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Modeling Energy Recovery Potential from Municipal Solid Waste Using MATLAB: A Case of Mbeya City

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Abstract

The increasing generation of municipal solid wastes (MSW) posses both environmental and energy challenges. The study investigates the energy recovery potential from MSW generated in Mbeya City using computational modelling in MATLAB. The research focuses on characterizing the waste stream, assessing its calorific value and simulating waste to energy (WTE) conversion process including incineration, gasification and anaerobic digestion. Key parameters such as feedstock composition, process efficiencies and emissions are integrated into the model to optimize energy recovery. Results indicate that Mbeya City's annual MSW could generate substantial electricity and heat contributing to solutions while mitigating environmental impacts. The model serves as a decision making tool for policy makers and engineers, providing insights into the feasibility and performance of WTE technologies in urban settings. This study underscores the potential of computational tools like MATLAB in advancing waste management and energy recovery systems in developing cities. In this model the results obtained for anerobic digestion process was 25895.33 MJ/day, in case of incineration daily energy produced was 420,000 MJ/day and gasification produce 756,000 MJ/day. Tola energy daily energy which can be produced in Mbeya City is 1201895.33 MJ/day.

Keywords

Municipal Solid Waste, Energy Recovery, Waste to Energy, MATLAB, Mbeya City, Sustainable Energy, Waste Management

1. Introduction

Management of MSW in urban localities is a very important issue since it emanates large volumes of wastes every year. In the world context, it is estimated that wastes will reach 3.4 billion tons by 2050, with cities being the key contributors towards this increase [1]. Waste-to-Energy (WtE) technologies are one such sustainable solution that recover energy from waste materials and therefore decrease the dependency on landfills while also displacing fossil fuel combustion. Municipal solid waste management has become one of the emerging challenges due to rapid urbanization, industrialization, and population rise. Again, there is a potential for waste-to-energy technologies based on proper waste composition, appropriateness of technology, and local conditions.

Some of the challenges facing current models include heterogeneous waste composition, poor integration of advanced technologies, region-specific modeling, gaps relating to environmental and economic impacts, and a lack of predictive capabilities. The principal research gap is related to the absence of an integrated model that is adaptive and dynamic. The present paper proposes a MATLAB-based model for the estimation of energy recovery potential from MSW. The model considers the composition of waste, thermal properties, and various efficiencies in conversion technologies.

The subject is significant due to the implementation of modelling energy recovery possibilities from municipal solid wastes. Waste to energy might provide a sustainable frame work for simultaneous solid waste management and energy provision, addressing the detrimental waste management and potentially fulfilling the nations energy requirement via renewable sources. Optimization of an energy recovery system, so promoting sustainability resource management, environmental impact assessment, cost benefit analysis, specialization, data analysis and predictive skills. MATLAB enables advanced modelling and simulation of process such as anaerobic digestion, incineration and gasification, allowing for forecasts and testing prior to real implementation. MATLAB also facilitates the environmental impact evaluation of waste to energy systems, the elimination of deleterious by-products and the calculation of return on investment. Its adaptability facilitates the creation of models customized for particular waste compositions while its integrated data analysis and visualization capabilities. MATLAB provides prediction models for future energy production.

1.1. Definition of the Key Terms

MATLAB

MATLAB is a high-level technical computing language and tool for the development of algorithms, data visualization, analyses, and numerical computation, which goes hand in hand with other advanced applications of mathematical computation, such as Maple, Mathematica, and MathCad [2]. MATLAB is an innovative application software used in chemical engineering, integrating manual calculations with high-tech technology. Such technology ensures that the obtained data is reliable and effective for analyzing chemical phenomena. The software is intelligent, simplifies calculations, saves significant computation time, and enhances accuracy. Its application areas and functions are extensive, it is easy to write and maintain, and it has an operating system with multiple platforms. MATLAB has shown a huge impact in chemical engineering experiments and is considered a technological breakthrough.

MSW: Valuable Resource

Municipal solid waste is a useful resource that can be utilized in ways that contribute to resource conservation, economic development, and sustainability. Energy can be produced from it using waste-to-energy technologies and recyclable materials, reducing dependence on fossil fuels and producing renewable energy. MSW reduces environmental burdens in landfills, waste, and greenhouse gas emissions. Additionally, it creates job opportunities and generates revenue, contributing to a circular economy. MSW may also help address challenges related to urbanization and support the achievement of sustainability goals.

Streams of MSW

Any material which is unused, unwanted, or discarded and is solid in nature is termed solid waste. Semisolid food wastes and municipal sludges may also be classified as solid waste. As urbanization accelerates worldwide, the generation of Municipal Solid Waste (MSW), a significant byproduct of modern life, is increasing even faster. Poor waste management practices affect the economy, public health, and the environment. In many cases, improper waste management leads to greater costs over time compared to the initial expenses required for efficient disposal. MSW also contributes to greenhouse gas emissions [3].

In Mbeya City, the solid waste generation rate is about 400 tonnes per day, with an average of 0.7 kg per person per day. The collection capacity is approximately 140 tonnes per day (35%), while the recycling capacity remains unknown due to a lack of clear data. According to a study, the waste composition in Mbeya City is largely dominated by food waste, accounting for 76% of the total waste [4].

Energy Recovery Potential

Options for converting waste into energy are a superior strategy for handling waste management and dealing with the energy problem at the same time [5]. Even though waste management technologies may increase energy availability, city centers in developing countries are currently experiencing an energy crisis. Waste exhibits different characteristics, which makes thermal recovery challenging [6]. Some of the thermal properties include calorific values, chemical composition, thermal degradation behavior, and chemical kinetics. Our study compares these properties with those of biomass and sub-bituminous coal to provide further insights.

1.2. Research Gap

The research on modelling energy recovery potential from municipal solid wastes using MATLAB is notably deficient in areas such as accurate waste characterization, incorporation of waste to energy technologies, formulation of environmental impact metrics, development of regional and site specific model, assessment of economic viability, cost modelling and integration with circular economy principles and resource recovery. Rectifying these deficiencies may improve the precision, scalability and relevance of the MATLAB models hence increasing their efficacy in forecasting energy recovery potential and managing municipal solid waste.

1.3. Aim of the Study

This study seeks to develop a complete MATLAB model to enhance energy recovery from municipal solid waste. It assesses energy production potential from several waste systems, including waste characterization data, analyze environmental and economic implications, give dynamic model, integrate environmental sustainability measure and optimize the energy recovery process. The model evaluates the decrease of landfill use and reliance on fossil fuels. This paper is organized in a logical manner beginning with the introduction, followed literature review, methods, findings and discussion and concluding with conclusion as shown in Figure 1 below.

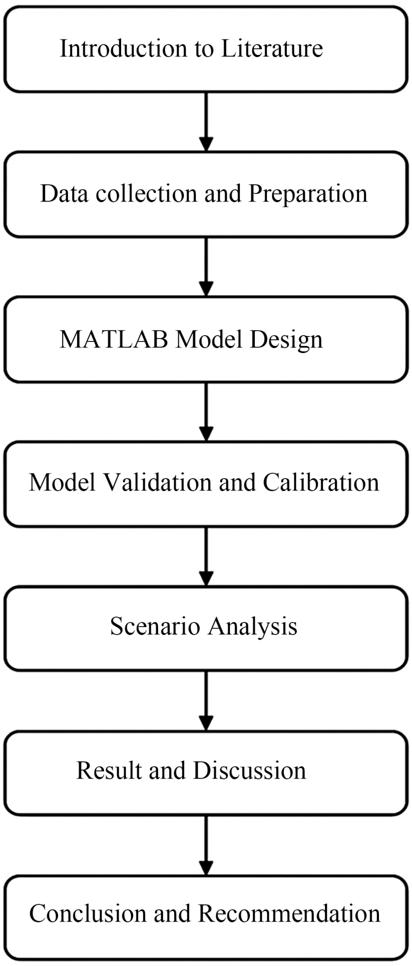

Figure 1. Modelling of energy recovery potential from municipal solid wastes by using MATLAB.

