

Performance evaluation and Exergetic analysis of a pilot-scale vertical biodigester using cow dung

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Abstract

Fossil fuels dominate global energy consumption, necessitating the shift to sustainable alternatives like biogas. This study investigates the thermodynamic and economic feasibility of cow dung-based biogas as a small-scale cooking fuel in a Nigerian context. Biogas was produced using cow dung feedstock in a locally fabricated 0.165m³ vertical drum reactor operated in a semi-continuous mode. Gas composition was measured using the wet chemistry method, followed by a boiling test for heat value determination and a second-law (exergy) analysis to assess thermodynamic efficiency. Finally, a breakeven analysis compared biogas viability against common household fuels, kerosene, and Liquefied Petroleum Gas (LPG). The biogas contained 70% methane, yielding a heating value of 25,098 kJ/m³, indicating high methane quality typical of well-digested slurry. However, the second-law efficiency was only 4.87%, reflecting significant exergy losses primarily due to burner inefficiencies. The breakeven analysis demonstrated that the biodigester investment becomes cost-effective after approximately 337 nominal days when replacing LPG, and 525 nominal days when replacing kerosene. These findings confirm the strong potential of cow dung biogas as an environmentally friendly and economically viable long-term energy source. Improved burner efficiency is critical to maximising the thermodynamic potential and speeding up the adoption of this technology.

Keywords: Biogas; Cow Dung; Cooking Fuel; Economic Feasibility; Exergy

1. Introduction

Energy is the backbone of economic development and human well-being. However, the global energy landscape remains heavily dependent on fossil fuels, which account for approximately 80% of primary energy consumption and drive anthropogenic climate change [1]. Additionally, fossil fuels are finite, with projected depletion times of 133-139 years for coal, 47-56 years for oil, and 49-52 years for natural gas based on available reserves and consumption rates in 2024 [2]

In the Nigerian context, the urgency for such alternatives is critical. According to the United Nations Framework Convention on Climate Change (UNFCCC), an estimated 98% of Nigerian households lack access to quality cooking and lighting fuels, compelling families to rely on inferior, health-damaging sources such as firewood and kerosene [3]. This dependence, as claimed by the UNFCCC, imposes a severe burden on women, who face the daily drudgery of gathering wood from depleting forests, and exposes households to hazardous indoor air pollution caused by soot-laden kerosene fumes. While various clean energy initiatives exist, the scarcity and cost of commercial fuels remain a barrier. Consequently, adopting biogas technology powered by cow dung, an abundant resource in rural farming settlements, presents a vital, decentralized solution. It directly addresses these challenges by converting agricultural waste into a clean-burning fuel, thereby mitigating the health risks of indoor pollution and reducing the economic strain of kerosene dependency.

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This study aims to convert cow dung into biogas, providing a rich alternative energy source. Objectives include collecting cow dung for biogas production, analyzing the energy content of the biogas, conducting exergy analysis, and evaluating the cost-effectiveness of using biogas for cooking and heating compared to some fossil fuels. The study directly addresses environmental issues by preventing methane emissions and promoting sustainable agriculture practices. By providing a stable, local energy source, especially in rural areas, biogas production can improve energy security and reduce reliance on fossil fuels.

The potential beneficiaries of this study include rural households, livestock farmers, and agricultural communities with significant cattle farming. The target market comprises rural areas lacking access to clean cooking fuel. Expected contributions include advancements in renewable energy, sustainable agriculture, waste management, and climate change mitigation, serving as a model for broader adoption.

2. Materials and methods

2.1. Generation of Biogas

A single feedstock, cow dung, was used for biogas production. The cow dung was obtained from the University of Ibadan Teaching and Research Farm, Ibadan, Oyo State. The biodigester was made from a 0.165 m³ (165 litres) plastic drum, purchased at a local market in Ibadan, Oyo State. Some of the reasons for choosing plastic for the biodigester include its cost-effectiveness which plays an important role in ensuring the viability of the biodigester, flexibility in design, durability and ability to withstand harsh environmental conditions crucial in environments characterised by fluctuating temperatures, and exposure to ultraviolet radiation, and ease of maintenance which help to minimise the risk of microbial contamination and ensure optimal performance over an extended service life. The items listed in Table 1 were used to set up the biodigester.

The plastic digester, a vertical drum reactor operated in a semi-continuous mode, was fed up to 85% of its capacity (approximately 140 litres) with cow dung substrate. To simulate accessible rural operating conditions, no external inoculum or seed sludge was introduced. The digestion process relied entirely on the indigenous microbial population present in the fresh cow dung (self-inoculation).

