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ORIGINAL RESEARCH ARTICLE

Unlocking Sustainable Energy: Nutritional Profiling and Biomethane Potential of Cereal Food Waste for Sustainable Energy Recovery

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ABSTRACT

Cereal food waste represents a significant untapped resource for bioenergy, yet its optimal utilization remains constrained by insufficient data on substrate-specific nutritional profiling and biomethane potential. This study addresses this gap by characterizing the nutrient composition and theoretical biomethane yield of cereal-based food waste in Malumfashi, Nigeria, to evaluate its viability for large-scale energy recovery. Waste samples from local restaurants were analyzed using the Association of Official Analytical Chemists (AOAC) methods for proximate composition (total solids, volatile solids, crude fiber, etc.). Biomethane potential was estimated via the Baserga model, with electrical conversion calculated assuming 35% efficiency. Results revealed high total solids (93.66%) and volatile solids (85.62%), with nitrogen-free extracts (73.75%) dominating the waste profile. The estimated biomethane yield reached 577.3 m^3/kgVS (52.3% methane), translating to 1,057 kWh/ton of electricity. This work demonstrates cereal food waste as a high-potential substrate for anaerobic digestion, directly supporting SDG 7 (Affordable Energy) and SDG 12 (Responsible Consumption). Findings provide policymakers with evidence to integrate food waste valorization into renewable energy strategies, particularly in urban settings of developing economies.

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INTRODUCTION

The world faces an unprecedented energy crisis, exacerbated by dwindling fossil fuel reserves, geopolitical instability, and the urgent need to mitigate climate change (Belaïd *et al.*, 2023). As global energy demand continues to rise, projected to increase by 50% by 2050, the transition toward renewable energy sources has become imperative (Hassan *et al.*, 2024). Among these, bioenergy derived from organic waste streams presents a sustainable and circular solution, simultaneously addressing waste management challenges and energy deficits (Vasileiadou, 2024).

Food waste, in particular, represents a vast and underutilized resource. Approximately 1.3 billion tons of food are lost or discarded annually, accounting for nearly one-third of global food production (FAO, 2021). When disposed of in landfills, this waste decomposes anaerobically, releasing methane, a greenhouse gas 25 times more potent than CO_2 (Urugo *et al.*, 2024), while squandering valuable organic matter that could otherwise be converted into energy (Kiehbadroudinezhad *et al.*, 2024). Recent studies suggest that harnessing the bioenergy potential of food waste could supply up to 10% of the world's primary energy demand by mid-century, significantly offsetting fossil fuel dependence (El-Araby 2014).

Cereals constitute over 60% of the world's food supply (FAO, 2022), and their processing generates substantial residues, around 12.9% of all food waste globally (Fărcaş *et al.*, 2022). Despite their high biodegradability and energy density, these materials are often landfilled, leading to environmental pollution (Ma & Liu 2019). For instance, rice husk alone accounts for 20% of paddy weight, yet only

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30% is repurposed, with the rest treated as waste (Ramírez *et al*., 2024).

Anaerobic digestion (AD) offers a promising pathway for converting cereal wastes into biomethane, a renewable energy source with a carbon-neutral footprint (Subbarao *et al*., 2023). Biomethane production through AD reduces greenhouse gas emissions from decomposing waste and reduces fossil fuel use, contributing to circular bioeconomy goals (Alengebawy *et al*., 2024).

Standardized biomethane potential (BMP) assays are essential for quantifying the energy recovery potential of cereal wastes, as they simulate real AD conditions while accounting for substrate-specific biodegradability (Luna del Risco, 2011). However, the efficiency of this process depends heavily on substrate characteristics, including proximate composition (moisture, ash, volatile solids) and ultimate analysis (C, H, O, N ratios) (Ogwang *et al*., 2021; Efetobor & Ikpeseni 2022). For instance, high-lignin cereal residues (e.g., rice husks) exhibit lower methane yields due to recalcitrance (Jabeen *et al*., 2015), while starch-rich wastes (e.g., spoiled wheat) demonstrate faster degradation kinetics (Iris *et al*., 2017).

Previous studies have explored BMP for selected food waste agro-wastes; for Example, Salim *et al*. (2024) evaluated the nutrient composition and biogas potential of root and tuber waste as a feedstock for biogas production using the Baserga model equations. This study was conducted to assess the nutritional profile of cereal food waste, evaluate its biomethane potential, and estimate the potential for electricity generation, thereby providing insights into its viability as a bioenergy source.

