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Assessment of Energy Recovery Potentials of Solid Waste Generated in Mbeya City, Tanzania

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Abstract

This paper presents an assessment of the energy recovery potential of solid waste generated in Mbeya City, Tanzania. Through a comprehensive analysis of waste composition, available technologies, and socio-economic factors, the study aims to provide insights into the feasibility and benefits of energy recovery initiatives. A study in Tanzania found that waste streams can be used for energy recovery processes. In Mbeya City, Tanzania, food waste is the largest fraction, followed by plastic bottles. The study analyzed the energy potential of municipal solid waste (MSW) in Mbeya City, focusing on food waste and plastic bottles. The study found that food waste can be reduced through composting, recycling programs, public awareness campaigns, and food recovery initiatives. Plastic bottles can be managed more effectively through improved recycling infrastructure and reusable containers. The study analyzed the energy potential of municipal solid waste (MSW) in Mbeya City, focusing on food waste, plastic bottles, and plant trimmings. The total MSW generated is 3254.5 kg/day, with food waste being the largest fraction at 62.4%. Reducing food waste can be achieved through composting, recycling programs, public awareness campaigns, and food recovery initiatives. Plastic bottles can be managed more effectively through improved recycling infrastructure and reusable containers. The study also estimated the energy recovery potentials of MSW in Mbeya City, Tanzania, based on their calorific value. High energy recovery materials like plastic bottles and nylon are ideal for incineration, while moderate materials like textiles, paper, and leather are suitable for energy recovery processes. Composting and anaerobic digestion can be effective for food waste and plant trimmings, producing biogas and compost. Anaerobic digestion technology offers renewable energy and nutrient recycling, with an ERP of 1,998,858,351 MWh/day, enough for the city's electricity demand.

Keywords

Waste-to-Energy, Energy Recovery, Municipal Solid Waste Management, Material Flow Analysis, Circular Economy

1. Introduction

The challenge of solid waste management is growing due to urbanization and population growth. Traditional methods like landfilling pose environmental and health risks. Energy recovery from solid waste can address these issues by converting waste into energy resources (Nixon et al., 2013). This paper assesses the viability of different energy recovery technologies.

Mbeya City, located in the southern highlands of Tanzania, is experiencing rapid urbanization, leading to an increase in solid waste generation. Inadequate waste management infrastructure and practices pose environmental and health risks to the city's residents. However, solid waste also represents a valuable resource for energy production through various technologies such as incineration, anaerobic digestion, and gasification. This paper evaluates the energy recovery potential of solid waste in Mbeya City, considering its composition, technological options, and socio-economic context.

Energy recovery potential is one of the techniques of treating municipal solid wastes generated for useful applications. Human activities including residential, commercial, industrial, agricultural, commercial and so on, produce waste. These wastes can contribute significantly to the production of energy if they are used creatively, but if they are not, they will negatively affect living circumstances (Akinshilo et al., 2019). In Mbeya City, the following types of municipal solid wastes are generated daily these are: nylon, textile, plastics, food wastes, leather, paper, wood and others (Mwangomo, 2019). The amount of MSW generated worldwide is currently 1.3 billion tons annually, and by 2025, that amount is predicted to rise to 2.2 billion tons (Omar et al., 2014).

The following are some variables that lead to the rising amount of MSW in urban areas including Mbeya City. Urbanization, economic development, population increase and a lack of infrastructure. By taking the hierarchy of waste management into account. This is where MSW is converted into energy that can be used, like in landfilling and incinerator processing facilities. These facilities have the ability to generate both heat and power in areas with limited energy sources, particularly in Mbeya City.

The energy potential of a fuel is a measure of its calorific value (Ngegba & Bertin, 2020), the energy released by the combustion of one unit weight of MSW measured in J/Kg (Kito & Stultz, 2005). Therefore, in order to calculate the energy potential of MSW, the lower calorific value (LCV) rather than the higher calorific value (HCV) is needed because during normal combustion, the LCV is obtained because the latent heat is lost where water leaves as steam, where in calorimeter experiments, wastes develop the HCV.

Aim of the Study

The aim of this study is to analyze waste composition, evaluate energy recovery technologies, calculate energy potential, analyze economic and environmental impacts, develop optimization strategies, and provide recommendations for stakeholders to adopt and implement effective energy recovery solutions from MSW. This includes assessing waste composition, evaluating energy recovery technologies, and integrating them with existing waste management systems.

Research Gap

Research is needed to understand the variability in waste composition, the impact of waste sorting and preprocessing techniques on energy recovery potential, the potential of emerging waste streams, the integration of renewable energy systems, and the lifecycle and environmental impact of energy recovery from municipal solid waste. Dynamic models should be developed to account for seasonal and temporal fluctuations in waste types and quantities. Comprehensive lifecycle assessments of environmental impacts are also needed to ensure sustainable energy recovery methods.

Wast Characterization

Characterizing solid waste involves analyzing waste composition, including organic waste, plastics, metals, paper, and glass. The calorific value of these materials determines their suitability for energy recovery.

Waste-to-Energy (WtE) Technologies

Waste-to-energy (WtE) technologies convert various types of waste into usable forms of energy, typically electricity, heat, or fuels. Here’s a brief overview of some common WtE technologies:

Incineration: This is one of the oldest and most widely used WtE technologies. It involves burning solid waste at high temperatures in specially designed facilities called incinerators. The heat produced is used to generate steam, which drives turbines to produce electricity. Incineration can reduce the volume of waste and recover energy, but it can also generate air pollutants if not properly controlled (Patil et al., 2014). Efficiency of incineration process is ranging from 20% to 30% (Themelis & Ulloa, 2007).

Anaerobic digestion: This process involves breaking down organic waste in the absence of oxygen to produce biogas (mainly methane and carbon dioxide) and digestate. The biogas can be used directly as a fuel for heating or electricity generation, or it can be upgraded to biomethane for injection into the natural gas grid or use as a transportation fuel. Anaerobic digestion is particularly suitable for treating organic waste streams, such as food waste and sewage sludge (Náthia-Neves et al., 2018). Efficiency anaerobic digestion process is ranging from 40% to 60% (Mata-Alvarez et al., 2000).

Gasification: Gasification converts solid waste into a synthesis gas (syngas) consisting mainly of carbon monoxide, hydrogen, and methane, through a thermochemical process in the presence of oxygen and steam. The syngas can be combusted directly in a boiler or used as a feedstock for producing biofuels, chemicals, or hydrogen. Gasification offers higher energy efficiency and lower emissions compared to incineration but requires more complex technology (Pereira et al., 2012). Efficiency of gasification process is ranging from 60% to 80% (Arena, 2012).

Pyrolysis: Pyrolysis involves heating waste in the absence of oxygen to produce a mixture of gases, liquids (pyrolysis oil), and solids (char). The pyrolysis oil can be refined into biofuels, while the char can be used as a solid fuel or soil amendment. Pyrolysis offers the advantage of producing a higher-quality bio-oil compared to gasification but may require pre-processing to remove contaminants (Cekirge et al., 2015). Efficiency pyrolysis process is up to 70% (Motasemi & Afzal, 2013).

Landfill gas recovery: Landfills produce methane as organic waste decomposes anaerobically. Landfill gas recovery systems capture this methane and use it to generate electricity or heat. While not a direct conversion technology, landfill gas recovery helps mitigate greenhouse gas emissions and harnesses energy from waste that would otherwise be emitted into the atmosphere (Srivastava & Chakma, 2020).

Environmental Impact Assessment

Incineration produces greenhouse gases and pollutants; modern facilities use emission control systems (Astrup et al., 2009). Anaerobic digestion has minimal emissions; biogas combustion generates some CO_2 (Holm-Nielsen et al., 2009). Gasification has lower emissions compared to incineration; syngas cleanup is essential (Arena, 2012). Pyrolysis produces fewer emissions than incineration and requires careful management of by-products (Motasemi & Afzal, 2013).

