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Characterization of Municipal Solid Waste for Useful Energy Application in Mbeya City

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ABSTRACT

Municipal solid waste (MSW) management has emerged as one of the challenges facing environmental protection authorities in developing countries, Tanzania inclusive. This paper presents a characterisation study of MSW generated in Mbeya City, Tanzania. The characteristics of the MSW were determined in terms of the components' percentage of mass (kg) and physical and chemical properties. The study aimed to explore the potential of MSW as a feedstock for energy recovery processes. A study in Mbeya City found that food, organic, paper, plastic, and nylon waste make up a significant portion of municipal solid waste (MSW), with over 62.4% being organic and food waste. The study found that food waste can be used as a feedstock in anaerobic digestion plants to produce biogas and biofertilizer compost. The study also found that waste with higher carbon and hydrogen content is suitable for thermochemical waste-to-energy processes. Understanding MSW is crucial for effective waste management strategies and promoting a circular economy.

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1.0 Introduction

The management of municipal solid waste is a significant problem for local authorities in both small and major cities within developing nations. This is mostly attributable to the rising production of municipal solid waste and the burden imposed on the local authority budget alongside the substantial expenses. Solid management is linked to a deficiency of comprehension regarding the several aspects that influence the overall handling system (Abdel-Shafy and Mansour, 2018). The growth of population, fast-moving urban development, a strong economy, and better living conditions have led to a significant increase in the amount and quality of municipal solid waste produced in cities (Zhang *et al.,* 2024).

Wastes from these sources are not uniform, are heterogeneous by nature, and have variable physical characteristics depending on their sources. An increase of MSW generated leads to various problems in transportation, storage, and disposal of waste, which reduces efficiency of solid waste management (Ozcan *et al.,* 2016). Generation and composition of municipal solid waste data is very important in order to plan for long-term waste management in a sustainable manner. The municipal solid waste management includes transportation, handling, treatment, and disposal of waste (Aguilar-Virgen *et al.,* 2010). Characterising Municipal Solid Waste (MSW) is a critical process that provides valuable insights necessary for efficient waste management and the optimisation of waste-to-energy (WtE) technologies. The heterogeneous nature of MSW, which includes a variety of materials with different physical, chemical, and thermal properties, necessitates thorough characterisation to determine the most appropriate handling, processing, and energy recovery methods. The importance of characterising MSW can be outlined in several key areas: optimising waste-to-energy technologies, enhancing waste management practices, informing policy and regulatory decisions, economic benefits, and supporting research and development (Cheela *et al.,* 2021).

The amount of solid waste generated is increasing beyond the capacity of the local authorities to collect and dispose of it. This leads to endangering human health and the environment. Lack of data on the types of waste produced makes it difficult to have a proper solid waste management plan. The availability of data on MSW characterisation is very important in developing an integrated solid waste management plan (Tambe *et al.,* 2016).

With available data of MSW characterising well-prepared MSW management schemes, the quality of the urban environment could be enhanced, employment could be generated, environmental health could be protected, and the efficiency and productivity of the economy could be supported (Nyampundu *et al.,* 2020). Mbeya City Council has no information on the characterisation of MSW. In addition, waste collection frequency by city authority is not commensurate with waste generation, resulting in waste disposal. This paper aims to quantitatively and qualitatively characterise MSW generated in Mbeya City at the selected wards.

1.1 Municipal Solid Waste (MSW)

Municipal solid waste is unwanted and abandoned material produced daily by anthropogenic activity (Ubuoh *et al.,* 2021).

1.2 Composition of MSW

MSW composition varies based on location, socioeconomic status, and seasonal factors. Common components include organic waste, paper and cardboard, plastics, metals, glass, and other materials. Understanding the MSW composition is crucial for selecting appropriate WTE technologies and optimising their efficiency, as it helps in selecting materials for recycling and reducing waste. (Sharma and Jain, 2020).

1.3 Characterization of Municipal Solid Waste

Characterisation of municipal solid waste is a crucial process for determining the types and amounts of elements being disposed of in a waste stream. Understanding the physical, chemical, and biological characteristics of waste is essential for selecting appropriate solid waste management strategies. The leachate and gas generation from landfills are influenced by the type and source of MSW (Mirakovski *et al.,* 2011).

1.4 Energy Potential

Energy potential is the theoretical amount of energy that can be extracted from a resource system under ideal conditions. It can be applied to renewable and nonrenewable sources. MSW can be harnessed through various technologies, including combustion, gasification, pyrolysis, and anaerobic digestion. Combustion produces heat and electricity, gasification converts organic materials into syngas, pyrolysis decomposes materials without oxygen, and anaerobic digestion breaks down biodegradable materials (Malkow, 2004).

1.5 Research Gap

The research gap in waste characterisation in Mbeya City is primarily due to a lack of comprehensive data, the informal sector, socioeconomic factors, and technological limitations. The city council lacks up-to-date data on waste types and quantities, making it difficult to understand waste composition and effective waste management planning. Additionally, the informal sector's role and impact on waste characterisation and management are not well understood. Technological limitations also hinder advanced waste characterisation studies.

1.6 Aim of the Study

The MSW characterisation study aims to understand the physical and chemical composition of MSW streams and optimise energy recovery processes. By analysing the properties of different waste fractions, the study identifies suitable waste-to-energy technologies for each type of waste component. The result optimises the energy recovery process, contributing to sustainable waste management and reducing environmental impact.

1.7 Research Problem

Mbeya City's MSW is understudied, requiring a comprehensive characterisation to determine its characteristics and potential energy sources. The heterogeneous nature of MSW, with its diverse components and properties, poses a challenge in energy recovery processes. Therefore, comprehensive characterisation is essential for selecting suitable waste-to-energy technologies and optimising their performances.

2.0 Literature Review

2.1 Composition and Variability of Municipal Solid Wastes

Municipal solid waste is quite diverse, comprising a wide range of items such as biological trash, plastics, paper, metals, glass, and textiles (AbdAlqader and Hamad, 2012). Seasonal variations, socioeconomic conditions, and geographical location all have a substantial impact on the composition of MSW. In contrast to rural areas, which have a higher proportion of MSW. Studies conducted in urban areas typically reveal higher fractions of plastics and electronics in MSW fractions.

