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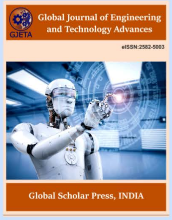

(Research Article)

EXPERIMENTAL INVESTIGATION OF BIOGAS QUALITY AND ENERGY POTENTIAL FROM SYNERGISTIC CO-DIGESTION OF CASSAVA PEELS AND COW DUNG

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ABSTRACT

The conversion of agricultural residues into renewable energy offers an environmentally sustainable solution to waste management and energy security. Cassava peels and cow dung are abundant biodegradable resources with considerable potential for anaerobic digestion; however, information on the influence of substrate blending on biogas quality and energy performance remains limited. This study investigated the effect of cassava peel–cow dung blending ratios on biogas composition, calorific value, and engineering performance to identify the optimum substrate combination for renewable energy generation. Biogas was produced using a 0.218 m^3 laboratory-scale floating-drum anaerobic digester operated under batch mesophilic conditions. Five substrate blending ratios (100:0, 70:30, 50:50, 30:70, and 0:100, w/w) were evaluated. Methane (CH_4), carbon dioxide (CO_2), and hydrogen sulphide (H_2S) concentrations were measured in triplicate. The lower heating value (LHV) was estimated from methane concentration, while generator calibration was used to determine biogas consumption rate, substrate requirement, digester size, and carbon dioxide emission reduction. The 50:50 cassava peel–cow dung blend produced the highest methane concentration (63.4%), the lowest carbon dioxide concentration (35.0%), and the highest lower heating value (22.7 MJ m^{-3}). The calibrated biogas consumption rate was 0.37 m^3 h^{-1}, producing an average electrical output of approximately 1.5 kW. Continuous 24-hour operation required 8.88 m^3 day^{-1} of biogas, 33.84 kg day^{-1} of substrate, and a 100.8 m^3 digester. Replacing petrol with biogas reduced carbon dioxide emissions by up to 38.81 kg day^{-1}. Co-digestion of cassava peels and cow dung significantly improved biogas quality and energy potential. The 50:50 blending ratio produced the highest-quality biogas and demonstrated the feasibility of utilising agricultural residues as a sustainable feedstock for decentralised renewable energy generation.

Keywords: Cow Dung; Biogas; Cassava peels; Co-digestion; Methane; Renewable energy.

1 INTRODUCTION

The global transition from fossil fuels to sustainable, low-carbon energy sources is increasingly urgent due to rising energy demands, population growth, and industrialisation. Biomass has emerged as a significant renewable energy source, capable of converting agricultural residues and organic waste into energy, thus supporting circular bioeconomy principles and addressing waste disposal issues [1-3]. Among biomass conversion technologies, anaerobic digestion has gained attention for its dual benefits of waste management and renewable energy production. This process biologically decomposes organic materials in oxygen-free environments, producing biogas and nutrient-rich digestate. Biogas primarily consists of methane (CH_4) and carbon dioxide (CO_2), with methane being essential for energy applications such as heating and power generation [1, 4]. Agricultural activities generate significant amounts of biodegradable waste, which is often improperly disposed of, leading to greenhouse gas emissions and other environmental issues. Utilising anaerobic digestion for this waste transforms it into valuable energy while reducing environmental impacts, yet agricultural residues remain underutilised in bioenergy production [3, 4]. Cassava (Manihot esculenta Crantz) is among the most widely cultivated food crops in tropical regions and serves as a major source of carbohydrates for millions. The processing of cassava roots into flour, starch, chips, and other products generates vast quantities of peels, which represent a significant agro-industrial waste stream. Given that cassava peels contain considerable amounts of biodegradable organic matter, they have significant potential for anaerobic digestion and renewable energy production. However, untreated cassava residues are often discarded indiscriminately, leading to environmental and public health issues while representing a loss of recoverable bioenergy resources. Recent studies have highlighted the increasing interest in using anaerobic digestion to valorise cassava residues as part of a circular bioeconomy approach [3, 5]. Despite the significant energy potential of cassava peels, digestion of the substrate alone may not always provide optimum reactor performance because of nutrient imbalance, variable carbon-to-nitrogen ratio, and limitations in microbial activity. For this reason, recent investigations have increasingly explored the co-digestion of cassava residues with animal manure and other biodegradable wastes to improve process stability and methane production. Co-digestion enhances nutrient availability, supplies active microbial populations, and improves buffering capacity within the digester, thereby creating favourable conditions for methanogenic microorganisms. Experimental studies have demonstrated that blending cassava peels with cow dung or other agricultural residues generally produces superior digestion performance compared with mono-digestion, although the optimum mixing ratio varies with substrate characteristics and operating conditions [5-8]. Cow dung remains one of the most effective inoculum sources for anaerobic digestion because it supplies diverse methanogenic microorganisms, essential nutrients, trace elements, and buffering compounds that support microbial stability throughout the digestion [1, 9]. The microbial diversity naturally present in cattle manure promotes efficient degradation of complex organic materials and accelerates methane formation, making cow dung one of the most widely adopted co-substrates for agricultural residues [10, 11]. Recent studies have further demonstrated that co-digestion of cow dung with biodegradable crop residues enhances substrate biodegradability, improves volatile solids reduction, and increases methane recovery compared with mono-digestion [7, 12]. Cassava peels constitute one of the largest agro-industrial wastes generated during cassava processing, particularly in tropical countries where cassava serves as a staple food and industrial raw material. Although cassava peels possess appreciable carbohydrate content suitable for anaerobic digestion, their relatively low nitrogen concentration and fibrous lignocellulosic structure may limit microbial activity when used as the sole substrate. Consequently, several researchers have recommended co-digestion with nutrient-rich animal manure to improve digestion efficiency and methane production [3, 5, 8, 13]. Experimental evidence indicates that blending cassava peels with cow dung provides a more balanced substrate composition, thereby creating favourable conditions for microbial growth and stable methane generation. Co-digestion has therefore emerged as a practical strategy for improving anaerobic digestion performance because it balances the carbon-to-nitrogen ratio, enhances microbial synergy, and minimises process inhibition. Numerous investigations have shown that appropriate substrate combinations improve methane concentration, reduce process instability, and shorten the lag phase associated with anaerobic digestion [8, 9, 12]. However, the optimum substrate ratio varies considerably among studies owing to differences in feedstock characteristics, reactor configuration, inoculum source, hydraulic retention time, and operating temperature. These variations highlight the importance of experimentally determining the most suitable blending ratio for individual feedstocks rather than relying on generalized recommendations. The engineering value of biogas depends not only on the quantity produced but also on its composition. Methane determines the combustible energy available for thermal and electrical applications, whereas carbon dioxide reduces the energy density of the gas because it is non-combustible. Hydrogen sulphide, although present in relatively small quantities, remains one of the principal contaminants because it promotes corrosion of metallic components and reduces the service life of engines, pipelines, and storage vessels. Consequently, simultaneous determination of methane, carbon dioxide, and hydrogen sulphide provides a more comprehensive evaluation of biogas quality than cumulative gas production alone [8, 9]. The lower heating value of biogas is directly proportional to its methane concentration and therefore represents an important indicator of fuel quality. Biogas with higher methane content possesses greater energy density and improved combustion characteristics, making it more suitable for electricity generation and combined heat and power applications. For this reason, recent studies increasingly recommend integrating gas composition analysis with calorific value estimation to provide a more realistic assessment of biogas performance in engineering applications [5, 8]. Despite the growing body of literature on anaerobic digestion of agricultural residues, several important knowledge gaps remain. Many published studies have concentrated primarily on cumulative biogas yield, methane yield, or digestion kinetics, while comparatively fewer have simultaneously evaluated methane concentration, carbon dioxide concentration, hydrogen sulphide concentration, and the corresponding calorific value of the produced biogas. In addition, relatively few investigations have systematically examined multiple cassava peel–cow dung blending ratios to identify substrate combinations that optimize fuel quality for energy applications rather than simply maximizing gas volume [3, 5].