In case of Life Cycle Assessment (LCA)**,** Evaluates the environmental impact from waste collection to energy production (Arena et al., 2015).

Economic Analysis

Cost-Benefit Analysis: Compares costs of waste processing and energy recovery with revenues from energy sales and landfill savings. Positive net benefits indicate economic viability (Dobraja et al., 2016). Investment and Operational Costs: Incineration has high capital costs; anaerobic digestion has moderate costs; gasification has high capital costs; pyrolysis has moderate to high costs (Themelis & Ulloa, 2007; Holm-Nielsen et al., 2009; Arena, 2012; Motasemi & Afzal, 2013).

Regulatory and Social Considerations

This research aims to identify multiple waste streams in energy recovery processes at Mbeya City, focusing on the challenges of integrating various types of municipal solid waste streams efficiently. The study evaluates the feasibility and viability of harnessing energy from various types of solid waste, conducting comprehensive analyses to assess the amount, composition, and calorific value of waste streams. It seeks to identify opportunities for maximizing energy recovery while minimizing environmental impacts, economic costs, and logistical challenges. Advanced waste characterization and research activities are needed to prepare customized energy recovery solutions for Mbeya City (Malkow, 2004) and (Rogers & Simmons, 2011).

Procedure of the Study

This summary outlines the process of energy recovery from municipal solid waste (MSW), including literature review, waste characterization, selection of energy recovery technologies, and energy potential assessment. It involves reviewing academic papers, industry reports, and case studies on waste composition, energy recovery potential, and environmental impact (**Figure 1**). The summary also includes a detailed analysis of waste composition, technology maturity, and economic feasibility.

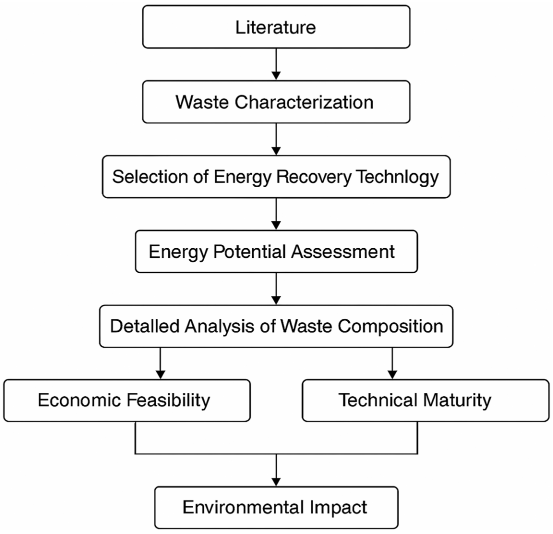

Figure 1. Assessment of energy recovery potential flow diagram.

Structure of the Paper

The study explores the importance of energy recovery from municipal solid waste (MSW) and its challenges. It outlines the study's goals, research questions, and significance. The literature review identifies gaps in current research and technologies related to MSW. The methodology includes waste characterization, technology selection, experimental setup, data collection, and analysis techniques. Results include waste composition, technology performance, energy potential, and economic and environmental impact. The study's interpretation and comparison with existing literature and technologies are discussed.

2. Materials and Methods

2.1. Study Area

Mbeya City Council, located in the South West of Tanzania, has a population of 541,603 people and 153,100 households (URT et al., 2024). The city's population growth rate is 3.2%, similar to the national average of 3.2% per annum (URT et al., 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 & 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 Regional (NBS & MCC, 2016).

Mbeya City is part of the Mbeya Region, which includes other councils such as Mbeya District, Kyela, Busokelo, Mbarali, and Rungwe. Its area is 214 Sq Km and is bordered by Mbeya Rural District, Rungwe District, Ileje District, and Mbozi District in Songwe Regional (**Figure 2**).

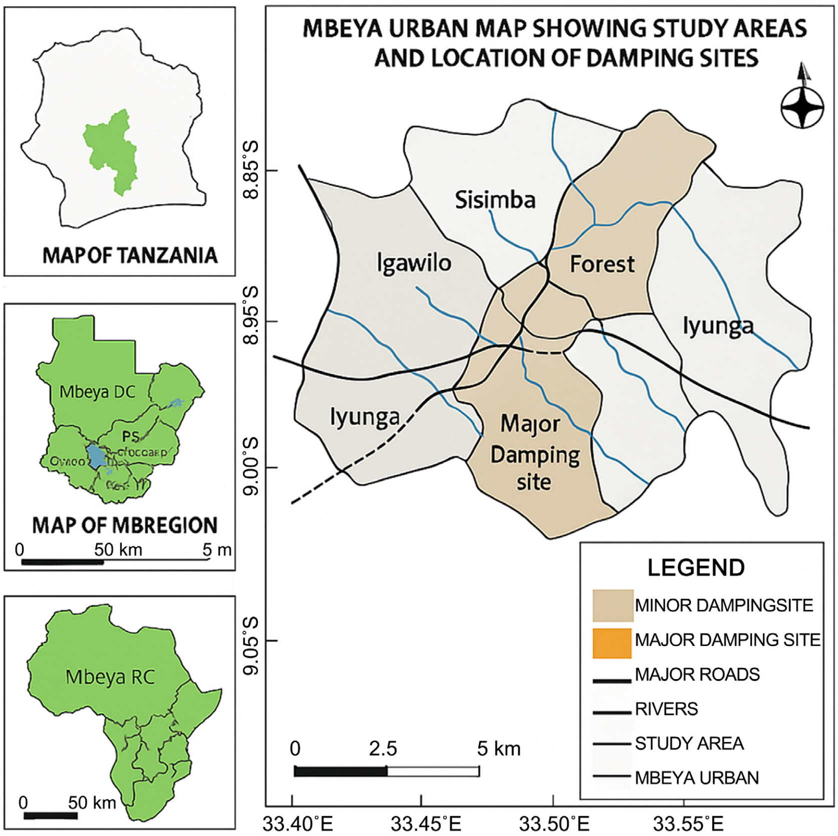

Figure 2. Map of Mbeya City showing six selected Wards. Source (Author, 2024).

2.2. Sample Analysis

This study analyzed waste characterization in Mbeya City's Nsalaga Sanitary Landfill and six selected Wards (**Figure 3**). 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 characterization of MSW in these areas involved assembling composites, cornering and quartering, collecting grab samples, and manually collecting waste columns (Gawaikar & Deshpande, 2006).

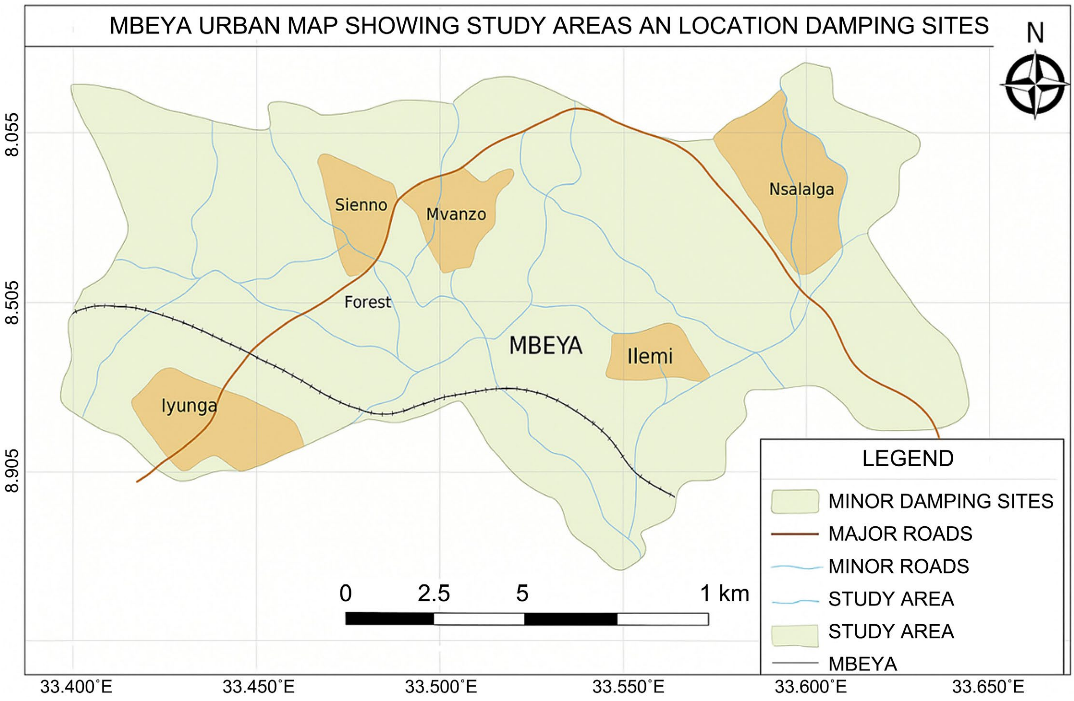

Figure 3. Six selected wards of municipal solid wastes.

