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Assessment of Municipal Solid Waste to Energy Conversion Pathways: A Case Study of Nsalaga Dumpsite, Mbeya City, Tanzania

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ABSTRACT

Growing urban populations and increasing energy demand in Tanzania have increased the urgency to develop sustainable waste management strategies that also contribute to renewable energy generation. This study assessed waste-to-energy potential at Nsalaga Dumpsite, Mbeya City, through waste quantification, physical and chemical characterisation, calorific-value determination and multicriteria technology screening. Quantification of waste inflows showed that approximately 34,244 tonnes of municipal solid waste are delivered to the dumpsite annually, with organic waste dominating the stream at 76.8% and presenting high moisture content. Calorific value was determined experimentally for selected combustible fractions using oxygen bomb calorimetry in accordance with ASTM D5865/D5865M-19. The measured higher heating values (HHV) were 39.95 MJ/kg for plastic bottles, 33.87 MJ/kg for nylon, 19.00 MJ/kg for paper, 18.22 MJ/kg for food/organic waste and 17.02 MJ/kg for textiles. These results show that dry synthetic and paper-based fractions have stronger thermal recovery potential, while the dominant moisture-rich organic fraction is better suited to anaerobic digestion or composting. The gross energy potential of the mixed waste stream was estimated at 239.7 TJ, equivalent to about 66.6 GWh per year, corresponding to about 16.6 GWh of electricity at an assumed net electrical efficiency of 25%. The study contributes a site-specific evidence-to-decision framework that links Nsalaga waste characterisation, measured calorific values and MCDA screening to a practical integrated WTE pathway for Mbeya City.

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1.0 Introduction

Municipal Solid Waste (MSW) management represents a critical global challenge, primarily driven by rapid urbanisation, industrial growth, and rising population density (Sharma & Jain, 2020). Current estimates indicate that more than 2 billion tonnes of MSW are generated annually worldwide (Maalouf & Mavropoulos, 2023; Valavanidis, 2023), yet recovery through recycling, composting or energy conversion remains limited.

Consequently, large quantities continue to be landfilled or openly dumped, increasing greenhouse gas emissions, leachate contamination, land degradation and public health risks (Themelis, 2023; Un, 2023).

In Sub-Saharan Africa, waste management challenges are particularly acute (Ali & Gujiba, 2024). Open dumping accounts for nearly 69% of waste disposal practices, reflecting weak infrastructure, limited financial resources, and inadequate enforcement of environmental policies (Amugsi *et al.,* 2022; Emery *et al.,* 2020; Offer, 2018). As a result, most urban centres across the region suffer from waste accumulation, uncontrolled emissions, and inefficient land use.

Waste-to-energy (WTE) technologies have been recognised as a potential dual-benefit solution, offering both waste reduction and renewable energy generation (Tsui & Wong, 2019). Thermal pathways such as incineration, gasification, and pyrolysis are most effective for dry, high-calorific fractions, while biological processes like anaerobic digestion (AD) are more suitable for wet organics (Giwa *et al.,* 2019; Panepinto *et al.,* 2015; Potts & Martin, n.d.; Torri *et al.,* 2025).

Several African cities, including Kigali, Kampala, and Nairobi, have attempted to adopt WTE solutions, particularly through pilot composting and landfill gas projects. However, many initiatives face obstacles such as high moisture content in waste, lack of technical expertise, high initial investment costs, and inconsistent policy support. These barriers can be reduced through (i) source separation and diversion of wet organics to biological treatment (e.g., anaerobic digestion/composting) to improve the calorific value of the remaining stream; (ii) simple pre-treatment such as drying, shredding and preparation of refuse-derived fuel (RDF) for thermal routes; (iii) capacity building for operation and maintenance; and (iv) enabling policy/finance mechanisms (e.g., long-term tipping-fee and power-purchase arrangements) that lower investor risk and support stable plant operation.

In Tanzania, the problem is pronounced in cities such as Dar es Salaam, Arusha, and Mbeya, where rapidly growing waste streams are handled primarily through open dumping, with minimal recovery or valorisation (Biswas, 2021; Onesmo, 2023). Mbeya City, in particular, presents a significant challenge, as the Nsalaga Dumpsite receives increasing volumes of waste without treatment even as the city faces rising electricity demand and a lack of renewable energy diversification (Mwangomo, 2019).

Previous studies in Mbeya City and comparable Tanzanian and East African urban areas provide useful baseline evidence, but they do not fully resolve the technology-selection problem addressed in this study. For Mbeya City, Mwangomo (2019) assessed the municipal solid waste management system and reported a waste-generation rate of about 279 tonnes/day, equivalent to approximately 0.68 kg/capita/day, with continuing growth and persistent collection and disposal constraints. That study established the scale of the municipal waste management challenge, but it did not experimentally determine the calorific values of selected waste fractions or rank WTE pathways for the Nsalaga Dumpsite.

In Arusha, Omari *et al.* (2014) examined energy recovery routes from municipal solid waste and showed that Tanzanian urban waste streams can support energy recovery where recoverable fractions are properly separated; however, the work was not based on Nsalaga-specific composition, moisture, calorific value and disposal context data.

Other comparable studies from Tanzania and East Africa report similar structural patterns: high organic content, weak source separation, dependence on open dumping, informal material recovery and limited treatment infrastructure (Senzige *et al.,* 2014; Komakech *et al.,* 2014; Yhdego, 2016; Bbira, 2020). These findings are important because they confirm that many urban waste streams in the region are organic-rich and institutionally constrained. However, most of these studies either emphasise waste generation and management practices or assess single recovery options; they do not integrate local waste classification, annual inflow quantification, proximate and ultimate properties, experimental calorific values and multicriteria pathway screening in one decision framework for Mbeya City.