MSW are classified into the following categories: organics (paper, food waste, yard waste, leaves, plastics, leather, wood, textiles, and rubber); inorganics (glass, metals, aluminium, and inert materials); and miscellaneous (nappies, sanitary napkins) (Girdarakos *et al.,* 2006). Studies indicate that policies related to waste management, consumer trends, and economic development all have a significant impact on the composition of MSW. While low-income areas produce more organic and inert trash, high-income regions produce more packing and electronic waste. The nature of waste is also influenced by seasonal fluctuations; organic waste is most abundant during harvest seasons and holidays (AbdAlqader and Hamad, 2012).

2.2 Physical Characteristics of Municipal Solid Wastes

The moisture content, density, particle size distribution, and composition of MSW are its main physical characteristics. The efficiency, handling, and processing of waste-to-energy technologies are influenced by these features (Lak *et al.,* 2024).

2.2.1 Moisture Content

The amount of moisture has a big influence on how MSW is handled and processed. Elevated moisture content, commonly present in organic waste, lowers the calorific value and makes thermal treatment procedures like burning more difficult. Research suggests that to improve energy recovery, high-moisture waste should undergo pretreatments that involve drying. (Nath and Siddiqui, 2018).

2.2.2 Density

One of the most important characteristics of municipal solid waste (MSW) is density. It affects how trash collection, transportation, and processing systems are built and run. Gaining insight into MSW density can help minimise environmental effects, enhance waste-to-energy (WtE) technology efficiency, and optimise waste management procedures (Ngohayon and Tulagan, 2022).

2.2.3 Composition Analysis of Municipal Solid Waste

It is essential to comprehend the composition of municipal solid waste (MSW) to create effective waste management and waste-to-energy (WtE) plans. The process of composition analysis entails classifying the different MSW components and calculating their corresponding amounts. The information provided by this research is crucial for creating suitable recycling, treatment, and disposal strategies.

2.3 Chemical Characterization of Municipal Solid Waste

Municipal solid waste (MSW) is characterised chemically by examining its elemental and compound makeup. Understanding the potential of various waste fractions for energy recovery, recycling, and safe disposal depends on this analysis. It facilitates the design of effective Waste-to-Energy (WtE) systems, the optimisation of waste treatment procedures, and the mitigation of environmental effects. (Cheela *et al.,* 2021).

2.4 Technological Considerations

The selection of a suitable WTE technology depends on the composition and properties of MSW, as well as economic and regulatory factors. Technologies must be tailored to handle the specific characteristics of the waste stream to maximise energy recovery and minimise environmental impact. Combustion: Suitable for high-calorific and low-moisture wastes. Modern incinerators include pollution control systems to reduce emissions. Gasification and Pyrolysis: Effective for converting mixed and heterogeneous wastes into cleaner fuels. Require precise control of process conditions. Anaerobic Digestion: Ideal for high-moisture and organic-rich wastes. It generates renewable energy and valuable by-products such as compost (Zhang *et al.,* 2010).

2.5 The Value of Global and Regional Research in MSW Characterization for Energy Recovery

When addressing the challenge of converting municipal solid waste (MSW) into useful energy, especially through technologies like anaerobic digestion, it is essential to understand what has already been done elsewhere—both globally and regionally. By examining other studies and projects, researchers can better position their own work, identify gaps, and strengthen the relevance of their findings. For the case of Mbeya City in Tanzania, comparing local MSW characteristics and energy recovery options with those in other African cities can add valuable depth and insight.

Across many African urban centres, the story is the same—fast-growing cities, mounting solid waste, and under resourced waste management systems. Nairobi, for instance, produces large volumes of organic waste, which accounts for over 60% of its MSW stream (UN-Habitat, 2023). Similarly, in Addis Ababa, the successful implementation of the waste-to-energy plant has shown how biogas and energy can be harnessed from MSW at scale (Zamora & Alemayehu, 2017). Lagos also presents a compelling comparison, especially in terms of its challenges with informal waste collection, low recycling rates, and inconsistent segregation

(Ibarra-Esparza *et al.,* 2023). These cities share many of the same issues as Mbeya—yet some have made strides in integrating technology, policy, and infrastructure in ways that can inform new projects like the one proposed in this study.

Looking at Tanzania's policy environment, there is clear support for environmental sustainability and renewable energy—seen in national documents like the Environmental Management Act and the National Energy Policy. However, implementation is often slow or lacks practical mechanisms. For instance, there are no firm regulations requiring households or businesses to separate organic waste from other refuse, making it difficult to efficiently feed digesters with high-quality material (URT, 2021). In contrast, countries like South Africa have made more progress in incentivising waste-to-energy (WtE) investments, and Rwanda has put systems in place to enforce segregation and reduce landfill dependency (IRENA, 2022). These examples show that for a centralised biogas system to work in Mbeya, supportive policies and proper enforcement will be just as important as technical design.

Another critical reason to explore existing research is to identify where previous studies have fallen short—particularly in the African context. Many waste characterisation studies stop at estimating waste volumes or general composition. They rarely dive deeper into properties that really matter for energy recovery, such as moisture content, calorific value, or the elemental makeup of waste components (Zhang *et al.,* 2022). Without this information, it's hard to determine whether a waste stream is truly suitable for processes like anaerobic digestion or incineration. That is where this study makes a stronger contribution—it goes beyond the basics to calculate energy yields, evaluate biogas potential, and recommend suitable digestion parameters. By doing this, it fills a critical gap in local research and provides data that decision-makers can use for infrastructure development and policy design.

Importantly, this study also draws on recent research and global trends. New innovations in MSW management include the use of co-digestion—where food waste is combined with agricultural residues or industrial organic waste to improve gas yields (Karki *et al.,* 2022). There's also growing interest in using artificial intelligence and automation to improve sorting at transfer stations, as well as the emergence of hybrid WtE systems that combine digestion, composting, and gasification (Appels *et al.,* 2011). These ideas are especially relevant for Mbeya, where waste streams are often mixed and infrastructure is limited. Learning from other cities and current research ensures that the recommendations made in this study are not only grounded in data but also aligned with international best practices.