2. Literature Review

2.1. Waste-to-Energy Technologies

WtE technologies are crucial in lessening the environmental impact of MSW by converting them into usable energy. The three major technologies for converting MSW into energy are:

Incineration:

Incineration is a thermal conversion of biomass into heat and power in the presence of air. This occurs due to the quick oxidation of biomass used a s a fuel (with necessary drying) to generate heat, carbon dioxide and water. Since the primary constituents of the original feedstock are carbon, hydrogen and oxygen and the process is conducted with an excess of air [7].

Involves the burning of wastes at high temperatures, thereby generating heat and electrical energy. It is one of the most widely adopted methods and is particularly effective in reducing the volume of MSW [8].

Gasification

Gasification is a thermochemical process that transform biomass into gaseous biofuel through partial oxidation. The required temperatures for this process ranges from 650˚C to 1200˚C [9]. This process transforms waste into syngas, a mixture of hydrogen, carbon monoxide, and other gases, which is usable for energy production or as chemical feedstock [10]. In addition, gasification also can be employed to convert coal into gas, a technique utilized two centuries ago.

Anaerobic Digestion

Anaerobic digestion comprises many metabolic events initiated by microbes capable of surviving in the absence of oxygen. These microbes transform organic biomass molecules into simpler chemical compounds. The ultimate products of the preceding conversion mostly consist of methane and carbon oxides, with a somewhat lower proportion (under 1% of the gas volume) of ammonia, hydrogen and hydrogen sulphide [7]. The mixtures of the gases produce in anerobic digestion process is called biogas, which can be used as renewable energy source for heating and electricity energy production for both in industries and domestic applications [11]. The choice of WTE technology depends on factors like the composition of the waste, environmental regulations, and the desired energy output.

2.2. Modeling Approach

The energy recovery potential from MSW is determined by the waste composition and the efficiency of energy conversion technology used. The equation for estimating this potential is:-

$$E_{\text{recovery}} = \sum_i W_i * HHV_i * \eta$$

where:

E_{Recovery} = total energy recovery (MJ of kWh),

W_i = mass fraction of the ith waste component,

HHV_i = Higher heating value (MJ/Kg) and

η = Selected waste to energy technology efficiency.

2.3. Development of the MATLAB Model

The scripts begin by clearing the workspace and command window to ensure a clean environment for calculations. The total municipal solid wastes (MSW) generated is set to 140,000 Kg/day and the waste composition is divided into organic fraction, combustible and gasifiable fractions. The retention time is set to 60 days of anaerobic digestion. The scripts calculate the amount of waste in each category based on the defined fractions.

The anaerobic digestion model uses Monod kinetics to model the biological break down of organic waste with parameters such as, maximum specific growth rate, half-saturation constant, yield coefficient and decay coefficient defined. The system is solved using the ode 45 solver over 60 days. Biogas production is calculated based on biogas yield and methane content and the energy potential was calculated.

The incineration model calculates the energy potential from incineration using the calorific value of the combustible fraction of municipal solid wastes. Gasification model calculates the energy potential from gasification based on syngas yield and its energy content by using the gasifiable fractions of the municipal solid wastes.

The separate plots are generated to show the cumulative energy potential from anaerobic digestion, incineration and gasification process. The Monod kinetic functions define the systems of equations for substrate consumption and biomass growth base on Monod kinetics.

2.4. Waste Composition Data

The MSW stream is typically composed of a mixture of organics, plastics, paper, and other materials. Each component in this composition has an associated higher heating value (HHV), which is crucial for calculating energy recovery [12].

MATLAB a robust computational instrument has been widely used to study and improve energy systems. Prior research has shown its effectiveness in modelling municipal solid waste energy recovery scenarios, enhancing system performance and performing sensitivity evaluation.

3. Material and Methods

3.1. Study Area and Sample Collection

Mbeya City Council, located in the South West of Tanzania, has a population of 541,603 people and 153,100 households [13]. The city's population growth rate is 3.2%, similar to the national average of 3.2% per annum [13]. 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 [14]. 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 in Songwe Regional, and to the west by Mbozi District in Songwe Regional [13].

Six wards were puposively selected in this study namely as Iyunga, Forest, Sisimba, Iganzo, Ilomba and Nsalaga as shown in the **Figure 2**.

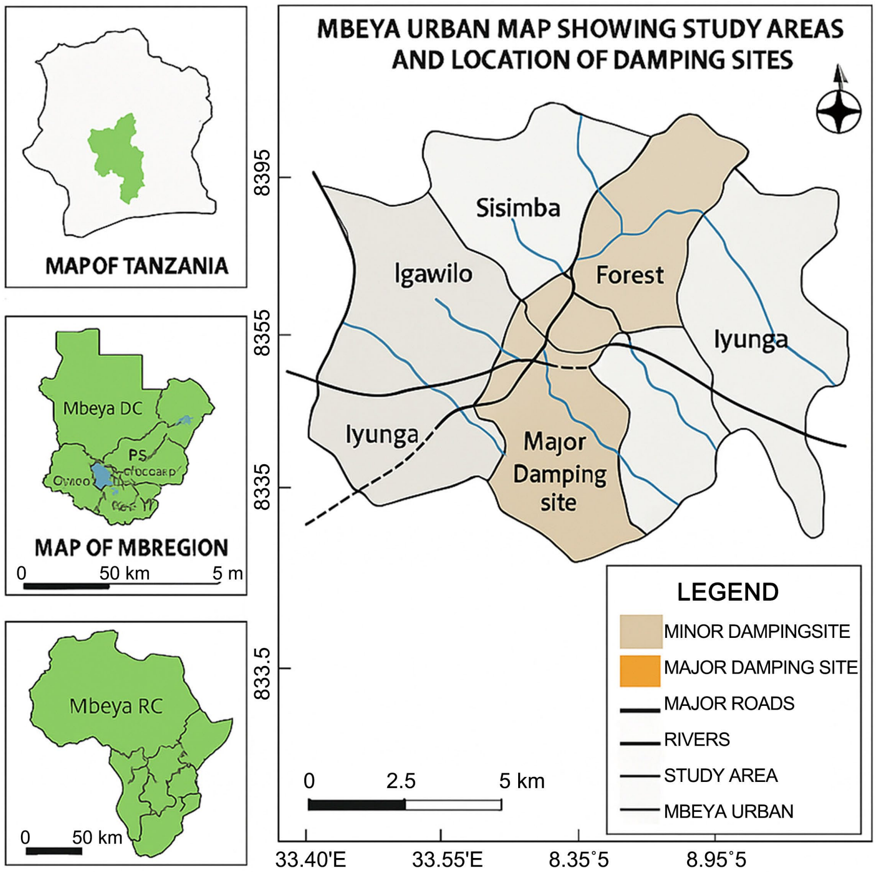

Figure 2. Map of Mbeya city showing six selected Wards. Source: Author, 2024.

3.2. Methods

This section outlines the step-by-step approach for developing a MATLAB-based model to assess the energy recovery potential from municipal solid waste (MSW). The methodology involves waste characterization, model design, simulation of waste-to-energy (WTE) technologies, sensitivity analysis, and validation against real-world data.