The present study improves upon previous work by using Nsalaga-specific evidence to connect the waste-management problem directly to WTE pathway selection. It combines the measured annual inflow of approximately 34,244 tonnes/year, the observed dominance of organic waste at 76.8%, laboratory-based calorific value results for selected combustible fractions, and MCDA screening based on technical, economic, environmental and social criteria. The contribution is therefore not merely to confirm that Mbeya has a municipal waste-management challenge but also to provide a site-specific and implementable pathway: anaerobic digestion or composting for source-separated organics and RDF preparation or controlled thermal recovery only for segregated dry high-HHV fractions.

Despite the existence of feasibility studies on WTE in African cities, there remains a significant research gap in optimising technology pathways based on local waste characteristics, site realities, and multi-dimensional sustainability criteria. Most studies focus on single technologies without accounting for the heterogeneity of waste streams and the need for integrated solutions.

This study bridges that gap by combining (i) detailed MSW characterisation at the Nsalaga dumpsite, (ii) estimation of energy recovery potential using heating value on a wet basis (i.e., lower heating value, LHV), and (iii) a multi-criteria decision analysis (MCDA) framework to rank feasible technology scenarios. In this study, "optimisation" is realised by matching specific waste fractions to the most suitable conversion routes (e.g., anaerobic digestion for wet organics and thermal conversion for high-LHV dry fractions) and by evaluating integrated scenarios across technical, economic, environmental and social indicators to identify the most appropriate WTE pathway for Mbeya City.

2.0 Materials and Methods

2.1 Study Area: Municipal Waste Management Context

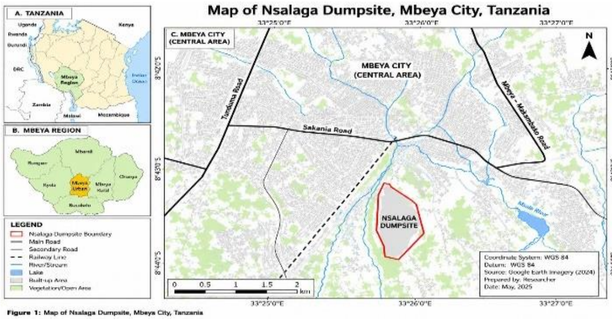
Mbeya City Council is the urban local government authority responsible for municipal service delivery in Mbeya City, southwestern Tanzania. According to the 2022 Population and Housing Census, Mbeya City Council had 541,603 residents, making it the most populous council in Mbeya Region (URT, 2024). The city functions as an administrative, commercial and transport centre, and its solid-waste stream is generated mainly from households, markets, institutions, commercial premises and small industries. A previous assessment estimated municipal solid waste generation in Mbeya City at about 279 tonnes/day, equivalent to approximately 0.68 kg/capita/day, with a reported increase of about 45% over the preceding decade and a projected rise to about 332 tonnes/day within the following planning period (Mwangomo, 2019).

Nsalaga Dumpsite is located about 15 km from the central business district and serves as the principal official disposal site for waste delivered by Mbeya City Council collection services and contracted operators. In the present study, verified delivery records indicated that the dumpsite received approximately 34,244 tonnes/year, equivalent to about 93.8 tonnes/day. When compared with the earlier city-wide generation estimate of 279 tonnes/day, the measured Nsalaga inflow represents an approximate collection-to-official-disposal share of 34%. This indicates that formal collection and controlled disposal do not capture the entire generated waste stream; some waste is likely affected by informal recovery, local burning, temporary storage, or disposal in unauthorised locations.

The current disposal practice at Nsalaga is open dumping rather than engineered sanitary landfill operation. Waste is generally delivered as mixed refuse, with limited source separation, limited pre-treatment, no systematic leachate control, no methane capture, and dependence on informal recovery of recyclable materials. The main management challenges are, therefore, incomplete collection coverage, weak segregation at source, unsafe informal waste picking, limited material-recovery infrastructure, high organic moisture content, open burning risks and the absence of engineered environmental-control systems. These conditions justify a fraction-specific WTE approach for Mbeya City: biological treatment for source-separated organics and RDF or controlled thermal recovery only for segregated dry high-calorific fractions.

Figure 1

Map of Nsalaga Dumpsite, Mbeya City, Tanzania



2.2 Research Design and Analytical Workflow

A mixed-methods research design was adopted to link field-based waste quantification, physical sorting, laboratory characterisation and decision-support analysis. The workflow followed four sequential stages:

i. review of municipal waste delivery records to establish monthly and annual inflows to Nsalaga Dumpsite;
ii. field sampling and manual sorting of mixed municipal waste to determine composition by mass;
iii. laboratory analysis of representative sorted fractions for proximate, ultimate and calorific value properties; and
iv. multicriteria decision analysis (MCDA) to match the measured waste characteristics with feasible WTE conversion pathways. This structure ensured that the recommended pathway was based on local waste data rather than on a generic technology preference.

2.3 Sampling Procedures

Sampling followed ASTM D5231-92 (2016) for the determination of the composition of unprocessed municipal solid waste. The field sample size consisted of five daily composite samples collected from fresh mixed waste delivered to Nsalaga Dumpsite over five consecutive operating days. On each sampling day, waste was obtained from different points of the delivered mixed refuse, manually homogenised as far as practicable, and sorted into the main physical categories used in this study: organic waste, plastics, metals, paper and cardboard, textiles and glass. Each category weighed separately using a calibrated weighing scale, and its percentage contribution was calculated as the mass of that category divided by the total sorted mass for the corresponding composite sample.

For laboratory characterisation, representative sub-samples were prepared from the sorted combustible fractions, namely plastic bottles, nylon, textiles, leather, wood, paper, food/organic waste and plant trimmings. The sub-samples were air-dried where required; size-reduced, mixed and stored in labelled containers prior to analysis. Proximate analysis was performed in triplicate on approximately 1.00 g of analytical portions from each homogenised fraction; ultimate-analysis determinations for nitrogen and sulphur were performed in duplicate, and calorific-value testing was conducted on selected combustible fractions using representative prepared samples. The five-day sampling campaign, therefore, provides a cross-sectional characterisation of normal disposal conditions, while seasonal variation remains a limitation requiring future wet-season and dry-season monitoring.