The drum was meticulously cleaned to ensure that it was devoid of any contaminants or residues that may interfere with the anaerobic digestion process. A gas collection mechanism was installed at the top of the drum to which a transparent PVC gas hose was connected. The hose linked the digester to the gas storage, which comprised an automotive inner tube (tyre tube) serving as a flexible gas holder. The tyre tube is a cost-effective alternative to a biogas storage bag. Its availability, ease of installation, durability, and flexibility make it a better choice.

The daily yield was quantified by measuring the circumferential expansion of the tube using a flexible tape measure. These dimensional changes were correlated to volume using the torus geometry of the inflated tube. On the lower side of the digester, a 3-inch pipe was connected at an angle to the drum to feed the digester with slurry. A 1-inch pipe with an air valve was also connected to a point 75cm from the base of the drum for the effluent as shown in Figure 1.



Figure 1 Biodigester

Table 1 Bill of Materials

Item	Description	Quantity
1	165 litres Plastic Drum	1
2	3-inch Pipe	1
3	1-inch Pipe	1/2
4	Hose Clip	5
5	Hose	4 yards
6	1-inch Elbow Joint	1
7	1-inch Air Valve	1
8	1-inch Back Nut	1
9	Gas Control Valve	1
10	Nozzle	1
11	Gas Storage Tube	2

2.2. Operational Conditions and Feedstock Characteristics

The biodigester was loaded with 25kg of cow dung slurry, and gas production commenced 21 days after loading. The anaerobic digestion process was conducted at mesophilic ambient conditions, with daily operating temperatures ranging from 29°C to 33°C (mean: 31.4°C). The influent feedstock was prepared by diluting fresh cow dung with water at a 1:1.8 ratio [4]. Adopting the standard total solids (TS) value of approximately 18% for fresh cow dung [5], the resulting slurry was estimated to have a TS content of approximately 6.4%, which ensures optimal fluidity for the gravity-fed system.

The digester operated on a semi-continuous feeding regime, receiving a daily load of 10 litres of slurry for an initial period of 14 days, corresponding to a theoretical Hydraulic Retention Time (HRT) of 14 days based on the operational volume of 140 litres. This daily feeding strategy was employed to maintain microbial population stability, ensure consistent biogas production, and facilitate substrate mixing. Regarding process stability, the system relied on the inherent buffering capacity of the substrate rather than external pH control. The observed 21-day lag phase indicates an initial period of acidification followed by a recovery to neutral conditions as methanogenesis stabilised. This lag phase is typical of non-inoculated digesters, where rapid hydrolysis leads to volatile fatty acid (VFA) accumulation that temporarily inhibits methanogenesis [6].

2.3. Biogas Compression and Flammability Test

The biogas stored in the tube was passed through a scrubber containing steel wool. This material, rich in iron and zinc, interacts with H₂S, thereby reducing its concentration in the biogas [7]. The removal of H₂S from the biogas is important due to its corrosive nature and hazardous impact on health and the environment. The set-up for the gas compression process is shown in Figure 2. The inlet pipe of a dry scrubber was connected to the biogas storage tube, while the outlet was connected to the suction line of an electric compressor. The compressor discharge line was then attached to a gas cylinder using a hose and secured with a hose clip. After the compression of the biogas in a gas cylinder, a flammability test was carried out to ascertain that the gas produced was truly biogas. The cylinder was connected through a hose to a biogas stove, and the stove was then ignited after opening the gas valve. The gas was found to combust, confirming the produced gas to be biogas.

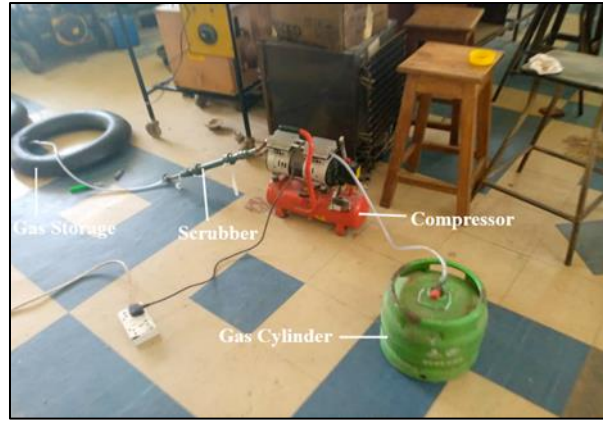


Figure 2 Setup for Harvesting and Compressing the Biogas

2.4. Determination of Biogas Methane Content

To determine the amount of methane in the biogas produced, the Wet Chemistry CH₄ measuring method was used, since neither a gas chromatograph nor a gas analyser was available. A 500-ml graduated measuring cylinder and a 1-litre container were utilised for the test. 0.5 M hydrochloric acid (HCl) was poured into the cylinder and then inverted into the container. Some volume of HCl was also added to the container. The biogas was introduced into the cylinder through a hose, and bubbles could be seen as it displaced some of the HCl and settled at the top of the cylinder. The volume of gas (V₁, ml) was then read. Next, NaOH was added until the pH of the solution rose to 11. The solution was then left for some hours for the absorption of CO₂ and H₂S. This absorption reduced the volume of gas in the measuring cylinder to V₂. The volume V₂ was an estimate of CH₄ in the gas. The difference between the initial and final volume corresponded to the CO₂ content in the biogas. The H₂S concentration was considered negligible compared to the CO₂ concentration.

