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## DESIGN OF CENTRALIZED ANAEROBIC DIGESTION SYSTEM FOR SOLID WASTE MANAGEMENT AND ENERGY RECOVERY IN MBEYA CITY, TANZANIA

By

Emmanuel Anosisye Mwangomo<sup>1</sup>, Matobola Joel Mihale<sup>2</sup>, Lawi Yohana<sup>2</sup><sup>1</sup>Department of Mechanical and Industrial Engineering, BOX 131 Mbeya Mbeya University of Science and Technology<sup>2</sup>Department of Physical and Environmental Sciences, Faculty of Science, Technology and Environmental Studies, The Open University of Tanzania, P.O. Box 23409, Dar es Salaam, Tanzania.

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### Abstract

Municipal solid waste (MSW) management in Mbeya City, Tanzania, is currently characterized by unsorted collection, open dumping, and minimal energy recovery, contributing to serious environmental and public health concerns. This study addressed the urgent need for sustainable waste treatment solutions by proposing the design of a centralized anaerobic digestion (CAD) system tailored to the city's organic waste profile. The main objectives were to quantify the biodegradable waste stream, estimate biogas production potential, and develop a technically and economically feasible CAD system. A ten-day sampling campaign revealed an average generation of 45,000 kg/day of organic waste, predominantly food scraps with high moisture content (65–78%), suitable for biogas production. The proposed CAD system was designed to process 6 m<sup>3</sup>/day of substrate, generating 1,080 m<sup>3</sup>/day of biogas, equivalent to 2.16 MWh of electricity and 23,760 MJ of heat per day. Thermal system design ensured energy self-sufficiency under thermophilic conditions (55°C), supported by heat recovery efficiencies of 80%. Environmental analysis projected annual greenhouse gas reductions of 16,948.95 tons CO<sub>2</sub>-equivalent and 60% diversion of organic waste from landfills. Economic evaluation revealed a capital cost of \$320,000, a payback period of 2.8 years, and an internal rate of return (IRR) of 25.1%. The study concludes that a CAD facility, integrated with improved waste segregation and supported by public-private partnerships, offers a viable pathway to circular economy practices in Mbeya City. Policy support, technical training, and community engagement are essential for successful implementation and replication in similar urban contexts.

**Keywords:** Centralized Anaerobic Digestion; Municipal Solid Waste Management; Biogas Energy Recovery; Thermophilic Digestion Systems; Sustainable Urban Waste Solutions

### 1. Introduction

Municipal Solid Waste (MSW) management remains a critical and escalating environmental challenge in rapidly urbanizing regions, particularly in developing countries where institutional, technical, and financial capacities are often constrained. Globally, cities generate over 2.01 billion tonnes of MSW annually, with at least 33% not managed in an environmentally safe manner [1]. In Sub-Saharan Africa, this figure is even more alarming due to high urban population growth and inadequate waste infrastructure. Conventional disposal methods such as open dumping, landfilling, and incineration contribute significantly to environmental degradation through greenhouse gas (GHG) emissions,

leachate contamination, and the release of toxic pollutants ([1]; [2]; [3]). These approaches are increasingly being viewed as unsustainable in the face of global climate commitments and urban environmental health concerns, as they represent a linear approach to waste management that fails to harness the inherent resource potential within the waste stream.

As a response to these challenges, anaerobic digestion (AD) has gained global recognition as a sustainable waste-to-energy (WtE) technology. AD utilizes microbial processes in oxygen-free environments to break down organic waste into biogas—a renewable energy source composed primarily of methane—and digestate, a nutrient-rich biofertilizer ([4], [5] [6]; [7]). Biogas yields from municipal organic waste range from 0.45 –



0.55m<sup>3</sup>/Kg VS in Dar es salaam Tanzania [41] and 0.35 – 0.50m<sup>3</sup>/Kg VS in Addis Ababa Ethiopia[38]. Operational and maintenance (O&M) costs in Lagos, Nigeria range from \$15 – 25 per tonne of waste processed [42]. While similar systems in Kampala Uganda reports \$12 – 20 per tonne [46]. They emphasized that typical hydraulic retention time in African Urban AD systems range from 20 – 35 days, with feedstock homogenization improving digester stability. These metrics provide a practical technical framework for the expected biogas production and operational costs of the proposed Mbeya CAD system. Beyond reducing landfill loads and associated emissions, AD offers the dual benefit of energy generation and resource recovery, aligning with circular economy principles and several Sustainable Development Goals (SDGs), including SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), and SDG 13 (climate action) [8] The versatility of AD allows for the treatment of diverse organic feedstocks, including food waste, agricultural residues, and sewage sludge, making it a highly adaptable technology for various contexts ([9] &[6]).

In Tanzania, despite growing interest in renewable energy, the adoption of biogas technology remains limited and fragmented. Early initiatives led to the installation of 3,819 biogas plants by 2013, up from just 103 in 2009, yet these systems were primarily small-scale and dispersed [10]. Factors such as low public awareness, inadequate technical training, insufficient maintenance services, and high upfront costs have constrained wider adoption, particularly in semi-arid and rapidly urbanizing regions ([11]; [12]; [13] More recently, there has been growing interest in hybrid renewable systems—such as biogas integrated with solar photovoltaic (PV) as a means of improving energy reliability and resilience in off-grid and underserved areas[23]. This integration can provide a more robust and consistent energy supply, overcoming the intermittency challenges often associated with standalone renewable energy systems.

Mbeya City represents a pertinent case study in this context. The bulk of this waste in this city is disposed of in open dumpsites or unmanaged landfills, posing serious environmental and public health threats, including waterborne diseases, vector infestations, and methane emissions ([14]; [15]). With the high organic fractions in MSW, cities like Mbeya presents significant untapped potential for centralized anaerobic digestion (CAD) systems, which can process diverse organic inputs—including food scraps, market waste, and agricultural residues—while producing renewable energy and reducing GHG emissions ([16]; [17]; [18]).

Approximately 62.4% of Mbeya's MSW is food wastes which are suitable for anaerobic digestion(Malisa et al., 2024). For comparison , Arusha City generates about 67% biodegradable waste while Dar es salaam MSW contains over 50% organic material[24]; [41]). These figures demonstrate that Mbeya has substantial energy recovery potential from biodegradable waste, comparable to or singly lower than other urban centers in Tanzania, providing a strong technical basis for the proposed centralized anaerobic digestion system.