2.4 Laboratory Analyses

2.4.1 Determination of Proximate Analysis of Solid Waste Sample

Proximate analysis was used to determine moisture content, volatile matter, ash content and fixed carbon for the prepared MSW fractions. These parameters were selected because they directly influence fuel quality, combustibility, residue formation and suitability for thermal or biological WTE routes. Moisture content indicates the drying burden; volatile matter indicates the tendency of a fraction to release combustible gases; ash content indicates the expected inert residue after conversion; and fixed carbon represents the solid combustible portion remaining after volatile release.

2.4.2 Determination of the Percentage Moisture Content of the Municipal Waste Samples

Silica crucibles were pre-dried, cooled in a desiccator, and weighed to the nearest 0.1 mg. From the dried, milled and thoroughly homogenised composite sample, approximately 1.00 g (±0.01 g) was weighed into each crucible for proximate analysis determinations. This small analytical mass is standard for proximate analysis methods (e.g., ASTM D5142) provided that the bulk sample is representative and well-homogenised. To improve representativeness and repeatability, all proximate parameters were determined in triplicate, and the mean value was reported.

$$\%\mathrm{M.C} = ((W_2 - W_3)/(W_2 - W_1))\mathrm{x}100 \qquad (1)$$

where:

W_2 - W_1 is the initial weight of the solid waste sample and

W_2 – W_3 is the loss in weight of the solid waste sample.

2.4.3 Experimental Determination of the Percentage Volatile Matter of the Municipal Solid Waste Samples

A unit weight of moisture-free pulverised solid waste sample in the silica crucible was weighed on the digital weighing balance as w_3(g). The sample was further heated in a crucible fitted with a cover in a muffle furnace at a temperature of 950°C for 7 minutes, ISO 562/1974. It was cooled in the desiccator and weighed on the digital weighing balance as w_4(g). The percentage volatile matter in the combustible components of the municipal solid waste was determined using equation 2.

$$\%V.M = ((W_3 - W_4)/(W_3 - W_1))x100 \quad (2)$$

Where:

$W_3 - W_4$ is the loss in weight of moisture free waste.

$W_3 - W_1$ is the initial weight of the moisture free solid waste.

The procedures to determine the volatile matter of the combustible components of municipal solid waste were replicated three times and the average values of the volatile matter of each of the components obtained were presented in the composite Table 2.

2.4.4 Experimental Determination of the Percentage Ash Content of the Municipal Solid Waste Samples

The crucible was weighed on the digital weighing balance and recorded as w_1(g). A spatula was used to fetch 1.00 g of solid waste sample into the silica crucible. It was then measured and recorded as w_6(g). The sample in the open crucible was thereafter burnt in the presence of air at a temperature of 750°C in a muffle furnace till a constant weight was achieved. The residue ash was measured and recorded as w_7(g). The procedure was repeated three times for each of the combustible components of the municipal solid waste samples, ASTM D 2017. Equation 3 was used to determine the percentage of ash content in the combustible components of the municipal solid waste.

$$\%\text{ Ash content in the solid waste} = \frac{W_7 - W_1}{W_6 - W_1} \quad (3)$$

Where:

$W_7 - W_1$ is the weight of residual ash formed.

$W_6 - W_1$ is the weight of solid waste initially taken.

This procedure was replicated three times and the average values of % ash in the solid waste of each of the components obtained were presented in the composite Table 2.

2.4.5 Determination of the Percentage of the Fixed Carbon of the Municipal Solid Waste Samples

The percentage fixed carbon was determined directly by deducting the total of moisture, volatile matter and ash percentage from 100

$$\%\text{ Fixed carbon} = 100 - (\%\text{moisture contnt} + \%\text{volatile matter} + \%\text{ash content}) \quad (4)$$

2.4.6 Ultimate Analysis of Waste Samples

Ultimate analysis was also carried out to determine the percentage total carbon (C), percentage nitrogen (N), percentage Sulphur (S), percentage hydrogen and oxygen (H_2 and O_2) present in the combustible components of the municipal solid waste generated.

2.4.7 Determination of the Total Carbon in the Municipal Solid Waste Samples

The percentage total carbon of the waste sample was determined directly by adding the volatile matter and the fixed carbon together as in equation 5.

$$\%Total\ Carbon = Volatile\ matter + Fixed\ carbon \quad (5)$$

The percentage total carbon of each of the components obtained was also presented in the composite Table 3.

2.4.8 Experimental Procedure to Determine the Percentage of Nitrogen in the Municipal Solid Waste Samples

Total nitrogen in the solid waste sample was determined using the Kjeldahl method. Briefly, a known mass of the dried and ground sample (w, g) was digested with concentrated H_2SO_4 in the presence of a catalyst to convert organic nitrogeninto $(NH_4)_2SO_4$. After digestion, the solution was made alkaline with NaOH, and the released NH_3 was distilled and captured in a boric acid receiver.

When a clear solution is obtained that is when all the nitrogen present is converted to ammonium sulphate. The solution was treated with 50% NaOH (Sodium hydroxide) solution. The ammonia formed was distilled over and absorbed in a known quantity of standard H2SO4 solution. The volume of an unused acid was then determined by titration against a standard solution of NaOH. The amount of acid neutralised by liberated NH3 from the solid waste sample was then evaluated, and equations 5 and 6 were then used to determine the titre value and the percentage of nitrogen in the solid waste sample, respectively.

$$\text{Titre Value (Vt)} = V_1 - V_2 \quad (6)$$

Where:
V_1 is the volume of H_2SO_4 neutralised (cm^3)
V_2 is the volume of H_2SO_4 neutralised in determination (cm^3)

$$\%Nitrogen\ in\ the\ solid\ sample = \frac{V_t x 1.4}{W_8}\ x\ \frac{100}{1} \quad (7)$$

Where:
V_1 is the volume of H_2SO_4 neutralised (cm^3)
The above procedure was replicated two times and the average values of the % nitrogen content of each of the components obtained were computed and presented in the composite Table 3.