MATERIALS AND METHOD

Materials used

i. Mortar and pestle
ii. Oven
iii. Sieve
iv. Analytical balance
v. Furnace
vi. Laboratory glassware
vii. Crucibles
viii. Deionized water
ix. Sulfuric acid (H_2SO_4)
x. Sodium hydroxide (NaOH)
xi. Mercury
xii. Petroleum Ether

2.1 Sample collection and preparation for Laboratory Analysis

The Cereal Food Waste was gathered from five restaurants in Malumfashi, including Sahaf, Mima, Mama Ojo, Dan Sadi, and IBC. In order to eliminate contaminants that could skew the test results, the collected wastes were rinsed with deionized water. To get rid of the surface moisture, the wastes were allowed to air dry after being rinsed. Following the guidelines set forth by the Association of Official Analytical Chemists (AOAC), the cereal food wastes were mechanically ground into a powder using a mortar and pestle, sieved, and sent to a central laboratory at Umaru Musa Yar'adua University for standard analysis in order to obtain a representative sample (Salim *et al*., 2024).

2.2 Nutritional Profiling of the Cereal Wastes

The Association of Official Analytical Chemists' standard procedures were used to ascertain the sample's nutritional profile (AOAC, 2005). Total solids (TS), volatile solids (VS), oils, nitrogen-free extracts (NFE), moisture content, crude fiber (CrF), and crude protein (CrP) were all included in these analyses. The AOAC methods are widely recognized for assessing the nutrient composition of organic waste materials (Salim *et al*., 2024).

2.2.1 Total Solids and Moisture Content

The quantity of total solids corresponds to the residual dry material left in a sample once all water has been eliminated. This measurement was obtained by subjecting the sample to an oven-drying process at a temperature of 105 °C until no further change in mass was observed. The level of moisture was then ascertained by deducting the final weight of the dried solids from the sample's original weight. (Salim *et al*., 2024).

2.2.2 Volatile Solids and Ash Content

Volatile solids refer to the constituents that dissipate when a sample is subjected to ignition at a temperature of 550 °C. The determination of this parameter involved an initial step of drying the sample to achieve a stable weight at 105 °C. Subsequently, the sample was exposed to a high-temperature furnace at 550 °C for a duration of four hours. The material remaining post-ignition was identified as ash, whereas the volatile solids content was quantified by calculating the difference between the pre-ignition dry weight and the post-ignition residue (Salim *et al*., 2024).

2.2.3 Crude Fiber

Crude fiber is composed of intricate carbohydrate structures, such as authentic cellulose and non-soluble lignin. Its content was quantified by measuring the weight loss upon ignition of the residual material following treatment with 1.25% sulfuric acid (H_2SO_4) and 1.25% sodium hydroxide (NaOH) solutions. The procedure entails subjecting the sample to boiling in these solutions for a duration of 30 minutes, followed by a resting period of one minute. After filtration, the remaining solid is transferred to a flask containing boiling sodium hydroxide for an additional 30 minutes, with another one-minute resting interval. Finally, the residual material is thoroughly rinsed, desiccated, and subsequently weighed (Salim *et al*., 2024).

2.2.4 Crude Protein

Estimating crude protein was conducted by quantifying its nitrogen content through applying the Kjeldahl technique. This procedure entails the digestion of the sample in concentrated sulfuric acid, facilitated by a catalyst such as mercury or selenium, to ascertain the total nitrogen concentration. The Kjeldahl method serves as the established protocol for determining protein levels in organic waste materials and is also utilized in the evaluation of their biogas generation capacity (Salim *et al.*, 2024).

2.2.5 Crude Fat

Crude fat represents the collection of substances within a sample that are soluble in fats. Its analysis involves the extraction of lipids through the use of petroleum ether, followed by the determination of the weight percentage prior to the removal of the solvent. This technique is widely employed for quantifying lipid concentrations in a range of organic waste samples (Salim *et al.*, 2024).

2.2.6 Nitrogen-Free Extracts

Nitrogen-free extracts encompass organic compounds that are soluble but devoid of nitrogen, such as starches and sugars. These extracts are quantified by deducting the combined proportions of crude fiber, crude protein, crude fat, and ash from the total solids content (AOAC, 2005). This methodology is employed to evaluate the carbohydrate levels and nutritional composition of organic waste materials, particularly in the context of biogas generation.