MSW generation in Mbeya City is approximately 400 tonnes per day of which only 35% is formally collected and transferred to the Nsalaga dumpsite, implying that around 65% remaining uncollected and is likely disposed to informally in open dumping[24].

Although several studies in African Cities have assessed the feasibility of anaerobic digestion for municipal solid wastes(MSW), most remain at a conceptual or small scale level without delivering detailed engineering design outputs([47];[48]). More ever, there is a lack of localized MSW characterization integrated directly into centralized anaerobic digestion (CAD) systems design, particularly for contexts like Mbeya City where food and organic waste constitute approximately 62 – 64 % of the waste stream([36];[37]). This study addresses that gap by developing s technical design of a CAD system tailored to Mbeya's MSW profile, including digester sizing, process modelling and quantification of energy recovery potential. By doing so, it not only validates feasibility but also provides a practical engineering ready blue print for medium sized Cities in Sub-Saharan Africa seeking sustainable waste to energy solution. In Lagos they adopt feedstock pre-treatment and dilution practice to manage high organic content waste([42]; from Copenhagen they proposed a modular framework for future co-digestion with sewage sludge[43]; from Addis Ababa they incorporate buffer storage and homogenization to address feedstock variability([38]; and from Mumbai they adopted organic loading rate (ORL) limits of 2 – 3 KgVS/m<sup>3</sup> day to prevent digester souring[39]. They further indicated that on the policy side Lagos and Mumbai highlighted the importance of source segregation of organic, while Copenhagen demonstrated the role of feeding tariffs and renewable energy incentives, which were recommended for Mbeya. The authors emphasized that unlike earlier feasibility studies in Tanzania that remained largely conceptual ([40];[41]) their work explicitly translates these international lessons into localized design parameters, operational safeguards and policy strategies suitable for municipal -scale implementation in Mbeya City. The study explains how the proposed CAD design for Mbeya City overcomes feedstock heterogeneity and logistics barriers through technical and operational innovations. Literature reported that feedstock variability is managed using mechanical sorting, homogenization and controlled organic loading rates to stabilize digester performance ([40];[41]).

The CAD systems offer multiple benefits over decentralized or small-scale systems, especially in urban contexts. These include economies of scale, improved feedstock consistency, centralized management, and enhanced energy recovery rates and efficiency [19]. Moreover, centralized facilities are more conducive to monitoring, automation, and quality control, thereby improving overall system efficiency and economic viability. However, implementation remains constrained by challenges such as feedstock heterogeneity, collection and transport logistics, high capital investment, and a lack of supportive policy frameworks ([20]; [21], [22]; [23]). These multifaceted barriers often limit the scalability and effective

deployment of CAD systems, particularly in developing country contexts. Feedstock heterogeneity is managed using mechanical pre-sorting, homogenization and controlled organic loading rates (2-3 Kg VS/m<sup>3</sup> day to stabilize substrate quality). Logistics challenges are addressed via satellite transfer stations and modular digester units, reducing transport distances and enabling phased deployment operational. Operational stability is enhanced through automated monitoring, pH, temperature and biogas production, along with buffer storage to manage feedstock surges. Unlike previous Tanzanian studies which focused mainly on feasibility without operational innovations ([40];[41]), the proposed design provides practical, locally adapted solutions that overcome identified barriers for municipal-scale implementation in Mbeya City.

To address these critical barriers and unlock the potential of AD in an urban African context, this paper proposes a context-specific design for a centralized anaerobic digestion system meticulously tailored to the waste composition, energy needs, and socio-economic conditions of Mbeya City. The study draws insights from international best practices in cities such as Lagos, Addis Ababa, Copenhagen, and Mumbai, and is grounded in local data, including waste audits, energy demand assessments, and stakeholder consultations. Through a multidisciplinary approach encompassing technical design, operational strategies, and economic feasibility analysis, the study aims to demonstrate how CAD can fundamentally transform waste management in Mbeya while contributing meaningfully to Tanzania's broader renewable energy targets, climate commitments, and urban sustainability agenda.

## 2. Methodology

This study employed a multi-phase methodological framework to guide the development of a CAD system for MSW management in Mbeya City. The phases included the characterization of the study area, assessment of existing waste management practices, evaluation of suitable AD technologies, selection of an appropriate site, system design, and financial and economic analysis. The approach was designed to ensure that the proposed AD system is technically viable, economically feasible, environmentally sustainable, and socially acceptable.

### 2.1 Study Area

The study was conducted in Mbeya City Council, situated in the southwestern highlands of Tanzania. The city had a population of 541,603 people and approximately 153,100 households, with an annual population growth rate was 3.2% [15]. Administratively, Mbeya City is divided into two divisions Iyunga and Sisimba comprising 36 wards and 181 hamlets. Economically, the city was sustained by commerce, agriculture, livestock keeping, industrial production, and service delivery. Notably, 33.3% of the population depend on agriculture for their livelihood, while 21% are public employed, and 43.4% are involved in informal sector activities such as small-scale trading and production of agricultural goods [15].

### 2.2 Initial Assessment and Waste Characterization

The initial phase of this study aimed to develop a comprehensive understanding of Mbeya City's current waste generation patterns, existing management practices, and local energy demands. Structured questionnaires were administered to randomly selected households and businesses to gather primary data on waste generation rates and current disposal behaviors. Concurrently, interviews were conducted with key municipal officials and waste handlers to gain insights into the institutional framework and operational challenges of the city's waste management system. These data were complemented by direct field observations across various waste collection points and disposal sites. The survey was conducted using 400 purposively selected households in selected Mbeya City Wards namely: Iyunga, Nsalaga, Sisimba, Ilomba, Forest and Iganzo. Other areas which are: 10 major markets; 50 restaurants and 60 street food vendors were surveyed during the study. The sample size was calculated to achieve a 95% confidence level with a 5% margin error following standard statistical practice. This methodology ensures that the survey results are representative of the wider Mbeya population and provide reliable input for designing the centralized AD system.

A detailed waste assessment was subsequently conducted through field surveys across diverse areas within Mbeya City. To ensure a representative dataset, waste samples were obtained from households, markets, restaurants, and food vendors. The organic portion of the collected waste was meticulously separated and weighed to determine its exact contribution to the total waste volume. These samples were then subjected to rigorous laboratory analysis to determine crucial parameters such as moisture content, volatile solids (VS), and biodegradability. The findings consistently confirmed the presence of high-moisture content and volatile solids, key indicators of suitability for anaerobic digestion. This comprehensive analysis provided critical baseline information essential for quantifying the daily input of feedstock for the proposed AD system and for informing the initial sizing of the digestion chambers.

