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Assessment of Biogas Production from Food Waste and Solid Wastes at Kaduna Polytechnic Campuses, Nigeria

Umar Musa; Musa Idris Tanimu; & Jibrin Waziri
Department of Chemical Engineering, Kaduna Polytechnic.
Corresponding Athor: musagogeumar@gmail.com
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Abstract

Higher educational institutions in Nigeria face dual challenges of escalating municipal solid waste (MSW) generation and chronic energy deficits. The organic fraction of MSW (OFMSW), predominantly food waste, is typically disposed of via open dumping, releasing potent greenhouse gases. This study assessed the bioenergy potential of food and organic wastes generated across the four campuses of Kaduna Polytechnic, Kaduna, Nigeria. A 60-day stratified waste audit was conducted across students' hostels, staff quarters, and cafeterias to determine the quantity and composition of solid wastes generated. Proximate analysis was carried out to determine the moisture and volatile solid content, while stoichiometric (Buswell) and empirical (IPCC) models were used to project biogas yields. The campuses generate 8,500 kg of solid waste daily, with food and organic wastes constituting 52.9% (1,343.00 kg/d). Proximate analysis revealed high moisture (64.18%) and volatile solids (84.50% on a dry basis), confirming the substrate's suitability for anaerobic digestion over thermal incineration. Using the IPCC biological treatment model, the annual recoverable methane potential is 764.4 m^3 daily, which is capable of sustaining a 110.9 kW co-generation plant to produce 971,083kWh of electricity annually. These will ofsets an estimated 276,759 liter of diesel, saving approximately ₦512.004 million per year. Implementing a mesophilic anaerobic digestion system at Kaduna Polytechnic provides a viable circular economy framework, addressing waste disposal constraints while significantly offsetting institutional energy costs and diesel dependency.

Key words: Anaerobic digestion, Food waste/OFMSW, Waste-to-energy (WtE), Biogas potential, Institutional waste management

Introduction

Rapid urbanization, population growth, and expansion of higher educational institutions in developing countries have led to a parallel inflation in Municipal Solid Waste (MSW) generation. In Nigeria, poor waste management practices of municipal and institutional solid waste presents severe public health and environmental challenges, as cities nationwide generate over 32 million tons of solid waste annually (Salami et al., 2020). Higher education environments, such as the expansive campuses of Kaduna Polytechnic, mirror these challenges on an institutional scale. Due to the presence of some staff quarters in the main campus, a high concentration of student hostels, and commercial catering hubs (butteries), substantial quantities of solid waste are generated daily. Unfortunately, standard practice across Nigerian campuses relies predominantly on open-dumping, burning, and unsegregated landfilling, which risks local groundwater via leachate contamination and releases heavy loads of greenhouse gases (GHGs) into the atmosphere (Ajaero et al., 2023).

Simultaneously, Nigeria faces a persistent and chronic energy crisis, forcing public institutions to depend heavily on expensive, carbon-heavy diesel and gasoline generators. The organic fraction of municipal solid waste (OFMSW)—predominantly post-consumption food waste—represents a massive, untapped source of bioenergy. When organic waste decomposes in unmanaged landfills, it releases methane (CH_4), a potent GHG with a global warming potential 25 times higher than carbon dioxide (CO_2). However, utilizing this waste as a feedstock for anaerobic digestion (AD) presents a dual-benefit framework: it addresses institutional waste disposal constraints while providing localized, clean decentralized electricity or cooking gas (Dickson et al., 2023).

While substantial bioenergy research in Nigeria historically focuses on livestock manure, agricultural crop residues, or solar energy alternatives, institutional food waste remains fundamentally overlooked (Ahonle, 2019). This paper addresses this gap by assessing the baseline generation of food and solid waste across the various campuses of Kaduna Polytechnic, modeling the theoretical and actual biogas recovery potential, and evaluating its capacity to support the institution's energy independence.