$$\text{Percentage concentration of Methane, } X_{CH_4} = \frac{V_2}{V_1} \times 100\% \quad 1$$

Percentage concentration of Carbon dioxide,

$$X_{CO_2} = \frac{V_1 - V_2}{V_1} \times 100\% \quad 2$$

The calorific value of the biogas, H_{u, act} was evaluated using the equation below as prescribed by Von Mitzklaff [8]:

$$H_{u, act} = X_{CH_4} \times \rho_{CH_4, act} \times H_u \quad 3$$

Where H_u is the lower calorific value of biogas (kJ/kg), X_{CH₄} is the percentage concentration of methane in the biogas, and ρ_{CH₄, act} is the actual density of methane in the biogas.

$$\rho_{CH_4, act} = \rho_{CH_4, std} \times \frac{P_{act}}{P_{std}} \times \frac{T_{std}}{T_{act}} \quad 4$$

Where ρ_{CH₄, std} is the density of methane at standard conditions (i.e., 298 K, 1013mbar=0.1013 MPa) given as 0.7168kg/m³ [9], P_{std} is the pressure of methane under standard conditions (1013mbar), T_{std} is the temperature of methane under standard conditions (298K), P_{act} is the actual pressure of biogas, T_{act} is the actual temperature of biogas

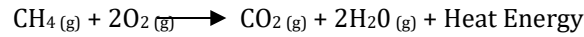
2.5. Biogas Boiling Test

A standardized water boiling test was conducted using a biogas burner based on the design by Ademuwagun [10], which has a reported efficiency of 42.32%. The experimental setup involved heating 300 ml of water in an aluminium vessel.

During the test, the water temperature rose from an initial value (T₁) of 31.4°C to a final boiling point (T₂) of 98°C, with a total heating time of 505 seconds. The ambient temperature (T₀) during the experiment was maintained at 33°C. Fuel consumption was quantified gravimetrically, with the mass of the gas cylinder measured before (M₁) and after (M₂) the boiling process, recording values of 8.6495 kg and 8.5508 kg, respectively. The total mass of biogas consumed (m) was subsequently calculated as the difference between these initial and final weights.

2.6. Exergy Analysis of Biogas When Used for Boiling

The type of exergy involved in the combustion of fuels is primarily chemical exergy. Chemical exergy represents the maximum work that can be obtained when a substance undergoes a complete chemical reaction to a reference state, typically at standard conditions. In the case of combustion, the chemical exergy is associated with the energy released as the fuel reacts with oxygen to form combustion products, such as carbon dioxide, water, and other compounds, releasing heat energy. When biogas is combusted, the methane component is the primary fuel that releases energy. The methane is oxidized to CO₂ and H₂O during the combustion process, releasing heat that can be used to generate electricity or provide heating. The combustion of biogas can therefore be represented with the chemical equation below:



During combustion, the oxygen (O₂) in air is the reactive component that combines with methane (CH₄) to produce carbon dioxide (CO₂) and water (H₂O). Nitrogen, being inert, does not participate in the reaction. Including nitrogen in the equation would not change the stoichiometry or the reaction's outcome, so it is typically left out for simplicity. The system's boundary contains the biogas cylinder, the connecting hose, the biogas burner and the pot.

The chemical exergy of the combustion of biogas described in the previous section was evaluated using the formula from Moran M.J *et al* [11].:

$$E_{e, ch} = m \left[\left[\bar{g}_f + \left(a + \frac{b}{4} \right) \bar{g}_{O_2} - a \bar{g}_{CO_2} - \frac{b}{2} \bar{g}_{H_2O_{gas}} \right] (T_0, p_0) + RT_0 \ln \left[\frac{(y_{O_2})^{a+\frac{b}{4}}}{(y_{CO_2})^a (y_{H_2O})^{\frac{b}{2}}} \right] \right] \quad 5$$

Where $E_{x, ch}$ denotes the standard chemical exergy of methane expressed in kJ/kmol, while m represents the mass of the biogas consumed (in kg). The terms $\bar{g}_f$, $\bar{g}_{O_2}$, $\bar{g}_{CO_2}$, and $\bar{g}_{H_2O}$ correspond to the standard Gibbs free energy of formation (kJ/kmol) for methane, oxygen, carbon dioxide, and water vapour, respectively. For the stoichiometric and environmental parameters, a and b represent the number of moles of carbon and hydrogen atoms in the fuel molecule, R is the Universal Gas Constant (kJ/kmol), and y denotes the mole fraction of the component gases in the reference environment. Finally, T_0 and P_0 refer to the standard ambient temperature and pressure conditions.