2.3 Biomethane Potentials

The theoretical biomethane potential of the feedstock materials was estimated through the application of the Baserga model (Baserga, 1998). This approach determines the theoretical biogas yield by considering the compositional makeup of nutrients, such as crude fiber, crude protein, crude fats, ash, and moisture levels. The model operates under the assumption that the entirety of the organic matter is transformed into biomethane.

Baserga Model Digestibility Constants and Conversion Factors

The digestibility factors represent the percentage of each nutrient component that can be converted during anaerobic digestion (Table 1). These values are adapted from (Salim *et al.*, 2024).

These factors (Table 2) convert digestible components into their corresponding gas yields.

The methane content (Table 3) represents the proportion of methane in the biogas produced from each component.

Table 1: Digestibility Factors

Parameter	Symbol	Digestibility Factor (%)
Crude Fiber	CrFd	74.3
Crude Protein	CrPd	65.09
Crude Fat	OAHd	67.51
Nitrogen-Free Extracts	NFEd	69.97

Source: Adapted from Salim *et al.*, 2024

Table 2: Gas Yield Conversion Factors

Component	Symbol	Gas Yield (L/kg)
Carbohydrates	GYCf	790
Proteins	GYPf	700
Fats	GYOf	1250

Source: Adapted from Salim *et al.*, 2024

Table 3: Methane Content of Biogas

Component	Symbol	Methane Content (%)
Carbohydrates	MCf	50
Proteins	MPf	71
Fats	MOf	68

Source: Adapted from Salim *et al.*, 2024

Calculated parameters

The following parameters were calculated based on AOAC (2005) methods

$$NFE = 100 - (CrP + CrF + OAH + Ash + Moisture) \quad (1)$$

$$VS = (CrP + CrF + OAH + NFE) \quad (2)$$

Definition of Formulae parameters

VS: Represents the Volatile Solids content of the sample.

CrP: Represents the Crude Protein content of the sample.

CrF: Represents the Crude Fiber content of the sample.

OAH: Represents the content of Crude Fats.

NFE: Represents the Nitrogen-Free Extracts content of the sample.

Baserga Equations

The Baserga model is a predictive method employed to estimate the biomethane potential of organic substrates based on their proximate composition. This study determined key parameters including crude fibre, crude protein, crude fat, and nitrogen-free extracts using standardized AOAC methods and subsequently used as input variables in the model. These values were applied in a series of mathematical equations, as outlined below:

Step 1: Digestible Components (g/kg Dry Matter Basis)

The digestible components were calculated as follows:

Digestible Carbohydrate $\left(\frac{g}{kg} DMB\right) DC = ((CrF \times CrFd) + (NFE \times NFEd)/10$ (3)

Digestible Crude Protein $\left(\frac{g}{kg} DMB\right) DP = (CrP \times CrPd)/10$ (4)

Digestible Crude Fat $\left(\frac{g}{kg} DMB\right) DO = (OAH \times OAHd)/10$ (5)

And:

Step 2: Digestible Components per Volatile Solids (kg/kg VS)

The digestible components were normalized to volatile solids (VS):

Digestible Carbohydrate $\left(\frac{kg}{kg} VS\right) DCv = DC/(VS \times 10)$ (6)

Digestible Crude Protein $\left(\frac{kg}{kg} VS\right) DPv = DP/(VS \times 10)$ (7)

Digestible Crude Fat $\left(\frac{kg}{kg} VS\right) DOv = DO/(VS \times 10)$ (8)

And:

Step 3: Gas Yields (L/kg VS)

The gas yields for each component were calculated as follows:

Gas Yield Carbohydrate $\left(\frac{l}{kg} VS\right) GYC = DCv \times GYCf$ (9)

Gas Yield Protein $\left(\frac{l}{kg} VS\right) GYP = DPv \times GYPf$ (10)

Gas Yield Fat $\left(\frac{l}{kg} VS\right) GYO = DOv \times GYOf$ (11)

Total Gas Yield $\left(\frac{l}{kg} VS\right) TGY = GYC + GYP + GYO$ (12)

And:

Step 4: Methane Content (%)

The methane contribution from each component was calculated as follows:

Methane Share for Carbohydrate (%) $MC = GYC \times MCf/TGY$ (13)

Methane Share for protein (%) $Mp = GYP \times MPf/TGY$ (14)

Methane Share for Fat (%) $MO = GYO \times MOf/TGY$ (15)

Total Methane Content (%) $TMC = MC + MP + MO$ (16)

And:

Step 5: Gas Yield per Ton of Fresh Matter

The total gas yield per ton of fresh matter was calculated as follows:

Gas Yield $\left(\frac{m^3}{tonne}\right) of\ Fresh\ Matter = (TGY \times VS)/100$ (17) (Baserga, 1998).