### 2.3 Site Selection and Feasibility Analysis

Site selection for the centralized anaerobic digestion (AD) facility was a critical step, executed through a multi-faceted approach combining GIS mapping, stakeholder consultations, and legal and environmental reviews. Spatial analysis considered several crucial factors: proximity to major waste generation sources to minimize transportation costs, accessibility for collection vehicles, land availability for the facility's footprint, and distance from sensitive ecological areas to prevent environmental impact. Spatial analysis was conducted using ArcGIS 10.8 (ESRI, USA) with datasets including high resolution satellite imagery municipal land use, and administrative maps from Mbeya City Council and GPS coordinates of surveyed households, markets, restaurant and food vendors collected during fieldwork GIS mapping supports visualization of waste hotspots, assessment of transport logistic and identification of suitable CAD system, enhancing the operational feasibility of

the proposed design. For the design of a centralized anaerobic digestion (AD) system for MSW management and energy recovery in Mbeya City Tanzania, the site should be located within a maximum of 10Km from major waste sources such as urban centers, markets and residential areas to minimize transportation costs and emissions. The minimum land area should be 1 hectare (10,000 m<sup>2</sup>) to accommodate digesters, pre-treatment facilities, storage and buffer zones. The site should have a flat or gently sloping terrain, stable soil and be outside flood-prone and groundwater recharge areas to ensure environmental safety. Proximity to all weather roads, utilities (water, electricity and telecommunication) and ideally within 5Km of the power grid is essential for operational efficiency and integration of biogas electrical power plant. The facility should be at least 500 meters from residential areas to reduce odor and noise impacts, complying with industrial zoning regulations and incorporate community engagement to ensure social acceptance.

The selection process also involved extensive consultation with local communities to gauge social acceptability and gather insights into potential concerns regarding odor, traffic, or other operational aspects. Furthermore, a thorough Environmental and Social Impact Assessment (ESIA) was conducted. This assessment systematically evaluated the potential effects of the proposed facility on air quality, water resources, soil, land use change, displacement risks, public perception, and biodiversity. Based on the ESIA findings, specific mitigation strategies were developed to address any identified negative impacts and to ensure full compliance with local environmental and planning regulations. This phase aimed to confirm the overall feasibility and social acceptance of the project location.

#### **2.4 Technological Evaluation and System Sizing**

The selection of an appropriate anaerobic digestion technology was based on several key criteria, including compatibility with local waste characteristics, expected biogas yield, ease of operation, capital and operating costs, and scalability for an urban setting in a developing country. Various AD technologies were rigorously assessed based on their proven performance in similar contexts globally. A comprehensive comparison was conducted among available digestion systems, including fixed-dome, plug-flow, and continuous stirred-tank reactors (CSTR).

The evaluation concluded that CSTR technology was most suitable for Mbeya City. This decision was driven by its demonstrated ability to effectively handle heterogeneous waste streams, maintain consistent mixing for optimal microbial activity, and support mesophilic conditions conducive to efficient biogas production. System sizing was directly informed by the estimated daily feedstock availability, accounting for projected segregation efficiency and using standardized biogas yield coefficients specific to the organic waste composition identified in Mbeya. This phase also provided a robust projection of the potential daily biogas output, which was anticipated to be substantial given the high organic content and biodegradability of the city's waste stream.

#### **2.5 System Design**

The technical design of the centralized anaerobic digestion system focused on developing an integrated process layout, meticulously outlining each stage from waste reception to digestate utilization. The proposed system encompasses several key components: dedicated waste reception and sorting areas for managing incoming organic waste and facilitating preliminary separation; mechanical pretreatment units for efficient contaminant removal and particle size reduction, crucial for optimizing feedstock quality; and the core digestion tanks. Specifically, the design incorporates Continuous Stirred Tank Reactors (CSTRs) with a capacity of 120 m<sup>3</sup> each, intended to operate under thermophilic conditions (50° – 60°C) with a hydraulic retention time (HRT) of 20 to 30 days to ensure optimal microbial activity and biogas production.

Following the digestion process, comprehensive biogas handling systems were integrated, including scrubbers for removing impurities such as moisture and carbon dioxide, compressors for gas pressurization, and storage tanks for purified biogas. The purified biogas was envisioned for use in a Combined Heat and Power (CHP) unit, assumed to have an electrical efficiency of 45%, which translates to an overall energy recovery efficiency of approximately 80%. Concurrently, digestate treatment facilities were included for nutrient recovery. The digestate was to undergo dewatering, with the solid fraction designated for use as compost and the liquid fraction applied as organic fertilizer. These valuable byproducts were intended to support local agricultural practices, effectively closing the waste-to-energy-to-soil nutrient loop and enhancing circular economy principles.

Design assumptions were rigorously made based on local realities and detailed waste characterization data. It was assumed that the facility would primarily process freshly collected, source-separated organic wastes with minimal storage time to preserve its biodegradability and ensure high biogas yields. Waste audits and city records indicated a projected daily intake of approximately 45,000 kg of organic waste, can be obtained, predominantly comprising food and green waste. The biogas yield was estimated at 0.45 m<sup>3</sup> per kg of volatile solids, with a consistent methane content of about 60%, ensuring both sufficient volume and energy quality.

Since seasonal changes, potential inconsistencies in household sorting, and contamination levels could significantly impact both biogas yield and the required HRT, sensitivity analysis was done to account for inherent variations in feedstock moisture content and composition. To enhance overall process stability and performance, the system was designed to strategically incorporate buffer storage capacity, adjustable feed rates, and provisions for co-digestion with other organic substrates to account for fluctuations due to heavy rainfall or variations in food waste content could dilute the feedstock and potentially reduce methane output, presence of high-carbohydrate or lipid-rich feedstocks, that could risk process instability, and presence of slow degrading lignocellulosic materials, which could necessitate either longer HRTs or specific pretreatment steps.

A MATLAB – based sensitivity analysis was performed to identify critical factors affecting the centralized anaerobic digestion system in Mbeya City. Key inputs such as OLR, HRT, TS, VS fraction, BMP, temperature, C:N ratio, TAN, pH and mixing were varied with defined range using Latin Hypercube sampling. The Morns method and Sabol Indices (18,000 simulations) quantified parameters influence, while PRCCs assessed correlations results highlighted methane yield LCOE and GHG mitigation as the most sensitive outputs providing a robust basis for design decision making.