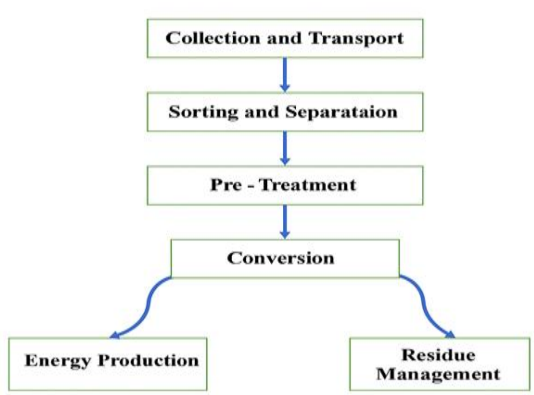
Finally, aligning with global development goals—such as the United Nations Sustainable Development Goals (SDGs)—adds another layer of significance. By focusing on SDG 7 (clean energy), SDG 11 (sustainable cities), and SDG 12 (responsible consumption and production), this study shows how local action in waste management can contribute to broader environmental and social goals (United Nations, 2022). In short, looking outward to other cities, policies, and scientific advancements helps bring the work done in Mbeya into global conversation—and strengthens the case for real, actionable solutions.

3.0 Material and Method

The process of characterising municipal solid waste (MSW) in Mbeya City included determining the goal, conducting research, defining the scope, designing the sampling method, collecting samples, handling and transporting them, and analysing the data. Stratified random sampling was used during the sample design, taking sampling frequency and municipal solid waste creation trends into account. The sites were chosen accurately from six selected wards of Mbeya City, namely, Nsalaga, Iyunga, Ilomba, Sisimba, Iganzo, and Forest, as shown in figure 2 below, to reflect the MSW produced in each stratum. Sample collection procedures, including time, date, location, container types, amount, and label, were established in the selected wards. The samples were tested in the laboratory to determine the following: - chemical analysis, physical analysis, moisture content, and calorific value. A bomb calorimeter was used to determine the calorific value and establish categories for MSW fractions used for calculations. To strengthen the scientific variability and reproducibility of the study on MSW characterisation for energy applications in Mbeya City, the methodology clearly presents key operational details, including a sampling frequency of twice per week, a total collection of approximately 250 kg of waste per ward, and a sorting duration limited to four hours post-collection to minimise degradation. Quality control procedures were outlined, such as colour-coded clean collection bags to prevent contamination and calibrated weighing scales. Therefore, each session followed a standardised 10-fraction sorting protocol adopted from UNEP guidelines and independently cross-verified all recorded data entries. Sampling occurred only during the dry season of 2024; two peripheral urban wards were excluded due to accessibility challenges. Industrial and institutional waste streams were not considered, and per capita generation rates were not assessed. Comprehensive characterisation aids in the design of sustainable and efficient MSW management and utilisation systems by local authorities and is a multi-step process that includes sample preparation, collection, and detailed physical and chemical analysis (Figure 1). These procedures yield vital data for optimising waste management practices and choosing suitable waste-to-energy technologies.

Figure 1

Characterization of Municipal Solid Waste for Energy Production Flow Diagram



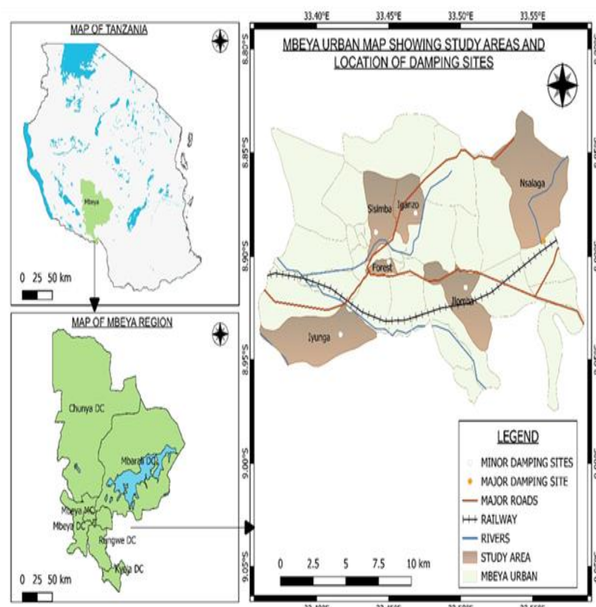
Source (Author, 2024)

3.1 Study Area

Mbeya City Council, located in the southwest of Tanzania, has a population of 541,603 people and 153,100 households (URT, 2024). The city's population growth rate is 3.2%, similar to the national average of 3.2% per annum (URT, 2024). Mbeya City is divided into two divisions, Iyunga and Sisimba, and has 36 wards, 181 hamlets, and 89,602 households. The city's major economic activities include commerce, trade, agriculture, livestock keeping, industrial production, and service provision. 33.3% of the city's residents depend on agriculture for their livelihood, while 21% are employed in the public sector. 43.4% are engaged in the informal sector, mainly small-scale production and selling of agricultural crops (NBS and MCC, 2016). Mbeya City is part of the Mbeya Region, which includes other councils such as Mbeya District, Kyela, Busokelo, Mbarali, and Rungwe. The city is bordered to the north by Mbeya Rural District, to the east by Rungwe District, to the south by Ileje District, and to the west by Mbozi District in Songwe Region (figure 2 below) (NBS and MCC, 2016).

Figure 2

Map of Mbeya City Showing Six Selected Wards



Source (Author, 2024)

3.2 Sample Preparation

This study analysed waste characterisation in Mbeya City's Nsalaga Sanitary Landfill and six selected wards. Methods used included assembling composites, cornering and quartering, collecting grab samples using front-end loaders, and manually collecting waste columns from randomly selected locations. The characterisation of MSW in these areas involved assembling composites, cornering and quartering, collecting grab samples, and manually collecting waste columns. (Gawaikar and Deshpande, 2006).

Waste characterisation was done through standard methods, which are ASTM (American Society for Testing and Materials). Standards test method for determination of the composition of unprocessed MSW-D5231_92 (2008), (ii) UNEP/IETC—development of an integrated solid waste management plan, Volume 1, waste characterisation and quantification with projections for the future (UNEP, 2009).

To facilitate waste segregation at the source, two containers were supplied to participating households, one designated for organic waste and the other for inorganic waste. After seven days, the collected MSW was retrieved and subjected to a detailed sorting process. The segregation of waste was carried out to classify the different physical components, including fruit and vegetable waste, paper, rubber, leather, metals, and inert materials. Each of these components was weighted separately to determine the proportion of various waste types in the overall MSW composition.