Definition of Equation

DC: Digestible Carbohydrate (g/kg DM)

CrFd: Digestibility factor for Crude Fiber

NFEd: Digestibility factor for Nitrogen-Free Extract

DP: Digestible Crude Protein

CrPd: Digestibility factor for Crude Protein

DO: Digestible Crude Fat

OAHd: Digestibility factor for Crude Fat

DCv: Digestible Carbohydrate

DPv: Digestible Crude Protein

DOv: Digestible Crude Fat

GYC: Gas Yield from Carbohydrate

GYCf: Gas Yield Conversion Factor for Carbohydrates

GYP: Gas Yield from Protein

GYPf: Gas Yield Conversion Factor for Protein

GYO: Gas Yield from Fat

GYOf: Gas Yield Conversion Factor for Fat

TGY: Total Gas Yield

MC: Methane Share for Carbohydrate

MCf: Methane Content of Carbohydrates

TGY: Total Gas Yield

Mp: Methane Share for Protein

MPf: Methane Content of Protein

MO: Methane Share for Fat

MOf: Methane Content of Fat

TMC: Total Methane Content

RESULTS AND DISCUSSION

3.1 Nutritional Profile of Cereal Food Waste

Proximate analysis revealed that cereal food waste contains a substantial proportion of total solids (TS), accounting for 93.66% (Table 4). This elevated percentage signifies a significant presence of nonvolatile constituents within the waste material. Additionally, the volatile solids (VS) content, which reflects the organic fraction capable of being converted into biogas during anaerobic digestion, was measured at 85.62%. This high VS content indicates considerable potential for biogas generation from cereal food waste. The crude protein (CrP) content, which indicates nitrogenous substances, was found to be 0.85%. This relatively modest protein level is characteristic of many food waste types, which often exhibit higher carbohydrate concentrations. Furthermore, the nitrogen-free extracts (NFE), representing carbohydrates excluding crude fiber, were quantified at 73.75%. This notable value highlights the predominance of carbohydrates in cereal food waste, which plays a critical role in biogas production.

The crude fiber (CrF) content, indicative of indigestible components, was recorded at 4.00%. This moderate CrF level suggests that while some indigestible materials are present, they do not dominate the overall composition. The crude fat (OAH) content, reflecting lipid concentration, was determined to be 7.02%, a significant but not excessive level compared to other organic waste streams. The ash content, representing the inorganic residue remaining after complete combustion, was measured at 8.04%, a moderate value typical of many organic waste materials. Lastly, the sample's moisture content was found to be 6.34%, a relatively low figure that is advantageous for storage and processing.

These results align with those reported by Salim et al. (2024) in their investigation of the nutritional characteristics and biogas generation potential of root and tuber wastes. Their findings revealed comparable nutritional attributes, including a total solids (TS) content of 94.70%, a volatile solids (VS) content of 87.60%, a crude protein (CrP) content of 0.10%, a nitrogen-free extract (NFE) of 5.1%, a crude fiber (CrF) content of 5.04%, a crude fat (OAH) content of 7.1%, and an ash content of 5.3%. In contrast, Opurum et al. (2021) documented differing results for cassava waste, underscoring the variability in waste composition across various organic materials. Their study on cassava waste for biogas prediction reported a moisture content (MC) of 2.39%, an ash content of 9.48%, fiber content of 21.50%, nitrogen content of 2.44%, a fat content of 2.59%, a crude protein (CrP) content of 15.35%, a total solids (TS) content of 87.61%, and a volatile solids (VS) content of 78.13%. Similarly, Manić et al. (2024) employed a novel approach integrating proximate and ultimate analyses, accounting for compositional variables such as moisture, ash, and elemental ratios (C: H:O:N:S). Their findings emphasize that substrate heterogeneity, particularly nitrogen and sulfur content, directly influences biogas quality.

Table 4: Nutritional Profiling result

Food Waste Sample	Parameters in %							
	TS	VS	CrP	NFE	CrF	OAH	Ash	Moisture
Cereal	93.66	85.62	0.85	73.75	4.0	7.02	8.04	6.34

These nutritional profiles offer valuable insights into the suitability of food waste for biogas production and other renewable energy applications. Cereal waste, rich in carbohydrates and low in lipids or proteins, undergoes more complete acidogenesis and acetogenesis phases, whereas lipid-rich food waste generates longer-chain fatty acids that inhibit methanogens (Dasa et al., 2016). This compositional distinction highlights the need for substrate-specific model calibration, particularly when comparing across waste categories. A comprehensive understanding of waste material composition is crucial for optimizing anaerobic digestion processes and enhancing energy recovery.