**2.6 Financial and Economic Analysis**

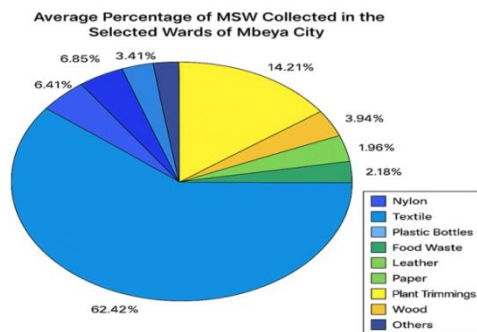
A financial and economic analysis was conducted to assess the feasibility and sustainability of the proposed system. The analysis included detailed cost estimates for capital investments, operational and maintenance expenses, and projected revenue streams from biogas and organic fertilizer sales. Funding options were explored, including public-private partnerships (PPPs), municipal funding, donor support, and community-based financing mechanisms. Potential stakeholders identified included local government authorities, private investors, development partners, and community organizations. The cost-benefit analysis aimed to ensure that the AD system was not only environmentally sound but also economically viable and capable of long-term operation under local conditions.

**3. Results and Discussion**

**3.1 MSW composition and Generation rates**

**3.1 MSW Composition and Generation Rates**

Analysis of MSW in Mbeya City revealed a predominant composition of food and other organic materials, alongside smaller proportions of paper, plastics, metals, glass, tires, and miscellaneous items. Organic waste consistently emerged as the dominant fraction, accounting for approximately 62.4% of the total MSW (Figure 1). This finding aligns with national estimates for biodegradable municipal waste, which typically range from 50% to 70% in Tanzania [25]. The significant presence of food waste specifically confirmed earlier studies that identified organics as the largest contributor to the waste stream in Mbeya [24]. This high organic content positions Mbeya City as an ideal candidate for organic waste-to-energy technologies, such as anaerobic digestion or composting.



**Figure 1: Average Percentage of MSW collected in the selected Wards of Mbeya City**

The overall rate of solid waste generation in Mbeya City was estimated at approximately 400 tonnes per day, translating to an average per capita generation rate of 0.7 kg/person/day [24]. This value is consistent with the national range of 0.66 to 0.95 kg/person/day reported across Tanzanian urban centers [25]. However, a critical challenge highlighted by the data was the limited waste collection capacity in Mbeya, which managed to collect only around 140 tonnes per day, representing a mere 35% of the daily waste generated. Data on formal recycling capacity remained largely undocumented, with no comprehensive figures available on waste recovery or material recycling within the city. Mbeya City generates about 400t/day of waste(0.7 Kg/cap/day) but only 35% is collected, significantly limiting feedstock availability for the centralized anaerobic digestion(CAD) system. This reduced collection directly lower potential biogas and energy production, requiring the CAD design to consider smaller or improved collection strategies to optimize plant performance and economic returns.

**Table: Specific Methane yield and energy recovery from MSW under different composition scenarios**

Feedstock Type	T S %	VS (% of TS)	BM P(M <sup>3</sup> CH <sub>4</sub> /Kg VS)	CH <sub>4</sub> yield(M <sup>3</sup> /t wet)	Kwh /t (the rmal )	Kwh/t @3 5%	Elect ricity / day (Kwh)
Mixed( OFMS W)	20	85	0.38	64.6	642	225	456
Househo lds	18	82	0.36	53.1	528	185	376
Market	22	88	0.42	81.3	809	283	575
Restaura nt	25	90	0.45	101.3	1007	352	715

Notes:

Calculations assume methane lower heating value(LHV) = 35.8 MJ/m<sup>3</sup> and 1Kwh = 3.6 MJ. Electrical recovery assumes 35% conversion efficiency via gas engine generator. Daily scale – up of 3,254.5 Kg/day with 62.4 organics

Among the surveyed wards, Ilomba and Iganzo exhibited the highest levels of waste generation, likely attributable to their higher population densities, greater economic activity, and elevated consumption rates. Conversely, Iyunga and Sisimba generated the least amount of waste. The average daily waste collected specifically across the six surveyed wards (Nsalaga, Ilomba, Iganzo, Sisimba, Forest, and Iyunga) was 464.93 kg/day. Based on local demographic data for these specific wards, the calculated per capita waste generation rate was approximately 0.00527 kg/day/person. This figure was notably low and may reflect factors such as modest household consumption, active informal waste minimization practices, or potential underreporting due to collection inefficiencies. Using Mbeya City’s total waste generation of 400t/day and an



estimated population of 571,000, realistic per capital generation is approximately 0.71 Kg/day consistent with literature values for urban Tanzania. Considering the 35% collection efficiency and an organic fraction of 62.4%, the actual feedstock available for the centralized anaerobic digestion system is roughly 87.4 t/day. This correlated figure should be used for digester sizing, biogas and energy recovery estimate.

In addition to the dominant food waste, plastic bottles and textiles emerged as significant components of the waste stream, indicating potential areas for targeted recycling interventions. The "Others" category comprised nearly 14% of the waste and likely included mixed residuals or non-recyclable items such as contaminated packaging, ceramics, and sanitary waste. The high proportion of biodegradable material in the city's waste profile strongly supports the need for strategic investment in advanced organic waste treatment systems.

### 3.2 Site Selection and Feasibility Analysis

Site selection for the centralized anaerobic digestion system involved a multi-criteria feasibility analysis focusing on the proximity to MSW generation sources, availability of land, ease of access, availability of utilities (such as water and electricity), and environmental and social considerations. This evaluation aimed to ensure logistical efficiency, minimize transportation costs, and reduce potential negative impacts on surrounding communities and ecosystems.

Based on these criteria, three key locations within Mbeya City Soweto Market, Sokomatola, and Uyole were identified as suitable due to their proximity to dense commercial activities and consistent waste generation. Additionally, the Nsalaga landfill site was considered due to its current use as a disposal area, potential for co-location of infrastructure, and existing municipal engagement in waste management activities. The feasibility study also factored in environmental regulations and land-use policies to ensure compliance with local planning and legal frameworks.

### 3.3 Design of the CAD System

The design of the CAD system for Mbeya City was meticulously developed based on the comprehensive data gathered on MSW generation and composition, and it strictly adhered to established standardized engineering principles for sustainable waste management. This phase focused on creating an integrated process layout that would efficiently manage the organic waste stream from reception to valuable resource recovery.