Beyond the physical characterisation, a sample of collected waste was taken to the laboratory for further analysis. This step was essential for assessing the physical and chemical properties of the waste, which is crucial for evaluating its energy recovery potential. Understanding the characteristics of MSW not only provides insights into waste generation patterns but also supports the development of efficient waste-to-energy solutions.

By systematically collecting, sorting, and analysing MSW, this study contributes valuable data to the field of waste management. The findings can help inform strategies for sustainable waste disposal and resource recovery, ultimately promoting environmental conservation and energy sustainability in urban settings.

3.3 Physical Characterization

The physical characterisation was obtained by determining the moisture content and density of each MSW component. These parameters influence the handling, processing, and energy conversion efficiency of the waste.

3.3.1 Determination of Bulk Density

Density of municipal solid waste samples was measured by using a wooden box (1 m^3 capacity) and a spring balance that can weigh up to 50 kg. The box was filled with municipal solid waste, and the weight (W1) was noted. From that, density was calculated by dividing weight (W1) by the volume used. For uncompacted waste, an appropriate container of capacity 1 m^3 (V1) was used. The wastes were poured into the container until it overflowed. After weighing, the wastes in a container were compacted completely, and new volume and weight (W2) were obtained.

3.4 Chemical Characterization

3.4.1 Moisture Content

A sample of municipal solid waste was weighed (w) and dried to a temperature around 105°C to 110°C until a constant weight(d) was achieved. The dried MSW sample was weighed again and the moisture content was calculated by using the following formula.

$$MC = \frac{w - d}{w} x100 \quad \text{...(1)}$$

Where:
w = wet weight
d = weight after drying

Chemical analysis was performed to ascertain the elemental composition (C, H, O, N, S), proximate analysis (moisture, ash, volatile matter, fixed carbon), and higher heating value (HHV) of each waste fraction. These characteristics are essential for assessing the energy potential and environmental impact of waste conversion processes.

3.4.2 Proximate Analysis

One gram of the ground MSW sample was weighed and placed in an oven at 110 ∘C for 1 h. After drying, the weight loss was recorded to determine the moisture content of the sample. The dried sample was placed in a crucible and heated in a furnace at 950 ∘C for 7 min. The weight loss after heating was recorded to determine the volatile matter content of the sample. Then the sample was combusted in a muffle furnace at 550 ∘C for 4 h until all the carbon was burned off. The residue was then weighed to determine the ash content of the sample (Hassan *et al.*; 2023)

3.4.3 Ultimate Analysis

The sample is first ground into a fine powder and dried in an oven at a temperature of around 105 °C to remove any moisture content. The sample was then weighed accurately, about 0.1 g and placed in a tin capsule. The tin capsule containing the sample was loaded into a Muffle furnace, and a stream of pure oxygen was passed through the combustion furnace to completely burn the sample. The resulting combustion products are then passed through a series of columns containing specific absorbents to separate the individual components. The carbon, hydrogen, nitrogen, sulfur, and oxygen components were then detected and measured using appropriate detectors (Hassan *et al.;* 2023).

3.4.4 Determination of Calorific Value

The calorific value of a sample was determined by using standard bomb calorimeter (Wastech Gallen Kamp Auto Bomb). MSW was dried and grinded to small particles. The particles were sieved and compressed to form pellets. The bomb was assembled and filled with pressurized Oxygen (30bars approximately). The firing circuit was tested and the calorimeter was adjusted by weighing sufficient water into the calorimeter vessel to submerge the bomb completely. The bomb was fired and after the temperature stabilization the difference were noted and recorded. The higher calorific value (HCV) of MSW was calculated according to ASTM D240.

$$HCV = \frac{\Delta T C_p}{mg} \quad \text{...(2)}$$

Where ∆T, Cp and mg are change in temperature in K, heat capacity in MJ/Kg and mass of sample in Kg respectively.

Lower calorific value (LCV) of MSW was calculated by using

$$(LCV)i = (HCV)i + 9 \times (H\%)i \times LHS \ldots (3)$$

Where:
(LCV) i = lower calorific value of each component in Kcal/kg,; (HCV) i = Higher calorific value of each component in Kcl/Kg., LHS = Latent heat of steam which is 587 Kcal/kg and (H %) i = Hydrogen percentage of each component sample.

4.0 Results and Discussion

The study analysed the chemical and physical characteristics of municipal solid waste (MSW) in Mbeya City, focusing on food/organic, paper/cardboard, plastic bottles, and nylon bags. The results showed that over 60% of MSW in Mbeya City is organic and food waste. The study aimed to understand the composition of the MSW stream, both physical and chemical, to address its potential as a feedstock for energy recovery processes like waste-to-energy facilities. The study provided detailed descriptions of different characteristics and their importance in waste management decision-making and waste-to-energy technologies planning.

4.1 Estimation of Municipal Solid Waste Generated in Mbeya City

Mbeya City's primary waste storage is handled by city dwellers who store their waste in plastic sacks and dustbins. The city has communal collection points in different wards and streets, as well as collection points operated by the City Council. The collection system consists of door-to-door and communal collection points, with containers depending on the rate of daily solid waste generation. The city also employs city vehicles and private companies to handle waste collection in institutions with limited equipment and power. Currently, five vehicles are owned by the City Council, while two are owned by Tanzania Breweries Limited and Coca Cola Kwanza Company. The transportation of MSW in Mbeya City faces operational and maintenance costs, inaccessibility to some localities, improper planning of collection routes and frequencies, and lack of good supervision.

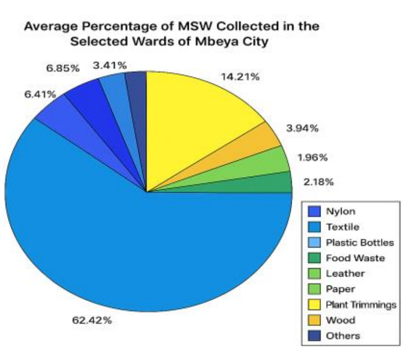
4.2 MSW Composition

Composition of MSW samples collected from six selected wards and at the Nsalaga landfill dumpsite as shown in figure 2 below. Municipal solid waste collected at Mbeya City is composed of the following: organic, paper, plastic, metal, glass, tires, and others, with the following percentages as shown.