2.4.9 Experimental Procedure to Determine the Percentage of Sulphur in the Municipal Solid Waste Samples

25 ml of the weighed samples were dissolved in water and pipette into 50 ml standard flasks followed by 20 ml gelatine $BaCl_2$ solution and made up to the 50 ml mark. The solutions were allowed to stand for 30 minutes. The absorbance of the standard solution (Na_2SO_4) and the samples was read from the spectrophotometer at 420 nm. The graphs of absorbance against concentration of standards were plotted and the sample concentration was evaluated from the graph. Equation 7 was used to calculate % Sulphur in the solid waste samples. The above procedures were repeated two times for each of the samples and the mean values obtained were presented in the composite Table 3.

$$\%\ \text{of sulphur in the solid sample} = \frac{\text{RxVxDF}}{\text{Mass of sample used}} \quad (8)$$

Where:
R is the Graph reading
V is the Total Volume = 25 ml
DF is the Dilution factor

2.4.10 Determination of % of Hydrogen and Oxygen in the Waste Sample

The percentage of hydrogen and oxygen in the waste sample was obtained analytically by the difference between the sum of the percentages of total carbon, nitrogen, and sulphur and 100. The results were presented in the composite Table 3.

$$\%\ Hydrogen + \%\ Oxygen = 100 - (\%\ C + \%\ N + \%\ S \quad (9)$$

The results obtained in the proximate analysis were used to determine the Net Calorific Value (NCV) of the combustible components of Municipal Solid Waste (MSW) biogenic and non-biogenic combustible components.

2.4.11 Experimental Determination of Calorific Value

The calorific value of selected combustible MSW fractions was determined experimentally as higher heating value (HHV) using an oxygen bomb calorimeter procedure consistent with ASTM D5865/D5865M-19. Each sorted fraction was air-dried where necessary, milled to obtain a representative particle size, homogenised and weighed before combustion in excess oxygen. The calorimeter was calibrated using a benzoic acid standard before sample testing. The raw calorimeter readings were recorded in cal/g and converted to MJ/kg using the relationship: HHV (MJ/kg) = calorific value (cal/g) x 0.004184. Replicate measurements were used to obtain mean HHV values for the selected fractions. For mixed-stream energy estimation, the wet-basis lower heating value (LHV) was treated separately from HHV to account for the high moisture content of the organic-rich waste stream.

2.4.12 Laboratory Standard Operating Procedure and Quality Control

Laboratory quality control followed a defined sequence: sample reception and labelling; removal of non-target materials; drying, milling and homogenisation; replicate proximate analysis; duplicate nitrogen and Sulphur determination; calorific-value testing; and verification of raw laboratory sheets before calculation. Abnormal replicate values were rechecked before averaging. The reported laboratory results therefore represent mean values from repeated measurements rather than single observations, improving reliability for the energy-potential calculation and the MCDA scoring.

2.5 Quantification of Waste Inflows

Waste inflow quantification was based on delivery records obtained from Mbeya City Council for waste transported to Nsalaga Dumpsite. The records were organised by month and converted into monthly and annual waste quantities. The annual inflow used in the analysis was 34,244 tonnes/year, equivalent to about 93.8 tonnes/day. These values were used as the mass basis for estimating gross energy potential and interpreting the scale of WTE implementation required in Mbeya City.

2.6 Estimation of Energy Recovery Potential

The gross energy contained in the MSW was estimated from the waste mass and calorific values. Because a WTE facility cannot convert all chemical energy in waste into usable electricity, a conservative net electrical conversion efficiency (eta) of 25% was applied. The main losses considered include heat losses in boilers or reactors, thermodynamic limits in steam or gas cycles, generator losses and internal plant consumption by pumps, fans and auxiliary systems. The 25% value was used only for electricity-output screening; overall energy utilisation could be higher where combined heat and power are technically and economically feasible.

$$\mathrm{ERP} = \frac{\mathrm{M \times CV}}{3.6 \times \eta} \quad (10)$$

The 25% net electrical efficiency assumption is consistent with performance reported for small- to medium-scale waste combustion facilities operating in developing-country contexts. Existing WTE facilities and pilot plants in East Africa and comparable regions commonly report electricity-only efficiencies ranging between 20% and 30%, depending on waste quality, pre-treatment, moisture reduction, and plant scale. Studies from operational facilities in Addis Ababa and pilot RDF systems in Nairobi and Kampala indicate that high-moisture mixed waste streams generally achieve lower efficiencies unless effective segregation and drying are implemented. Therefore, the use of 25% in this study provides a conservative and realistic estimate for Mbeya under improved waste segregation conditions.

where M is mass (kg), CV is calorific value (MJ/kg), 3.6 is the conversion factor to kWh, and η is conversion efficiency (assumed at 25%). This allowed estimation of both gross and net energy that could be recovered.

2.7 Multi-Criteria Decision Analysis (MCDA)

A multicriteria decision analysis (MCDA) framework was used to translate the measured Nsalaga waste characteristics into a transparent technology-selection decision. The candidate pathways assessed were anaerobic digestion, composting/co-composting, RDF preparation with gasification or pyrolysis, controlled combustion for prepared residual fuel, and landfill gas recovery as a long-term option after engineering upgrades.

Each pathway was scored against four criteria on a 1–5 scale, where 1 represented poor suitability and 5 represented strong suitability. The weights were assigned to reflect the objective of the study: selecting a pathway that is technically compatible with the local waste stream, financially realistic for municipal implementation, environmentally protective, and institutionally acceptable for Mbeya City.

Table 1 links the classification, quantification, calorific value, moisture content and contextual findings to the final WTE pathway recommendation. The table is therefore used as a decision frame rather than as a generic list.

Using this scoring logic, anaerobic digestion was prioritised for the dominant moisture-rich organic stream, while RDF preparation followed by gasification, pyrolysis or controlled combustion was retained for segregated dry high-HHV fractions. The resulting pathway interpretation is reported in Section 3.6.