The overall system design incorporated all necessary auxiliary components for a fully functional and efficient plant. This included feedstock preprocessing units (for shredding and contaminant removal), gas purification systems (for H<sub>2</sub>S and CO<sub>2</sub> scrubbing to ensure higher quality biogas), and digestate handling systems designed to produce both nutrient-rich compost from the solid fraction and liquid fertilizer from the liquid fraction, thereby promoting a circular economy.

Energy recovery was a central objective, integrated into the design through a Combined Heat and Power (CHP) system. This CHP unit was assumed to have an electrical conversion efficiency of 45% and an overall system efficiency of 80% in converting the energy from biogas into usable electricity and heat. These comprehensive specifications ensured that the proposed system was designed to efficiently treat approximately 45,000 kg of organic waste per day and support substantial energy generation while promoting environmental sustainability within Mbeya City.

#### 3.3.1 The Key Design Parameters and Calculations

The foundational elements of the AD system design were governed by a set of critical parameters, which informed the physical dimensions and operational characteristics of the digestion units and projected energy outputs. These key design parameters included: digester volume, daily substrate input, hydraulic retention time (HRT), organic loading rate (OLR), daily biogas production, specific gas production, dimensions of the digester, and estimated energy outputs.

The daily substrate input ( $S_d$ ) into the digester was determined as the sum of biomass (B) and water (W), both having equal volumes.

$$S_d = B + W = 3\text{m}^3/\text{day} + 3\text{m}^3/\text{day} = 6\text{m}^3/\text{day}$$

The hydraulic retention time (HRT) for the system was selected as 20 days, which ensures adequate degradation of organic materials and optimal biogas production. The system was designed to operate within a thermophilic temperature range of 50–60 °C, ensuring efficient digestion of organic material. The digestion process was configured as a two-stage batch system with wet feed, given that the solids content was less than 15%.

The volume of the digester ( $V_d$ ) was calculated using the daily substrate input and the retention time:

$$V_d = \text{Daily Substrate input} \left( \frac{\text{m}^3}{\text{day}} \right) \times \text{Retention Time (days)}$$

where  $V_d = 6\text{m}^3/\text{day} \times 20 \text{ days} = 120\text{m}^3$

The daily gas production was determined using the specific gas yield per kilogram of total solids. Assuming a total solid input of 300 kg/day and a specific gas yield of 0.36 m<sup>3</sup>/kg:

$$\text{Daily gas production (G)} = \text{Total solids inputs (V}_s\text{)} \times \text{Specific gas yield (G}_y\text{)}$$

$$G = V_s \times G_y = 300 \text{ Kg/day} \times 0.36\text{m}^3/\text{Kg} = 108\text{m}^3/\text{day}$$

The specific gas production per unit digested volume was then calculated:

$$\text{Specific gas production (G}_p\text{)} = \text{Daily gas production (G)} / \text{Digester Volume (V}_d\text{)}$$

$$G_p = \frac{G}{V_d} = \frac{1080}{120} = 9(\text{m}^3/\text{day})/\text{m}^3$$

The digester loading rate based on total solids (TS) was calculated as follows:

$$\text{Digester Loading Rate (L}_d\text{)} = \text{Total Solids Input (V}_s\text{)} / \text{Digester Volume (V}_d\text{)}$$

$$L_d = \frac{V_g}{V_d} = \frac{300 \text{ Kg/day}}{120 \text{ m}^2} = 2.5 \text{ Kg/m}^3 \text{ day}$$

The digester dimensions were determined from the calculated volume:

$$\text{Diameter } (D) = \left( \frac{V}{0.444701} \right)^{1/3} = \left( \frac{120}{0.444701} \right)^{1/3} = 5.646 \text{ m}$$

$$\text{Height } (H) = \frac{4V}{\pi D^2} = \frac{4 \times 120}{\pi \times 5.646^2} = 4.795 \text{ m}$$

The daily biogas production of 1080 m<sup>3</sup> was subsequently converted into thermal and electrical energy, leveraging the CHP system. This produced 23,760 MJ/day of heating energy and 2.16 MWh/day of electrical energy. The calculations for these outputs were as follows:

$$\text{Daily Heating Energy (DHE)} = \text{Daily biogas production} \times \text{Energy Content}$$

$$\text{Energy} = \frac{1080 \text{ m}^3}{\text{day}} \times \frac{22 \text{ MJ}}{\text{m}^3} = 23,760 \text{ MJ/day}$$

$$\begin{aligned} \text{Daily Electrical Energy (DEE)} \\ = \text{Daily Biogas Production} \\ \times \text{Electrical Efficiency} \end{aligned}$$

$$\text{Energy} = \frac{1080 \text{ m}^3}{\text{day}} \times 2 \left( \frac{\text{Kwh}}{\text{m}^3} \right) = 2.160 \left( \frac{\text{Mwh}}{\text{day}} \right)$$

A two-stage, thermophilic (50–60 °C) wet-feed (<15% TS) batch AD system is specified to treat 6 m<sup>3</sup>/day of substrate (3 m<sup>3</sup>/day biomass + 3 m<sup>3</sup>/day water) with an HRT of 20 days, giving a 120 m<sup>3</sup> working volume and cylindrical dimensions of about D = 5.65 m and H = 4.80 m. With 300 kg TS/day at a specific gas yield of 0.36 m<sup>3</sup>/kg, the plant produces 1,080 m<sup>3</sup>/day of biogas, equivalent to a specific gas production of 9 m<sup>3</sup>·m<sup>-3</sup>·day<sup>-1</sup> and a TS loading rate of 2.5 kg·m<sup>-3</sup>·day<sup>-1</sup>. This biogas corresponds to approximately 23,760 MJ/day of thermal energy (22 MJ/m<sup>3</sup>) and ~2.16 MWh/day of electricity assuming 2 kWh per m<sup>3</sup> via CHP.

Designed centralized biogas plant design for Mbeya City aligns with evidence that staging decouples acidogenesis from methanogenesis to improve stability and energy recovery for complex waste streams ([59];[48.b]). Thermophilic regimes generally accelerate hydrolysis and can shorten required retention while aiding hygienisation, provided temperature and time are sufficient ([57];[55]). For defensible performance claims, BMP testing, TS/VS characterization, and reporting of OLR/HRT should follow recognized guidance ([51];[58];[50]). Converting daily biogas to useful energy using an LHV of ~16–28 MJ m<sup>-3</sup> (typical range) or ~21 MJ m<sup>-3</sup> (central estimate) and gas-engine CHP electric efficiencies up to ~43% yields on the order of ~2 kWh<sub>el</sub> per m<sup>3</sup> of biogas with substantial recoverable heat, matching widely reported practice ([52];[53];[49]). Finally, benchmarking the specific gas production against full-scale experience suggests typical volumetric production rates around ~1–4 m<sup>3</sup> m<sup>-3</sup> d<sup>-1</sup> depending on feedstock and configuration, a range your scenario should be checked against during validation ([56];[54]).