Waste characterization was done through standards methods which are: 1) ASTM (American society for the testing and materials). Standards test method for determination of the composition of unprocessed (ASTM, 2002, 2008, 2004a, 2004b, 2004c, 2006a, 2006b); 2) UNEP/IETC—development integrated solid waste management plan Volume 1, waste characterization and quantification with projections for future (UNEP, 2009).

Forty eighty samples were collected from six wards as mentioned above. Some selected households and commercial areas. For a period of one week during 2019. Additional samples were taken from Nsalaga landfill dumpsite. Two containers were supplied to the households one for organic wastes and other for inorganic wastes. The MSW were collected after seven days and then were sorted. Segregation of sample was done into a various physical component such as fruit and vegetable waste, paper, plastics, rags, glass, rubber, leather, metals and inerts. After separation all components were weighed separately. A sample of wastes was taken to the laboratory for testing on its physical and chemical properties.

2.3. Physical Properties of the Solid Waste Sample

In determining the physical characteristics of municipal solid waste (MSW) generated in Mbeya City, it done by involving assessment of various parameters that describe its composition, volume, density, moisture content, and other physical properties.

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

2.4. Chemical Properties of the Solid Waste Sample

Proximate, ultimate analysis were conducted to measure chemical and physical characteristics of municipal solid waste basing on standard testing procedures.

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).

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).

2.5. Calorific Value Determination

Bomb Calorimeter

Calorific value of a fuel is the amount of heat liberated by that fuel under a specific condition of combustions. Heating value can be determined by the following methods; full scale boiler as calorimeter, Laboratory Bomb calorimeter and Calculation. Most of the data on the energy content of the organic components of MSW are based on the results of bomb calorimeter. The bomb Calorimeter measure the calorific value of MSW by burning completely a known mass of MSW in a presence of excess oxygen in a closed vessel, and the heat liberated is made to transfer to previously weighed water. By measuring the rise in temperature of water and using its specific heat value, the calorific value of MSW will be estimated. By using ultimate and proximate values obtained, the higher heating value of a MSW can also be calculated by using Dulong and as given in the Equation (1) below

$$\text{Heat Energy} = 337C + 1428\left(H - \frac{O}{8}\right)\frac{\text{kJ}}{\text{kg}} \tag{1}$$

where C = carbon (%), H = Hydrogen (%), O = Oxygen (%) and S = Sulphur (%).

On the other hand, lower calorific value of a MSW can be obtained by using Dulong equation as shown in the Equation (2) below

$$H_n = 81C + 342.5(H - O) + 22.5S - 6(9H + W) \tag{2}$$

where

H_n = net calorific value (Kcal/Kg); C = Carbon (wt %); H = Hydrogen (wt %); O = Oxygen (wt %); S = Sulphur (wt %) and W = Percentage of moisture content in dry basis.

Estimation of Energy Content in MSW by Using Dulong Formula

The energy potential in MSW components is calculated using the Dulong formula and the elemental composition received from the final analysis results. The lower heating value (LHV) of MSW components is calculated using the Equation (3) below.

$$\text{LHV} = 81C + 342.5\left(H - \frac{O}{8}\right) + 22.5S - (W + 9H) \tag{3}$$

where

C = carbon content (wt %); O = Oxygen content (wt %); H = Hydrogen Content (wt %) and W = moisture content (%).

The LHV obtained from Equation (3) above can be used to calculate energy generation potential as shown in Equation (4) below

$$\text{ERP}\,\frac{\text{GWh}}{\text{day}} = \text{Dry Waste}\left(\frac{\text{kg}}{\text{day}}\right) * \text{LHV of Waste}\left(\frac{\text{kWh}}{\text{kg}}\right) \tag{4}$$

2.6. Estimation of Energy Recovery Potential Using Waste to Energy Options

The energy recovery potential of waste-to-energy (WtE) options is determined by evaluating factors such as waste type, efficiency, and energy output potential, following several waste to energy options.

Landfill Gas (Anaerobic Digestion)

Methane emission from sanitary landfills is given by Equation (5) below

$$Q_{\mathrm{CH_4}} = \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=0.1}^{1} K \cdot L_o \left(\frac{M_i}{10}\right) \mathrm{e}^{-k \cdot t_{ij}} \tag{5}$$

where

$Q_{\mathrm{CH_4}}$ = annual generation of methane in a year (m³/year); M_i = amount of disposed waste (t/year); L_o = methane generation potential (m^3/t) (84); K = constant of the methane generation index (1/year) (0.08); n = the difference between the year of the calculation and the initial year of waste acceptance; i = 1-year time increment.

j = is a 0.1-year time increment and t_{ij} = age of the jth section of waste accepted in year i.

Energy recovery potential from the landfill gas is calculated by using the following Equation (6)

$$\mathrm{ERP}_{\mathrm{LG}} = \mathrm{LCV}_{\mathrm{biogas}} \cdot Q_{\mathrm{CH}_4} \cdot \Upsilon \cdot \eta \tag{6}$$

where

LCV = lower calorific value of the biogas in (kWh/m^3); Υ = efficiency of the biogas recovery system (80%) and η = electrical efficiency of the technology used to generate electricity (33%) (Alzate et al., 2019).

According to Ogwueleka and Ogwueleka (2010) energy content in the Municipal Solid Waste cab be determined by using the following empirical models: Proximate Analysis, Physical Composition Analysis and Ultimate Analysis.

Anaerobic Digestion

This method is used to determine the organic fraction of MSW, whose Energy Recovery Potential is given by the following Equation (7) below.

$$\mathrm{ERP}_{\mathrm{AD}} = P \cdot R_{AC} \cdot f \cdot M_{\mathrm{OFSW}} \cdot Q \cdot \eta \tag{7}$$

where

P = number of inhabitants (Inhab); R_{AC} = annual production of waste per capital in (t/inhab-day); f = organic fraction of solid waste (%); M_{OFSW} = methane generation per ton of organic fraction of solid waste (OFSW) (Nm^3/t); Q = is the LCV of biogas due to the methane (MJ/m^3) and η = efficiency of the process which is set to (26%).

Buswells Equations to Calculate Amount of Biogas Produced from Organic Matter

Theoretical calculations on the volume of biogas and the concentration of methane and Carbon dioxide are done by using the following general equation based on the content of C, H, O, N and S. (Yuen PK and Lau CMD, 2023) as shown in Equation (8) below.

$$\begin{aligned} &\mathrm{C}_c\mathrm{H}_h\mathrm{O}_o\mathrm{N}_n\mathrm{S}_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)\mathrm{H_2O} \\ &= \frac{1}{8}(4c + h - 2o - 3n - 2s)\mathrm{CH_4} + \frac{1}{8}(4c - h + 2o + 3n + 2s)\mathrm{CO_2} \\ &\quad + n\,\mathrm{NH_3} + s\,\mathrm{H_2S} \end{aligned} \tag{8}$$

The constants c, h, o, n and s are assumed to be 5, 7, 2, 1 and 0 respectively i.e. $c = 5$, $h = 7$, $o = 2$, $n = 1$ and $s = 0$. Since all ammonia (NH_3) dissolved in the slurry. We only calculate CO_2 and CH_4.