Table 1
MCDA Criteria Weights and Scoring Framework Used for Technology Optimisation

Evaluation Criterion	Description	Weight (%)	Rationale
Technical Performance	Efficiency, reliability, operational feasibility, and compatibility with local waste characteristics	35	High importance due to heterogeneous waste composition and operational sustainability
Economic Viability	Capital cost, operation & maintenance cost, energy revenue potential, and affordability	25	Necessary to ensure financial feasibility under municipal budget limitations
Environmental Impact	Emissions reduction, residue management, pollution control, and climate benefits	25	Important for minimising environmental and public health impacts
Social Acceptance	Community acceptance, employment creation, policy alignment, and public safety	15	Ensures community support and long-term implementation success
Total		100	

2.8 Data Analysis Approach

Data analysis was conducted using descriptive statistics, unit conversion and weighted scoring. Waste composition was calculated as percentage by mass for each sorted category. Monthly waste quantities were aggregated to obtain the annual Nsalaga inflow, while calorific-value readings were converted from Cal/g to MJ/kg using 1 Cal/g = 0.004184 MJ/kg. Gross energy was calculated as waste mass multiplied by calorific value, then converted from MJ to kWh by dividing by 3.6. Estimated electricity output was obtained by applying the 25% net electrical efficiency assumption.

For technology selection, the MCDA used a weighted sum logic in which each candidate pathway was evaluated against technical suitability, economic suitability, environmental performance and social/institutional readiness. The scoring drew on the measured waste composition, moisture-related constraints, HHV values, disposal context at Nsalaga and the implementation issues discussed in the literature. This approach allowed the study to move from characterisation results to an evidence-based WTE pathway recommendation for Mbeya City.

2.9 Ethical Considerations

This study adhered to ethical standards in data collection and reporting. Field access and waste inflow data were obtained through permission from Mbeya City Council. No personal or household-identifiable data were collected during the study. Waste handling followed basic occupational safety procedures, including use of protective equipment during sampling and sorting, and results were reported honestly without manipulation of field or laboratory data.

3.0 Results and Discussion

3.1 Waste Composition

The data in Table 2 and Figure 2 indicate that organic waste is by far the largest component of the municipal solid waste stream at Nsalaga, averaging 76.8% of the total composition. This dominance has critical implications for both energy recovery potential and environmental sustainability. Such a high proportion of biodegradable waste is characteristic of many low- and middle-income countries, where organic fractions typically range between 50% and 70% due to food waste, agricultural residue, and limited source separation (Paritosh *et al.,* 2018). The value recorded at Nsalaga exceeds these averages, indicating a waste stream heavily dominated by biodegradable materials. The high proportion of organics highlights both the challenge of managing moisture-rich waste and the opportunity to apply biological conversion technologies such as anaerobic digestion.

The non-organic component of the municipal solid waste stream at Nsalaga Dumpsite constitutes 23.2% of the total waste, which is a substantial fraction with major consequences for resource recovery, energy generation, and environmental management. The presence of plastics (5.36%), metals (4.24%), paper and cardboard (4.01%), textiles (5.09%), and glass (4.34%) reflects common generation patterns observed in rapidly urbanising East African cities (Kebede *et al.,* 2025; Komakech *et al.,* 2014; Senzige *et al.,* 2014). Comparable studies in Dares Salaam, Arusha, Kampala, and Nairobi show non-organic fractions ranging from 18% to 30%, indicating that Nsalaga aligns closely with regional waste profiles (Bbira, 2020; Yhdego, 2016). This portion of the waste stream represents a valuable resource pool that, if properly segregated and processed, could substantially reduce the volume of waste requiring disposal while contributing to energy recovery and economic opportunities.

Plastics, though relatively small in proportion, present both environmental risks and high-value energy potential due to their elevated calorific value of 35–45 MJ/kg (Sharma & Chandel, 2021), making them suitable for refuse derived fuel (RDF), co-combustion, or pyrolysis. Metals, despite forming only 4.24% of the waste, have substantial recycling value, requiring up to 95% less energy to recycle than to produce from raw ores (Shopeju, 2024) , and their presence at Nsalaga reflects inflows from workshops and small industries.

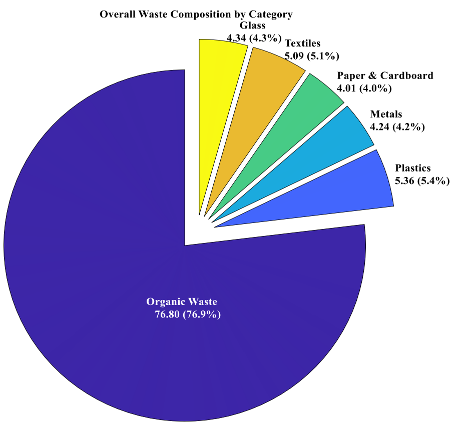
Textiles, accounting for about 5.09%, mirror rising trends across African cities where used clothing markets contribute significantly to textile waste (Sumo, 2024), and their calorific values of 16–20 MJ/kg make them viable for thermal energy systems and material recovery processes.

Overall, the 23.2% non-organic fraction represents a substantial resource that could support recycling industries, enhance energy generation through RDF or pyrolysis, and reduce the dumping burden at Nsalaga. This aligns with evidence from Nairobi, Addis Ababa, and Johannesburg, where non-organic waste streams have been leveraged for material recovery and energy production despite systemic challenges (Kiche, 2024; Manikandan, n.d.). Efficient management and valorisation of this fraction could significantly enhance Mbeya City's circular economy potential while mitigating environmental risks associated with unmanaged disposal.

Table 2
Overall Waste Composition by Category

Waste Category	Overall (%)
Organic Waste	76.8
Plastics	5.36
Metals	4.24
Paper & Cardboard	4.01
Textiles	5.09
Glass	4.34
Total	100.0

Figure 2
Overall Waste Composition by Category



3.2 Proximate Analysis

The results presented in Table 3 indicate significant variation in the proximate properties of the different waste fractions analysed from the Nsalaga Dumpsite. Moisture content was highest in food and organic waste (15.46%) and lowest in nylon (2.59%), reflecting the intrinsic nature of biodegradable and synthetic materials. Volatile matter content ranged from 73.15% in paper to 85.69% in nylon, indicating the high flammability and energy release potential of plastic-based waste materials. Ash content was lowest in plastics (0.54–0.69%) and highest in paper (7.19%), demonstrating that inorganic residue generation during combustion is minimal for synthetic wastes but substantial for fibrous or biomass-derived materials.