### 3.3.2 Waste Collection and Transportation System

The waste collection and transportation system for the CAD facility was structured to ensure efficiency, segregation, and minimal environmental impact. Color-coded containers were

used for source separation of organic, recyclable, and non-recyclable waste. These containers facilitated proper sorting at the household and community level. Compactor trucks were deployed for transporting the segregated waste to the digestion facility, reducing volume during transit and minimizing fuel use. Additionally, strategically located community drop-off points were established to enhance accessibility and reduce indiscriminate dumping, thereby promoting cleaner neighborhoods and improved waste recovery rates.

### 3.3.3 Pre-treatment System

The pre-treatment system was designed to prepare incoming organic waste for optimal digestion by reducing particle size and eliminating contaminants. A sorting facility was used to separate non-digestible materials, followed by a shredding system to achieve uniform feedstock texture. The pre-treatment facility was designed to handle a throughput of 7.2 m<sup>3</sup> per day. For enhanced biodegradability, an optional hydrothermal pre-treatment unit was incorporated. This unit heated and hydrated the feedstock, making complex organic molecules more accessible to microbial action in the digester.

### 3.3.4 Feeding System

The feeding system facilitated the regulated transport of pre-treated waste into the digestion units. Pump-based feeders were used to ensure continuous and controlled feeding. Feedstock storage tanks with a total recommended capacity of 12 m<sup>3</sup> were installed to serve as buffers, regulating the flow of waste and accommodating variations in supply or demand. This system helped maintain process stability and allowed flexibility during operational fluctuations.

### 3.3.4 Biogas Handling System

The biogas handling system was developed to capture, purify, store, and distribute biogas produced during anaerobic digestion. Flexible membrane gas holders were used for biogas storage, allowing for pressure balancing and space efficiency. A scrubbing unit was included to remove hydrogen sulfide (H<sub>2</sub>S) and carbon dioxide (CO<sub>2</sub>), thereby upgrading raw biogas to biomethane quality. The system also included compressors and high-pressure piping to transport the purified gas either to storage tanks or directly into distribution systems for energy utilization.

### 3.3.5 Digestate Management System

The digestate management system handled the by-product from the digestion process through separation and reuse. The system included separation units that divided the digestate into solid and liquid fractions. The liquid fraction was managed through an irrigation application system and stored in 12 m<sup>3</sup> tanks, while the solid fraction was processed and packaged as organic compost. This closed-loop system enabled sustainable nutrient recycling and minimized environmental discharge, supporting agricultural productivity in surrounding areas.

### 3.3.6 Heat and Energy Recovery System

The heat and energy recovery system converted biogas into usable forms of energy, including electricity and heat. A Combined Heat and Power (CHP) unit was employed, generating approximately 2.16 MWh/day of electricity and 23,760 MJ/day of thermal energy. The thermal output was partially reused within the system to maintain thermophilic operating temperatures in the digester, enhancing microbial activity and process efficiency. Excess electricity was sold to the national grid, contributing to the facility's revenue stream and supporting renewable energy generation in the region.

### 3.3.7 Monitoring and Control System

The monitoring and control system was developed to ensure operational reliability, early fault detection, and efficient process management. It consisted of sensors installed to measure key parameters including temperature, pH, gas composition, pressure, and slurry levels. These sensors were integrated with automated control software, which allowed for real-time data visualization and process adjustments. Remote access capabilities were also implemented to enable operators to monitor system performance and respond promptly to any irregularities, enhancing safety and consistency.

### 3.3.8 Environmental Protection Measures

A range of environmental protection measures was integrated into the system to minimize negative environmental impacts and ensure compliance with national standards. A leachate collection system was included to prevent groundwater contamination, and odor control was achieved using biofilters that treated gaseous emissions from the waste handling areas. Additionally, a wastewater treatment plant was incorporated to treat process effluents before discharge, further ensuring that the entire operation met regulatory thresholds for environmental sustainability.

## 3.4 Heating, Electrical, and Mixing System Requirements

### 3.4.1 Heating System Requirements

To maintain optimal thermophilic conditions within the anaerobic digester, specifically a temperature range of 50–60°C (with an operating set point of 55°C) two main heating demands were considered: the energy required to heat the incoming feedstock and the heat losses through the digester's walls. The daily volume of substrate processed was 6 m<sup>3</sup>, with a density of 1,000 kg/m<sup>3</sup> and a specific heat capacity of 4.18 kJ/kg·K. The temperature difference between the ambient environment (20°C) and the digester temperature (55°C) was 35°C. The thermal energy required to heat the daily feedstock input was calculated as 876.9 MJ/day.

In addition to this, heat losses through the digester's cylindrical walls were evaluated. With a radius of 2.823 m and a height of 4.795 m, the total surface area of the digester was approximately 84.996 m<sup>2</sup>. Using a heat loss coefficient of 0.7 W/m<sup>2</sup>·K, the daily heat loss was estimated at 179.1 MJ. Therefore, the total heat requirement for the system was 1,056 MJ/day. This demand was well within the available thermal energy generated from biogas combustion. Given a daily

biogas production of 1,080 m<sup>3</sup>, with a calorific value of 22 MJ/m<sup>3</sup> and assuming an 80% recovery efficiency from the combined heat and power (CHP) unit, the system was capable of providing up to 19,008 MJ/day of usable heat. This confirmed that the digester's heating needs could be fully met using internally generated biogas without requiring external energy sources.

### 3.4.2 Annual Electrical Energy Production

The anaerobic digestion system was also designed to generate electrical energy through a CHP unit. With a projected daily output of 2.33 MWh, the annual electricity production was estimated at 850.45 MWh. This energy was intended to meet the internal power needs of the facility, such as for mixing, pumping, and automation systems. Additionally, any surplus electricity could be fed into the local grid or sold to nearby users, enhancing the project's financial sustainability.