The rate of generation of solid waste in Mbeya City is about 400 tonnes/day with an average generation rate of 0.7 kg/person/day. The collection capacity is about 140 tonnes/day (35%), and the recycling capacity is unknown, as there is no clear data for this. According to the study conducted, the waste composition in Mbeya City is largely dominated by food and other organic wastes (Mwangomo, 2019).

Food waste comprises 62.4% (Figure 3); this is the largest component of MSW available in Mbeya City.

Figure 3
Average Percentage of MSW Collected in the Selected Wards of Mbeya City



The data reveals the municipal solid waste (MSW) generation across six regions, including Nsalaga, Ilomba, Iganzo, Sisimba, Forest, and Iyunga. The dominant waste fraction is food waste, which accounts for 62.4% of total waste generated. The region's waste generation is highest in Ilomba and Iganzo, with Iyunga and Sisimba generating the least. The average daily waste generation across the six regions is 464.93 kg/day, with food waste being a significant factor. The per capita waste generation is calculated at 0.00527 kg/day/person, which could be due to lower overall consumption, effective waste reduction strategies, or a higher population.

The waste composition is dominated by food waste at 62%, suggesting that managing organic waste through composting or biogas generation could significantly reduce overall waste. Plastic bottles and textiles are also significant contributors, offering opportunities for waste management solutions focusing on recycling programs. Regional differences in waste production are noted, with Ilomba and Iganzo producing more waste due to larger populations, economic activities, or consumption patterns. The "Others" category, which accounts for nearly 14% of the total, likely includes mixed or non-recyclable waste. Recommendations for action include investing in organic waste management facilities, promoting recycling programs, and raising awareness about waste reduction, particularly focusing on food and single-use plastics.

Due to the findings obtained in this study, organic and food fractions contain the largest percentage of MSW collected in Mbeya City; these MSW fractions are not disposed of carefully, and hence, they are causing pollution and public health problems. However, to alleviate this problem, food waste can be used as a feedstock in the anaerobic digestion plants to produce biogas and biofertilizer compost, which are used for useful applications. Currently food fractions, which are collected in Mbeya City, are disposed of at the Nsalaga landfill and generate methane gas, which contributes a lot to greenhouse gas emissions. According to the study done by Mgimba and Sanga (2016) on municipal solid waste characterisation in Mbeya City, they obtained similar results, which show that food waste generated in Mbeya City is about 57% of all MSW generated. This result does not differ from the findings obtained in this study. The results also correspond to the findings obtained by Kinemo (2019) from organic waste composition found to carry more weight, 53.3%, in Morogoro Municipal Council. The findings imply that the Mbeya City Council has a role to educate people to sort MSW before disposing of it and bringing it to the collection centres.

The majority of municipal solid waste (MSW) is food waste, which can be significantly reduced through composting and recycling programs. Plastic bottles, the second-largest fraction, can be managed more effectively through improved recycling infrastructure and reusable containers. The "Others" category needs further analysis to identify specific waste types. Regional waste management strategies include Nsalaga and Forest focusing on reducing food waste through composting and food rescue programs, Sisimba enhancing recycling programs for plastic bottles due to their high volume, and Iyunga implementing programs for handling various waste streams.

There are some limitations that occur during this study; one of them is the sample size constraints. It was not possible to collect samples from all wards of the Mbeya City Council. Another limitation is the seasonal variation. There are some seasons where certain types of MSW components appear to be more than other types. For example, during rainy season organic waste is much more common in localities compared to other MSW components. Due to the rapid urbanisation of Mbeya City, updated solid waste management data have to be researched and obtained so as to help in the planning of projects and development.

4.3 Physical Characterization

The physical properties of solid waste are comprised of density and composition, for which the obtained results are explained below.

4.3.1 Density of MSW

The bulk density of MSW generated in Mbeya City was measured by a 1 m^3 wooden box and a spring balance. A bulk density of 333 kg/m^3 was determined. This result is similar to the research done by Alabdraba and Qaraghully (2013) in Tikrit City, Iraq, which shows that the bulk density of municipal solid waste was 229.088 kg/m^3.

4.4 Chemical Characterization

The chemical properties of solid waste are composed of moisture content, volatile solids, ash content, calorific value, and elemental composition of MSW.

4.4.1 Moisture Content of MSW

The percentage of moisture content for municipal solid wastes generated in Mbeya City was measured in the laboratory, and the results are shown in table 1 below, which shows that food waste has the highest percentage of moisture content compared to other MSW collected in Mbeya City. The higher moisture content MSW can be used for the anaerobic digestion process, and the lowest MSW moisture content is suitable for incineration processes. Types of waste with high moisture content, such as food waste (53.75%) and plant trimmings (13.25%), are ideal candidates for composting. High moisture levels help in the decomposition process, promoting microbial activity. Proper moisture levels are crucial for effective composting. Too much moisture can lead to anaerobic conditions and odour problems, while too little can slow down the composting process. Wastes like nylon (1.21%) and textile (4.25%) have low moisture content, making them easier to process and recycle. Low moisture reduces the need for drying, saving energy and costs. High moisture content can lead to contamination of recyclable materials. For example, wet paper and cardboard are harder to recycle and often end up being discarded.

Table 1

Moisture Content of Municipal Solid Waste at Mbeya City

S/N	Type of Waste	% Moisture Content
1	Nylon	1.21
2	Textile	4.25
3	Plastic Bottles	13.6
4	Food Waste	53.75
5	Leather	13.25
6	Paper	7.35
7	Wood	13.55
8	Plant Trimmings	13.25

The moisture content of waste varies significantly, with high moisture content being the wettest waste at 53.75%. Other waste types have moderate moisture content, such as plastic bottles, leather, wood, and plant trimmings. Low moisture content, like nylon and textile, is less likely to cause moisture-related issues. Management of high moisture content requires careful handling to prevent odour, leachate generation, and contamination. Moderate moisture content can be handled with standard landfill or recycling methods, while low moisture content may be more efficient.