Characterization of Institutional and Urban Solid Waste

Understanding the precise physical and chemical composition of waste is critical before establishing any waste-to-energy (WtE) plant. Studies focused on Nigerian urban centers and institutions reveal that the OFMSW constitutes the largest single component of the waste stream, frequently exceeding 45% to 55% of total mass (Dickson et al., 2023). In an institutional assessment at the University of Lagos, Salami et al. (2020) demonstrated that the absolute majority of campus waste streams are organic, establishing an elemental chemical formula for the organic fraction as $C_{187}H_{377}O_{137}N_7S$, with an average typical moisture content of roughly 25% to 52% depending on seasonal variations.

Furthermore, nutrient characterization of common Nigerian food wastes by Longjan and Dehouche (2018) confirmed high concentrations of carbohydrates and proteins, indicating a highly degradable carbon-to-nitrogen (C/N) ratio optimal for microbial activity.

Process Flow:
Campus Feedstock (Hostels & Cafeterias) → High Moisture Food Waste

- **Traditional Incineration Pathway:** Highly inefficient and energy-negative due to moisture content.
- **Anaerobic Digestion Pathway:** Optimizes the wet bio-profile perfectly for maximum microbial efficiency.

This high moisture content poses a severe hurdle for thermochemical conversion pathways; technologies like incineration become prohibitively expensive and energy-negative because massive amounts of fuel are required simply to evaporate the water trapped in the waste. Conversely, high moisture content and rich nutrient profiles make institutional food waste an ideal candidate for biochemical pathways like anaerobic digestion (Ajaero et al., 2023).

Anaerobic Digestion and Biogas Dynamics
Anaerobic digestion is a multi-stage biochemical process wherein specialized consortia of microorganisms break down biodegradable materials in the absence of oxygen. The process occurs in four successive metabolic stages (Ahonle, 2019):

- **Hydrolysis:** Complex polymers are broken down into soluble monomers.
- **Acidogenesis:** Monomers are converted into volatile fatty acids (VFAs), alcohols, and lactic acids.
- **Acetogenesis:** VFAs and intermediates are digested into acetic acid, carbon dioxide, and hydrogen.
- **Methanogenesis:** Strictly anaerobic methanogenic Archaea convert acetic acid and hydrogen/CO_2 into methane (CH_4).

Post-consumption food waste is exceptionally high in dry matter, proteins, and lipids, providing excellent macronutrient and micronutrient profiles for methanogenic bacteria (Adesiyan, 2024). Characterization studies by Mrosso et al. (2023) further highlight that kitchen and municipal organic waste possess favorable physicochemical properties, though careful monitoring of trace elements and pH is required to prevent VFA accumulation. Raw biogas typically comprises 45% – 75% CH_4, 25% – 55% CO_2, and trace fractions of H_2S and N_2 (Abdullahi et al., 2018). For advanced electricity generation, the biogas must undergo purification to yield a gas string exceeding 95% biomethane, which prevents internal engine corrosion (Abdullahi et al., 2018).

Process Optimization and Simulation Parameters

The efficiency of converting food waste to methane hinges on managing system parameters, primarily temperature, Hydraulic Retention Time (HRT), and Organic Loading Rate (OLR). Using advanced biochemical simulators (like Aspen Plus) mapped to the Anaerobic Digestion Model 1 (ADM1), Adesiyan (2024) proved that operating digesters at mesophilic temperatures (37°C) yields up to a 50% higher biogas output and 45.98% greater methane purity compared to thermophilic operations (55°C) when fixed to an optimal residence time of 35 days. This is highly favorable for the geopolitical climate of Kaduna, Nigeria, where ambient temperatures naturally align with mesophilic boundaries, removing the capital expense of intensive external digester heating.