### 3.4.3 Mixing System Requirements

Effective mixing was considered essential for maintaining homogeneity within the digester, ensuring uniform temperature distribution, preventing scum formation, and improving microbial contact with the substrate. For a digester capacity of 120 m<sup>3</sup>, the mixing energy requirement was approximately 1.2 kW, based on the standard energy demand range of 0.5–1.5 kW per 100 m<sup>3</sup>. This modest power requirement was well supported by the system's internal electricity generation, contributing to efficient and uninterrupted operation. The mixing system was also designed for automation, with the aim of reducing operational costs and enhancing process reliability.

## 3.5 The Centralized Anaerobic Digestion System Design and Engineering Overview

The CAD system was designed for the treatment of MSW generated in Mbeya City. The design, illustrated in Figures 3, 4, and 5, was based on calculated inputs and aimed to convert organic waste into biogas for energy recovery, while ensuring environmental sustainability.

The integrated system included several major components: a waste collection and transportation system, a pre-treatment facility, a feeding mechanism, the digester itself, biogas production and handling units, environmental protection infrastructure, and a monitoring and control system.

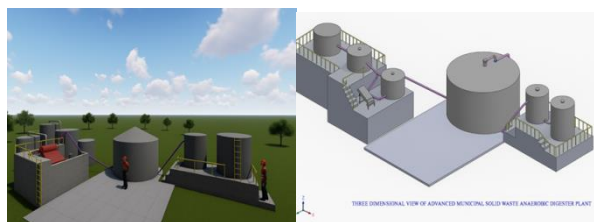
The collection system used 240-liter bins and 10–15 m<sup>3</sup> capacity compactor trucks to transport waste. The pre-treatment facility processed 7.2 m<sup>3</sup>/day of organic waste through sorting, shredding, and hydrothermal methods to enhance biodegradability.

The feeding system operated on a two-stage wet batch process with <15% solid content, using a feedstock regulation tank to ensure consistent input. The digester was designed for thermophilic conditions, maintaining a 35°C rise above ambient temperature. This system supported efficient microbial activity and gas yield, with a specific gas production rate of 9 m<sup>3</sup> per cubic meter of digestate per day.

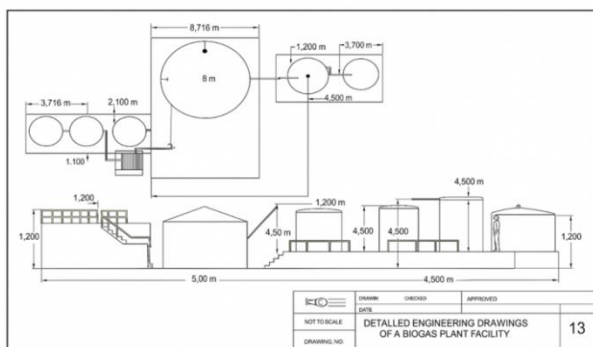
Daily biogas output was estimated at 1,080 m<sup>3</sup>, sufficient to produce 23,760 MJ of thermal energy and 2.16 MWh of

electricity. With only 1,056 MJ/day required for heat maintenance, a surplus of 19,008 MJ/day could be utilized or sold. Annually, the system was projected to generate approximately 850.45 MWh, supporting Tanzania’s energy diversification goals [60].

Gas scrubbing units were included to remove contaminants like H<sub>2</sub>S and CO<sub>2</sub>, and flexible membrane tanks stored upgraded biogas. The mixing system, consuming 1.2 kW, ensured uniform feedstock distribution and minimized sedimentation, although energy use optimization was recommended.



**Figure 2: 3D Model of an Integrated Biogas Plant Featuring Feedstock Input, Digesters, and Biogas Storage Units**

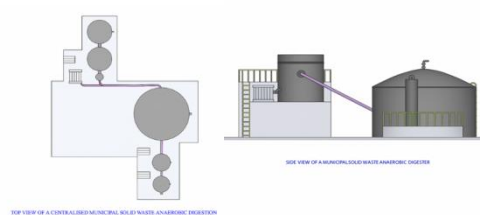


**Figure 3: Detailed Engineering Drawings of a Biogas Plant Facility**

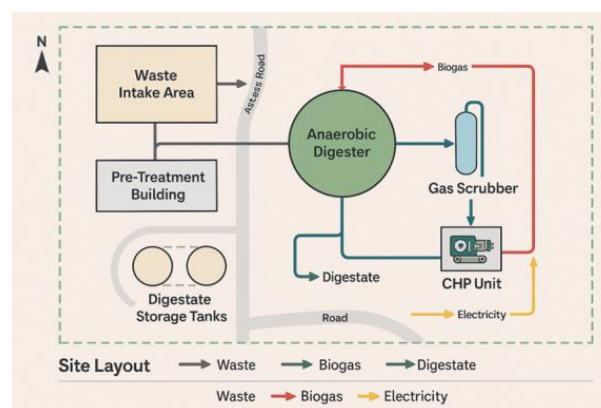
The digestate management system separated solid and liquid fractions. Liquids were directed to irrigation systems as biofertilizer, while solids were packaged. The facility included leachate collection, wastewater treatment units, and odor control systems to meet environmental compliance and protect groundwater.

The engineering layout featured a large cylindrical digester, smaller tanks for pre-treatment and hydrolysis, a dome-shaped biogas storage tank, conveyor belts for waste movement, and piping for biogas transfer. Structural elements included elevated walkways, stairs, and support columns for safety and maintenance access.

While the system design showed strong capabilities in waste conversion, gas capture, and environmental protection, potential improvements included adding better insulation, space for expansion, and integrating a backup biogas storage or flare system.



**Figure 4: Top (L) and Side view (R) of the Centralized Municipal Solid Anaerobic Digestion Plant Projections**



**Figure 5: Process Flow Diagram of an Anaerobic Digestion Plant**

### 3.6 Comparative and Technical Analysis of the Centralized Anaerobic Digestion System

This section thoroughly examines the CAD system, evaluating both its technical performance and environmental impact. It goes beyond the basic metric like retention time and biogas yield to also consider design and sustainability, aiming to give a clear picture of how the system works and its potential benefits.

#### 3.6.1 Comparative Analysis with Similar Systems in Developing Regions

The proposed CAD system in Mbeya City is engineered to recover approximately 2.16 MWh of energy daily from 1,080 m<sup>3</sup> of biogas, positioning it competitively among similar waste-to-energy systems in sub-Saharan Africa.