As the moisture content of solid waste directly influences leachate formation, microbiological activity, pollutant leaching, and energy consumption during thermal treatment, moisture content determination is crucial in guiding the recycling, treatment, and disposal of solid waste.

The moisture content affects the calorific value of waste. High moisture content in waste like food waste reduces its energy content, making it less efficient for energy recovery through incineration. Wastes with low moisture content burn more efficiently and generate more energy. Therefore, separating high-moisture waste from low-moisture waste can improve the efficiency of waste-to-energy plants.

4.4.2 Proximate Analysis of MSW

Proximate analysis is an indication of how the MSW components can be used in a proper category of waste-to-energy processes. For thermochemical processes like incineration, gasification, and pyrolysis. High calorific value of a fuel is needed with high fixed carbon and lower moisture content, volatile matter, and ash residue. For the case of MSW collected in Mbeya City, nylon, textile, and plastic bottles are suitable for the thermochemical processes since they have high fixed carbon. Table 3 below shows proximate analysis test results of MSW generated in Mbeya City.

Nylon has the highest fixed carbon content (55.11%), indicating its potential as a fuel source. Wood has the lowest fixed carbon content (4.05%), indicating it is less efficient as a fuel source in terms of fixed carbon. Wood has the highest volatile matter (93.3%), which means it can easily decompose and release gases. Nylon has the lowest volatile matter (37.9%), indicating it is more stable and less prone to decomposition. Food waste has the highest ash content (16.9%), which means it leaves more residue after combustion. Plastic bottles have the lowest ash content (1.51%), indicating cleaner combustion. Food waste has the highest moisture content (53.75%), which affects its calorific value and makes it less efficient for energy recovery. Nylon has the lowest moisture content (1.21%), making it more efficient for combustion (table 2).

Table 2

Proximate Analysis of Municipal Solid Waste

S/N	Type of Waste	% Fixed Carbon	% Volatile matter	% Ash	% Moisture Content
1	Nylon	55.11	37.9	6.99	1.21
2	Textile	21.41	76.95	1.64	4.25
3	Plastic Bottles	23.19	75.3	1.51	13.6
4	Food Waste	8.95	74.15	16.9	53.75
5	Leather	15.47	76.55	7.98	13.25
6	Paper	17.66	75	7.34	7.35
7	Wood	4.05	93.3	2.65	13.55
8	Plant Trimmings	5.88	78.8	15.32	13.25

Here are ANOVA test results for the four proximate analysis properties across different types (table 3).

Table 3

ANOVA Results Test for Proximate Analysis of MSW

Property	F - static	P - value	
% Fixed	1746.64	1.84×10^{-39}	Significant differences exist among waste types
% Volatile	1196.00	7.72×10^{-37}	Significant differences exist
% Ash	220.48	3.19×10^{-35}	Significant differences exist
% Moisture	1218.27	5.75×10^{-37}	Significant differences exist

All four parameters show statistically significant variation across different waste types (p _ value << 0.05). This justifies considering each type of waste independently when assessing its energy recovery potential or suitability for specific waste – to – energy technologies.

On the other hand, for the anaerobic digestion process a feedstock with high moisture content are needed. Food waste with 53.75 % moisture content is suitable for this process (table 3 above). And availability of food and other organic waste in Mbeya City is very high, which means anaerobic digestion facilities can be used to generate biogas for useful applications

The analysis of waste materials reveals that Nylon has the highest fixed carbon content at 55.11%, making it a stable material for combustion. Wood has the lowest fixed carbon content at 4.05%, indicating most of its content is volatile or moisture. Food waste and plant trimmings have the highest ash content at 16.9% and 15.32%, respectively, indicating significant inorganic material presence. Textile has the lowest ash content at 1.64%, suggesting fewer residues after combustion. Food waste has the highest moisture content at 53.75%, requiring specific handling methods. Wood, wood, and plant trimmings have similar profiles, suitable for incineration with appropriate emission controls.

Combustion and waste management implications include nylon, textile and plastic bottles, food waste, leather and paper, wood, and plant trimmings. Nylon has high fixed carbon and low moisture content, making it suitable for combustion with high energy yield. Bottles have moderate fixed carbon content and low ash content, while food waste has high moisture and ash content, making it suitable for composting or incineration.

4.4.3 Ultimate Analysis of MSW

Carbon and hydrogen have a significant in the combustion of a fuel. The higher the percentage of C and H the better the quality of a fuel. Carbon and hydrogen are determined in ultimate analysis experiment. A table 4 below shows ultimate analysis test results of MSW generated in Mbeya City.

Table 4

Ultimate Analysis of Municipal Solid Waste

S/N	Type of Waste	% Total Carbon	% Nitrogen	% Sulphur	% Hydrogen	% Oxygen
1	Nylon	93.01	0.46	0.044	0.72	5.766
2	Textile	98.36	0.2	0.061	0.15	1.23
3	Plastic Bottles	98.49	Nil	0.034	0.164	1.312
4	Food Waste	83.1	1.7	0.04	1.684	13.48
5	Leather	92.02	5.14	0.095	0.31	2.44
6	Paper	92.66	0.2	0.048	0.788	6.304
7	Wood	97.35	0.3	0.057	0.255	2.038
8	Plant Trimmings	83.8	1.1	0.042	1.673	13.385

Here are the ANOVA based on simulation on simulated replicate data for each elemental property (table 5). The very low P – values across all properties indicate statistically significant differences in Total Carbon, Nitrogen, Sulphur, Hydrogen and Oxygen content among the different types of waste.

Table 5
ANOVA Results Test for Ultimate Analysis of MSW

Element	F - Statistic	P - Value
Nitrogen	3580.01	2.43×10^{-24}
Sulphur	54.56	5.53×10^{-10}
Hydrogen	470.91	2.60×10^{-17}
Oxygen	459.06	3.18×10^{-17}

In Mbeya City, MSW components like plastic bottles, nylon, textiles, and wood have higher carbon and hydrogen content; therefore, they can be used in the thermochemical waste-to-energy processes such as incineration, gasification, and pyrolysis to generate energy for useful applications.

Textiles (98.36%) and plastic bottles (98.49%) have the highest total carbon content, indicating their potential as fuel sources due to high carbon content. Food waste (83.1%) and plant trimmings (83.8%) have lower carbon content, which affects their energy content.