With a biogas stove of efficiency η , the actual exergy input, $E_{x, act}$ was evaluated as:

$$E_{x, act} = \eta \times E_{x, ch} \quad 6$$

$E_{x, act}$ therefore, represents the useful heat energy supplied by the biogas to the pot and water during heating.

The heat gained by the pot and the change in exergy of the water from its initial to final temperatures constitute the useful energy, E_{out} , supplied by the biogas during the heating process.

The change in the thermomechanical exergy, ΔE_{water} , of the water was obtained using equation 7:

$$\Delta E_{water} = \rho_{water} \cdot V_{water} [(u_2 - u_1) + P_0(v_2 - v_1) + T_0(s_2 - s_1)] \quad 7$$

In this expression, ΔE_{water} represents the change in the thermomechanical exergy of the water contents. The terms ρ_{water} and V_{water} denote the density (kg/m³) and volume (m³) of the water, respectively. The thermodynamic properties u , v , and s correspond to the specific internal energy (kJ/kg), specific volume (m³/kg), and specific entropy (kJ/kg.K) of the water at the initial state (subscript 1) and final state (subscript 2). P_0 and T_0 refer to the ambient pressure (kPa) and ambient temperature (°C) during the experiment.

The heat gained by the aluminium pot, E_{pot} , during the cooking, was estimated using equation 8:

$$E_{pot} = m_{pot} \cdot c_p \cdot (T_{p2} - T_{p1}) \quad 8$$

m_{pot} denotes the mass of the pot (kg). The term c_p is the specific heat capacity of aluminum (kJ/kg, K), and T_{p1} and T_{p2} indicate the initial and final temperatures of the pot in degrees Celsius (°C), respectively.

Therefore, the total exergy output, E_{out} , was estimated as:

$$E_{out} = \Delta E_{water} + E_{pot} \quad 9$$

The exergy destroyed (Irreversibility), $E_{destroyed}$, during the cooking process was thus estimated as:

$$E_{destroyed} = E_{x,biogas} - E_{out} \quad 10$$

The second law efficiency, η_{II} , was then evaluated as:

$$\eta_{II} = \frac{E_{out}}{E_{x,biogas}} \times 100\% \quad 11$$

2.7. Assessment of the Effectiveness of Biogas as a Source of Heat

Assessing the effectiveness of biogas as a source of heat involves evaluating its performance compared to other heating sources in terms of various factors such as energy efficiency, cost-effectiveness, environmental impact, and practicality. Investigation was done by comparing biogas with Liquified Petroleum Gas (LPG) and kerosene, two popular fossil fuels used in Nigerian homes. Table 2 gives a detailed description of the installation cost of the biodigester, which is the major starting structure for biogas production.

Table 2 Bill of Materials with Costs

Item	Description	Unit Price (N)	Quantity	Cost(N)
1	165 LITRES PLASTIC DRUM	11,500	1	11,500
2	3-INCH PIPE	3,000	1	3,000
3	1-INCH PIPE	1500	1/2	750
4	HOSE CLIP	120	5	600
5	HOSE	600/YARD	4 YARDS	2,400
6	1-INCH ELBOW JOINT	120	1	120
7	1-INCH AIR VALVE	600	1	600
8	1-INCH BACK NUT	600	1	600
9	GAST CONTROL VALVE	1500	1	1,500
10	NOZZLE	5000	1	5,000
11	GAS STORAGE TUBE	7,000	2	14,000
12	BUCKETS	1500	2	3,000
13	BIOGAS STOVE (SINGLE BURNER	50,000	1	50,000
14	LABOUR COST	10,000		10,000
15	GUM	1,200	2	2,400
	TOTAL			105,470

A boiling test was done for kerosene in order to compare it with biogas. 300 ml of water, just as it was used in the biogas boiling test above, was boiled, and the average volume of kerosene used was recorded. The initial and final temperatures of the water were ensured to be the same as that of the previous biogas test, and the same stove was used for the boiling.

The average volume of the kerosene used for the boiling was found to be 10 ml.

Similarly, the boiling procedure was repeated using Liquified Petroleum Gas (LPG) and 300 ml of water at the same initial and final temperatures as the previous two experiments. To measure the mass of LPG used for heating, the initial mass of the cylinder containing the gas was measured, and the final mass after boiling was measured.