3.2.1. Waste Characterization

Waste characterization was done through standards methods which are: 1) ASTM (American society for the testing and materials) [15]-[21]. Standards test method for determination of the composition of unprocessed MSW-D5231_92(2008), 2)

UNEP-development integrated solid waste management plan Volume 1, waste characterization and quantification with projections for future [22].

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 inert. After separation all components were weighed separately. A sample of wastes was taken to the laboratory for testing on its physical and chemical properties.

3.2.2. Model Development Utilizing MATLAB

This model design has an input variable including waste composition, calorific values, moisture content and operating parameters [23]. A processing layer then develops algorithms to mimic the energy conversion processes associated with different waste to energy systems. The output layer calculates the projected energy recovery potential for each device across various situations [8].

Explanation of Model Steps

The MATLAB based waste to energy model is a tool used to simulate three waste to energy process anaerobic digestion, incineration and gasification. The MATLAB script uses the Monod Kinetics model to simulate biomass growth and methane production, calculates energy based on the calorific value of combustible waste and estimates syngas production and energy content. The ODE solution solver (ode 45) is used to solve the ODE equations and the process is divided into input and output units. The ODE solver parameters include the time span (0 to 60 days) and initial conditions. The ode 45 solver is used to solve the Monod Kinetics equations and the process is summarized in simplified flowchart (see **Figure 3** below). The MATLAB model is used to calculate energy from waste, biomass and syngas and to calculate the energy content of the waste. The process is then plotted and displayed to provide a detailed understanding of the process. The MATLAB model is a valuable tool for understanding waste to energy processing and their potential applications.

Waste to energy model for anaerobic digestions, incineration and gasification in this study were described in Equations (1) to (7) as follows:

Substrate Consumption (Monod Kinetics)

$$\frac{\mathrm{d}S}{\mathrm{d}t} = -\frac{\mu_{\max}}{Y} \cdot \frac{S}{K_s + S} X \tag{1}$$

Biomass growth

$$\frac{\mathrm{d}X}{\mathrm{d}t} = \mu_{\max} \frac{S}{K_s + S} X - K_d X \tag{2}$$

Biogas Production

$$\text{Biogas Production} = Y_{\text{biogas}} \times \left(S_o - S\right) \tag{3}$$

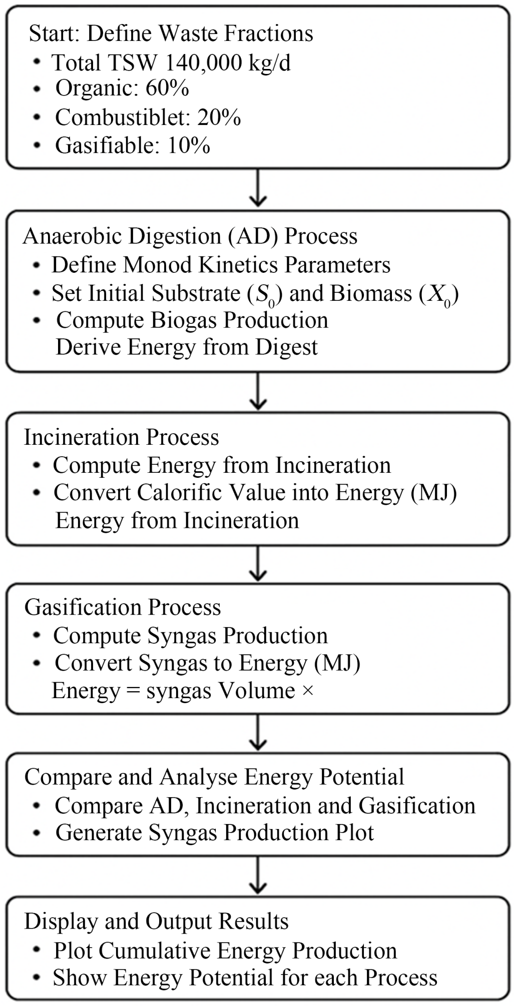

Figure 3. Modelling of waste to energy potential flow chart.

Energy from biogas (anaerobic digestion)

$$\text{Energy}_{\text{anaerobic}} = \text{Biogas Production} \times 35.8 \tag{4}$$

Energy from incineration

$$\text{Energy}_{\text{incineration}} = \text{Combustible Waste} \times 15 \tag{5}$$

Syngas production

$$\text{Syngas Production} = Y_{\text{syngas}} \times \text{Gasifiable Waste} \tag{6}$$

Energy from gasification

$$\text{Energy}_{\text{gasification}} = \text{Syngas Production} \times 12 \tag{7}$$

where:

S = Substrate concentration (kg)

μ_{max} = Maximum specific growth rate (1/day)

Y = Yield coefficient (Kg biomass/ Kg Substrate)

X = Biomass concentration (Kg)

$\mathrm{d}S/\mathrm{d}t$ = Rate of substrate consumption (Kg/day)

K_d = Decay coefficient (1/day)

dX/dt = Rate of biomass growth (Kg/day)

Y_{biogas} = Biogas yield (m^3 CH_4 per Kg of organic waste)

S_o = Initial substrate concentration overtime (Kg)

S = Substrate concentration overtime (Kg)

Y_{syngas} = Syngas yield (m^3/Kg of gasifiable waste)

The simulation model conducts many simulations with varying waste compositions processing conditions and waste to energy technologies, facilitating comparisons across diverse scenarios [24]. Efficiency parameters are integrated to ascertain process-specific efficiency, including heat efficiency for incineration and conversion efficiency for anaerobic digestion [25]. Calculations of environmental effect are included to estimate emissions from energy recovery processes and efficiency of each waste to energy technique [26].

3.2.3. Modelling of Waste to Energy Technologies Sensitivity Analysis

The research examines the modelling of waste to energy systems, including incineration, anaerobic digestion and gasification and pyrolysis. These systems use models to asses the energy recovery potential from MSW. The technique encompasses the calculation of emission, by products and energy output predicted on calorific value, efficiency of the process [23]. The model mimics biogas generation from the organic portion of MSW via anaerobic digestion, where is then transformed into power or heat. Biogas mostly comprises of methane (CH_4), and carbon dioxide (CO_2). With the model including conversion efficiency influenced by microbial activity and operational characteristics [24] and [27]. The research further formulates models for gasification and pyrolysis which replicate the transformation of waste inti syngas and bio-oil respectively. These models assess energy production base on waste composition and operational parameters including temperature and pressure. The simulations evaluate the energy recovery potential of these procedures in comparison to incineration and anaerobic digestion [8] and [23].

Sensitivity Analysis

Sensitivity analysis is a crucial instrument for comprehending the variations in essential input parameters that characterize the potential for energy recovery. The main characteristics evaluated are waste composition, calorific value, waste to energy technology efficiency and moisture content. This entails examining the models responses to these alterations to determine most influential elements impacting energy recovery [8] and [23].

3.2.4. Verification of the Environmental and Economic Assessment Model

The MATLAB model integrates environmental and economic evaluations to provide a comprehensive perspective on waste to energy potential. This encompasses emissions modelling for greenhouse gases and air pollution, lifecycle analysis and cost modelling for capital investment, operating expenses and maintenance costs [23]. The model further evaluates income from sellable recovered energy and by-products while a cost benefit analysis is preferred to determine the economic feasibility of different waste to energy technologies [26] and [28]. This thorough methodology assesses waste to energy potential across several industries taking into account environmental effects and economic benefits [16].