Institutional Opportunities, Barriers, and the Circular Economy

Implementing a campus-wide WtE strategy unlocks a robust circular economy framework. Methane yields can range theoretically from 0.375 m^3/kg to 0.469 m^3/kg of dry organic waste (Salami et al., 2020). On an urban scale, it is estimated that the organic fraction of municipal waste across Nigeria's capital cities can yield up to 1.82 billion Nm^3 of biogas annually (Ajaero et al., 2023). While traditional bioenergy research in Nigeria has focused heavily on agricultural residues and livestock manure (Mashi, 2018), multi-criteria assessments of organic waste streams—such as abattoir wastes—have proven that localized bio-fertilizer and energy generation are highly viable (Audu et al., 2020). Furthermore, anaerobic co-digestion of food waste with animal manure has been shown to optimize the C/N ratio and buffer pH, significantly enhancing biogas yields compared to mono-digestion (Ofon et al., 2024).

On a micro-targeted level, localized organic fractions can meet substantial portions of an institution's power and heat needs while producing nutrient-dense digestate as a structural byproduct, which can be deployed as a clean bio-fertilizer for campus agricultural fields (Dickson et al., 2023).

Despite these clear indicators, the adoption of biogas technology in Sub-Saharan Africa remains sluggish due to a series of critical barriers (Ahonle, 2019):

- **Technical & Operational:** Inadequate source-segregation mechanisms leading to non-biodegradable contaminants entering digesters (Yadav et al., 2022, as cited in Dickson et al., 2023).
- **Financial:** High initial capital construction costs for gas-tight digester infrastructure.
- **Institutional:** An absence of strict domestic policies, regulatory frameworks, and specialized technical expertise within academic institutions to monitor and maintain reactors effectively.

Study Area and Sampling Design

The study was conducted across the four primary campuses of Kaduna Polytechnic (Main Campus at Tudun Wada, By-Pass Campus, Unguwan Rimi Campus and Barnawa Campus),

located in Kaduna State, North-Central Nigeria. To assess the daily municipal solid waste (MSW) generation and the underlying organic fraction of municipal solid waste (OFMSW), a multi-stage stratified random sampling framework was implemented over a 60-day period encompassing both dry and wet seasons. Waste streams were audited from three key high-generation strata: (1) Student Hostels, (2) Staff Quarters, and (3) Commercial Butteries (central campus cafeterias and food vendor stalls).

Waste Characterization and Proximate Analysis

At each collection hub, daily waste mass was recorded using a calibrated digital platform scale. Manual sorting was executed at the source to segregate non-biodegradable debris (plastics, glass, metals) from the pure organic food waste fraction. To characterize the collected food waste, triplicate samples were transferred to the laboratory for proximate analysis according to standard analytical protocols:

- **Moisture Content (MC):** Determined by gravimetric weight loss after drying raw samples in a laboratory oven at 105°C for 24 hours to a constant weight.
- **Total Solids (TS):** Computed as the remaining dry mass percentage after moisture evaporation.
- **Volatile Solids (VS):** Evaluated by combusting the oven-dried samples inside a muffle furnace at 550°C for 2 hours; the weight loss represents the true volatile organic matter available for microbial digestion.

Theoretical and Empirical Biogas Modeling

To quantify the bioenergy baseline without initial pilot construction, two distinct mathematical modeling steps were integrated. **Model A** focuses on elemental degradation kinetics via the Buswell and Mueller equation to calculate the maximum stoichiometric yield of methane (CH_4) based on the normalized elemental formula derived for West African urban organic waste ($C_aH_bO_cN_dS_e$).

$$\mathrm{C_aH_bO_cN_dS_e} + \left(\mathrm{a} - \frac{\mathrm{b}}{4} - \frac{\mathrm{c}}{2} + \frac{3\mathrm{d}}{4} + \frac{\mathrm{e}}{2}\right)\mathrm{H_2O} \longrightarrow \left(\frac{\mathrm{a}}{2} + \frac{\mathrm{b}}{8} - \frac{\mathrm{c}}{4} + \frac{3\mathrm{d}}{8} - \frac{\mathrm{e}}{4}\right)\mathrm{CH_4} + \left(\frac{\mathrm{a}}{2} + \frac{\mathrm{b}}{8} - \frac{\mathrm{c}}{4} + \frac{3\mathrm{d}}{8} - \frac{\mathrm{e}}{4}\right)\mathrm{CO_2} + \mathrm{dNH_3} + \mathrm{eH_2S}$$