For instance, Kigali’s Nduba landfill biogas project in Rwanda processes 600 m<sup>3</sup> of biogas daily to produce around 1.2 MWh/day, though it struggles with seasonal feedstock variation and poor waste sorting [26]. Nakuru, Kenya, utilizes an AD plant handling 850 m<sup>3</sup>/day to generate about 1.7 MWh/day [27]. Meanwhile, a campus-based system at Kwame Nkrumah University of Science and Technology in Accra, Ghana, generates 1.1 MWh/day from 500 m<sup>3</sup> of biogas [28].

What sets Mbeya apart is its tailored approach to local conditions: it uses fresh, source-separated organic waste, operates at 35°C aligned with the ambient climate, and includes plans for co-digestion with agro-waste to balance seasonal input variability. Additionally, the reuse of digestate in nearby farms promotes circular economy principles by enhancing soil fertility.



**3.6.2 Waste Characterization and Sampling Overview**

A ten-day waste audit revealed that Mbeya City generates 38,000–52,000 kg/day of organic waste, averaging 45,000 kg/day. The waste, mostly biodegradable food scraps, has a moisture content ranging from 65% to 78%, ideal for biogas production. Based on laboratory analysis and literature benchmarks, biogas yields range between 0.38 to 0.5 m<sup>3</sup>/kg of volatile solids, providing a robust basis for system sizing and energy yield projections.

**3.6.3 Environmental Impacts**

An Environmental Impact Assessment (EIA) identified potential issues such as air emissions, leachate, odors, and noise. Mitigation strategies include biofilters for odor control, leachate collection, wastewater treatment, noise barriers, landscaping, and traffic management plans.

The CAD system is projected to reduce greenhouse gas emissions by 16,948.95 tons of CO<sub>2</sub>-equivalent annually, divert approximately 60% of organic waste from landfills, and improve soil fertility through digestate application. These benefits are consistent with global findings. [29] showed that using digestate as fertilizer significantly reduces methane emissions, while [30] reported that anaerobic digestion can achieve a 282% GHG reduction compared to landfill disposal. [31] confirmed digestate enhances soil organic matter and microbial activity.

**3.6.4 Economic and Financial Viability**

The proposed 120 m<sup>3</sup> plant has a capital cost of USD 320,000 and annual operating costs of USD 35,000. Projected revenues of USD 90,000 from biogas, USD 25,340 from digestate, and about USD 6,000 from carbon credits yield a total of USD 121,340/year.

The payback period is 2.8 years, with a return on investment (ROI) of 25.1% annually. This is more favorable than similar systems studied by [32] and [33], which had payback periods of 4–6 and 5 years, respectively.

Using a 10% discount rate and a 10-year analysis window, the system’s net present value (NPV) is positive and internal rate of return (IRR) remains strong at 25.1%, confirming the project's economic attractiveness. Variations in electricity pricing (\$0.08–\$0.14/kWh) and inflation (5%) were incorporated to assess risk and return stability.

Comparatively, Tanzania’s large-scale waste-to-energy projects in Dar es Salaam and Mwanza had investment costs of USD 400 million and USD 250 million respectively ([25]), while managing 2,000 MT and 900 MT of waste per day. The relatively smaller scale of the Mbeya system offers greater flexibility and faster returns. The sensitivity analysis shows that the CAD systems revenue and payback are highly dependent on electricity price and plant uptime. Daily and annually revenue decline substantially under lower electricity prices or reduced operational time, extending payback periods, while higher prices and improved uptime increase profitability and shorten payback. This highlights that financial performance is sensitive to market and operational conditions, emphasizing the need to incorporate realistic

fluctuations in electricity tariffs, downtime and O&M cost where assessing the economic viability of the Mbeya CAD system.

**Table: Sensitivity of CAD Economic Performance and Downtime**

Scenario	Electricity Price \$/Kwh	Plant Uptime (%)	Daily Revenue (\$/day)	Annual Revenue (\$/Yr)	Simple Payback Impact
Base Case	0.10	100	2,177	794,605	Baseline Payback
Low Price	0.08	100	1,742	635,684	Longer Payback
High Price	0.12	100	2,612	954,726	Shorter Payback
90% Uptime	0.10	90	1,959	715,145	Slightly Longer Payback
80% Uptime	0.10	80	1,742	635,684	Noticeably Longer Payback
Low Price + 80% Uptime	0.08	80	1,394	508,547	Significantly Longer Payback
High Price + 90% Uptime	0.12	90	2,351	857,253	Payback Reduced

**4. Conclusion**

This study successfully designed a CAD system tailored for MSW management in Mbeya City. The findings demonstrate that the system is not only technically feasible but also economically viable and environmentally beneficial. By targeting the city's predominant organic waste fraction—comprising over 60% of the total MSW the proposed system offers a practical solution for converting waste into renewable biogas and nutrient-rich digestate, aligning with both national sustainability goals and global climate commitments.



The analysis highlighted that the organic portion of MSW in Mbeya City remains largely underutilized despite its high potential for biogas production. The CAD system was designed to process these biodegradable materials efficiently, integrating advanced pre-treatment technologies, optimized feeding systems, and robust environmental safeguards. The energy recovery potential is substantial, with estimated outputs of 2.16 MWh/day of electricity and 23,760 MJ/day of thermal energy. Furthermore, the project supports circular economy principles by closing the loop between waste generation and resource recovery, thereby reducing reliance on fossil fuels and chemical fertilizers.

Despite its promise, the system's implementation faces challenges such as inconsistent waste segregation, high initial investment costs, and limited public awareness. Addressing these barriers will require a coordinated approach involving policymakers, private sector stakeholders, and the broader community. Strategic recommendations include establishing mandatory waste segregation policies, offering subsidies for renewable energy infrastructure, and fostering public-private partnerships to finance AD projects. Moreover, public education campaigns and engagement with community leaders will be essential to build local support and ensure cultural alignment.

To enhance system performance and scalability, future expansions could incorporate co-digestion with agricultural residues or wastewater sludge to improve biogas yield. Continued research and pilot testing under real-world conditions are also recommended to validate design assumptions and refine operational parameters.

The CAD system proposed for Mbeya City represents a transformative and replicable model for sustainable urban waste management. If implemented alongside supportive policies and community engagement, this initiative could significantly improve urban sanitation, reduce greenhouse gas emissions, generate renewable energy, and support Tanzania's broader environmental and development goals. The project not only paves the way for cleaner and healthier cities but also sets a benchmark for integrated waste-to-energy systems across the country and the region.

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