By using the Equation (8) above with the constants given above we obtain the following Equation (9).

$$C_2H_7O_2N + 3H_2O \rightarrow 25CO_2 + 2.5CH_4 \quad (9)$$

Incineration

Energy Recovery Potential (ERP) is obtained by using the following Equation (10)

$$\mathrm{ERP}_i = \frac{\eta\left(M \cdot \mathrm{LCV}_{\mathrm{MSW}}\right)}{1000} \quad (10)$$

where

ERP = Energy recovery potential (MWh/day); M = Total mass of dry solid waste (Kg/day); $\mathrm{LCV}_{\mathrm{MSW}}$ = Lower Calorific Value of Waste (KWh/Kg) and Total processing efficiency (Assume 18 %).

Gasification

Energy Recovery Potential (ERP) through gasification process is given by the Equation (11).

$$\mathrm{ERP}_{\mathrm{G}} = 0.28 \cdot G \cdot R_f \eta \cdot \mathrm{LCV}_{\mathrm{MSW}} \quad (11)$$

where

G = number of tons processed per day (t/day); η = energy recovery efficiency for gasification process (ranges from 50% to 80%) and R_f = percentage of rejection after the mechanical treatment. Assumed to be 23%.

3. Results and Discussion

3.1. Results

The objective of this study was to assess the MSW energy potential in order to address its potential as a feedstock for energy recovery processes such as waste to energy facilities or other forms of conversion into useful energy. Different wastes to energy options technology potential were obtained and explained in the following sections.

Composition of Municipal Solid Wastes in Mbeya City

The total amount of municipal solid waste (MSW) generated in the Philippines is 3254.5 kg/day, with food waste being the largest fraction at 2031.5 kg/day, accounting for 62.4% of the total municipal solid wastes generated (see **Figure 4**).

Plastic bottles make up 6.65% of the total, followed by other mixed categories at 462.5 kg/day. The highest amounts of food waste are generated in Nsalaga and Forest, while Sisimba contributes significantly to plastic bottles. Iyunga contributes notably to nylon, food waste, and plant trimmings. The average daily MSW generation is 464.93 kg/day.

Proximate and Ultimate Analysis

Proximate Analysis

The moisture content of food waste is the highest at 53.8%, affecting its energy recovery potential. Nylon has the lowest at 1.2%, making it less susceptible to moisture-related issues. Wood has the highest volatile matter content at 93.3%, suggesting a large portion can be vaporized during combustion. Nylon has the lowest at 37.9%, suggesting a more stable material with lower emissions (Table 1).

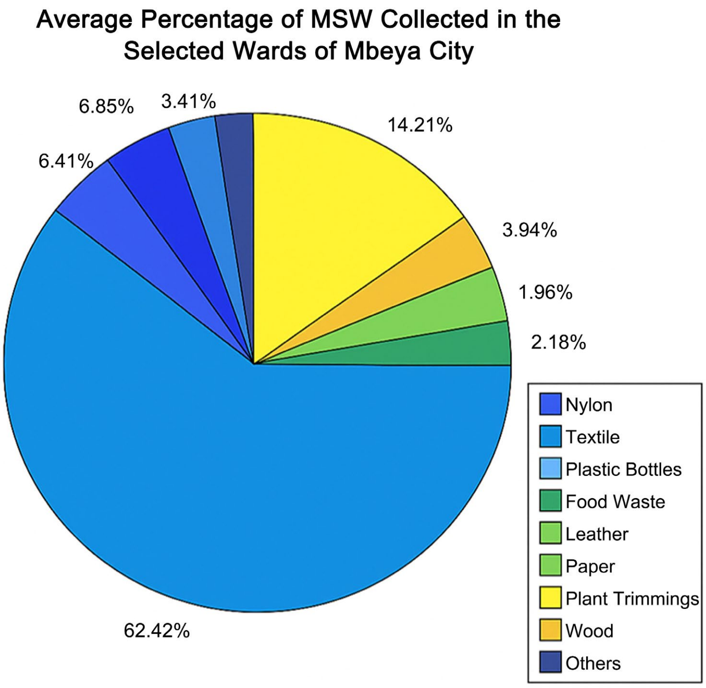

Figure 4. Average percentage of MSW collected in the selected wards of mbeya city.

Table 1. Proximate values.

Type of wastes	PMC	PVM	PAC	PFC
Nylon	1.2	37.9	7	55.1
Textile	4.3	77.0	1.6	21.4
Plastics	13.6	75.3	1.5	23.2
Food wastes	53.8	74.2	16.9	9
Leather	13.3	76.6	8.0	15.5
Paper	7.4	75.0	7.3	17.7
Wood	13.6	93.3	2.7	4.1
Plant trimmings	13.3	78.8	15.3	5.9

Food wastes and plant trimmings have high ash contents at 16.9% and 15.3%, respectively, indicating significant inorganic material presence. Textile has the lowest ash content at 1.6%, suggesting fewer residues after combustion. Nylon has the highest fixed carbon content at 55.1%, making it suitable for energy recovery.

Ultimate Values

The carbon content of materials is a key factor in their composition. Plastics and textiles have the highest carbon content, making them highly carbonaceous materials. Food wastes and plant trimmings have the lowest carbon content, reflecting their higher oxygen content. Leather has the highest nitrogen content, likely due to its protein content. Textile and paper have very low nitrogen content, while plastics have no detectable nitrogen content. Food wastes and plant trimmings have higher hydrogen content, indicating their organic and water content (Table 2).

Table 2. Ultimate values.

Type of wastes	%C	%N	%H	%O	%S
Nylon	93.0	0.5	0.7	5.7	0.04
Textile	98.4	0.2	0.2	1.2	0.06
Plastics	98.5	-	0.2	1.3	0.03
Food wastes	8.3	1.7	1.7	13.5	0.04
Leather	92.0	5.1	0.3	2.4	0.1
Paper	92.1	0.2	0.8	6.3	0.05
Wood	97.4	0.3	0.3	2.0	0.06
Plant trimmings	83.8	1.1	1.7	13.4	0.04

Oxygen content is highest in food wastes and plant trimmings, while textiles and plastics have the lowest. The highest sulfur content is in leather, which can contribute to sulfur dioxide emissions during combustion.

Estimation of Energy Recovery Potentials of Municipal Solid Wastes

The Higher and lower Calorific Values of various MSW components were determined by using bomb calorimeter and its lower calorific value and energy recovery potentials were calculated by using empirical Equations (1) and (2) the results of high and lower calorific values are shown in Table 3 below.

Table 3. Calorific value (HHV) of municipal solid wastes in mbeya city.

S/N	Type of Sample	Calorific Value (cal/g) (HHV)	Lower Calorific Value (cal/g) (LHV)	Mass of MSW Component (Kg)	Energy Recovery Potential (Kwh)
1	Nylon	8090.2	33,895.73	1,278,663	50,275,810,338
2	Textile	4065	17,019.34	1,557,529	30,749,414,109
3	Plastic bottles	9541.2	39,947.09	3,756,766	1.74083×10^{11}
4	Food Waste	4351	18,216.76	32,806,339	6.93245×10^{11}
5	Leather	5072.3	21,236.70	1,083,774	26,698,308,635
6	Wood	4297.2	17,991.51	1,104,372	23,048,411,063
7	Plant Trimmings	3886	16,269.90	918,989.5	17,344,166,029
8	Paper	4537.4	18,997.18	1,437,109	31,669,181,289
				Total	**179,785,291,463**

The energy density of materials is influenced by their calorific value (HHV and LHV). Plastic bottles have the highest HHV at 9541.2 cal/g, while textiles have the lowest at 4065 cal/g. Lower LHV values are given for each type, typically lower than HHV due to energy lost during combustion. Food waste has the highest mass at 32,806,339 Kg, while plant trimmings have the lowest mass at 918,989.5 Kg. Food waste has the highest energy recovery potential at 6.93245×10^{11} KWh, while plastic bottles contribute significantly with a potential of 1.74083×10^{11} KWh. The total potential energy recovery from all waste components is 179,785,291,463 KWh.

