating to an estimated daily electricity generation of 156.86 MWh. This potential energy source derived from waste can effectively alleviate the energy deficits in RCC. Another significant advantage of Waste-to-Energy (WTE) conversion lies in its ability to reduce pollution in surface water, groundwater, and the atmosphere, which commonly occurs with open dumping practices. Furthermore, the sale of the generated power can generate reasonable profits. For a comprehensive grasp of RCC's waste management, various factors like the worth of recyclable waste and pollution levels should be duly considered. Notably, the survey revealed that none of the households practiced waste separation. Thus, it is recommended to introduce source separation of waste for a more efficient municipal waste management process. Controlled dumping methods should replace open dumping. This work delves into future waste management recommendations, taking into consideration the present conditions of MSW generation and management in RCC, while also proposing potential treatment strategies. With the escalating rate of MSW generation in RCC, the prompt establishment of an effective waste management system is of utmost importance. Given the substantial energy potential within this waste, precedence should be accorded to WTE conversion. Anaerobic digestion, particularly suited due to the predominant composition of food and vegetable waste, presents a reliable solution. The calculated energy potential from anaerobic digestion totals 30,137 MWh annually, which can effectively resolve the energy crisis in this city corporation.

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