4. Results and Discussion

4.1. MSW Composition

Composition of MSW samples collected from Six selected wards and at Nsalaga landfill dumpsite as shown in **Figure 3**. Municipal solid waste collected at Mbeya City composed of the following: organic, paper, plastic, metal, glasses, 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 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 [4].

Food wastes comprise of the 62.4% (**Figure 4**) this is a largest component of MSW available in Mbeya City.

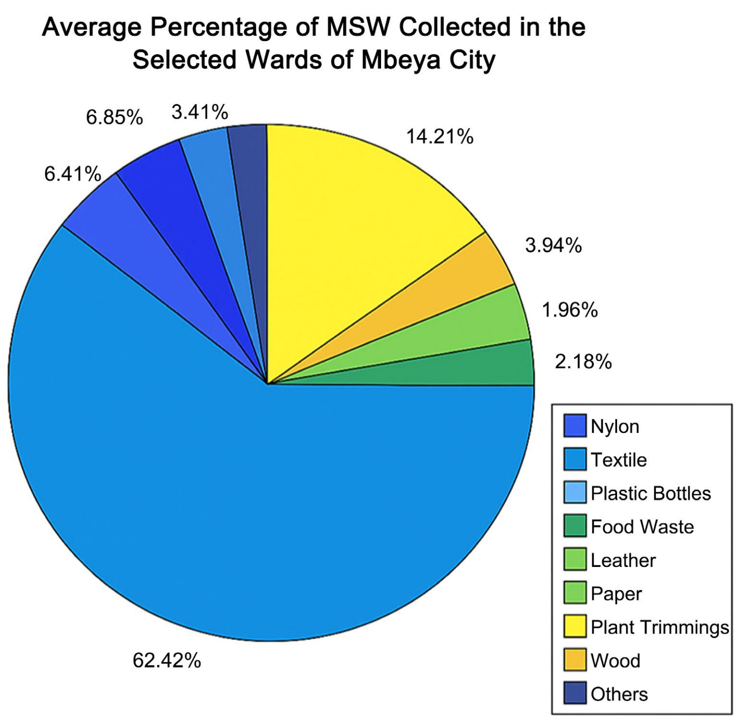

Figure 4. Average percentage of MSW collected in the selected wards of Mbeya city.

This study highlights that food waste dominates municipal solid waste (MSW) in Mbeya City, making up 62.4% of total waste. Ilomba and Iganzo generate the most waste, while Iyunga and Sisimba produce the least. The city's daily waste generation averages 464.93 kg, with a per capita rate of 0.00527 kg/day/person.

Improper disposal of food waste, particularly at the Nsalaga landfill, contributes to pollution and methane emissions. Studies by Mgimba and Sanga [29] and Kinemo [30] confirm similar waste composition trends. Investing in composting, biogas production, and improved recycling programs—especially for plastic waste—can significantly enhance waste management.

Challenges include sample size limitations and seasonal variations affecting waste composition. Given Mbeya City's rapid urbanization, continuous research and updated data are essential for effective planning and sustainable waste management.

4.2. Proximate Analysis of MSW

Proximate analysis helps determine which types of municipal solid waste (MSW) are best for energy recovery. In Mbeya City, nylon, textiles, and plastic bottles are the most suitable for thermochemical processes like incineration, gasification, and pyrolysis because they have high fixed carbon and low moisture content.

Nylon stands out with the highest fixed carbon (55.11%), making it an efficient fuel, while wood, with the lowest (4.05%), burns less effectively. Wood also has the highest volatile matter (93.3%), meaning it decomposes easily, whereas nylon is more stable. Food waste leaves the most ash (16.9%), while plastic bottles burn the cleanest with the least ash (1.51%). Moisture affects energy efficiency, with food waste holding the most (53.75%) and nylon the least (1.21%), making it the best for combustion (**Table 1**).

Table 1. 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

Anaerobic digestion works best with waste that has high moisture content, making food waste (53.75% moisture) an ideal choice. With plenty of food and organic waste available in Mbeya City, biogas production through this process could be a valuable energy source.

When it comes to waste management and combustion, different materials have different implications. Nylon, with high fixed carbon and low moisture, is great for high-energy combustion. Plastic bottles have moderate fixed carbon and low ash, making them a cleaner option. On the other hand, food waste, with its high moisture and ash content, is better suited for composting or incineration.

4.3. Ultimate Analysis

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 analysis values of MSW.

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.

4.4. Calorific Value of MSW

The Higher Calorific Value of MSW components was determined by using Bomb Calorimeter. Equation (2) was used to calculate its values as 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)	MJ/Kg
1	Nylon	8090.2	33.84
2	Textile	4065	17.00
3	Plastic bottles	9541.2	39.92
4	Food Waste	4351	18.20

Continued

5	Leather	5072.3	21.22
6	Boxes	3612	15.11
7	Wood	4297.2	17.97
8	Plant Trimmings	3886	16.25
9	Paper	4537.4	18.98

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 **Table 4** below.

Table 4. Calorific Value (LHV) of municipal solid wastes.

S/N	Type of Sample	Calorific Value (cal/g) (LHV)	MJ/Kg
1	Nylon	7281.18	30.46
2	Textile	3658.5	15.30
3	Plastic bottles	8587.08	35.92
4	Food Waste	3915.9	16.38
5	Leather	4565.07	19.10
6	Boxes	3250.8	13.60
7	Wood	3867.48	16.18
8	Plant Trimmings	3497.4	14.63
9	Paper	4083.66	17.08

Calorific value (LHV) is a measure of energy released when a material is burned. Plastic bottles have the highest calorific value at 39947.09 cal/g, making them a highly energy-dense fuel source. Plant trimmings have the lowest at 16269.90 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 33895.73 cal/g, while textiles have a moderate energy potential. Wood has a calorific value of 17991.51 cal/g, comparable to textiles and biofuels. Paper has a calorific value of 18997.18 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. Waste to Energy Processes Model Parameters

Waste to energy process models considers key parameters like feed stock characteristics, MSW organic fractions, anaerobic digestion, incineration and gasification. MATLAB specific inputs ensure comprehensive modeling and evaluation of waste to energy systems, considering emission factor, energy recovery efficiency and by product revenue. Table 5 below shows waste to energy parameters used in this model.

Table 5. Waste to energy processes model parameters.

Parameter	Value	Description
Total MSW	140,000 Kg/day	Total municipal solid waste generated daily
MSW Fractions		
Organic Fractions	62% of MSW (86,800 Kg/day)	Used in anaerobic digestion
Combustible Fraction	20% of MSW (28,000 Kg/day)	Used for incineration
Gasifiable Fraction	18% of MSW (25,200 Kg/day)	Used for gasification
Anaerobic Digestion		
Retention Time	60 days	Time period simulation for digestion process
Maximum specific growth rate (μ_max)	0.4 (1/day)	Maximum rate of microbial growth in Monod Kinetics
Half-saturation constant (Ks)	50 Kg/L	Constant representing substrate concentration at half maximum growth rate
Yield Coefficient (Y)	0.5 Kg biomass/Kg Substrate	Biomass produced per Kg of Substrate
Decay Coefficient (K_d)	0.05 (1/day)	Rate at which biomass decays in the system
Initial Concentration	Based on fraction input	Initial values for organic waste and biomass concentration
Biogas Production	0.5 m^3 CH_4/Kg organic waste	Methane yield per Kg of organic waste consumed
Energy content of Methane	35.8 MJ/m^3	Energy potential of Methane produced
Incineration		
Calorific value of combustible fraction	15 MJ/Kg	Energy content of combustible fraction
Total energy from incineration	Mass of combustible waste*15 MJ/Kg	Energy content from incinerating combustible fraction

Continued

Gasification		
Syngas Yield	2.5 m^3/Kg of waste	Syngas production per Kg of gasifiable fraction waste
Energy content of syngas	12 MJ/m^3	Energy content produced of syngas
Total energy from gasification	Total syngas produced × 12 MJ/m^3	Energy calculated based on syngas yield and energy content per unit of syngas

By using input parameters as shown in **Table 5** above, MATLAB codes were developed to calculate energy recovery potential of municipal solid wastes in Mbeya City (see **Appendix**).