High energy recovery materials like plastic bottles and nylon are ideal for incineration and energy recovery due to their high calorific values. Food waste, despite its lower calorific values, has a high total energy recovery potential. Moderate energy recovery materials like textile, paper, and leather are suitable for energy recovery processes due to their substantial masses. Wood and plant trimmings, although having lower energy recovery potential, still contribute significantly to the waste stream. To maximize energy recovery, incineration facilities should prioritize high-energy waste like plastic bottles and nylon. Composting and anaerobic digestion can be effective for food waste and plant trimmings, producing biogas and compost. Recycling paper and textiles can also be more energy-efficient than incineration.

Projected energy recovery potential projected ten years is shown in the **Figure 5** below.

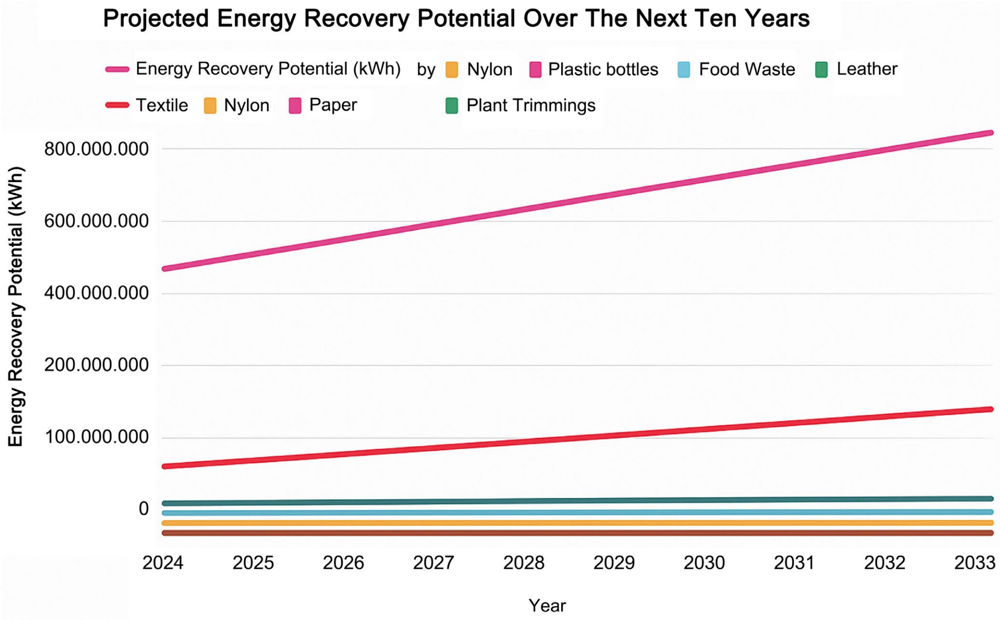

Figure 5. Energy recovery potential from municipal solid wastes in mbeya city from year 2024 to 2033.

Figure 6 below shows the higher calorific value (HHV) of each type of waste, with Plastic Bottles and Nylon showing the highest HHV (~9000 cal/g). Food waste, despite its high mass, has a significantly lower calorific value (~4000 cal/g). Textile, Wood, Leather, and Paper have moderate calorific values (~4000 - 5000 cal/g). These waste materials have the highest potential for energy recovery when incinerated or processed for energy conversion.

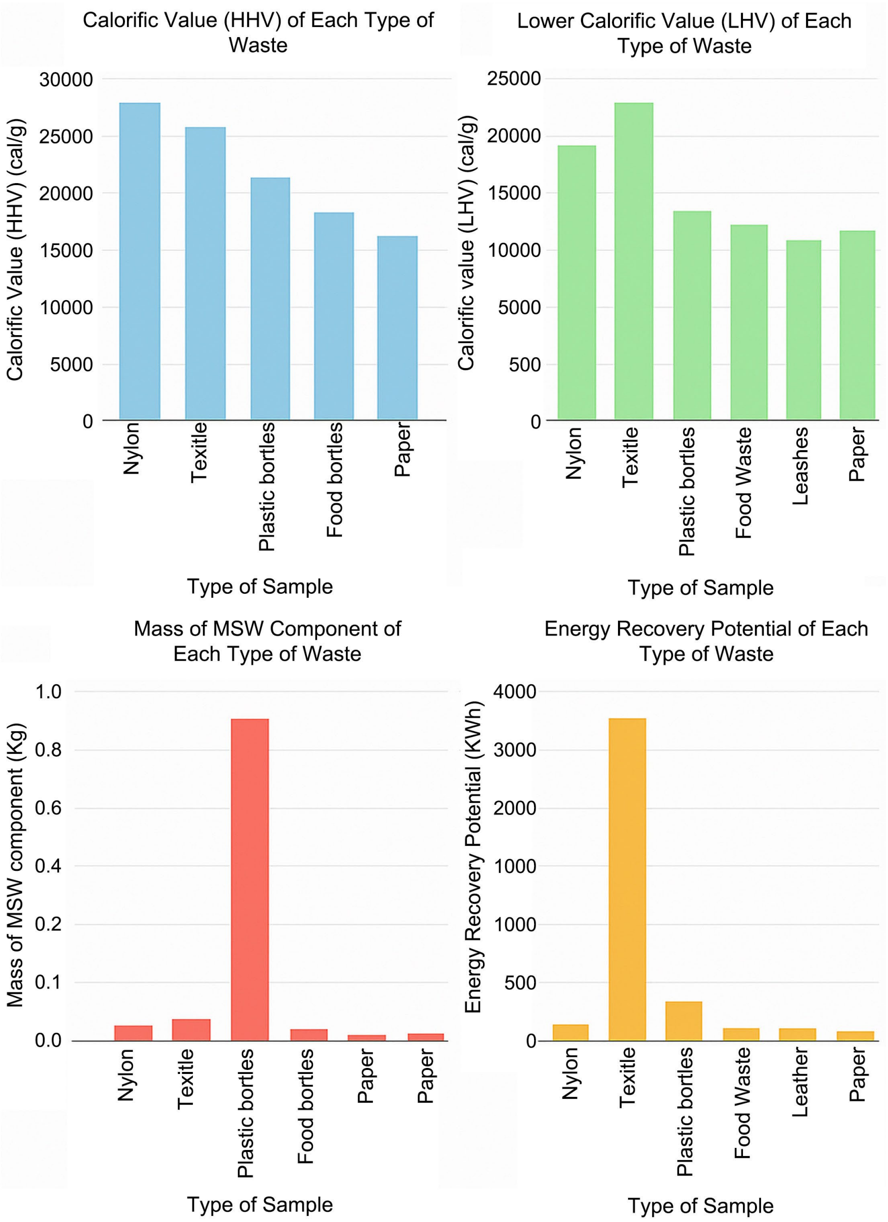

Figure 6. Characterization of municipal solid wastes in selected wards of mbeya city.

The lower calorific value (LHV) of various waste types is also displayed, with Plastic Bottles and Nylon having the highest LHV (~35,000 cal/g). Despite their lower energy density, these materials offer superior energy recovery potential in systems that account for LHV.

The mass of MSW components is also shown, with Food Waste dominating the chart with an enormous mass (~3 × 10^7 kg). Despite its lower calorific value, Food Waste has the highest energy recovery potential due to its sheer mass. Plastic Bottles and Nylon follow as distant second and third contributors to energy recovery, primarily due to their high calorific values.

In conclusion, Plastic Bottles and Nylon are highly valuable for energy recovery due to their superior calorific values, while Food Waste has the highest energy recovery potential due to its large volume. Efficient processing of food waste could greatly benefit waste-to-energy systems.