Previous investigations often treated biogas quality as a secondary outcome, despite its crucial role in fuel utilisation. Methane concentration directly affects energy content, while carbon dioxide and hydrogen sulfide influence combustion efficiency and equipment performance. Evaluating these parameters together is essential for the design of biogas energy systems [8, 12]. This study addresses these gaps by investigating the effects of five cassava peel–cow dung ratios on biogas composition and energy potential. Methane, carbon dioxide, and hydrogen sulfide concentrations were measured, and the lower heating value of the biogas was estimated from the methane concentration. Unlike previous studies that focused on cumulative gas production, this research examines the impact of substrate blending on gas composition and fuel quality, aiming to identify optimal feedstock combinations for renewable energy generation. The findings reveal how substrate synergy affects methane enrichment, carbon dioxide reduction, hydrogen sulfide formation, and biogas energy value. This information aids in optimising feedstock selection for sustainable waste-to-energy systems. Cow dung is an effective inoculum for anaerobic digestion, providing essential nutrients and microorganisms that enhance methane formation [1, 9]. Co-digestion of cow dung with crop residues has been shown to improve biodegradability and methane recovery compared to mono-digestion [7, 12]. Cassava peels, a significant agro-industrial waste in tropical countries, have a high carbohydrate content suitable for anaerobic digestion. However, their low nitrogen levels and fibrous structure can hinder microbial activity when used alone. Researchers recommend co-digesting cassava peels with nutrient-rich animal manure, like cow dung, to enhance digestion efficiency and methane production [3, 5, 13]. This co-digestion improves the carbon-to-nitrogen ratio, microbial synergy, and overall process stability, leading to better methane concentration and shorter lag phases [8, 10, 12, 14]. The engineering value of biogas is determined by its quantity and composition. High methane content enhances energy density and combustion efficiency, making biogas more suitable for energy applications. Factors like the presence of hydrogen sulfide can lead to corrosion issues. Therefore, analyzing the composition of biogas, including methane, carbon dioxide, and hydrogen sulfide, alongside calorific value estimation is essential for a comprehensive evaluation of biogas performance [5, 9, 14]. Despite the growing literature on anaerobic digestion of agricultural residues, significant knowledge gaps remain. Most studies have primarily focused on cumulative biogas yield, methane yield, or digestion kinetics, with fewer addressing methane concentration, carbon dioxide concentration, hydrogen sulfide concentration, and the calorific value of biogas. Additionally, limited research has explored various cassava peel and cow dung blending ratios to optimize fuel quality for energy applications rather than just maximizing gas volume [5, 9]. Furthermore, biogas quality is often treated as a secondary outcome, even though it directly affects fuel utilization. Methane concentration determines energy content, while carbon dioxide and hydrogen sulfide influence combustion efficiency and equipment performance. Evaluating these parameters together is essential for advancing biogas-based energy systems beyond the laboratory [12, 14]. This study addresses these gaps by investigating the effects of five cassava peel–cow dung blending ratios on biogas composition and energy potential. Methane, carbon dioxide, and hydrogen sulfide concentrations were measured, and the lower heating value of the biogas was estimated based on the methane concentration. Unlike many prior studies, this research focuses on the relationship between substrate blending, gas composition, and fuel quality, aiming to identify optimal feedstock combinations for renewable energy generation.

2 MATERIALS AND METHODS

2.1 Materials

Fresh cassava peels and cow dung were used as the substrates for biogas production. Cassava peels were collected from local cassava processing centres in Bayelsa State, Nigeria. At the same time, fresh cow dung was obtained from the Faculty of Agriculture Farm, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria. The cassava peels were manually sorted to remove foreign materials, thoroughly washed with clean water, and chopped into smaller pieces to enhance microbial degradation during anaerobic digestion. Fresh cow dung was sieved to remove coarse impurities before mixing with the cassava peels. Five cassava peel-to-cow dung blending ratios (100:0, 70:30, 50:50, 30:70, and 0:100, w/w) were prepared to investigate the influence of substrate synergy on biogas quality and energy generation. Each treatment was conducted in triplicate.

2.2 Experimental Digester

Biogas production was carried out using a laboratory-scale floating-drum anaerobic digester fabricated from a cylindrical high-density polyethylene drum with an effective working volume of 0.218 m^3 (218 L). The digester had an internal diameter of 0.57 m and a height of 0.85 m. The system comprised an inlet chamber, digestion chamber, slurry outlet, gas outlet, gas purification unit (desulphurizer and biological scrubber), gas storage unit, and a modified spark-ignition generator for energy evaluation. The digester operated under batch mesophilic conditions. After charging the prepared slurry, the reactor was sealed to maintain anaerobic conditions throughout the digestion period. Biogas generated during fermentation displaced the floating gas holder and was subsequently purified before gas composition analysis and generator testing.

Figure 1: Cassava Peel and Cow dung

2.3 Digester Design

The digester was designed based on the floating-drum biogas system proposed by Karki (2002), with modifications to incorporate a separate gas collection chamber to improve gas measurement. The required digester volume was estimated using the hydraulic retention time method:

$$V_d(m^3) = S_d(m^3/day) \times HRT(day) \quad (1)$$

where: Vd = digester volume (m^3); Sd = daily slurry input ($m^3\ day^{-1}$); HRT = hydraulic retention time (day).