4.6. Calculated Energy Potential from the Model

The energy potential form waste to energy model was calculated by integrating feedstock energy content, process efficiency and system operation (**Figure 5** below). The energy content was determined by Higher Heating value (HHV) or Lower Heating Value (LHV) multiplied by the municipal solid waste mass. The recoverable energy was then calculated by applying conversion process efficiency.

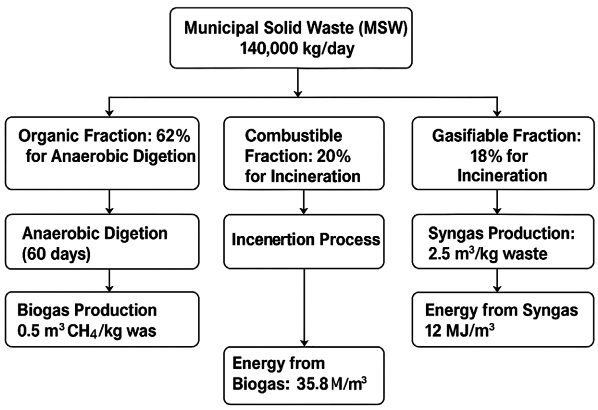

Figure 5. Energy potential from waste to energy pathways.

The graph illustrates the energy potential of anaerobic digestion (**Figure 6** below), which rises sharply after 20 days, reaching 1.5 million MJ before leveling off. This is because the biological breakdown process begins slowly, accelerates after a lag period, and then stabilizes. Anaerobic digestion produces significantly more cumulative energy compared to incineration or gasification.

Incineration, a method of energy production, delivers a fixed output of 400,000 MJ, providing a steady, instant energy release but with a lower total potential over time compared to anaerobic digestion. Gasification, similar to incineration, has a constant energy potential of 600,000 MJ, offering more energy than incineration but less than anaerobic digestion, with immediate but limited energy yield.

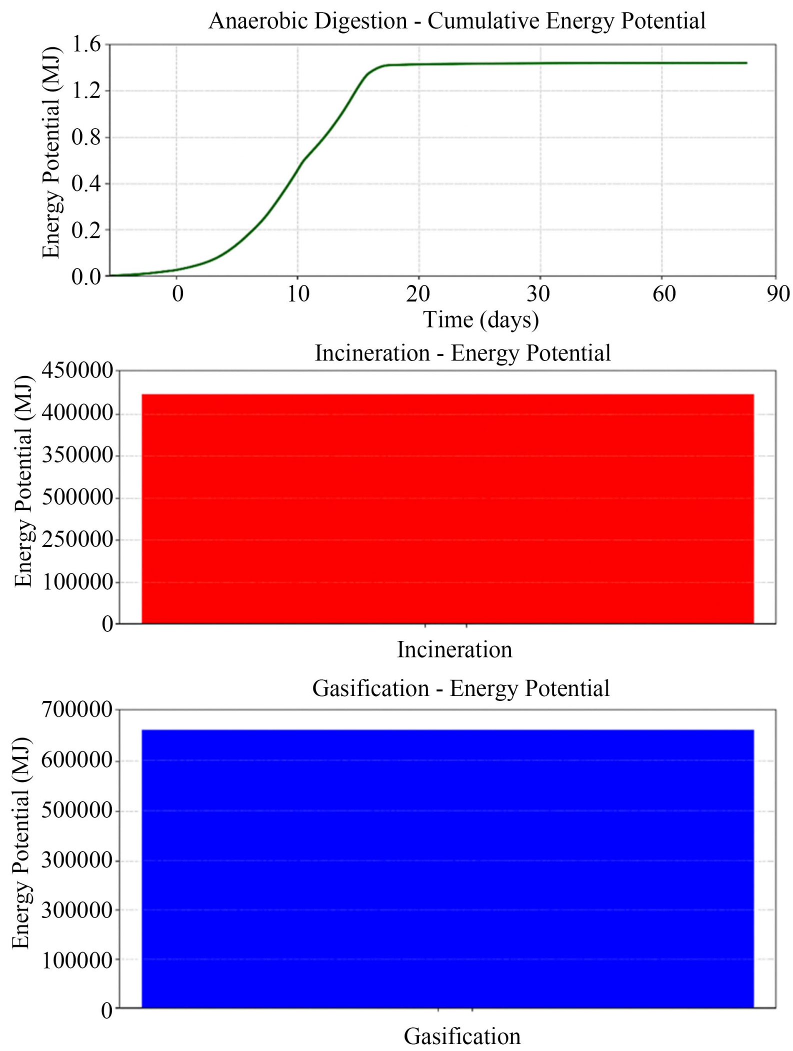

Figure 6. Simulation results of waste to energy MATLAB model.

Anaerobic digestion has the highest energy potential among the processes, though it takes more time to reach peak output. Incineration and gasification provide quicker, lower energy outputs. While anaerobic digestion is more efficient in terms of cumulative energy potential, it may be slower when immediate energy is required.

Mbeya City generates 140,000 kg of municipal solid waste (MSW) daily, divided into organic (62%), combustible (20%), and gasifiable (18%) fractions. Anaerobic digestion, modeled with Monod kinetics, processes organic waste over 60 days to produce biogas. Incineration provides immediate energy from burning the combustible fraction (15 MJ/kg), while gasification converts gasifiable waste into syngas for cleaner energy production.

The script generates energy potential plots for each method and a bar chart comparing their cumulative outputs. Anaerobic digestion gradually produces biogas, incineration delivers quick but emission-heavy energy, and gasification yields clean-burning syngas. Combining these methods can maximize waste-to-energy efficiency.

Incineration quickly converts combustible waste into energy but produces emissions and ash that require management. It is commonly used in urban areas where landfill space is limited and recycling is not an option.

Gasification, on the other hand, transforms waste into syngas—a cleaner fuel made of carbon monoxide, hydrogen, and methane. This process is more environmentally friendly than incineration and can handle mixed waste streams.

A final comparison shows that anaerobic digestion generates energy gradually, incineration delivers an immediate but emission-heavy output, and gasification provides a high energy yield with cleaner emissions. A combination of these methods can help maximize energy recovery and improve waste management.

In this model the results obtained for anerobic digestion process was 25895.33 MJ/day, in case of incineration daily energy produced was 420,000 MJ/day and gasification produce 756,000 MJ/day. Tola energy daily energy which can be produced in Mbeya City is 1201895.33 MJ/day.

4.7. Model Validation and Calibration

Validating waste to energy model in MATLAB involved comparing the output of the model with reliable reference data and theoretical calculations to ensure its accuracy and reliability. A proposed MATLAB model in case of a Mbeya city that generates 140 tons of MSW per day. Different waste compositions and WtE technologies were applied, and the energy recovery potential was calculated using the MATLAB code.