The study reveals that waste types like nylon and plastic bottles have the highest calorific values, while food waste and paper have the lowest. The higher the HHV, the more energy can be recovered from burning that type of waste. Plastic bottles and nylon dominate with LHVs above 30,000 cal/g, while food waste has a lower LHV around 2000 cal/g. Food waste has the highest energy recovery potential, while plastic bottles and nylon have high recovery potential but less mass.

Incineration Technology

Equation (10) was used to determine the potential energy recovery potential through incineration process. An assumption was made to collect 364.93 tons of MSW daily in Mbeya City and sorting to its main components before fed them into waste to energy conversion facilities. Table 4 below shows energy recovery potential through incineration for MSW generated and collected in Mbeya City annually. MSW which possess high calorific value are suitable for incineration process. These MSW components are nylon, plastic bottles, paper textile and wood.

Table 4. Energy Recovery Potential (ERP) by incineration.

S/N	Type of Sample	Mass of MSW component (Kg)	Calorific Value (cal/g) (LHV)	Energy Recovery Potential (MWh/day)
1	Nylon	10.838421	33,895.73	7.690653
2	Textile	12.444113	17,019.34	4.433624
3	Plastic bottles	24.267845	39,947.09	20.29404
4	Wood	7.152628	17,991.51	2.693925
5	Paper	8.247418	18,997.18	3.279891
	Total	**62.950425**		**38.39213607**

Energy Recovery Potential (MWh/day) for incineration process is Highest in Plastic bottles (20.29404 MWh/day) and Lowest in Wood (2.693925 MWh/day). Plastic bottles have the highest energy recovery potential, contributing significantly to the total energy recovery potential. Plastic bottles are a highly valuable component of the waste stream in terms of energy recovery. Their high calorific value and significant mass make them a critical focus for energy recovery efforts.

Anaerobic Digestion Technology

This method is used to determine the organic fraction of MSW, whose Energy Recovery Potential was determined given the Equation (7). An Organic Fraction of MSW consists of a high proportion of organic waste resulting from food residues, paper and plant trimmings waste, in this study food wastes were used to calculate energy recovery potential for anaerobic digestion process. In case of selected wards of Mbeya City Organic Fraction of MSW is about 62.42% of the total mass of MSW collected.

By using 7 energy Recovery potential through anaerobic digestion obtained was

$$\begin{aligned}\text{ERP} &= 520488.4757 \times 0.000701133 \times 62.42 \times 50 \times 26 \times 67.5 \\ &= 1998858351\ \text{MWh/day}\end{aligned}$$

If anaerobic digesters could be installed in Mbeya City, we could generate 1,998,858,351 MWh/day electrical energy daily which is enough for the demand of Mbeya City. Other application of biogas produced through these digesters are cooking and space heating which currently consume a lot of biomass and LPG.

Buswells Equations to Calculate Amount of Biogas Produced from Organic Matter

The molar ratio for CO_2 and CH_4 ais 2.5:2.5, thus the gas composition is 50% CO_2 and 50% CH_4. For 32,806,339 Kg of food/organic wastes generated in Mbeya City 1 Mol of substrate = 2.5 Moles of CH_4.

Ideal Gas law

$$PV = NRT \tag{12}$$

where

P = absolute pressure of the gas (atm), 1 atm; V = volume (L); n = amount of substance (mol), 2.5 mol; R = gas constant (0.082057471 $\text{L·atm·K}^{-1}\text{·mol}^{-1}$), and T = absolute temperature (K), 273.15.

By using Equation (12) above

$$V = nRT/P = 2.5 \times 0.082057471 \times 273.15/1 = 56.03\ \text{L}$$

Molar mass of $C_5H_7O_2N$ = 5 × 12 + 17 × 1 + 16 × 2 + 14 = 113 g/mol.

The methane yield is 56.03/113 = 0.496 m^3/Kg.

For the 32,806,339 Kg of the food/organic wastes generated in Mbeya City.

Methane yield = 32,806,339 × 0.496 m^3 = 16,271,944.14 m^3 annually.

Since the same amount produced by methane is equal to the CO_2 yield, then Carbon dioxide yield will be 16,271,944.14 m^3. Biogas yield will be the sum of methane yield and carbon dioxide yield which is equal to 32,543,888.28 m^3.

Gasification Technology

Energy Recovery Potential (ERP) through gasification technology was obtained by using Equation (11) and its value is 35,780.53901 KWh/day as shown in Table 5 below.

Table 5. Energy recovery potential (ERP) by gasification.

S/N	Type of Sample	Mass of MSW component (Kg)	Annual Mass of MSW component (tonnes)	Calorific Value (cal/g) (LHV)	Energy Recovery Potential (KWh)
1	Nylon	10.838421	3.956023665	33,895.73	7167.502
2	Textile	12.444113	4.542101245	17,019.34	4132.030178
3	Plastic bottles	24.267845	8.857763425	39,947.09	18913.55578
4	Wood	7.152628	2.61070922	17,991.51	2510.672567
5	Paper	8.247418	3.01030757	18,997.18	3056.778487
	Total	62.950425	22.97690513		35,780.53901

The total mass of MSW components is 62.950425 kg, with an annual mass of 22.97690513 tonnes. Plastic bottles have the highest calorific value at 39,947.09 cal/g, indicating high energy potential when incinerated. Nylon follows with 33,895.73 cal/g, while textile, wood, and paper have values ranging from 17,019.34 to 18,997.18 cal/g. The total energy recovery potential from these components is 35,780.53901 KWh, with plastic bottles having the highest potential at 18,913.55578 KWh.

Plastic bottles have the highest energy recovery potential, contributing significantly to the total energy recovery potential, while wood has the lowest.

Gasification for energy recovery potential for each municipal solid waste components is in Table 5 above. Gasification process offers considerable energy recovery and reduces the amount of potential pollutants emission. Furthermore, gasification could be suggested as workable substitute for traditional waste treatment methods by converting MSW into syngas, a gaseous energy form with potential use in the manufacturing of chemical or electricity.

Landfill Gas Technology

In Mbeya City there is only one sanitary landfill on which all municipal solid waste generated are disposed. Methane emission from sanitary landfills was obtained by Equation (5). Energy recovery potential from the landfill gas was calculated by using Equation (6) and its values obtained was 93,805.4062 MWh/day.

3.2. Discussion

Composition of Municipal Solid Wastes in Mbeya City

The majority of municipal solid waste (MSW) is food waste (Figure 4), which can be significantly reduced through composting and recycling programs. Public awareness campaigns and food recovery initiatives can also help reduce food waste at the source. Plastic bottles, the second-largest fraction, can be managed more effectively through improved recycling infrastructure and promoting reusable containers. Consumer behavior changes, such as using refillable bottles, can also help reduce plastic waste. The “Others” category needs further analysis to identify specific waste types and develop targeted waste management strategies. 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, and Iyunga implementing programs for handling various waste streams.

Proximate and Ultimate Analysis

Proximate Values

Nylon, textiles, plastics, food wastes, leather, paper, wood, and plant trimmings are all suitable for energy recovery and waste management. Nylon is a high-fixed carbon material with low moisture content, making it suitable for combustion with a stable burn and high energy output. Textiles have high volatile matter and low ash content, making them suitable for incineration with high energy yield and minimal residue. Plastics have high volatile matter content and moderate fixed carbon, making them efficient in energy recovery processes. Food wastes have high moisture and ash content, making them less suitable for combustion. Leather has moderate fixed carbon and high volatile matter, suggesting it can be used for energy recovery with careful management to control emissions. Paper has moderate fixed carbon and volatile matter, making it effective incinerated with moderate energy yield and manageable ash content. Wood has high volatile matter and low fixed carbon, making it suitable for biofuel applications.