Initial Mass of the Cylinder, $m_1 = 4.2852\text{kg}$, Final Mass of the Cylinder, $m_2 = 4.2693\text{kg}$, Mass of LPG used, $m = m_1 - m_2 = 0.0159\text{kg}$

$$\text{Heat gained by water during boiling, } E_{\text{water}} = \rho_{\text{water}} \cdot V_{\text{water}} \cdot C_{p, \text{water}} (T_2 - T_1) \quad 12$$

Where: $C_{p, \text{water}}$ is the specific heat capacity of water

A breakeven analysis was then conducted to determine when investing in a biogas installation to replace cooking for a family of four becomes profitable, serving as a model for large-scale adoption. To account for inflation's effect on fuel costs, Nigeria's official inflation rate for the period of study was applied. According to the National Bureau of Statistics, the headline inflation rate stood at 29.9% in January 2024 [12]. This value was used to project the future cost of kerosene and LPG in the economic viability analysis of biogas relative to these fossil fuels. The cumulative costs of kerosene and LPG were adjusted for inflation over time, and break-even calculations were conducted under both nominal and discounted conditions. Specifically, present-value analyses were performed using discount rates of 0%, 10%, 20%, and 30% to assess the sensitivity of economic outcomes to variations in capital cost assumptions. This approach ensured that the comparison between biogas, LPG, and kerosene reflected both current market prices and the realistic effects of inflation and discounting on long-term household energy expenditures.

The adjusted daily price C_t at day t was calculated as:

$$C_t = P_0 \times (1 + i)^{\frac{t-1}{365}} \quad 13$$

With P_0 representing the baseline daily cost, i is the annual inflation rate (29.9%), and t is the number of days from the starting point.

The present value (PV) of kerosene costs over time was calculated using the standard discounted cash flow formula:

$$PV = \sum_{t=1}^n \frac{C_t}{(1+r)^t} \quad 14$$

C_t is the cost of kerosene/LPG at day t , adjusted for inflation (29.9% per annum, NBS, 2024), r is discount rate (0%, 10%, 20%, 30%), and n is the number of days considered.

Several techno-economic studies assume annual maintenance and O&M (operations and maintenance) costs as a percentage of capital cost. In this study, a conservative 3% annual maintenance cost was adopted for the sensitivity analysis.

For the economic viability of biogas compared to kerosene and LPG, the following assumptions were made:

- There is a linear relationship between the volume of kerosene used and the heat energy produced.
- A litre (1000ml) of kerosene costs N1354 as of April 2024 [13].
- There is no maintenance cost, and the effect of inflation is uniform for all costs involved.
- A person consumes approximately 140g of rice per day [14].
- 210kJ of heat is required for cooking 140g of rice per day [15].
- The cost of a standard cooking kerosene stove is approximately N18,000.
- For biogas use, an annual maintenance cost of N3,164 was used.
- The price per kg of LPG is N1,100.
- There is a linear relationship between the mass of LPG used and the heat energy produced.

3. Results and discussion

3.1. Biogas Production

The results of this study offer valuable insights into the production of biogas from animal waste. The experiment demonstrated that anaerobic digestion of animal waste is a viable method for biogas generation, with several important factors influencing the process. The biogas yield obtained in this experiment was significant, indicating the effectiveness of the anaerobic digestion process. During the first 7 days after the feeding of the digester with new slurry was halted (equivalent to 21 days after the feeding of the digester was started), there was negligible biogas production. This

observation is similar to that given by [16], where it was observed that such lag phase in biogas production can occur as anaerobic microorganisms adapt to the new environment within the digester.

Significant gas production, however, started 7 days after the feeding of the digester with slurry was stopped. This was deduced by the physical inspection of the gas tube for expansion. The gas production reached its peak 5 days after gas production started, producing around 0.012m^3 (12 litres) in 24 hours. Biogas production declined sharply, approximately 50 days after the digester was fed. Research from previous related works indicates that this decline was due to the reduction in methanogenic bacteria present in the digester [17]. The decrease in the number of these bacteria resulted in a reduction of nearly 50% of the initial production rate.

Table 3 Summary of Biogas Production Phases and Environmental Conditions

Process Phase	Duration	Average Ambient Temperature	Observed Biogas Yield Status	Physicochemical State
Lag Phase	21 days	31.4 ± 2.0	Negligible: No visible inflation of the storage tube.	Hydrolysis/Acidogenesis: Initial pH drop and acclimatization of methanogens.
Active Phase	29 days	32.1 ± 2.5	Peak Production: Rapid daily inflation of the tyre tube.	Methanogenesis: Stable consumption of VFAs and high methane generation.
Decline Phase	10 days	30.8 ± 2.0	Diminishing: Slower inflation rate observed.	Substrate Depletion: Exhaustion of available biodegradable organic matter.