Validation objectives ensuring model outputs align with expected results and verifying its suitability for various waste scenarios. Dat preparations included real world waste comparison, energy outputs and emissions data. Key performance was developed and the model was simulated in MATLAB. Model outputs were compared with reference data using error neatness and visual comparison using MATLAB visualization tools as shown in Figure 7 below.

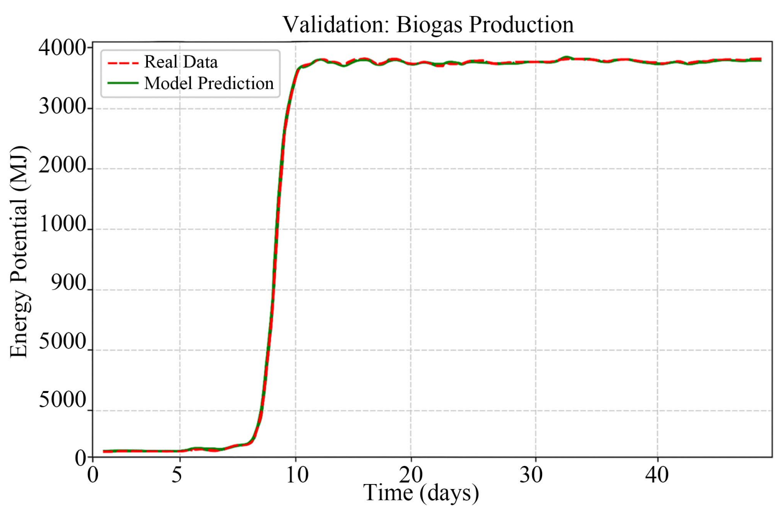

Figure 7. Alignment between model predictions and real data over 60 days.

Figure 7 shows a strong alignment between model predictions and real data over 60 days, confirming the model's reliability accuracy in biogas production trends.

Figure 8 accurately depicts the energy potential validation for incineration, highlighting gasification's higher potential and confirming model predictions accuracy with red markers and error bars.

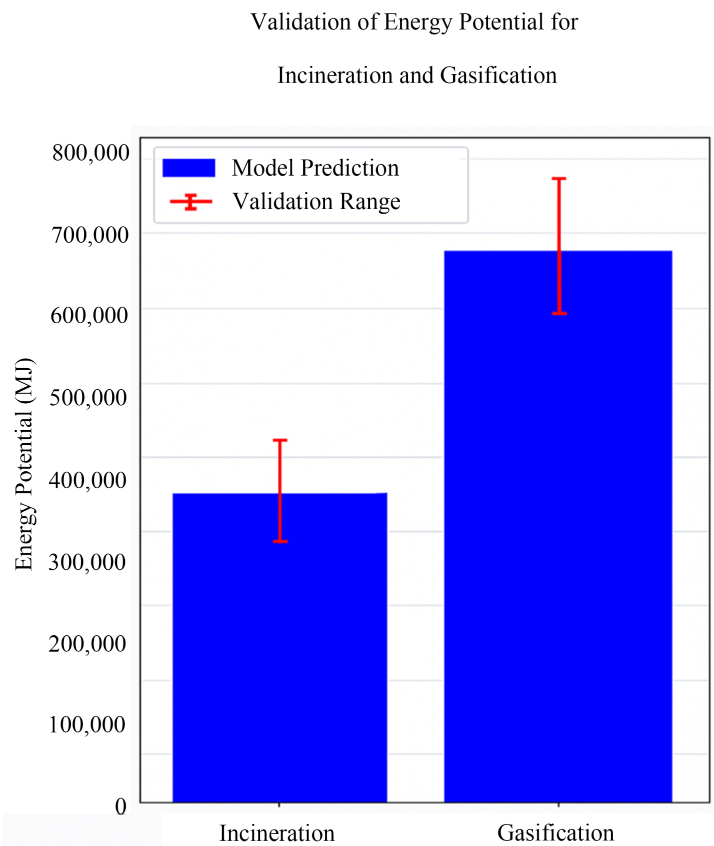

Figure 8. Validation of energy potential for incineration and gasification.

4.8. Sensitivity Analysis

Sensitivity is a crucial tool in waste to energy models to evaluate how changes in input parameters affect the models' output. It helps identifying critical factors influencing system behavior and asses the model's robustness under varying conditions. Common parameters in WTE models include waste characterization, operating conditions and output parameters like energy recovery, emissions and residual waste. Input parameters were selected and range of variation were defined and chosen in a sensitivity method, simulate model, measure output variation and analyze results to identify the most sensitive parameters.

Sensitivity Analysis: Retention Time

The following graph (Figure 9) illustrates the impact of retention time variations on the energy potential derived from anaerobic digestion. Extended retention periods often provide greater energy output.

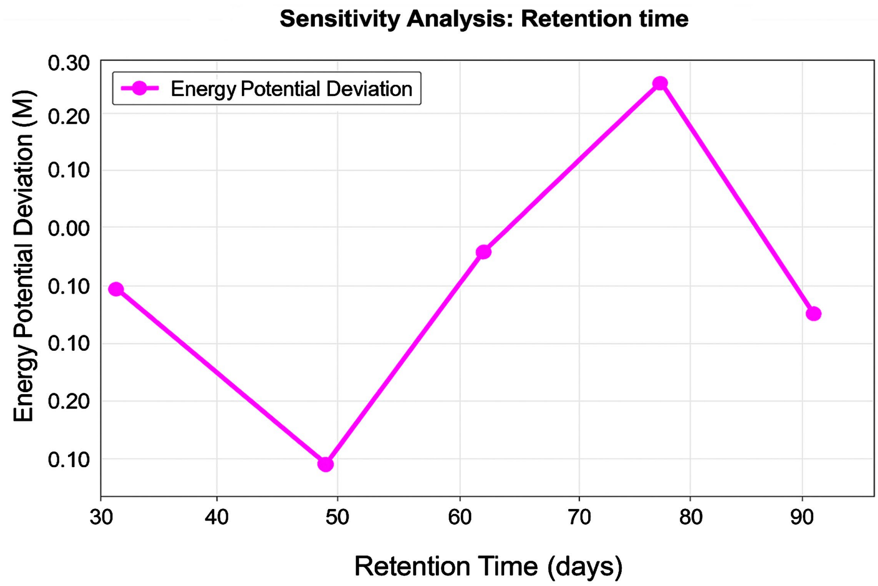

Figure 9. Sensitivity analysis for retention time.

Figure 9 above shows minimal energy potential fluctuations with retention time ranging from 30 to 90 days indicating that retention time has minimal impact on energy potential.

Sensitivity Analysis: Organic Fraction:

This graph (Figure 10) depicts the influence of altering the organic component of municipal solid waste on energy potential. An increased organic component leads to enhanced energy recovery.