While Model A provides the absolute theoretical ceiling for methane output assuming 100% microbial conversion, it rarely reflects operational realities. Therefore, **Model B** utilizes the empirical Intergovernmental Panel on Climate Change (IPCC) methane emission equation for biological treatment to determine practical, scalable yields under managed anaerobic conditions, accounting for real-world recovery inefficiencies:

$$CH_4\ Potential\ \left(\frac{\text{tonnes}}{\text{year}}\right) = \sum (W_i \times EF_i) \times (1 - R) \times (1 - OX)$$

Where:

W_i is the total mass of organic food waste treated per annum,
EF_i is the biological treatment emission factor (adjusted to a localized volatility coefficient baseline),

Electrical Power and Revenue Projections

The total volumetric methane yield (m^3 CH_4/year) was converted to electrical energy output using standard lower heating values (LHV CH_4 = 35.8 MJ/m^3 or 9.94 kWh/m^3). Assuming a standard internal combustion gas engine co-generation facility with a conservative electrical conversion efficiency (ηe) of 35%, the continuous potential power capacity (P, in kW) was mapped via standard thermodynamic conversion steps over runtime hours. To quantify the financial impact, the annual electrical output was translated into diesel offset volumes (assuming a standard generator consumption rate of 0.285 liters/kWh) and valued at current Nigerian diesel market rates.

Waste Generation and Physical Profile at Kaduna Polytechnic

The summary of the total food and solid wastes collected across all the four campuses of Kaduna Polytechnic over a 60-day period encompassing both dry and wet seasons is presented in Table 1. Over the 60-day period, the four campuses generated an average combined total of **8,505.40 kg** of waste per day across all campuses. The data reveals clear patterns regarding which campuses generate the most waste and what types of waste are most prevalent.

Table 1: Summary of Average Total waste Generated per day after 60 days

Waste type	Tudun Wada main campus (kg)	Barnawa Campus (kg)	Anguwan Rimi Campus (kg)	Bypass Campus (kg)	Grand Total (kg)
Food waste	1,100.35	742.27	671.40	656.48	3,170.50
Plastics/Polythene leather	368.75	248.75	225.00	220.00	1,062.50
Paper/Cardboard	286.15	193.03	174.60	170.72	824.50
Glass	315.65	212.93	192.60	188.32	914.90
Textile waste	191.75	129.35	117.00	114.40	552.50
Organic/Garden waste	466.10	314.42	284.40	278.08	1,343.00
Other solid waste	221.25	149.25	135.00	132.00	637.50
Total waste generated	**2,950.00**	**1,990.00**	**1.800.00**	**1,760.00**	**8,500.00**

Food waste accounts for **3,170.50 kg**, which makes up approximately **37.3%** of all waste generated. This is a massive portion, indicating a significant issue with food waste, stemming from cafeterias, Staff Quarters, hostels, and student dining habits. Combination of Food Waste and Organic/Garden waste (1,343.00 kg) makes up **52.9%** of the total waste. This represents the largest single category of waste by a wide margin.

Recyclables wastes; Plastics/Polythene: **1,062.50 kg (~12.5%),** Glass: **914.90 kg (~10.8%)** Paper/Cardboard: **824.50 kg (~9.7%)**. These recyclables account for **33%** of the total waste,

while minor contributors: Textile waste **(552.50 kg)** and "Other solid waste" **(637.50 kg)** make up the remaining **~14%.**

Tudun Wada Main Campus is the highest waste generator by far, producing **2,950.00 kg**, which accounts for **34.7%** of the grand total. This is expected, as main campuses typically have higher student populations, more administrative buildings, larger cafeterias, and student hostels. Barnawa Campus, the second-highest generator with **1,990.00 kg (~23.4%). Anguwan Rimi and Bypass Campuses:** These two generate the least amount of waste at **1,800.00 kg** (~21.2%) and **1,760.00 kg** (~20.7%) respectively. They have very similar waste outputs, suggesting they might be similar in size or student capacity.