Food waste and plant-based materials are more moisture and volatile-heavy, with higher PMC and lower PFC, indicating less stable carbon content and higher residue after processing. Nylon, with high PFC and low PMC, is an interesting waste type with high stability and energy potential. Wood and plant trimmings have high PVM, indicating a large proportion of volatile components, reflecting their biomass nature. Plastics and textiles have similar characteristics, with high PVM, lower PAC, and moderate PFC. These waste materials' compositions influence their management and disposal potential.

Ultimate Values

Plastics and textiles, with high carbon content, are ideal for incineration due to their high energy yields and minimal ash residue. Nylon, with moderate nitrogen and sulfur content, is suitable for energy recovery but may produce emissions. Leather, with its high nitrogen content, may produce nitrogen oxides, requiring proper emission controls. Food wastes and plant trimmings, with low carbon but high oxygen and moisture content, are ideal for composting or anaerobic digestion due to their high organic matter content. Paper and wood, with high carbon content and moderate oxygen content, are suitable for combustion with decent energy yields but low nitrogen and sulfur emissions, minimizing potential emissions.

Plastics and textiles are highly energy-dense materials, but their stability and low biodegradability make them less suitable for natural decomposition. Biodegradable materials like food waste and plant trimmings have lower carbon content but higher oxygen, hydrogen, and nitrogen, making them suitable for composting or biological treatment processes. Leather, with high nitrogen and sulfur content, could produce harmful NOx and SOx emissions during combustion. Paper and wood, with high carbon content but minimal nitrogen and sulfur, have potential for recycling and energy recovery. High-nitrogen wastes like leather, food, and plant trimmings may be better suited for composting or biological treatments, while low-sulfur wastes, except leather, have less potential to contribute to sulfur emissions.

Energy Recovery Potentials of Municipal Solid Wastes

Calorific value of MSW obtained shows that plastic bottles, nylon, and leather have the highest value compared to plant trimmings, wood, textiles, and food, which recorded the lowest values. According to the study done in Lagos, Nigeria, by Akinshilo et al. (2019) plastic and paper wastes possess higher calorific values compared to food and organic wastes. This result is similar to the results obtained in this study, as shown in the table above. The presence of higher moisture in food wastes lowers its calorific values. To increase the calorific value of MSW, sorting and drying of wastes have to be done before using it. MSW, which contains a high calorific value, is suitable for thermal chemical energy conversions like incineration, gasification, and pyrolysis.

Theoretical energy recovery potential was also calculated by using empirical equations for each waste to energy conversion processes. These processes were incineration, anerobic digestion, gasification, landfilling gas and Dulong Model equation. The presence of MSW generated in Mbeya City is an essential parameter of generating renewable energy from the MSW. The collected MSW should be treated by sorting and drying before being used as a feedstock in the waste to energy processing facilities.

Plastic bottles and nylon are energy-dense materials suitable for incineration or waste-to-energy processes, but their combustion can release harmful emissions. Food waste, due to its mass, is the largest contributor to total energy potential. However, it's biodegradable, making composting or anaerobic digestion an alternative. Wood, plant trimmings, and paper can also be used for biomass recovery, providing cleaner alternatives to fossil fuels. The total energy recovery potential from these waste-to-energy components is nearly 180 billion KWh.

Incineration Technology

Plastic bottles and nylon have a highest ERP potential through incineration process of 20.294 and 7.6906 MWh/day respectively. Amount of MSW generated in Mbeya City can be used to generate 38.3921 MWh of electrical energy per day, compared to the electrical consumption of 104.29 Mwh/day as reported by Shibano and Mogi (2020). Most of the MSW generated in Mbeya City are food/organic wastes which are not suitable for incineration process. These types of wastes have lower calorific value and high moisture content, so they are not suitable for incineration process. If all generated MSW are incinerated they will be used for useful application like energy recovery, waste reduction and small size of land will be used and disposing hazardous waste by burning them. On other hand negative implications of incineration process are: air pollution, greenhouse gas emissions, ash disposal, public health concern and discouraging recycling.

Combustible waste fraction of MSW generated in Mbeya City can be used as a feedstock in incineration process. However large percentage of MSW generated are food/organic waste, this scenario is the same in other cities of Tanzania (Omari et al., 2014).

Anaerobic Digestion Technology

The implications of anerobic digestion are significant, encompassing environmental benefits, economic opportunities and social advantages. Anaerobic digestion process represents a sustainable approach to waste management renewable energy production and nutrient recycling contributing to a more resource efficient and environmentally friendly society. The biogas can be used to produce electricity heat and biofertilizer. Also, biogas produced can be upgraded into biomethane and used as a natural gas substitute. According to literatures typical 1 tonne of organic MSW produce 100 - 200 m^3 of biogas (Sharmin et al., 2025). Food waste has three times the methane production potential as biosolids, one tonne of food waste can produce 376 m^3 gas/tonne (Islam et al., 2012). In Mbeya City, 520,488.47 tonnes of MSW are produced per day then there is a potential of producing 78,073,275 m^3 of biogas daily which can be useful for applications.

Research in anaerobic digestion of MSW presents numerous opportunities for improving waste energy productions. Some of the recommended future research areas are: optimization of process parameters, pH, retention time and mixing regimes; pretreatment techniques; co-digestion strategies; inhibition management (such as heavy metals, ammonia and organic acids); digestate management; energy integration and upgrading life cycle assessment; microbiological studies and commercialization. By addressing these research areas, the aim would be to enhance the efficiency sustainability and practical applicability of anaerobic digestion for treatment of MSW while generating renewable energy and valuable by products.

Gasification Technology

Plastic bottles and nylon are the most significant contributors to energy recovery from MSW due to their high calorific values and mass. Prioritizing these materials for incineration can maximize energy recovery. Textile, wood, and paper also have significant energy recovery potential and can be efficiently used in waste-to-energy processes. Waste management strategies should focus on incineration of plastic bottles and nylon; while recycling or incineration of textile, wood, and paper can balance material recovery and energy generation.

Gasification of MSW holds potential for energy recovery and waste reduction, but it requires careful consideration and addressing potential challenges to ensure its environmental, economic, and socially acceptable implementation. Current gasification technology is not fully commercialized, especially in developing countries like Tanzania. Future research should focus on feedstock flexibility, tan reduction, improved gasifier design, advanced control systems, carbon capture and utilization, process integration, and system optimization. Biomass gasification is a competitive method for low value scattered lignocellulosic biomass to fuel gas for fuel cell and synthetic diesel production. Future research should focus on improving efficiency and environmental performance, including feedstock flexibility, tar reduction, carbon capture and utilization, advanced gas clean up, process integration, and economic viability.

Landfill Gas Technology

Landfilling has become the primary method of managing MSW worldwide due to the rise in MSW production. Landfills hold over 37% of the MSW produced worldwide (Urme et al., 2021). Concerns about the gasses released from landfills have grown as a result of this. The worldwide anthropogenic greenhouse gas emissions, which are harmful to the worlds environmental media have been greatly increased by these gases. While there have been certain wealthy countries where there has been tremendous progress in using landfill gas, there has not been any strategy or control over LFG emission in Africa. Given that 10,496 × 10^6 m^3 produced in Africa in 2012 (assuming that all waste generated was landfill) managing the LFG generated in Africa is critical (Urme et al., 2021).

Landfill gas technology has significant implications for MSW management offering environmental, economic and regulatory benefits. It provides an opportunity to turn a MSW products into a valuable energy resource while mitigating environmental impacts associated with landfill gas emission. Landfill gas is composed of a mixture of different gases like methane and carbon dioxide which is tapped and used for useful applications, they contribute to the greenhouse emission. Landfill gas systems are burnt and a significant amount of renewable energy is generated and utilized from the landfills in developed countries (Un, 2023). A strategic strategy was provided for the development of LFG technology which includes: 1) estimating final yield and generation rates of LFG based on the composition of the MSW 2) designing on LFG abstraction system suitable for the site and landfilling techniques and 3) developing economical gas usage strategies.