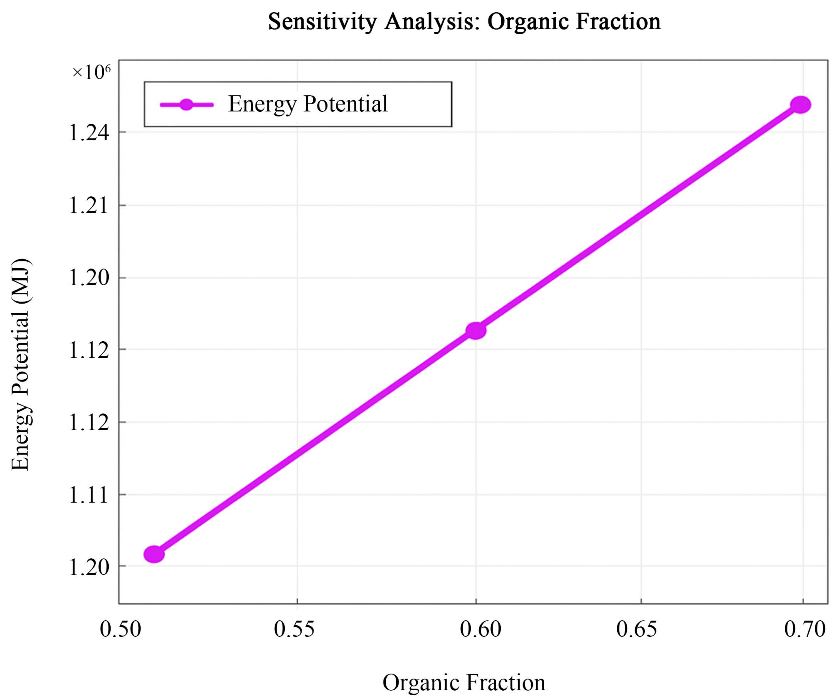

Figure 10. Sensitivity analysis for organic fraction.

Figure 10 demonstrates the linear relationship between organic fraction and energy potential, highlighting the importance of optimizing the organic fraction for improved energy recovery.

Sensitivity Analysis: Calorific Value in Incineration:

This graph (Figure 11) examines the influence of variations in the calorific value of combustible municipal solid wastes on energy potential. Elevated calorific values provide enhanced energy recovery.

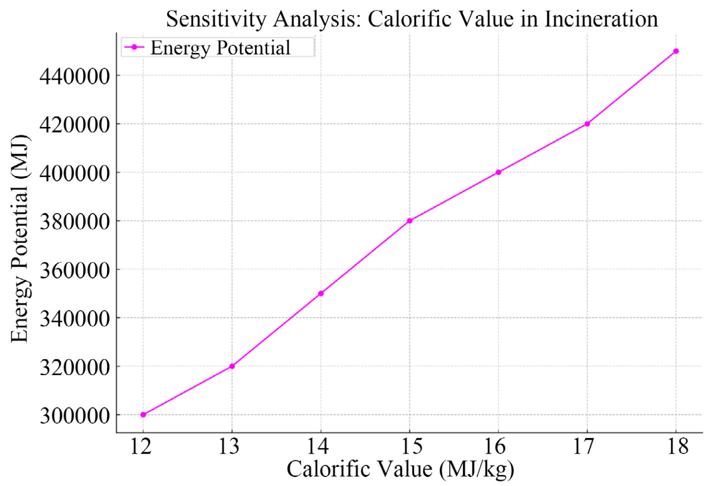

Figure 11. Sensitivity analysis for incineration calorific value.

Figure 11 above shows a linear trend indicating a direct relationship between calorific value and energy potential in incineration, emphasizing the importance of optimizing calorific value.

Sensitivity Analysis: Syngas Production in Gasification:

This graph (Figure 12) illustrates the correlation between syngas output and energy potential in the gasification process. An increased syngas yield substantially enhances energy production.

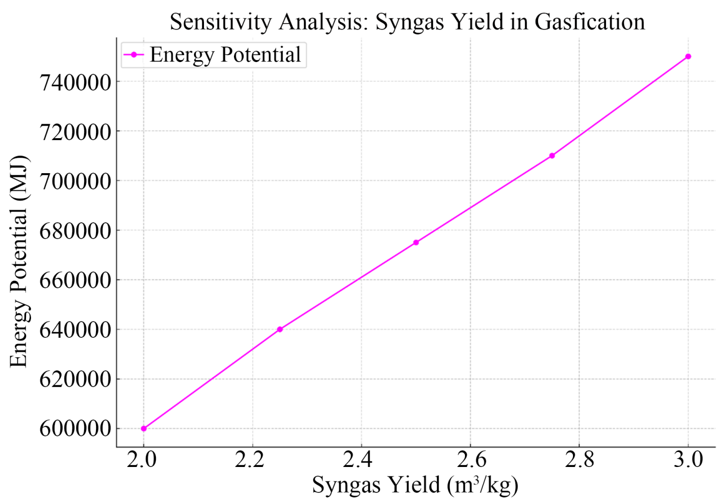

Figure 12. Sensitivity analysis for syngas yield.

Figure 12 demonstrates a strong correlation between syngas yield and energy potential, indicating that optimizing syngas yield improves energy recovery efficiency.

This study presents a MATLAB-based model for estimating energy recovery potential from municipal solid waste (MSW) using different waste-to-energy (WtE) technologies. The model provides a quick and adaptable way to evaluate energy potential, though results depend on waste composition and technology efficiency. Gasification, for example, offers higher energy recovery than incineration due to its greater efficiency [31].

Anaerobic digestion, an oxygen-free decomposition process, converts organic waste into methane-rich biogas, generating about 1,553,720 MJ over 60 days. This gradual energy output depends on microbial activity, with a biogas yield of 0.5 m^3 CH_4 per kg of organic waste.

Incineration, on the other hand, provides immediate energy by burning the combustible fraction (20% of MSW) with a calorific value of 15 MJ/kg, resulting in a one-time release of 420,000 MJ. While highly efficient, it is less sustainable than anaerobic digestion.

Gasification partially oxidizes waste to produce syngas (CO and H_2), generating 756,000 MJ with a syngas yield of 2.5 m^3 per kg and an energy content of 12 MJ/m^3. Though the gasifiable fraction is only 18%, syngas provides a flexible and cleaner energy source compared to incineration.

Each method has trade-offs: anaerobic digestion provides continuous but slower energy production, incineration delivers the highest immediate yield but lacks long-term sustainability, and gasification balances efficiency and flexibility, making it a promising option.

The MATLAB model is a valuable tool for urban planners, researchers, and engineers, offering insights into WtE project feasibility ([1] and [25]). Future improvements will include more complex waste compositions, environmental impact assessments, cost analysis, and optimization algorithms to identify the best WtE technology for specific local conditions ([10] and [13]).

Contrast the Proposed MATLAB Bases/WTE Model with Existing Model

The proposed MATLAB based model offers a comprehensive approach for calculating energy recovery potential from MSW through three distinct technologies, which are anaerobic digestion, incineration and gasification. This model provides a more holistic view and broader comparison of energy potential across technologies.

The model considers anaerobic digestion, incineration and gasification using appropriate mathematical representations such as Monod Kinetics Model for microbial growth and biogas production. It can be further refined with more complex models if needed. The model flexibility in parametrization allows users to adjust retention time, substrate concentration, waste fractions and specific kinetic parameters for anaerobic digestion.

The model is built on differential equations for anaerobic digestion, specifically incorporating Monod Kinetics for microbial activity. For incineration and gasification, the model uses direct multiplication of waste mass by calorific values and syngas yield. Making it computationally efficient and straightforward.

The simulation framework in the proposed model is designed to handle a 60-day retention period for anaerobic digestion, but can be easily adjusted to simulate longer or shorter period based on waste input rates. The model can be scale up or down depending on the total waste volume, making it adaptable for both small and large scale systems.

The model's novelty lies in its inclusion of all three processes, providing a more accurate and dynamic simulation of energy recovery from organic waste. Improvements include the flexibility to modify input parameters, computational efficiency and a user friendly platform for both small and large scale analysis.