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3.3 Methane yield potential per ton Cereal Food wastes

Results obtained using the Baserga model to analyze the biomethane potential of cereal food waste revealed a theoretical biomethane potential of 577.3 L/kg VS with 52.3% methane content (Table 5). These findings align closely with Salim et al. (2024), who reported a similar result using root and tuber waste with a biomethane potential of 572 L/kg VS, and a 52% methane but exceeding the values of general food waste by Surhatini et al. (2019) who reported a biomethane yield of 300 L/kg VS. This result highlights the potential of cereal food waste as a viable substrate for biogas production; this could help in waste management by cutting down greenhouse gas emission by food waste decomposition in landfills and supports sustainable energy generation.

Table 5: Biomethane Potential of Cereal Waste

Parameter	Value
Biomethane Yield	577.3 L/kg VS
Methane Content	52.3%

The Baserga model offers a realistic tool for analyzing biomethane potential by avoiding labor-intensive batch experiments. This makes it favorable for preliminary feasibility assessments for biomethane potential.

Despite this promising result, the Baserga Model neglect of compositional variability limits its accuracy for heterogeneous or recalcitrant substrates. The model 100% degradability assumption may not be realistic especially due to factors that affect the activities of microorganisms during the Anaerobic digestion or the composition of the substrates, especially the lignocellulosic biomass, characterized by high cellulose and lignin content, often resistance microbial activities this lower degradability of the substrate. These factors were not unaccounted for in the Baserga model. Future studies could explore the use of more complex models or experimental validation to address these limitations.

3.4 Electrical Potential

Suhartini et al. (2019) reported that the electrical potential derived from biomethane was estimated using the premise that each cubic meter of biomethane possesses a calorific value of 22 MJ. Assuming an electrical conversion efficiency of 35%, it was calculated that one cubic meter (1 m^3) of biomethane could generate approximately 2.14 kWh of electricity.

The total biomethane yield is estimated at 494 m^3 for fresh cereal food waste. Therefore, the total calorific value derived from this quantity of biomethane can be calculated as follows:

$$\text{Total Calorific Value} = 22\ \text{MJ} \times 494\ \text{m}^3 = 10868\ \text{MJ}$$

Subsequently, the total electricity that could potentially be harnessed from 1 ton of fresh cereal food waste is calculated using the previously mentioned biogas yield:

$$\text{Total Electricity} = 2.14\ \text{kWh/m}^3 \times 494\ \text{m}^3 = 1057\ \text{kWh/ton}$$

Thus, cereal food waste has an impressive electricity generation potential of 1057 kWh/ton and a calorific value of 10868 MJ/ton. This result is consistent with prior studies, which have highlighted the substantial potential of food waste (FW) as a bioenergy feedstock due to its high biogas production capacity and yield.

Suhartini et al. (2019) demonstrate that food waste holds significant promise for electricity generation, whether through single-digestion or co-digestion anaerobic processes. In their investigation, the electrical energy potential generated from the single digestion of food waste was determined to be 473.8 kWh per ton, while co-digestion with tofu solid waste at a 50:50 mixing ratio yielded 307.2 kWh per ton.

In a separate investigation conducted by Banks *et al.* (2011), which involved a thorough evaluation of energy and mass balances, it was revealed that the electricity potential derived from food waste amounted to approximately 405 kWh/ton. The study also noted a consistent biogas production rate of 642 m^3/ton volatile solids (VS) and a methane concentration of around 62%.

CONCLUSION

This study demonstrates that cereal food waste in Malumfashi, Nigeria, has strong potential for anaerobic digestion and biomethane generation. Proximate analysis confirmed high total and volatile solids with low moisture, and a carbohydrate-rich profile ideal for methane production. The estimated biomethane yield of 577.3 L/kg VS and electricity potential of 1057 kWh/ton affirm the viability of cereal waste as a renewable energy substrate.

Despite promising results, the study's reliance on theoretical modeling and composite sampling limits generalizability. Future research should include experimental digestion trials and explore co-digestion strategies to enhance yield and process stability. These findings offer a scientific basis for policy-driven food waste valorization and contribute toward achieving SDG 7 and SDG 12 through circular bioeconomy practices.

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