Biogas production was also noticed to be higher during the day when the atmospheric temperature is high and the sun is in direct contact with the digester. This observation was also noted by [18]. This suggests that a higher biogas production rate may occur at higher ambient temperatures, and that placing the digester under direct sunlight can also help achieve faster biodigestion.

Bottling the biogas significantly reduces the volume of biogas, making it easier to transport it for various experiments and also easing its storage.

Generally, cow dung serves as a potent substrate for anaerobic digestion, leading to a notable overall biogas output. This indicates the robust activity of anaerobic bacteria in cow dung, effectively breaking down the organic components of cattle manure, even when pH levels were not controlled.

3.2. Evaluation of the Heating Value of the Biogas

The results of the wet-chemistry test to determine the percentage of methane in the biogas sample are presented below. It was assumed that the biogas contained only methane and CO_2 , with other gases negligible.

From the experiment, V_1 gives 125ml and V_2 was 87.5ml. The percentage of CH_4 , X_{CH_4} , was 70% while the percentage of CO_2 , X_{CO_2} , was 30%. This result is close to that obtained by [19] where a 45-litre capacity prototype biogas plant was used for anaerobic digestion using cassava peel, cow dung, and cowpea as feedstocks, and the percentage of methane in the cow dung feedstock was found to be 67.9%. It should however be noted here that the wet chemistry method is approximate, and a more accurate result for the composition of the biogas can be obtained by using a gas chromatograph, if available. Taking the lower heating value of $\text{CH}_{4(\text{g})}$ to be $50,020\text{kJ/kg}$ [11], the calorific value of the biogas was calculated to be $25,098.04\text{kJ/m}^3$. This implies that if one cubic metre of the produced biogas is burnt completely, it produces approximately 25 MJ of heat. This calorific value is very close to the $20,799\text{ kJ/m}^3$ obtained by Anusha *et al.* [20] for biogas produced from cow dung without the removal of moisture content, and with the 21.83 MJ/m^3 reported by Roubík *et al.* [21] for small-scale biogas systems in Central Vietnam.

In comparison, standard commercial fuels exhibit significantly higher energy densities: gaseous Liquefied Petroleum Gas (LPG) has a Lower Calorific Value of approximately $93,200\text{ kJ/m}^3$, while liquid Kerosene contains roughly $35,000,000\text{ kJ/m}^3$ (35 GJ/m^3) due to its high liquid density [22]. Consequently, the volumetric energy density of the biogas is approximately 27% that of LPG and less than 0.1% that of liquid Kerosene. This necessitates significantly larger storage volumes and burner orifices for biogas to deliver equivalent thermal power

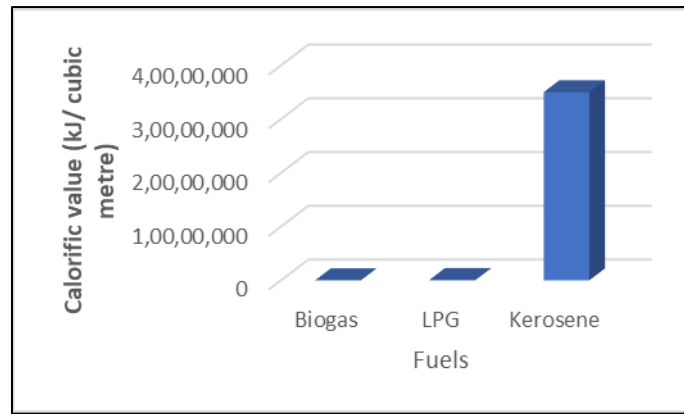


Figure 3 Plot of Calorific Values of Biogas, LPG and Kerosene

3.3. Evaluation of the Exergy of Biogas When Used for Boiling

The exergy analysis revealed the thermodynamic performance of the biogas during the boiling application. The total mass of biogas consumed for the test was 0.0987 kg. Based on the methane concentration of 70%, the specific standard chemical exergy of the biogas was calculated to be 35,980.46 kJ/kg.

When adjusting for the burner's first-law efficiency (42.32%), the actual chemical exergy available for the boiling process, $E_{x,act}$, was found to be 1,502.90 kJ, indicating that approximately 58% of the fuel's theoretical work potential was initially lost due to combustion inefficiencies in the burner.

The total useful exergy output ($E_{x,out}$), calculated as the sum of the exergy gains of the water and the aluminium pot, was 73.23 kJ. Specifically, the exergy change of the water was evaluated at 153.16 kJ using thermodynamic properties interpolated at 31.4°C and 96°C [22].

Consequently, the overall Second Law (Exergy) Efficiency of the system was calculated to be 4.87%. Interpreting this value, it is evident that only a small fraction of the available energy quality is effectively utilised for boiling. This signifies that a substantial portion of the energy input is lost due to exergy destruction (irreversibilities) inherent in the process. These irreversibilities are primarily driven by the biogas burner inefficiencies [23], the large temperature gradient between the flame and the pot [24], as well as convective heat losses to the surroundings [25]. The high exergy destruction confirms that the simple burner design is the major thermodynamic bottleneck, suggesting that optimising the burner geometry and insulation could significantly reduce entropy generation.