Fixed carbon, which represents the solid combustible portion remaining after volatile matter release, was relatively higher in textiles (15.84%) and paper (14.49%), signifying better findings suggest that dry fractions such as plastics, textiles, and paper possess superior thermal conversion potential compared to the high moisture organic fractions. Therefore, while organic materials are better suited for biological energy recovery (e.g., anaerobic digestion), plastic and textile wastes are more appropriate for thermal waste-to-energy applications such as gasification or incineration.

Compared with regional studies in Dar es Salaam, Arusha, Kampala and Nairobi, the proximate profile at Nsalaga follows the expected pattern for East African mixed MSW: high volatile matter in plastics, nylon, wood and organics, low ash in synthetic fractions, and higher ash in paper and plant-derived materials. The relatively lowmoisture values reported for individually sorted dry fractions support their suitability for thermal conversion after segregation, while the higher moisture of food/organic waste confirms the need to treat the organic stream biologically rather than mixing it with dry refuse-derived fuel.

Table 3
Proximate Analysis of MSW Fractions (%)

Type of Waste	% Moisture Content	% Volatile matter	% Ash	% Fixed Carbon
Plastic Bottles	7.32	80.32	0.69	11.67
Nylon	2.59	85.69	0.54	11.24
Textile	4.51	78.17	1.48	15.84

Type of Waste	% Moisture Content	% Volatile matter	% Ash	% Fixed Carbon
Leather	12.18	74.12	3.95	9.75
Wood	6.53	82.86	1.44	9.17
Paper	5.17	73.15	7.19	14.49
Food/organic Waste	15.46	74.17	2.05	8.32
Plant Trimmings	10.17	75.03	5.08	9.72

3.3 Ultimate Analysis

As shown in Table 4, the ultimate analysis revealed distinct elemental compositions among the different municipal solid waste fractions at the Nsalaga Dumpsite. Plastics and nylon recorded the highest carbon content (91.99–96.87%), coupled with low oxygen content (1.88–7.11%), reflecting their hydrocarbon-rich nature and confirming their high calorific potential. In contrast, food waste and plant trimmings exhibited lower carbon levels (82.49–84.75%) and higher oxygen content (10.19–14.38%), characteristics typical of biodegradable materials with lower energy density but high biodegradability. Hydrogen content ranged between 0.34% and 2.09%, while sulphur and nitrogen remained minimal across all waste types, indicating limited pollutant formation during combustion and an environmentally favourable characteristic. Leather and food waste showed relatively higher nitrogen content (0.56–1.40%), which could contribute marginally to NO_x emissions if thermally processed, but the values remain within acceptable limits for clean combustion. The high carbon and hydrogen ratios in plastics and textiles correlate with their high energy content, confirming their potential as key feedstocks in thermal WTE processes. Conversely, the higher oxygen content in organics and paper aligns with their reduced heating value and greater suitability for biological treatment pathways such as anaerobic digestion or composting.

Overall, the elemental composition underscores a clear differentiation between high-energy synthetic wastes and low-energy organic fractions, supporting an integrated waste management model in which thermal technologies target plastics, textiles, and paper, while organic materials are utilised for biogas production and composting.

Table 4

Ultimate analysis of MSW fractions (% by mass)

Type of Waste	% Total Carbon	% Nitrogen	% Sulphur	% Hydrogen	% Oxygen
Plastic Bottles	91.99	0.16	0.02	0.72	7.11
Nylon	96.87	0.54	0.37	0.34	1.88
Textile	94.03	0.33	0.08	1.47	4.09
Leather	83.87	0.56	0.31	1.69	13.57
Wood	92.03	0.22	0.17	0.47	7.11
Paper	87.64	0.80	0.11	1.03	10.42
Food/organic Waste	82.49	1.40	0.07	1.66	14.38
Plant Trimmings	84.75	2.49	0.48	2.09	10.19

3.4 Calorific Values

Calorific value represents the amount of heat energy released when a waste fraction is completely combusted. In this study, calorific value is reported as higher heating value (HHV) in MJ/kg and was determined using oxygen-bomb calorimetry as described in Section 2.4.11. The measured HHV values are presented in Table 5.

Table 5

Experimental Calorific Values Of Selected Combustible MSW Fractions at Nsalaga Dumpsite

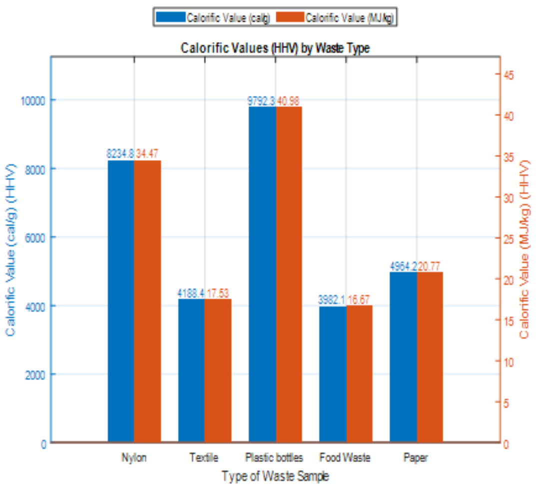
MSW fraction	HHV (MJ/kg)
Plastic bottles	39.95
Nylon	33.87
Paper	19.00
Food/organic waste	18.22
Textile	17.02

Plastic bottles (39.95 MJ/kg) and nylon (33.87 MJ/kg) recorded the highest HHV values, confirming that segregated dry polymer fractions have the strongest potential for controlled thermal recovery, RDF preparation, pyrolysis or gasification. Paper (19.00 MJ/kg) and textiles (17.02 MJ/kg) provide moderate combustible value and can supplement dry WTE feedstock when separated from wet organics. Food/organic waste recorded 18.22 MJ/kg on the tested sample, but its practical thermal performance is constrained by the high moisture content of the organic-rich waste stream; therefore, anaerobic digestion or composting remains the more appropriate route for this dominant fraction.