The digester volume was also determined from the cylindrical geometry of the reactor:

$$\text{Volume of digester } (V_d) = \frac{\pi}{4} HD^2 \quad (2)$$

where: D = digester diameter (m); H = digester height (m). Substituting the measured dimensions (D = 0.57 m and H = 0.85 m) gave

$$\text{The Volume of Digester } (V_d) = \frac{\pi}{4} \times 0.851 \times (0.572)^2$$

$$V_d = \frac{0.278}{4} \pi$$

$$\text{Hence, Volume of Digester } (V_d) = 0.0695 \times \frac{22}{7}$$

$$\text{Volume of Digester Unit } (V_d) = 218 \text{ Litres}$$

The amount of biogas created per day (G) is determined using the substrate's specific gas yield (Gy) and the volatile solids content of the daily substrate. Equation 3 (Joseph et al, 2022) shows how to calculate biogas production.

$$G = V_S \times G_Y \quad (3)$$

Where; V_S = Weight of feedstock available per day (in kg), G_Y = Specific gas yield (in m^3), G = daily biogas production (in m^3)

$$G_p = \frac{G}{V_d} \tag{4}$$

Where; G_p = Gas production rate (in m^3), G = Daily biogas production (in m^3), V_d = Container volume (in m^3) and Gas holder volume ($\boldsymbol{V_g}$)

According to Kossmam et al. (2011), the volume (-g.) of a gas holder is determined by the rate of gas generation and consumption. The gas container is designed to accommodate the highest amount of gas produced during the longest time of zero usage. It is also intended to cover the peak consumption rate during the period of maximum usage.

Experimental Procedure

Cassava peels and cow dung were blended according to the prescribed substrate ratios and mixed with water to obtain a homogeneous slurry suitable for anaerobic digestion. The prepared slurry was loaded into the digester, which was immediately sealed to establish anaerobic conditions. Digestion was allowed to proceed under mesophilic conditions until stable gas production was achieved. Biogas produced during the digestion process passed through a desulphurizer to reduce hydrogen sulphide concentration and subsequently through a biological scrubber for partial carbon dioxide removal before being stored for composition analysis and generator performance evaluation.

Figure 2: The complete fabricated biogas digester.

2.4 Biogas Composition Analysis

Biogas samples were analysed to determine methane (CH_4), carbon dioxide (CO_2), and hydrogen sulphide (H_2S) concentrations. Three independent measurements were obtained for each substrate ratio, and the average values were used for subsequent analyses. Methane concentration was used as the principal indicator of fuel quality because it represents the combustible component of biogas, whereas carbon dioxide and hydrogen sulphide were evaluated to assess gas purity and suitability for energy applications.

2.5 Estimation of Biogas Energy Content, Generator Calibration and Engineering Analysis

The calorific value (energy content) of biogas is governed primarily by its methane concentration, since carbon dioxide and other trace gases do not contribute to combustion energy. The lower heating value (LHV) of biogas, according to Weiland (2010), can be expressed as:

$$LHV_{biogas} = x_{CH_4} \times LHV_{CH_4} \tag{5}$$

where: x_{CH_4} = volumetric fraction of methane in biogas, LHV_{CH_4} = lower heating value of pure methane ($\approx$ 35.8 MJ/m^3).

2.6 Generator Calibration and Engineering Analysis

The chemical energy input rate supplied to the generator was evaluated using the measured daily biogas production rates and the calorific values derived from methane content, which, according to Heywood (2018) and Weiland (2010), states that the rate of chemical energy supplied to the engine is determined by the product of biogas volumetric flow rate and its calorific value, expressed as:

$$\dot{E}_{in} = \dot{V}_{bg} \times LHV_{biogas} \quad (6)$$

where: $\dot{E}_{in}$ is the chemical energy input rate (MJ/s), and $\dot{V}_{bg}$ is the biogas flow rate (m^3/s)

From the Energy input equation, it is evident that both gas quantity and gas quality jointly determine the usable energy supplied to the generator. For the 50:50 cassava peel–cow dung blend, the following experimentally established results are available: Average methane content $(CH_4) = 63.4\%$, Corresponding calorific value of biogas $(LHV) = 22.7\ MJ/m^3$. Generator rating; Electrical Output = 2.0 KW (Rated), Practical biogas operation = 75%. As such, the electrical load for the biogas system is taken as;

$$\mathrm{P_e} = 0.75 \times 2 = 1.5\ \mathrm{KW}$$

Also, for a small, single-cylinder SI engine operating on biogas: Typical electrical efficiency range: $20 - 28\%$, Well-tuned, methane-rich biogas: $\approx 25\%$, The study therefore adopted:

$$\eta_e = 25\% = 0.25$$

Electrical efficiency is defined as;

$$\eta_e = \frac{P_e}{\dot{E_{in}}} \quad (7)$$

So, the generator requires: $\dot{E}_{in} = 6.0 kJ/s$

$$\dot{E}_{in} = V_{bg} \times L\dot{H}V_{biogas} \quad (8)$$

$$V_{bg} = \frac{\dot{E}_{in}}{LHV_{biogas}} \quad (9)$$

At the estimated biogas flow rate of 0.95 m^3/h, continuous generator operation would require approximately 22.8 m^3 of biogas per day. However, laboratory-scale biogas production was significantly lower; therefore, generator operation will necessarily be intermittent, dependent on gas accumulation.