3.4. Cost-Effectiveness of Cooking with Biogas

Various research works have established that using biogas as fuel for cooking is more environmentally friendly than burning fossil fuels for the same purpose. However, there is a need to investigate the economic viability of cooking with biogas when compared with some fossil fuels combustion and the results of the cooking tests performed with biogas, kerosene and Liquefied Petroleum Gas (LPG) are applied to carry out this test.

3.4.1. Economic Viability of Biogas Compared with Kerosene

From the boiling test described in the previous chapter, the heat gained by the water during boiling, E_{water} , was 81.0kJ. Therefore, a proportion shows that approximately 25.93 ml of kerosene will be required to provide 210 kJ of cooking energy. This calculation assumes the same efficiency for both kerosene stoves used. Actual efficiency may vary based on the specific stove or cooking method. The price of 25.93ml kerosene for cooking for a family of 4 was then calculated to be N140.40

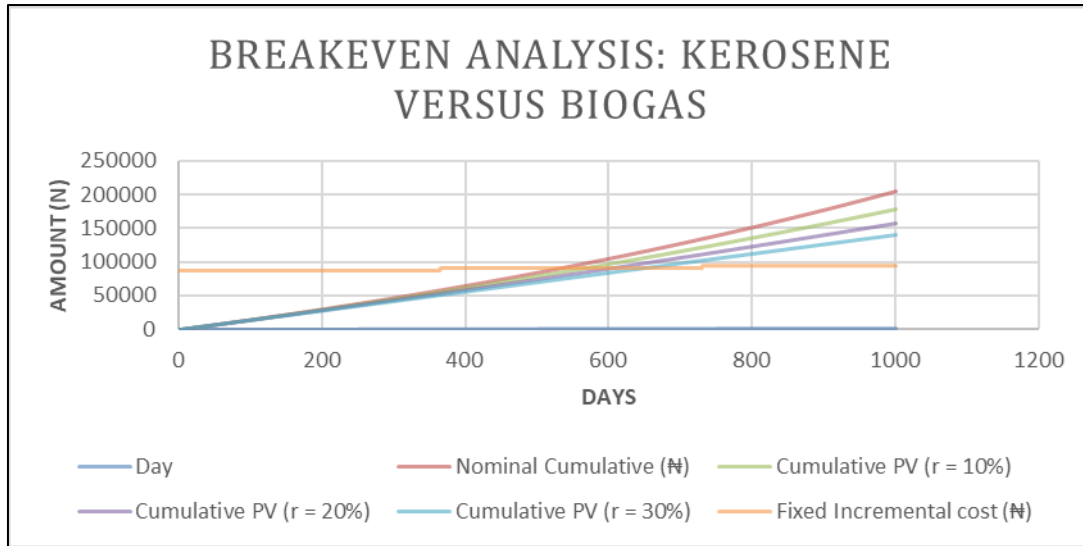


Figure 4 Breakeven Analysis for comparing biogas and kerosene

The breakeven analysis revealed that the biodigester system's payback period varies with the discount rate applied. Under nominal conditions (no discounting), the breakeven point was achieved in approximately 525 days (≈ 1.4). When discounting was introduced, the breakeven period extended to 560 days (≈ 1.5 year) at a 10% discount rate, 612 days (≈ 1.7 years) at 20%, and 653 days (≈ 1.8 years) at 30%. This trend indicates that higher discount rates, reflecting increased opportunity costs of capital, significantly delay cost recovery, underscoring the sensitivity of project viability to financial assumptions. Overall, biogas use proves economically viable.

3.4.2. Economic Viability of Biogas Compared with Liquefied Petroleum Gas

Since 0.0159kg of LPG supplies 81 kJ of heat, a proportion was set up to find the mass of LPG needed for 210 kJ, yielding 0.0412kg. The price of LPG for cooking for a family of 4 was then estimated at N181.28.