Leather has the highest nitrogen content (5.14%), which can be important for composting, as nitrogen is a key nutrient for microbial activity. Plastic bottles have no nitrogen content, indicating they are purely carbon-based materials. Sulphur content is low across all types of waste, which is good, as high sulphur content can lead to the production of harmful sulphur dioxide during combustion. Food waste (1.684%) and plant trimmings (1.673%) have higher hydrogen content, indicating a higher potential for energy release upon combustion. Textile has the lowest hydrogen content (0.15%). Food waste (13.48%) and plant trimmings (13.385%) have the highest oxygen content, which can influence the combustion process and calorific value. Textiles (1.23%) and plastic bottles (1.312%) have low oxygen content.

Combustion and waste management can be influenced by various materials, such as nylon, textiles, plastic bottles, food waste, leather, paper, and wood. Nylon has high carbon content and low nitrogen, sulphur, and oxygen content, making it efficient for combustion with minimal pollutants. Plastics have high carbon content and low nitrogen, sulphur, and oxygen content, making them suitable for incineration. Wood has high carbon and low nitrogen, sulphur, and oxygen content, making it a suitable fuel source.

4.4.4 Calorific Value of MSW

The higher calorific value of MSW components was determined by using a bomb calorimeter. Equation 2 above was used to calculate its values as shown in table 6 below.

Table 6
Calorific Value (HHV) of Municipal Solid Wastes in Mbeya City

S/N	Type of Sample	Calorific Value (cal/g) (HHV)
1	Nylon	8090.2
2	Textile	4065
3	Plastic bottles	9541.2
4	Food Waste	4351
5	Leather	5072.3
6	Boxes	3612
7	Wood	4297.2
8	Plant Trimmings	3886
9	Paper	4537.4

By using data of the HHV of Municipal Solid Waste obtained at Mbeya City, The Lower Heating Value of Selected Municipal Solid Waste was obtained by using the equation 3 and presented in the table 7 below.

Table 7
Calorific Value (LHV) of Municipal Solid Wastes

S/N	Type of Sample	Calorific Value (cal/g) (LHV)
1	Nylon	33,895.73
2	Textile	17,019.34
3	Plastic bottles	39,947.09
4	Food Waste	18,216.76
5	Leather	21,236.70
6	Wood	17,991.51
7	Plant Trimmings	16,269.90
8	Paper	18,997.18

Calorific value (LHV) is a measure of energy released when a material is burnt. Plastic bottles have the highest calorific value at 39,947.09 cal/g, making them a highly energy-dense fuel source. Plant trimmings have the lowest at 16,269.90 cal/g. Nylon, textiles, food waste, leather, wood, and paper are all energy-dense materials with varying calorific values. Plastic bottles have the highest calorific value at 33,895.73 cal/g, while textiles have a moderate energy potential. Wood has a calorific value of 17,991.51 cal/g, comparable to textiles and biofuels. Paper has a calorific value of 18,997.18 cal/g, making it an effective energy recovery material.

Plastic bottles and nylon are the most energy-rich waste types, making them ideal for incineration or energy recovery processes. Leather, food waste, and paper are moderate energy sources but may require preprocessing to handle moisture content. Textile, wood, and plant trimmings are lower energy sources but still valuable for bioenergy production when combined with other higher-energy materials. These materials can be used for energy recovery and other applications.

4.5 Technology Matching and Feasibility for Mbeya City

Food waste should be prioritised for anaerobic digestion or composting depending on energy recovery or soil amendment goals. Paper and wood waste offer versatile options across all four technologies, with minor constraints. Plastic and textiles are best directed to pyrolysis or gasification, with care to manage emissions. Proper segregation and preprocessing are critical for maximising energy recovery and minimising environmental impacts (see table 8).

Table 8

Technology Suitability Matrix

MSW Type	Anaerobic Digestion	Incineration	Gasification	Pyrolysis	Compost
Food Waste	High Suitability	Wet waste	Not Suitable, Not Ideal	Not Suitable	High Suitability
Paper/Cardboard	Moderate	High Suitability	High Suitability	Moderate	High Suitability
Plastics	Not Suitable	High Suitability	High Suitability	High Suitability	Not Suitable
Wood/Garden Waste	Pre- treatment	High Suitability	High Suitability	High Suitability	High Suitability
Textile/Leather	Not Suitable	Variable	High Suitability	High Suitability	Not Suitable

Anaerobic digestion converts methane from biogas into usable energy with a typical efficiency of 20–30%. It is ideal for organic waste and is circular economy friendly. Incineration has an atypical efficiency of 20–25% but has high emission risks and is not ideal for wet or recyclable materials. Gasification converts carbonaceous materials into syngas but has a typical efficiency of 25–40%. Pyrolysis has a typical efficiency of 15–30% and is based on plastics, tires, and biomass-rich fractions. However, it is not suitable for wet or inorganic waste and is underutilised commercially. Cities like Mbeya should prioritise anaerobic digestion and composting for wet fractions, while incineration and gasification could be used for selecting dry, high-energy materials if emission control systems are viable. Pyrolysis should be treated as an emergency option, particularly for problematic plastic and rubber (Table 9).

Table 9

Energy Conversion Efficiency and Environmental Impacts

Technology	Typical Efficiency (%)	Major Emissions/By products	Environmental Notes
Anaerobic Digestion	20 – 30 CH_4 to energy	CO_2, digestate	Low emissions good for organic waste
Incineration	20 – 25(electricity)	CO_2, NO, Dioxins	Require emission control systems
Gasification	25 - 40 (syngas)	CO, tar, slag	Flexible feedstock, medium emission risk
Pyrolysis	15 - 30	Bio – oil, syngas, char	High energy input emerging technology

4.6 Challenges in Implementing Waste to Energy Technologies

Mbeya faces challenges in implementing and sustaining renewable energy systems due to technical skills, infrastructure, capital costs, policy, and public awareness. To address these issues, Mbeya should adopt a multi-stakeholder phased implementation approach, including short-term awareness, medium-term infrastructure rollout, training, and long-term full-scale waste-to-energy integration (table 10).