Implications of landfill gas underscore the importance of effective management and mitigation strategies to minimize its negative impacts on the environment and public health while maximize its potential as a renewable energy resource. This requires careful planning, monitoring and the implementation of appropriate technologies and practices to address the challenges associated with landfill gas emission.

A workable way to replace fossil fuels in the production of electricity that produces sustainable energy is through the use of landfill gas. It is lessening fugitive landfill in addition to lowering greenhouse gas emission from fossil fuel power plants. Landfill gas emission are a valuable waste that ought to be recovered especially in terms of their methane energy content.

In Mbeya City there is one sanitary landfill dump site where all MSW collected from their source of generation are disposed there. The MSW disposed are neither sorted and not treated for further useful applications. In order to capture landfill gas at Nsalaga landfill presorting and pretreatment of MSW should be done prior to the disposal.

Life Cycle Analysis

The life cycle (LCA) of energy recovery technologies for MSW involves multiple stages, including waste collection, reprocessing, conversion energy utilization and environmental impact assessment. Incineration is the most efficient and environmentally friendly method with ERP of 38.392 Mwh/day. It reduces waste volume significantly bur requires high capacity costs and strict environmental regulations. Gasification is more efficient and environmentally friendly but requires advanced technology and high capital investment. Anaerobic digestion is the most efficient and environmentally friendly method with an ERP of 1,998,858,351 Mwh/day. It reduces methane emissions compared to landfilling but requires controlled conditions and biogas upgrading. Landfill gas on the other hand has a moderate energy recovery potential but is the least preferred option due to the long decomposition periods. It is sustainable alternative to landfills but contributes to climate change through the risk of methane leaks. Overall the LCA analysis shows that anaerobic digestion is the best for organic waste but depends on proper feedstock segregation.

Technical Economic Analysis of Waste to Energy Technologies

The economic analysis of energy recovery technologies in Tanzania reveals that landfill gas recovery is the most cost-effective option due to its low CAPEX and high revenue. Anaerobic digestion is also a viable sustainable solution, but requires organic waste segregation. Incineration and gasification require high investment and have longer payback periods due to higher costs. The levelized cost of energy (LCOE) analysis shows that landfill gas has the lowest LCOE making it the most cost effective option. Anaerobic digestion is competitive but gasification has the highest cost and lowest economic feasibility. The net present value (NPV) analysis shows that landfilling gas recovery has the highest positive NPV due to strong revenue and low costs. The final recommendations are that incineration is moderately viable due to high CAPEX and emission control, gasification is low due to high costs and complex processing and anaerobic digestion is high and requires organic waste segregation.

Anaerobic is economically viable in Tanzania, at Mbeya City this technology can generate $7.94 Million annually at an electricity price of USD 0.088/KWh. With an investment of $25 M - $50 M, the payback period ranges from 4 to 10 years, depending on capital cost and operation expenses. The LCOE is $50 - 100 making it competitive with incineration and gasification but more sustainable. The process also provides additional revenue from digestate fertilizer enhancing financial returns. Despite requiring waste segregation and efficient feedstock management. Anaerobic digestion is cost effective and environmentally friendly solution for organic waste to energy conversion in Tanzania.

In Depth Analysis of Waste to Energy Technologies in Mbeya City

Mbeya City a Tanzanian urban center faces challenges in waste management and energy access. The city's current waste management practices include limited waste segregation at source, uncontrolled dumping and open burning in some areas and landfill with inadequate gas recovery infrastructure. The city has four possible waste to energy technologies: incineration, gasification, anaerobic digestion and landfilling gas recovery. Incineration is moderately applicable due to its ability to process mixed waste, reduce landfill volume and provide stable energy output. Gasification is low due to its high CAPEX and complex technology, but it can process mixed MSW and biomass and produce syngas for industrial use. Anaerobic digestion is high due to its suitability for Mbeya's high organic waste, producing biogas for electricity and cooking and using digestate organic fertilizer. Landfilling gas recovery is very high due to its use of existing landfills . low CAPEX and low emissions.

In conclusion landfill gas recovery is the most cost-effective solution for Mbeya

City. Anaerobic digestion should be developed to handle high organic waste volumes, while incineration may become viable if Mbeya expands its industrial sector. Gasification is not recommended unless significant waste processing improvement occur. The City's infrastructure readiness includes existing organic waste sources, gas capture system. The best use case for each technology depends on the City's need and infrastructure readiness.

Statistical Methods or Modelling Techniques to Validate the Findings

Monte Carlo simulation method was used for evaluating and validating economic viability and technical feasibility of four waste to energy technologies in Mbeya City. Key variables and assumptions were defined. The results show that anaerobic digestion and landfill gas recovery emerge as the most viable technology for Mbeya City with high probabilities of positive NPV and relatively short payback periods. Incineration and gasification shows more variability in NPV outcomes, with incineration being particularly sensitive to capital and operating costs leading to higher uncertainty.

Justification for Efficiency and Rejection Rates

The energy recovery potential (ERP) for waste to energy technologies is influenced by their processing efficiency and rejection rates. Incineration, gasification, anaerobic digestion and landfilling gas recovery rate are the four technologies considered in Mbeya City. Incineration has an ERP of 38.392 Mwh/day with an efficiency of 20% - 30%. Anaerobic digestion has ERP of 250 Mwh/day with an efficiency of 60% - 80% depending on the waste composition and technology used. Gasification has an ERP of 35.78 Mwh/day with an efficiency of 30% - 50%. Landfilling gas has ERP of 93,805 Mwh/day with an efficiency of 30% - 50% depending on the technology used. Incineration has a low ERP due to heat losses and rejection of non-combustibles. Anaerobic digestion is more selective focusing on biodegradable waste, but effective pretreatment and sorting are necessary to minimize rejection rates and optimize the process. Landfill gas recovery has a low ERP due to the focus of on capturing methane produced by decomposing organic material, leaving behind non-degradability materials like metals, plastics and glass.

4. Conclusion

The potential for recovering energy from solid waste could be realized in Mbeya City through this assessment in Tanzania, ensuring best practices in sustainable waste management in rapidly urbanizing regions. An energy recovery project will save the environment from pollution, increase energy security, and promote inclusive growth by using available technologies within the limits of current socioeconomic conditions. However, an inclusive effort, collaborated on by government agencies, private sector players, and the local community, is what will uncover the full potential of solid waste as a source of renewable energy. The study evaluates the potential of solid waste in Mbeya City, Tanzania, for energy recovery. The majority of waste is organic garbage, plastics, paper, and other flammable materials, which have a high calorific value. These waste products could help

Mbeya City meet its energy needs, reduce its reliance on fossil fuels, and reduce environmental impacts like greenhouse gas emissions. Practical methods for turning waste into energy include gasification, incineration, and anaerobic digestion. The most promising methods are gasification or incineration for non-biodegradable waste streams and anaerobic digestion for organic garbage. However, careful consideration of economic, technological, and social factors is needed for sustainability and community acceptance.

5. Recommendations

Mbeya City should adopt an integrated waste management system that includes waste segregation, recycling, and energy recovery to optimize energy recovery and reduce landfill waste. The city should invest in waste-to-energy infrastructure, such as anaerobic digesters and incineration or gasification plants, and initiate pilot projects to demonstrate their feasibility. Public awareness campaigns should encourage household waste segregation and promote the benefits of waste-to-energy initiatives. The government should develop policies supporting waste-to-energy projects, including incentives for private sector investment and regulations mandating waste segregation. Collaborations between the government, private sector, academic institutions, and international organizations should be fostered for the development and operation of WtE projects.

The study suggests that high-energy wastes like plastic bottles and nylon should be prioritized in waste-to-energy systems like incineration or pyrolysis to maximize energy output from smaller waste volumes. Food waste, with low energy density but high moisture content, may be better managed through anaerobic digestion. A hybrid approach is suggested, with incinerators effective for high-energy waste and biogas production or composting for high-volume, low-energy waste like food waste. This approach allows for efficient waste handling and maximizes energy recovery potential. A targeted strategy is crucial for efficient energy recovery and waste management.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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