The calorific-value results therefore support a fraction-specific WTE strategy for Mbeya City: biological treatment for the dominant moisture-rich organic fraction and controlled thermal or RDF-based recovery for segregated high-HHV dry fractions. This avoids treating mixed waste as a uniform fuel and provides a clearer technical basis for technology selection.

Figure 3

Calorific Values of Sorted MSW Fractions at Nsalaga



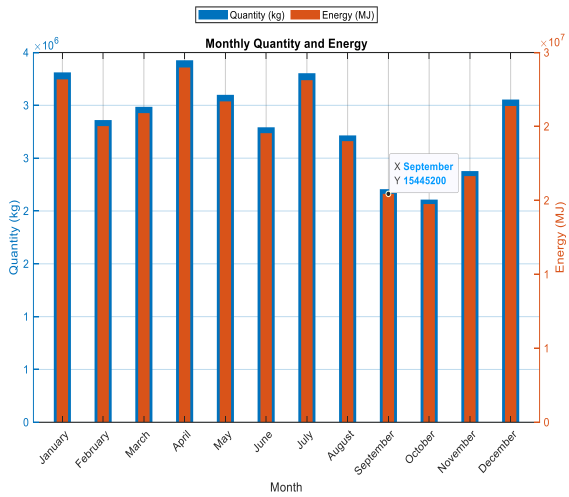
3.5 Waste Inflows and Energy Potential

The energy recovery potential of the Nsalaga waste stream was estimated by combining waste quantity with calorific value. Since the waste stream is dominated by organic waste (76.8%) and contains substantial moisture, the mixed-stream calculation used a conservative mass-weighted wet-basis LHV of 7.0 MJ/kg rather than the HHV of any single dry fraction. Using the annual waste inflow of 34,244 tonnes, the gross energy content was estimated as 34,244,000 kg x 7.0 MJ/kg = 239.7 TJ, equivalent to about 66.6 GWh/year.

At an assumed net electrical conversion efficiency of 25%, the recoverable electricity potential is approximately 16.6 GWh/year. This estimate is a screening-level planning value; actual output would depend on segregation efficiency, moisture reduction, plant availability, conversion technology and operational control. The HHV values measured in Table 5 indicate that plastics and nylon provide the strongest thermal fuel quality, while the high mass share of organic waste supports biological recovery. Therefore, the practical WTE implication is an integrated system that directs source-separated organics to anaerobic digestion and dry high-HHV fractions to RDF preparation, pyrolysis, gasification or controlled combustion where technically and environmentally feasible.

Figure 4

Monthly MSW Inflows and Energy Potential at Nsalaga for the Year 2024



3.6 Technology Optimisation (MCDA)

The MCDA results and the measured waste properties indicate that Mbeya City should adopt a fraction-specific and phased WTE pathway rather than a single mixed-waste technology. The primary pathway should be anaerobic digestion for sources of separated organic waste because organics form 76.8% of the Nsalaga waste stream and are moisture-rich, which makes direct thermal treatment inefficient without extensive drying. AD is technically better aligned with this dominant fraction because it converts biodegradable material into biogas and digestate while reducing uncontrolled methane formation from open dumping.

For the smaller dry combustible fraction, the recommended pathway is segregation followed by refuse-converted fuel (RDF) preparation and controlled thermal recovery through gasification, pyrolysis or carefully managed combustion where emission control capacity is available. This recommendation is supported by the measured HHVs of plastic bottles (39.95 MJ/kg), nylon (33.87 MJ/kg), paper (19.00 MJ/kg) and textiles (17.02 MJ/kg). Mass-burn incineration of unsegregated waste is not recommended as the first option for Mbeya because the mixed stream is organicdominated and moisturerich, and because incineration requires high capital investment, stable feedstock quality, skilled operation and flue-gas treatment. Landfill gas recovery should be treated as a longer-term option only if Nsalaga is upgraded from open dumping to engineered cells with compaction, daily cover, leachate control and gas collection infrastructure.

The specific pathway decisions for Mbeya City are therefore as follows:

Anaerobic digestion: recommended as the primary WTE pathway for source-separated organics because it matches the dominant biodegradable fraction and avoids the energy penalty associated with drying wet waste before combustion.

Composting/co-composting: recommended as a supporting biological option for organic residues not routed to AD, particularly during the early implementation phase when biogas infrastructure is still being scaled.

RDF, gasification and pyrolysis: recommended as secondary pathways for segregated dry high-HHV fractions such as plastic bottles, nylon, paper and textiles; these options require sorting, drying, shredding and controlled operation.

Incineration: recommended only as a conditional option for prepared residual fuel or RDF, not for the unsegregated mixed waste stream, because of the high organic share, moisture content, capital cost and flue-gas-treatment requirements.

Landfill gas recovery: recommended only as a long-term transition option if Nsalaga is upgraded from open dumping to engineered landfill cells with compaction, cover, leachate control and gas collection.

Accordingly, the most suitable pathway is an integrated system: immediate source separation and AD for organics; medium-term material recovery and RDF preparation for dry combustibles; and conditional deployment of thermal or landfill-gas technologies only after the required pre-treatment and environmental-control infrastructure is in place.

3.7 Practical Waste-to-Energy Implementation in Mbeya City

The practical implementation of WTE in Mbeya should be interpreted based on the measured characteristics of the Nsalaga waste stream rather than on a generic technology preference. The annual inflow of approximately 34,244 tonnes, the dominance of organic waste at 76.8%, and the measured HHV values of dry combustible fractions indicate that Mbeya requires an integrated and phased system. The immediate priority is therefore not mass-burn treatment of mixed waste, but source separation, biological treatment of wet organics, and controlled recovery of dry high-calorific fractions.