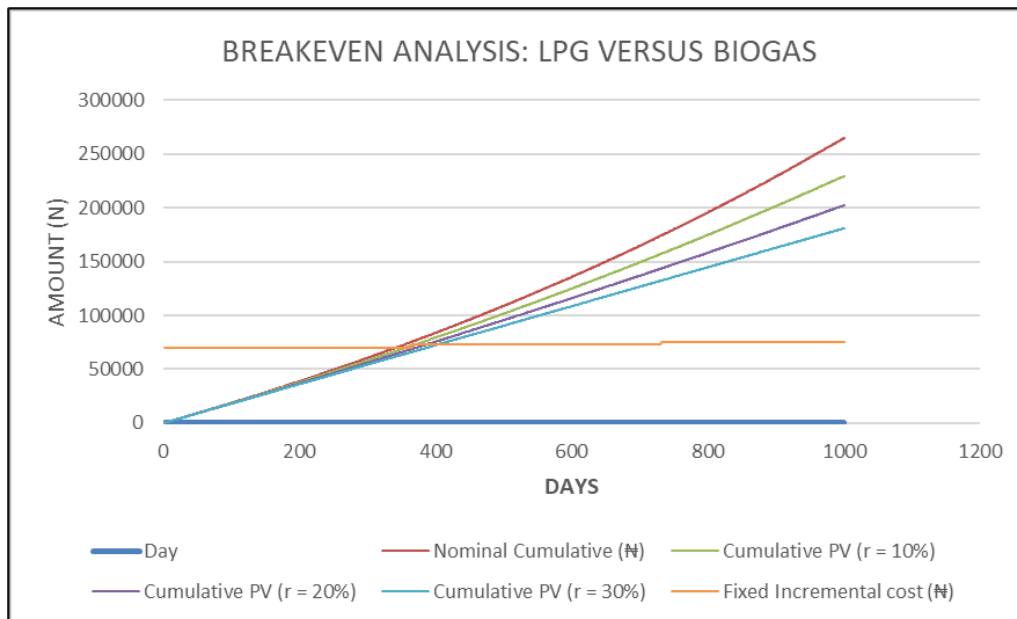


Figure 5 Breakeven Analysis for comparing biogas and LPG

When biogas is compared with LPG, the breakeven analysis shows a faster payback than with kerosene, but the same sensitivity to financial assumptions. In the nominal case (no discounting), the breakeven occurs at ≈ 337 days. Introducing discounting extends the payback to ≈ 351 days at 10%, ≈ 383 days at 20%, and ≈ 400 days at 30%. As with the kerosene comparison, higher discount rates — which reflect greater opportunity cost of capital or financing risk —

lengthen the present-value payback period. These results indicate that, under the study's cost and performance assumptions, household biogas becomes economically competitive with LPG within about one year under nominal conditions, but the timing of cost recovery is materially affected by financing conditions; policy measures (subsidies, low-interest finance) or reduced upfront costs would further shorten payback and improve adoption prospects.

3.5. Safety Considerations in Biogas Utilization

Although this paper focused on efficiency and economic analysis, it is important to highlight the safety aspects of biogas utilisation. Previous studies have emphasised that methane leakage, hydrogen sulphide exposure, and the risk of explosion in poorly ventilated spaces are major concerns for household digesters [26, 27]. These risks were not evaluated in this work, but they remain crucial considerations for large-scale adoption. Future studies should therefore integrate safety assessments, including leakage monitoring and household user training, alongside performance evaluations.

4. Conclusion

This study evaluated the technical and economic feasibility of a locally fabricated 0.165 m³ vertical drum biodigester using cow dung as a feedstock to address energy poverty in rural Nigeria. The anaerobic digestion process yielded biogas with a high methane content of 70% and a calorific value of 25,098 kJ/m³, confirming its quality as a potent alternative to conventional cooking fuels. However, the thermodynamic analysis revealed a low Second-Law (Exergy) Efficiency of 4.87%. This indicates that while the fuel quality is high, over 90% of the useful work potential is lost due to irreversibilities in the burner system, specifically through uninsulated heat transfer and convective losses. Economically, the system is viable; the breakeven analysis demonstrates a payback period of 337 days when substituting Liquefied Petroleum Gas (LPG) and 525 days when substituting Kerosene.

For rural Nigerian households, these findings suggest that cow dung-based biogas is a sustainable solution that simultaneously manages agricultural waste and provides affordable energy. The technology offers a pathway to reduce dependence on expensive fossil fuels and to mitigate the health risks associated with indoor pollution from wood and kerosene.

However, It is important to acknowledge the limitations of this pilot-scale study. First, the gas composition was determined using wet chemistry methods due to the unavailability of Gas Chromatography (GC) at the facility, which limits the precision of trace gas quantification. Second, the absence of automated pH and temperature control systems meant the process relied on natural buffering, resulting in a 21-day lag phase. Finally, the small digester volume (0.165 m³) limits the direct extrapolation of these results to community-scale or industrial systems without further validation.

To maximize this technology's potential, future research must focus on burner optimization, particularly the development of insulated and shielded combustion chambers to increase exergy efficiency. Additionally, studies investigating the use of starter inoculum to minimize the start-up lag phase and the implementation of low-cost temperature regulation techniques are recommended to enhance year-round stability.

Compliance with ethical standards

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Disclosure of conflict of interest.

The authors declare that there is no conflict of interest.

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