Table 10
Barriers to Adoption in Mbeya City

Barrier Category	Description in Mbeya City Context
Technical Skills	Lack of trained personnel for operating AD/Gasification units
Infrastructure	No existing centralized collection or segregation system
Capital Cost	High initial investment; limited financing option
Policy and Regulation	No clear WtE policy framework or incentives
Public Awareness	Low understanding of waste segregation or energy value

5.0 Conclusion

The findings of this study reveal that organic waste constitutes a significant proportion of the MSW stream in Mbeya City—over 50% by weight—with measured higher heating values (HHV) ranging between 12 and 16 MJ/kg for combustible fractions such as plastics and paper (appendix 1). These results underscore the untapped potential of MSW as a viable source for energy recovery, particularly through technologies such as anaerobic digestion and thermal conversion. The implications are far-reaching: improved waste-to-energy strategies can alleviate public health risks associated with uncollected or decomposing waste, reduce greenhouse gas emissions, and stimulate local economic opportunities in renewable energy development. However, to fully inform policy and technology adoption, future research should investigate seasonal variations in waste composition, conduct detailed life cycle assessments of proposed energy pathways, and evaluate the socio-economic feasibility of integrating waste-to-energy systems into Mbeya's urban infrastructure. This study thus lays a critical foundation for evidence-based planning toward sustainable waste management and energy recovery in the region.

In conclusion, the characterisation of municipal solid wastes is a critical process that plays a key role in understanding the composition, properties, and potential management strategies for solid waste in urban areas. Through comprehensive characterisation studies, waste management authorities and policymakers can gain valuable insights into the types of waste generated, their sources, and their impact on the environment and public health.

By identifying the various components of municipal solid waste, including organic, recyclable, and hazardous materials, stakeholders can develop tailored waste management plans that promote waste reduction, recycling, and proper disposal practices. Additionally, the data obtained from waste characterisation studies can inform decision-making processes regarding the implementation of waste-to-energy technologies, landfill management practices, and sustainable waste management policies.

Overall, a thorough understanding of the composition and characteristics of municipal solid wastes is essential for designing effective waste management strategies that aim to minimise environmental pollution, conserve natural resources, and promote a circular economy. By continuing to invest in waste characterisation efforts and incorporating the findings into planning and policy development, communities can work towards achieving a more sustainable and resilient waste management system for the benefit of current and future generations.

The comprehensive characterisation of MSW reveals significant potential for converting waste into valuable energy resources. The high calorific value and low moisture content of plastics and paper make them excellent candidates for thermal treatments, while the high moisture and volatile content of organic waste favour biological processes like anaerobic digestion. Understanding the detailed chemical and thermal properties of MSW allows for the optimisation of WtE technologies, ensuring efficient energy recovery, reduced environmental impact, and sustainable waste management. By leveraging these insights, municipalities can design and implement effective WtE systems that maximise resource recovery and contribute to sustainable development goals.

6.0 Recommendations

The findings of this study show a promising path forward for Mbeya City. One where waste is no longer just a burden but a valuable resource. Instead of reacting to mounting garbage through landfilling and open dumping. Mbeya City can take a proactive, forward-looking approach by using MSW to support clean energy, better public health, and sustainable city growth.

In the short term the city should focus on laying the groundwork for smarter management. This means educating communities about the importance of sorting waste at home, providing colour-coded bins to separate organic and inorganic materials, and launching neighbourhood awareness campaigns to build a culture of responsibility and participation.

In the medium term, Mbeya should invest in technical capacity. This includes piloting small-scale anaerobic digestion plants in high-waste areas such as markets and dense neighbourhoods. These pilots' plants will not only produce biogas for local use but also serve as proof of concept for larger investments. Training programs for city sanitation teams and technical staff will be key to operating and maintaining these systems effectively.

In the long term the city can move toward institutionalising sustainable waste-to-energy systems. This involves integrating solid waste data and energy zones into Mbeya's urban planning strategies and developing a dedicated waste-to-energy policy framework. Establishing a digital waste management system will help track how much waste is generated, its composition, and how much is being recovered, giving decision-makers the tools they need to plan smartly for the future.

By taking these steps, Mbeya City can become a model of how local knowledge, community involvement, and strategic planning come together to solve urban challenges, turning today's waste into tomorrow's energy.

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8.0 Conflict of Interest Statement

The authors affirm that there are no competing interests with respect to this manuscript's publication. Nothing in terms of money, people, or affiliations has impacted the work presented in this paper. Moreover, no organisations or entities that would profit monetarily or otherwise from the findings or interpretations of the paper were involved in the research. Although Mbeya University of Science and Technology has funded author Emmanuel Anosisye Mwangomo for related research, this has had no bearing on the findings or interpretations offered in this work.

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Appendix 1

Summary Table of Key Findings – MSW Characterization in Mbeya City

Category	Key Findings	Implications for Energy Recovery
Waste Composition	Organic waste = 54.3% (avg.), Plastics = 12.7%, Paper = 9.6%, Wood = 6.2%	High organic content supports anaerobic digestion and composting
Moisture Content	Organic waste = ~54%, Plastics & Paper = <15%	High moisture limits incineration efficiency; favors biological routes
Calorific Value (HHV)	Plastics = ~32 MJ/kg, Paper = 15 MJ/kg, Food waste = 10 MJ/kg	Plastics and paper are suitable for thermal processes (incineration, pyrolysis)
Volatile Matter Content	Most fractions >70%, e.g., Food Waste = 74.2%, Plastics = 75.3%	High volatile matter indicates good gasification or pyrolysis potential
Fixed Carbon & Ash Content	Plastics: FC = 23.2%, Ash = 1.5%; Food waste: FC = 8.9%, Ash = 16.9%	Low ash content in plastics/paper reduces slagging in thermal systems
Potential Technologies	Anaerobic digestion, pyrolysis, gasification, incineration	Technology selection depends on feedstock quality, moisture, and cost
Environmental Impacts	Open dumping and burning emit GHGs and pollutants	Energy recovery could reduce landfill volume and climate impact
Public Health Consideration	Poor MSW handling increases disease vectors and air pollution	Controlled energy recovery methods improve sanitation and air quality
Barriers Identified	Low technical capacity, poor waste segregation, high capital costs	Requires training, phased investment, and policy incentives

Category	Key Findings	Implications for Energy Recovery
Future Research Needs	Seasonal variation analysis; lifecycle assessment of WtE technologies	To guide robust planning and sustainable technology deployment