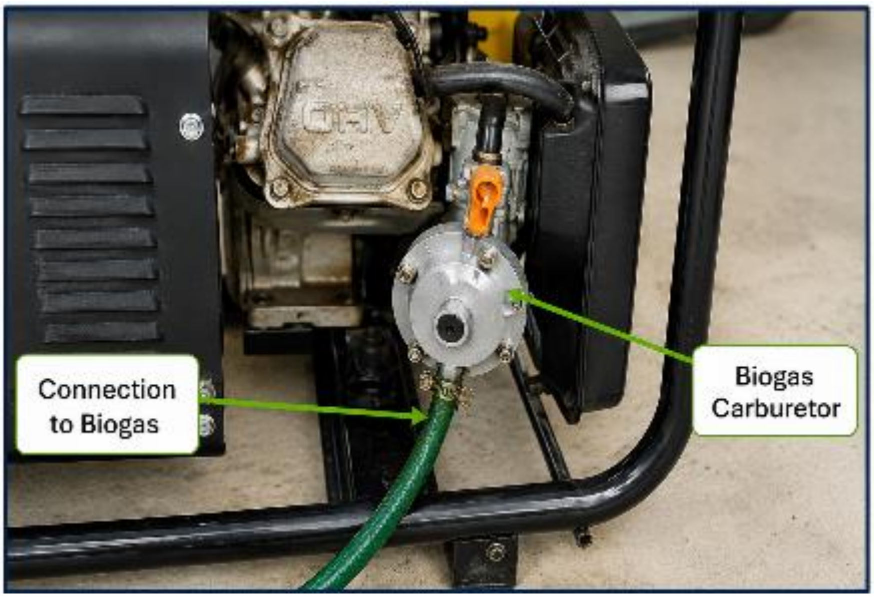

Figure 3: Power Generator Test Sample

2.7 Statistical Analysis

All experiments were performed in triplicate, and the results are presented as mean ± standard deviation. Statistical analyses were carried out using one-way analysis of variance (ANOVA) to evaluate the influence of substrate blending ratio on methane concentration, carbon dioxide concentration, hydrogen sulphide concentration, and lower heating value. Before ANOVA, data normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. Where significant differences were observed, Tukey's honestly significant difference (HSD) test was applied for pairwise comparison of treatment means. Statistical significance was accepted at $p < 0.05$.

3 RESULTS

3.1 Biogas Production

The daily biogas production profiles showed that substrate composition strongly influenced both the rate and stability of gas generation. Across the 30-day digestion period, the 50:50 cassava peel–cow dung blend consistently produced the highest biogas output, while cassava peel mono-digestion gave the lowest yield. The production curves also showed the expected batch-digestion pattern: an initial lag phase, a period of rapid gas generation, a peak around the middle of the run, and a gradual decline toward the end of the digestion period. This behaviour is typical of batch anaerobic systems in which microbial adaptation and the gradual depletion of readily degradable organics control the gas profile. The results agree with recent cassava-residue studies showing that co-digestion improves process stability and methane recovery compared with mono-digestion, especially when the feedstock is carbohydrate-rich but nutritionally unbalanced [3, 5, 15, 16]. The superiority of the 50:50 blend can be explained by the complementary roles of cassava peels and cow dung. Cassava peels supply readily biodegradable carbon, while cow dung contributes active methanogenic consortia, buffering capacity, and micronutrients required for stable digestion. That balance is important because cassava peels alone can acidify quickly, whereas excessive manure can dilute the readily fermentable fraction without necessarily improving total gas quality. Similar behaviour has been reported in recent co-digestion studies involving cow dung and food waste, cattle manure with crop residues, and other lignocellulosic substrates, where optimum performance was achieved at intermediate mixing ratios rather than at extreme [12, 17-19].

Table 1: Daily biogas production under different cassava peel–cow dung blending ratios.

Day	100:0 (Cassava)	70:30	50:50	30:70	0:100 (Cow dung)
1.0	0.004	0.003	0.007	0.003	0.001
2.0	0.002	0.007	0.006	0.003	0.004
3.0	0.003	0.009	0.01	0.011	0.006
4.0	0.009	0.013	0.015	0.01	0.01
5.0	0.007	0.014	0.018	0.013	0.01
6.0	0.013	0.014	0.021	0.02	0.017
7.0	0.012	0.021	0.025	0.017	0.019
8.0	0.013	0.019	0.032	0.022	0.017
9.0	0.014	0.022	0.038	0.028	0.018
10.0	0.017	0.029	0.036	0.03	0.025
11.0	0.022	0.029	0.042	0.033	0.027
12.0	0.021	0.033	0.044	0.032	0.03
13.0	0.023	0.036	0.048	0.039	0.031
14.0	0.026	0.036	0.053	0.04	0.035
15.0	0.029	0.037	0.059	0.045	0.035
16.0	0.031	0.043	0.064	0.044	0.04
17.0	0.029	0.046	0.066	0.049	0.041
18.0	0.024	0.05	0.072	0.054	0.037
19.0	0.024	0.045	0.075	0.053	0.036
20.0	0.024	0.045	0.078	0.053	0.037
21.0	0.022	0.043	0.076	0.047	0.032

22.0	0.02	0.042	0.071	0.046	0.029
23.0	0.024	0.039	0.066	0.047	0.029
24.0	0.022	0.036	0.066	0.045	0.03
25.0	0.017	0.035	0.062	0.04	0.024
26.0	0.02	0.033	0.06	0.041	0.028
27.0	0.016	0.029	0.054	0.039	0.023
28.0	0.019	0.028	0.05	0.038	0.024
29.0	0.017	0.029	0.052	0.032	0.023
30.0	0.012	0.024	0.047	0.033	0.02

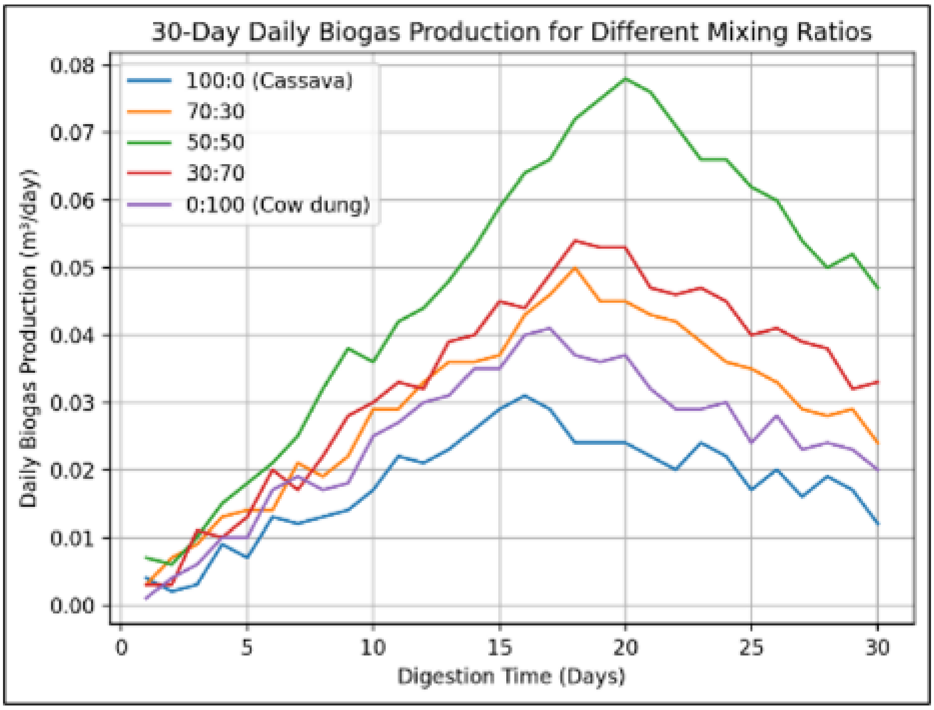

Figure 4: Daily biogas production during anaerobic digestion.