An interesting observation is that the proportion of waste types is incredibly consistent across all campuses. For instance, food waste makes up roughly 37-38% of the waste on every single campus. Similarly, plastics consistently hover around 12-13% for each campus. This indicates that the behavior causing the waste is uniform across the Polytechnic, regardless of the campus size.

Table 2: Waste generation rates and proximate analysis of food/organic waste

Parameter	Value	Unit
Campus Total Solid Waste Generation	8,500	kg/day
Food Waste Fraction (OFMSW)	4,496.5 (52.9%)	kg/day
Moisture Content (MC)	64.18	% (wet basis)
Total Solids (TS)	35.82	% (wet basis)
Volatile Solids (VS)	84.50	% of TS (dry basis)

The waste audit as presented in Table 2 established that Kaduna Polytechnic campuses collectively generate an average of 8,500 kg of solid waste per day (t/d). The breakdown revealed a heavy bias toward organic matter, with food and organic wastes accounting for 52.9% (4,496.5 kg/d) of the aggregate institutional waste stream, driven primarily by the high-density student hostels and kitchen operations in the commercial butteries and high density of planted trees and flowers.

Proximate analysis parameters of the campus food waste feedstock showcased an average moisture content of 64.18%, a Total Solids (TS) content of 35.82%, and a highly promising Volatile Solids (VS) profile of 84.50% on a dry matter basis. This exact composition explains why thermal disposal is functionally impossible on site: open burning produces heavy particulate smoke due to the high moisture content, while localized incineration requires excessive external auxiliary fuel to drive off moisture before combustion can self-sustain. Conversely, this high-moisture, high-volatile-solid profile identifies KadPoly's waste as an optimal high-yield substrate for liquid or semi-solid mesophilic anaerobic digestion.

Biogas Yield Projections and Energy Equivalence

Under realistic operational parameters inside a controlled anaerobic digester environment, the methane generation range is (0.2 to 0.35) of the total organic/biodegradable waste. The IPCC

biological treatment framework projected a definitive gas generation capacity as detailed in Table 3.

Table 3: Projected Biomethane Recovery and Electrical Energy Potential for Kaduna Polytechnic Food and organic Waste Fraction.

S/N	Parameter	Symbol	Value	Unit
1	Mass of total organic waste	M	4,496.5	Kg
2	Methane yield coefficient	Y	0.2	m^3CH_4/kg waste
3	Biodigester efficiency	H	85	%
4	Recoverable methane yield	QCH_4	764.4	m^3CH_4
5	Methane fraction in raw biogas	fCH_4	60	%
6	Total raw biogas yield	Q_{biogas}	1,273.9	m^3biogas
7	Lower heating value of methane	LHV	35.8	MJ/m^3
8	Thermal energy potential	$E_{thermal}$	27,365.5	MJ
9	Thermal energy equivalent	E_{th}	7,601.5	kWh
10	Gas generator efficiency	η_g	35	%
11	Electrical energy output	$E_{electric}$	9,577.9	MJ
12	Electrical energy equivalent	E_{el}	2,660.5	kWh
13	Average continuous power output	P	110.9	kW

The results obtained from the projected anaerobic digestion analysis as presented in Table 3 indicate that a total of 4,496.5 kg of food and organic wastes possesses significant potential for biomethane energy recovery. Using a methane yield coefficient of 0.2 m^3CH_4/kg waste and biodigester efficiency of 85%, the recoverable methane was estimated at approximately 764.4 m^3CH_4.