Comparison of the Findings with Global Case Studies

Comparing anaerobic digestion in Mbeya City with similar cities in developing nations can provide insights into performing benchmarking, scalability and influencing factors (Table 6 below). The biogas yield in Mbeya City is comparable to other developing cities, but the reported energy potential (250 Mwh/day) is significantly higher than expected. This suggest that the assumed efficiency, waste volume or conversion factors might need further validation. Cities like Pune, Nairobi and Dhaka have organic waste fractions which could enhance anaerobic digestion efficiency due to faster microbial activity. Technological differences and lack of infrastructure and policy support could hinder Mbeya anaerobic digestion application and potential. Recommendations for model validation include cross-checking methane yield assumptions with experimental or literature values considering seasonal waste variability and benchmarking against other waste to energy technologies.

Table 6. Waste to energy case study.

City/Country	Waste Processed (tons/day)	Biogas Yield m^3 (CH_4/ton of waste)	Energy Potential (Mwh/day)	Notes
Pune (India)	~200	50 - 70	~35	Community scale AD plant processing market waste
Nairobi (Kenya)	~150	60 - 80	~30	AD used for electricity and biofertilizer
Dhaka (Bangladesh)	~300	40 - 60	~80	AD integrated with composting projects
Bogota (Colombia)	~300	55 - 75	~50	Waste to energy policies support AD adoption
Mbeya (Tanzania)	~140	50 (assumed)	~250	Energy potential seems high compared to similar cities.

Qualitative LCA of Incineration Emissions

A lifecycle analysis (LCA) of incineration in Mbeya City reveals that MSW incineration releases several pollutants including carbon dioxide, nitrogen oxides, Sulphur oxides, particulate matter and highly toxic dioxins and furans. The incineration potential in Mbeya City is 38.39 Mwh/day and energy recovery of modern incinerators can reduce net emission by 0.47 - 0.7 tons of CO_2 per Mwh. Incineration also avoids long-term methane emissions which are 28 times the global warming potential of CO_2. Recommendations for reducing emissions include flue gas treatment, optimizing combustion and waste segregation. Comparing these results with other waste to energy methods will help determine the most sustainable option for Mbeya.

5. Conclusions

The study has pursued the potential energy recovery from municipal solid waste in Mbeya City using MATLAB based modelling. It integrates waste characterization, energy content analysis and modelling techniques to show how waste management challenges can be turned into sustainable energy solutions. Results indicated that the city's solid waste contains substantial recoverable energy that if harnessed would go along way toward addressing energy deficits, reducing environmental impacts, and contributing to sustainable urban development.

The analysis adopted in this study assessed important parameters: waste generation rates, composition, and calorific value. These parameters have been used in the MATLAB simulations in order to estimate recoverable energy by thermal conversion technologies including incineration and gasification and biological conversion technology which is anerobic digestion. The results of the model indicate that Mbeya City can generate a significant amount of renewable energy, highlighting economic and environmental advantages related to the introduction of energy recovery systems into waste management policies.

The research underlines the importance of comprehensive waste management strategies such as segregation of waste at source, public awareness campaigns, and investment in energy recovery infrastructure. Such measure would improve not only the efficiency of waste to energy conversion process but also concur with global sustainability goals pertaining to reduced greenhouse gas emissions and minimal dependence on fossil fuels.

Limitations of this study are the different assumptions made in the modelling process and the non-availability of real time data about waste characterization. Future research can consider dynamic variables such as, seasonal changes in waste generation and improvement in technology and update the estimated energy that can be recovered.

Conclusively, the modelling of energy recovery from MSW in Mbeya City provides evidence that integrates technological solution for waste management. It presents an avenue to develop frameworks that are scalable and replicable, which cities in similar contexts can adopt. This approach has addressed not only pressing problems in waste disposal but also contributed to sustainable energy generation, environmental conservation and increased resilience of urban areas.

Conflicts of Interest

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

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Appendix

Matlab Codes

```
% File: msw_to_energy.m
% Clear workspace and command window
clear;
clc;
% Define MSW fractions and retention time
total_msw = 140,000; % kg/day
organic_fraction = 0.62;
combustible_fraction = 0.2;
gasifiable_fraction = 0.18;
retention_time = 60; % days
% Waste distribution by fraction
organic_waste = total_msw * organic_fraction; % kg/day
combustible_waste = total_msw * combustible_fraction; % kg/day
gasifiable_waste = total_msw * gasifiable_fraction; % kg/day
%% Anaerobic Digestion Model
% Define Monod kinetics model parameters
mu_max = 0.4; % Maximum specific growth rate (1/day)
Ks = 50; % Half-saturation constant (kg/L)
Y = 0.5; % Yield coefficient (kg biomass/kg substrate)
Kd = 0.05; % Decay coefficient (1/day)
% Initial conditions for substrate and biomass
S0 = organic_waste; % Initial substrate concentration (kg)
X0 = 50; % Initial biomass concentration (kg)
% Time span for the simulation (updated to 60 days)
tspan = [0 retention_time];
% Solve the ODE system using ode45 solver
[t, C] = ode45(@(t, C) monod_kinetics(t, C, mu_max, Ks, Y, Kd), tspan, [S0; X0]);
% Extract substrate and biomass concentrations
S = C(:, 1);
X = C(:, 2);
% Calculate biogas production and energy potential
biogas_yield = 0.5; % m³ CH4/kg of organic waste
energy_content_methane = 35.8; % MJ/m³ CH4
biogas_production = biogas_yield * (S0 - S); % m³ of CH4 produced over time
energy_anaerobic = biogas_production * energy_content_methane; % MJ over time
%% Incineration Model
% Define calorific value for incineration
calorific_value_combustible = 15; % MJ/kg
% Calculate energy potential from incineration
```

```
energy_incineration = combustible_waste * calorific_value_combustible; % MJ
%% Gasification Model
% Define syngas yield and energy content for gasification
syngas_yield = 2.5; % m³/kg of gasifiable waste
energy_content_syngas = 12; % MJ/m³
% Calculate energy potential from gasification
syngas_production = syngas_yield * gasifiable_waste; % m³
energy_gasification = syngas_production * energy_content_syngas; % MJ
%% Plot the Results
% Plot cumulative energy potential from anaerobic digestion
figure;
subplot(3,1,1);
plot(t, energy_anaerobic, 'g', 'LineWidth', 2);
xlabel('Time (days)');
ylabel('Energy Potential (MJ)');
title('Anaerobic Digestion - Cumulative Energy Potential');
grid on;
% Plot energy potential from incineration
subplot(3,1,2);
bar(1, energy_incineration, 'r');
set(gca, 'XTickLabel', {'Incineration'});
ylabel('Energy Potential (MJ)');
title('Incineration - Energy Potential');
grid on;
% Plot energy potential from gasification
subplot(3,1,3);
bar(1, energy_gasification, 'b');
set(gca, 'XTickLabel', {'Gasification'});
ylabel('Energy Potential (MJ)');
title('Gasification - Energy Potential');
grid on;
% Comparison Plot
figure;
bar([energy_anaerobic(end), energy_incineration, energy_gasification]);
set(gca, 'XTickLabel', {'Anaerobic Digestion', 'Incineration', 'Gasification'});
ylabel('Energy Potential (MJ)');
title('Comparison of Energy Potential from MSW');
grid on;
% Monod kinetics model function
function dCdt = monod_kinetics(t, C, mu_max, Ks, Y, Kd)
  S = C(1); % Substrate concentration (kg)
  X = C(2); % Biomass concentration (kg)
  mu = mu_max * S/(Ks + S); % Specific growth rate (1/day)
```

```
    dSdt = -mu/Y * X; % Rate of substrate consumption (kg/day)
    dXdt = mu * X - Kd * X; % Rate of biomass growth (kg/day)
    dCdt = [dSdt; dXdt];
end
```