3.2 Methane Composition

Methane concentration increased markedly when cow dung was added to cassava peels, reaching a maximum mean value of **63.4%** at the **50:50** blending ratio. Cassava peel mono-digestion produced the lowest methane concentration (**51.3%**), whereas cow dung mono-digestion gave **57.2%.** The progressive rise from 100:0 to 50:50 indicates that co-digestion improved the methanogenic phase of digestion rather than simply increasing gas volume. In practical terms, this is the most important result because methane is the combustible fraction that determines the fuel value of biogas. A methane fraction in the low- to mid-60% range is generally regarded as suitable for small spark-ignition engines after basic gas cleaning [15, 20, 21]. The methane trend also reflects the inoculating effect of cow dung. Cow dung introduces an established anaerobic microbial community that helps convert volatile fatty acids into methane more effectively than cassava peels alone. Recent studies on cassava residues and cow-dung co-digestion have reported the same tendency: methane enrichment improves when the manure fraction is sufficient to stabilise the reactor but not so high that it dilutes the carbon-rich substrate. The present result is therefore consistent with recent reports that co-digestion can raise methane composition through better nutrient balance, improved buffering, and enhanced microbial synergy [5, 12, 22] .

Methane concentration is the most important indicator of biogas quality because it determines the energy available during combustion. The average methane concentrations obtained from the five substrate blending ratios are presented in **Table 2**, while the corresponding variation with substrate composition is illustrated in Figure 2. Methane concentration increased from 51.3% in the cassava peel mono-digestion (100:0) to 56.4% at the 70:30 blend and reached a maximum value of 63.4% at the 50:50 cassava peel–cow dung ratio. Beyond this optimum blend, methane concentration decreased slightly to 60.5% and 57.2% for the 30:70 and 0:100 substrate ratios, respectively. The observed trend indicates that methane production was strongly influenced by the interaction between the two substrates rather than by either substrate individually. The superior methane concentration obtained from the 50:50 blend suggests that this substrate combination provided the most favourable conditions for methanogenic microorganisms. Cassava peels supplied readily biodegradable carbohydrates that supported microbial metabolism, whereas cow dung contributed an active microbial consortium together with essential nutrients and buffering capacity required to stabilize the digestion process. The balanced carbon-to-nitrogen ratio created by the mixed substrates promoted efficient conversion of intermediate organic acids into methane, thereby increasing the combustible fraction of the produced biogas. The lower methane concentration observed during cassava peel mono-digestion can be attributed to nutrient limitations and insufficient buffering capacity, which may have resulted in the accumulation of volatile fatty acids and partial inhibition of methanogenic activity. Conversely, although cow dung mono-digestion provided an abundant microbial population, the reduced proportion of readily degradable carbon limited methane enrichment. These findings demonstrate that neither substrate alone provided optimum digestion conditions, whereas their combination generated a favourable biochemical environment for methane production. The methane concentrations obtained in the present study compare favourably with values reported for the anaerobic co-digestion of agricultural residues and livestock manure. Previous investigations have shown that methane concentrations between 55% and 65% are generally achieved during stable anaerobic digestion under mesophilic conditions, depending on substrate characteristics, reactor configuration, and operating conditions. The maximum methane concentration of 63.4% obtained at the 50:50 blending ratio therefore indicates that the produced biogas possesses sufficient fuel quality for small-scale electricity generation following appropriate gas cleaning. From an engineering perspective, increasing methane concentration directly enhances the calorific value of biogas and improves combustion efficiency. Consequently, the optimum substrate ratio identified in this study not only increased methane production but also improved the practical suitability of the produced biogas for renewable energy applications.

Table 2: Methane (CH_4), carbon dioxide (CO_2), and hydrogen sulphide (H_2S).

Synergistic Ratio	CH_4 T1 (%)	CH_4T2 (%)	CH_4T3 (%)	CH_4 MEAN (%)	CO_2 T1 (%)	CO_2 T2 (%)	CO_2 T3 (%)	CO_2 MEAN (%)	H_2S T1 (ppm)	H_2S T2 (ppm)	H_2S T3 (ppm)	H_2S Mean (ppm)
100:0	51.2	52.0	50.6	51.3	47.1	46.3	47.8	47.1	85	92	88	88
70:30	56.1	57.4	55.8	56.4	41.8	40.6	42.3	41.6	145	152	148	148
50:50	62.8	64.1	63.3	63.4	35.6	34.2	35.1	35.0	210	225	218	218
30:70	59.6	60.8	61.2	60.5	38.7	37.9	37.5	38.0	260	275	268	268
0:100	56.5	57.2	58.0	57.2	40.9	40.2	39.5	40.2	320	335	328	328

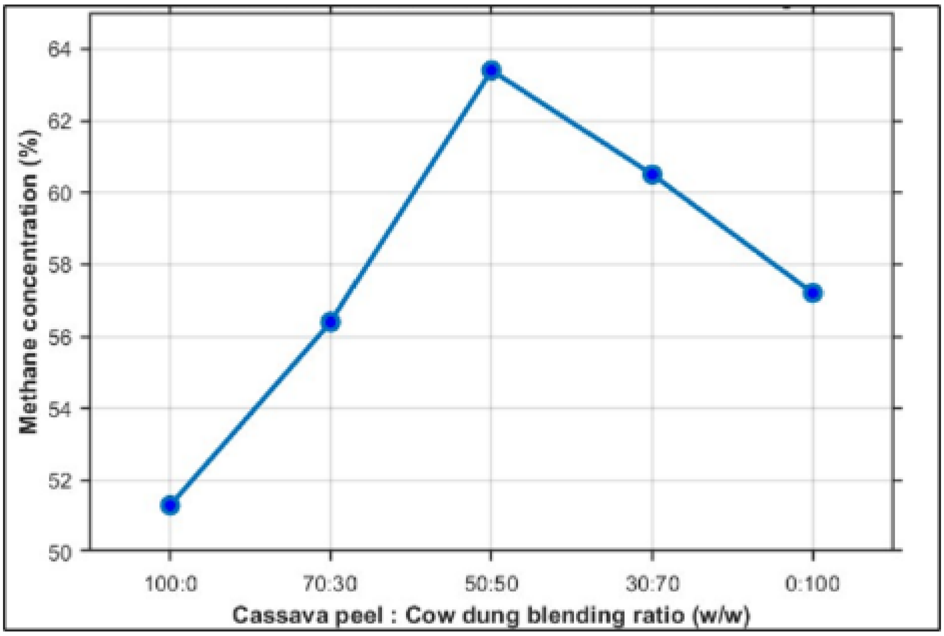

Figure 5: Methane concentration as a function of cassava peel–cow dung blending ratio

As the proportion of cow dung increased from 0% to 50%, methane concentration increased from 51.3% to 63.4%, after which it declined slightly with further increases in cow dung content (**Figure 5**). This trend indicates that the 50:50 cassava peel–cow dung blend provided the most favourable conditions for methanogenic activity.