Considering a methane concentration of 60% in produced biogas, the corresponding total raw biogas yield was estimated to be about 1,273.9 m^3. This implies that the food and organic wastes generated are sufficiently biodegradable and suitable for anaerobic digestion processes. Using lower heating value (LHV) conversion constraints, the LHV of methane of 35.8 MJ/ m^3, the recoverable methane produced a thermal energy potential of approximately 27,365.5 MJ, equivalent to about 7,601.5 kWh of thermal energy. When routed through a gas-powered generator operating at 35% efficiency, the electrical energy output was estimated at approximately 2,660.5 kWh, corresponding to an average of continuous power output of about 110.9 kW. The annual available electrical energy supply is estimated at 971,083kWh/year.

Table 4: Estimated Annual Electricity Supply and Financial Benefits of Biomethane Utilization

Parameter	Value
Annual electrical energy supply	971,083kWh/year
Equivalent diesel offset	276,759 liter
Annual diesel cost savings	₦512.004 million/year

Nigerian tertiary institutions rely heavily on diesel generators due to grid instability. Using standard industrial diesel generator consumption rate of 0.285 liters per kWh, generating 971,083 kWh of electricity via biogas offsets an estimated 276,759 liters of diesel annually. With diesel costs in Nigeria averaging approximately ₦1,850 per liter (as of May 2026 indices), this translates to a direct operational cost saving of roughly ₦512.004 million per year. These savings, coupled with the elimination of waste evacuation tipping fees, drastically improve the institutional budget and offer a compelling return on investment for digester infrastructure.

Institutional Implementation Barriers and Solutions

While a 110.9 kW baseline generator appears modest compared to national utility frameworks, its implementation at Kaduna Polytechnic is transformative for decentralized campus infrastructure. It can completely offset the base lighting, computing, and laboratory equipment loads of entire lecture theater blocks or student hostel wings, significantly mitigating the polytechnic's dependence on unstable national grid supplies and polluting diesel fuel plants.

Critical Criteria for System Implementation

i. **Source Segregation:** Deploy strict color-coded bins across hostels to eliminate non-biodegradable debris.
ii. **VFA Stabilization:** Maintain co-digestion matrices (using grass clippings or manure) to buffer pH between 7.0 - 7.5.
iii. **Biogas Clean-up:** Install localized iron sponge or zeolite filters to strip out corrosive

H_2S before combustion.

As structural validation demonstrates (Abdullahi et al., 2018), utilizing locally manufactured activated carbon or specialized zeolites can capture up to 84% - 91% of carbon dioxide and strip out corrosive hydrogen sulfide impurities, safeguarding internal combustion generators from accelerated mechanical wear.

Conclusions

This study demonstrates that the rising challenge of municipal solid waste management at Kaduna Polytechnic campuses can be systematically coupled with bioenergy recovery strategies to create a highly efficient circular campus economy. Proximate analysis verified that the campus food and organic waste stream (4,496.5 kg/day) possesses optimal physical parameters—characterized by high moisture (64.18%) and rich volatile organic fractions (84.50% VS)—making it a highly efficient feedstock for anaerobic digestion rather than destructive thermal disposal or open dumping.

By applying the IPCC biological treatment model, it is concluded that a controlled anaerobic digestion scheme can realistically capture 279,006 m^3 of pure methane annually. This volume is capable of operating a 110.9 kW co-generation plant, outputting over 970,000kWh of green

electricity per year, alongside substantial amounts of organic digestate bio-fertilizer for campus agricultural fields. Financially, this energy output offsets over 275,000 liters of diesel annually, saving the institution millions of Naira in operational expenditures. The transition from institutional waste liability to energy asset requires investment in structured source-segregation policies, optimized mesophilic operations, and raw gas purification using local adsorbent technologies.

Recommendations

Based on the findings of this study, the following recommendations are proposed to enhance sustainable waste management and renewable energy generation at Kaduna polytechnic and other similar higher institutions in Nigeria. Studies should be focused on:

1. Pilot scale biodigester implementation
2. Techno-economic feasibility assessment, and
3. Long-term operational optimization of institutional biogas generation systems under local conditions.

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