3.7.1 Technical Implementation

The first technical requirement is segregation at source and at the dumpsite reception point. Organic waste should be diverted to anaerobic digestion, where feedstock quality, moisture, and contamination can be controlled, while composting can handle organic residues that are not suitable for biogas production. Dry combustible fractions such as plastic bottles, nylon, paper and textiles should be separated, dried where necessary, shredded and prepared as RDF or feedstock for gasification, pyrolysis or controlled combustion. Direct incineration of unsegregated waste is not recommended at the initial stage because the mixed stream is organic-rich and moisture-sensitive, which would lower thermal efficiency and increase pre-treatment and emission-control requirements.

3.7.2 Economic Implementation

The estimated recoverable electricity potential of about 16.6 GWh/year provides a planning basis, but project viability will depend on phased capital investment, stable feedstock supply, operating capacity, tariffs, tipping-fee arrangements and markets for compost, recyclables and RDF. A practical financing model for Mbeya should begin with lowerrisk interventions such as source separation, organic waste collection, pilot anaerobic digestion and material recovery, before scaling to capital-intensive thermal systems. This sequencing reduces investment risk and allows Mbeya City Council to build operational evidence before entering larger public-private partnership arrangements.

3.7.3 Environmental Implementation

The strongest environmental gain would come from diverting biodegradable waste away from open dumping. Based on the measured composition, approximately 26,300 tonnes/year of organic material are delivered to Nsalaga; diverting 70-90% of this fraction would prevent about 18,400-23,700 tonnes/year of biodegradable waste from uncontrolled decomposition. This would reduce methane formation, odour, leachate generation, openburning risk and diseasevector exposure around the dumpsite. Dry-fraction recovery would also reduce the disposal burden, although thermal recovery must only be adopted where air-pollution control, ash handling and occupational safety measures can be assured.

3.7.4 *Institutional Implementation*

The proposed pathway requires Mbeya City Council to strengthen governance before full-scale investment. Priority actions include enforceable source-separation by-laws, reliable waste inflow records, and designated organic-waste collection routes, worker safety procedures, monitoring of moisture and calorific value, and formal integration of recyclable recovery activities. Nsalaga should also be progressively upgraded from open dumping to engineered disposal cells with controlled access, leachate management, and, in the long term, gas collection infrastructure. These institutional measures are essential because WTE performance depends not only on technology selection but also on feedstock discipline, operational accountability and sustained municipal financing.

Overall, the results support a phased implementation roadmap for Mbeya City: short term source separation and organic waste diversion; medium term anaerobic digestion, composting and material recovery; and long term RDF linked thermal recovery or landfill gas recovery only after the required pre-treatment and environmental control systems are in place. This approach links the study's findings directly to implementable municipal planning while avoiding overdependence on a single WTE technology.

4.0 Conclusion

This study concludes that municipal solid waste delivered to Nsalaga Dumpsite has measurable potential for integrated waste-to-energy development, but the appropriate pathway is not mass treatment of unsegregated mixed waste. The evidence shows that Nsalaga receives approximately 34,244.45 tonnes of MSW per year and that the stream is dominated by organic waste at 76.8%. This composition makes biological treatment the most suitable primary route, particularly anaerobic digestion for source-separated organics and composting for organic residues that are not suitable for biogas production.

The laboratory results further show that dry combustible fractions have stronger thermal value when separated from wet organics. Plastic bottles recorded the highest HHV at 39.95 MJ/kg, followed by nylon at 33.87 MJ/kg, paper at 19.00 MJ/kg, food/organic waste at 18.22 MJ/kg and textiles at 17.02 MJ/kg. Using a conservative wet-basis LHV of 7.0 MJ/kg for the mixed stream, the gross annual energy content is estimated at 239,711,150 MJ, equivalent to about 66.59 GWh/year, with a recoverable electricity potential of about 16.65 GWh/year at 25% net electrical efficiency. These findings support a phased WTE system for Mbeya City: biological recovery for source-separated organics, material recovery and RDF preparation for dry high-HHV fractions, and controlled thermal or landfill-gas options only after the required pre-treatment and environmental-control infrastructure is in place.

The study therefore contributes site-specific evidence to the decision framework that connects waste inflow records, composition data, laboratory HHV results and MCDA screening into a phased implementation recommendation for municipal planning, policy support and investment appraisal.

5.0 Recommendations

For Mbeya City Council, the priority should be to implement source separation and establish a phased organic-waste management system. The first operational step should be separate collection of biodegradable waste from markets, institutions and high-generation neighbourhoods, followed by pilot anaerobic digestion and composting. The Council should also maintain verified monthly waste inflow records, monitor moisture and calorific value periodically, formalise safe recyclable recovery, and progressively upgrade Nsalaga from open dumping toward engineered disposal cells with leachate control, access control and future gas-collection readiness.

For policymakers and regulatory institutions, the findings call for an enabling framework that treats WTE as part of integrated solid-waste management rather than as a stand-alone electricity project. Policy support should include enforceable source-separation by-laws, environmental safeguards for thermal treatment, quality standards for compost and RDF, and financing mechanisms such as tipping-fee rules, feed-in arrangements, green procurement and public-private partnership guidelines that reduce investment risk while protecting public health.

For researchers, future work should extend the sampling campaign across wet and dry seasons, test biogas yield from the dominant organic fraction, evaluate digestate and compost quality, and conduct detailed techno-economic and life-cycle assessments of anaerobic digestion, composting, RDF preparation, gasification, pyrolysis and landfill-gas recovery under Mbeya conditions. This will strengthen the design basis beyond the screening-level estimates reported in the present study.

For potential investors, the most realistic entry point is not immediate mass-burn incineration of mixed waste but staged investment in feedstock preparation, material recovery, anaerobic digestion and RDF production. Larger thermal or landfill-gas projects should be considered only where long-term waste supply agreements, segregation performance, power off-take arrangements, emissions-control capacity and municipal payment mechanisms are clearly defined.

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8.0 Declaration of Conflicting Interests

The authors declare no conflict of interest.

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