3.3 Carbon Dioxide Composition

Carbon dioxide (CO_2) is the principal non-combustible component of biogas and has a direct influence on its energy value. A reduction in carbon dioxide concentration increases the proportion of methane in the gas mixture, thereby improving combustion efficiency and the calorific value of the fuel. The measured carbon dioxide concentrations for the different cassava peel–cow dung blending ratios are presented in **Table 2**, while the corresponding variation with substrate composition is shown in **Figure 6**. The highest average carbon dioxide concentration (**47.1%**) was recorded for cassava peel mono-digestion (100:0), whereas the lowest value (**35.0%**) was obtained at the 50:50 cassava peel–cow dung blend. Further increases in the proportion of cow dung resulted in a slight increase in carbon dioxide concentration to 38.0% and 40.2% for the 30:70 and 0:100 substrate ratios, respectively. This trend was opposite to that observed for methane concentration, indicating that the optimum substrate ratio promoted efficient methanogenesis through the conversion of carbon dioxide and intermediate compounds into methane. The reduction in carbon dioxide concentration observed at the 50:50 substrate ratio suggests that co-digestion created favourable environmental conditions for methanogenic microorganisms. The balanced availability of carbon, nitrogen, and essential nutrients improved microbial metabolism and enhanced the conversion efficiency of organic matter during the methanogenic stage. Consequently, a greater proportion of the biodegradable substrate was converted into methane rather than remaining as carbon dioxide in the final biogas mixture. The relatively high carbon dioxide concentration obtained during cassava peel mono-digestion may be attributed to incomplete conversion of intermediate fermentation products arising from nutrient imbalance and reduced microbial activity. Although cow dung mono-digestion improved microbial stability, the lower proportion of readily biodegradable carbohydrates limited methane formation, resulting in a moderate carbon dioxide concentration. These findings demonstrate that substrate composition significantly influences not only the quantity of biogas produced but also its chemical composition and fuel quality. From an energy perspective, lower carbon dioxide concentration is advantageous because it increases the heating value of biogas and reduces the need for extensive gas upgrading before utilisation. The minimum carbon dioxide concentration of 35.0% obtained in the present study corresponds to the highest methane concentration and subsequently the highest lower heating value, confirming that the 50:50 cassava peel–cow dung ratio produced the highest-quality biogas among the substrate combinations investigated. The inverse relationship between methane and carbon dioxide observed in this study agrees with the expected biochemical behaviour of anaerobic digestion. As methanogenic activity becomes more efficient, carbon dioxide is progressively converted into methane through hydrogenotrophic and acetoclastic pathways, resulting in methane enrichment and improved fuel quality. Consequently, optimisation of substrate composition represents an effective strategy for enhancing both biogas quality and energy recovery from agricultural residues.

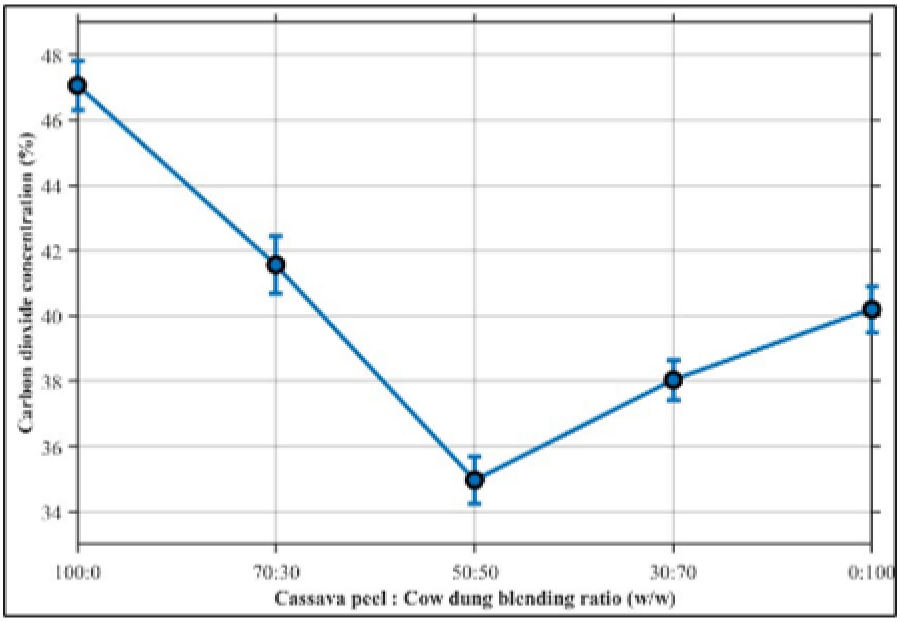

Figure 6: Carbon dioxide concentration is a function of substrate blending ratio.

3.4 Hydrogen Sulphide Composition

Hydrogen sulphide (H_2S) is an undesirable constituent of biogas because of its corrosive properties and adverse effects on combustion equipment. Although present in relatively low concentrations compared with methane and carbon dioxide, H_2S significantly influences the long-term performance and maintenance requirements of biogas-fuelled engines, pipelines, and storage systems. Consequently, evaluation of hydrogen sulphide concentration is essential when assessing the suitability of biogas for electricity generation. The measured H_2S concentrations for the different substrate blending ratios are presented in **Table 2**, while the corresponding variation is illustrated in **Figure 7**. The average hydrogen sulphide concentration increased progressively with increasing cow dung content in the substrate mixture. Cassava peel mono-digestion (100:0) produced the lowest H_2S concentration of 88 ppm, followed by 148 ppm for the 70:30 blend and 218 ppm for the 50:50 blend. Further increases in cow dung proportion resulted in hydrogen sulphide concentrations of 268 ppm and 328 ppm for the 30:70 and 0:100 substrate ratios, respectively. This gradual increase indicates that cow dung contributed a greater proportion of sulphur-containing compounds that were subsequently reduced to hydrogen sulphide during anaerobic digestion. The observed trend reflects the chemical composition of the feedstocks. Cassava peels generally contain relatively low sulphur levels and therefore generated biogas with lower hydrogen sulphide concentrations. In contrast, cow dung contains sulphur-bearing organic compounds originating from animal feed and metabolic processes. During anaerobic decomposition, sulphate-reducing bacteria convert these compounds into hydrogen sulphide, resulting in increased H_2S concentrations as the proportion of cow dung increased. Although the 50:50 cassava peel–cow dung blend produced a higher hydrogen sulphide concentration than cassava peels alone, it simultaneously generated the highest methane concentration and the lowest carbon dioxide concentration. This indicates that the moderate increase in H_2S represents a reasonable compromise for achieving superior fuel quality. Furthermore, the incorporation of a desulphurization unit into the gas purification system effectively reduced hydrogen sulphide prior to generator operation, minimizing the risk of corrosion and extending equipment service life. From an engineering perspective, hydrogen sulphide removal remains an important requirement for practical biogas utilization. Excessive H_2S concentrations accelerate corrosion of engine components, gas pipelines, storage vessels, and metallic fittings through the formation of sulphuric acid in the presence of moisture. Therefore, appropriate gas-cleaning technologies should be incorporated into biogas systems intended for continuous electricity generation. Overall, the results demonstrate that while increasing the proportion of cow dung enhanced methane production up to the optimum substrate ratio, it also increased hydrogen sulphide concentration. Consequently, selection of an appropriate substrate blend should consider both fuel quality and gas purification requirements. Among the substrate combinations investigated, the 50:50 cassava peel–cow dung ratio provided the most favourable balance between methane enrichment and acceptable hydrogen sulphide concentration for renewable energy applications.

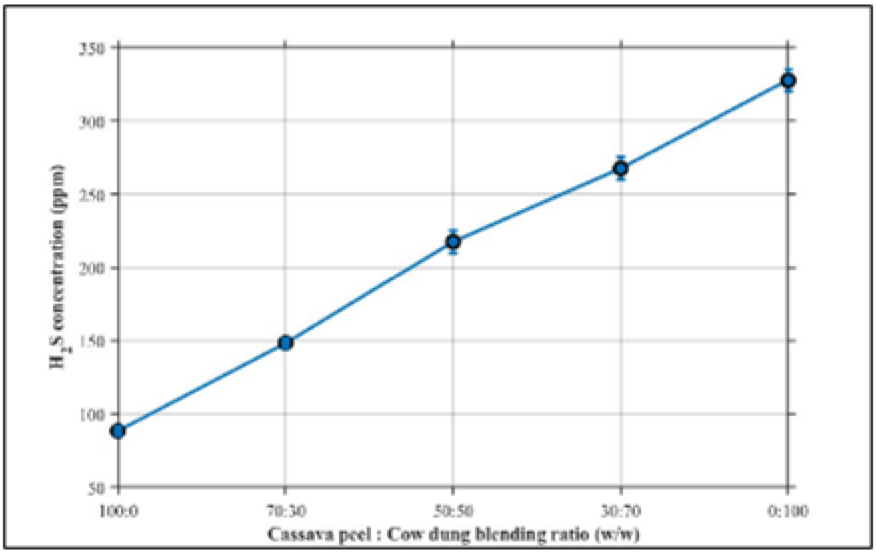

Figure 7: Hydrogen sulphide concentration as a function of substrate blending ratio.

3.5 Calorific Value of Biogas

The calorific value of biogas is a critical parameter for evaluating its suitability as a renewable fuel because it represents the amount of energy released during complete combustion. Since methane is the principal combustible component of biogas, the heating value is directly proportional to its methane concentration. The estimated lower heating values (LHV) for the different substrate blending ratios are presented in **Table 3**, while the relationship between methane concentration and calorific value is illustrated in **Figure 8**. The calorific value increased with increasing methane concentration, reaching a maximum value of 22.7 MJ m^{-3} at the 50:50 cassava peel–cow dung blending ratio. The corresponding methane concentration of 63.4% indicates that this substrate combination produced the highest-quality biogas among all the treatments investigated. Lower calorific values of 18.4 MJ m^{-3}, 20.2 MJ m^{-3}, 21.7 MJ m^{-3}, and 20.5 MJ m^{-3} were obtained for the 100:0, 70:30, 30:70, and 0:100 substrate ratios, respectively. These results demonstrate that substrate composition significantly influences not only methane concentration but also the energy content of the resulting biogas. The increase in calorific value observed at the optimum blending ratio is attributed to the improved methane enrichment achieved during co-digestion. The balanced interaction between cassava peels and cow dung created favourable conditions for methanogenic microorganisms, resulting in more efficient conversion of biodegradable organic matter into methane. Consequently, the combustible fraction of the biogas increased, leading to higher energy density and improved combustion characteristics. The close relationship between methane concentration and calorific value is evident from the results presented in **Figure 8**. As methane concentration increased from 51.3% to 63.4%, the corresponding lower heating value increased from 18.4 MJ m^{-3} to 22.7 MJ m^{-3}. This nearly proportional relationship confirms that methane concentration is an effective predictor of the fuel quality of raw biogas. Conversely, substrate combinations with lower methane concentrations produced lower heating values because a larger proportion of the gas consisted of non-combustible carbon dioxide. From an engineering perspective, biogas with a higher calorific value requires lower volumetric fuel consumption to produce the same power output, thereby improving generator efficiency and reducing fuel storage requirements. The maximum lower heating value obtained in this study indicates that the 50:50 cassava peel–cow dung blend is the most suitable substrate combination for decentralised electricity generation using biogas-fuelled spark-ignition generators. The results further demonstrate that optimising substrate composition provides a practical approach for improving biogas energy quality without additional upgrading processes.

Table 3: Lower heating value of biogas at different substrate blending ratios.

Synergistic Ratio	Average CH_4 (%)	Estimated LHV (MJ/m^3)
100:0 (Cassava peel)	51.3	18.4
70:30	56.4	20.2
50:50	63.4	22.7
30:70	60.5	21.7
0:100 (Cow dung)	57.2	20.5

Although advanced purification technologies can further increase methane concentration, the present findings show that careful selection of feedstock proportions alone can substantially improve the energy potential of biogas. This has important implications for rural and small-scale renewable energy systems, where simple and cost-effective process optimisation is often preferred over expensive gas upgrading technologies.

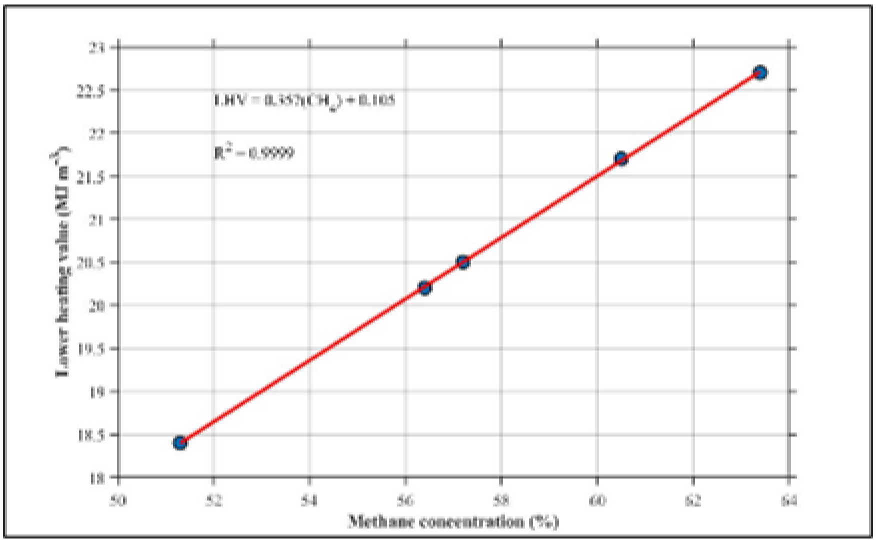

Figure 8: Relationship between methane concentration and lower heating value

The lower heating value increased almost linearly with methane concentration, indicating a strong positive relationship between biogas composition and energy content (**Figure 8**). The regression analysis yielded a coefficient of determination (R^2) of 0.9999, demonstrating an excellent linear fit between the measured methane concentration and the estimated lower heating value. The highest methane concentration (63.4%) corresponded to the maximum lower heating value (22.7 MJ m^{-3}), whereas the lowest methane concentration (51.3%) produced the lowest energy content (18.4 MJ m^{-3}). This relationship confirms that methane concentration is the principal determinant of the fuel quality of biogas. Consequently, improving methane enrichment through substrate optimization directly enhances the energy potential of the produced biogas for electricity generation.

4 DISCUSSION

4.1 Comparison with Previous Studies

The results of this study are consistent with previous reports showing that co-digestion improves anaerobic digestion performance by enhancing nutrient balance and microbial activity. The optimum 50:50 cassava peel–cow dung ratio produced the highest methane concentration (63.4%) and calorific value (22.7 MJ m^{-3}), confirming that balanced substrate mixtures generate higher-quality biogas than mono-digestion [3, 7]. Previous studies on cassava peels have reported that their high carbohydrate content favours biogas production but that low nitrogen availability limits methane generation during mono-digestion [3]. Likewise, cow dung provides an active microbial population and buffering capacity that improves digestion stability but performs better when combined with carbon-rich substrates [8]. Similar improvements have also been reported for food waste and other agricultural residues, where co-digestion increased methane production and process stability compared with single-substrate digestion [1, 23]. Overall, the present findings confirm that co-digestion is an effective strategy for improving biogas quality and energy recovery. In addition to evaluating methane production, this study incorporates calorific value, hydrogen sulphide concentration, generator performance, digester sizing, and environmental assessment, thereby providing practical engineering information for decentralised biogas energy systems.

Abbreviation

Abbreviation/Symbol	Definition/Unit
AD	Anaerobic digestion
Biogas	Biological gas produced during anaerobic digestion
CH_4	Methane
CO_2	Carbon dioxide
H_2S	Hydrogen sulphide
LHV	Lower heating value
HRT	Hydraulic retention time
VS	Volatile solids
COD	Chemical oxygen demand
C/N	Carbon-to-nitrogen ratio
ANOVA	Analysis of variance
SD	Standard deviation
HSD	Honestly significant difference
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
VBG	Biogas volume
VD	Digester volume
Msub	Substrate mass
G	Biogas production
Gp	Volumetric gas production rate
Sd	Daily slurry input
Ybg	Specific biogas yield
fVS	Volatile solids fraction
α	Effective digester productivity
ΔCO_2	Carbon dioxide emission reduction

t	Runtime/operating time (h/day)
V	Volume (m^3)
D	Digester internal diameter (m)
H	Digester height (m)
Q	Flow rate
kg	Kilogram
m^3	Cubic metre
h	Hour
day	Day
ppm	Parts per million
%	Percentage
MJ	Megajoule
kW	Kilowatt
w/w	Weight-to-weight ratio
p	Probability value
R^2	Coefficient of determination

5 CONCLUSIONS

This study evaluated the influence of cassava peel–cow dung blending ratios on biogas quality, energy potential, and engineering performance through laboratory-scale anaerobic digestion. Based on the experimental findings, the following conclusions are drawn:

- The anaerobic co-digestion of cassava peels and cow dung successfully produced biogas suitable for renewable energy applications, with substrate blending ratio significantly influencing gas composition and energy quality.
- The 50:50 cassava peel–cow dung blend produced the best overall performance, achieving the highest methane concentration (63.4%), the lowest carbon dioxide concentration (35.0%), and the highest lower heating value (22.7 MJ m^{-3}).
- Generator calibration established an average biogas consumption rate of 0.37 $m^3\ h^{-1}$, providing practical design data for estimating substrate requirement, digester capacity, and continuous electricity generation.
- The engineering analysis demonstrated that optimised co-digestion could support decentralised power generation while reducing fossil fuel dependence and achieving potential carbon dioxide emission savings of up to 38.81 kg day^{-1} when replacing petrol.
- The study demonstrates that combining cassava peels with cow dung is an effective waste-to-energy strategy that improves biogas quality, enhances energy recovery, and promotes the sustainable utilisation of agricultural residues.
- Future studies should investigate continuous reactor operation, process optimisation under different operating conditions, and techno-economic assessment to facilitate large-scale implementation of cassava peel–cow dung biogas systems.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Author Contributions

K.T.A.: Conceptualisation, Methodology, Investigation, Data Curation, Formal Analysis, and Research Execution. T.J.A.: Supervision, Methodology, Validation, and Critical Review. O.E.A.: Supervision, Validation, Methodological Guidance, and Critical Review. E.E.E.: Writing – Original Draft Preparation, Writing – Review & Editing, and Visualisation. All authors reviewed and approved the final version of the manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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