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TECHNO-ECONOMIC SUSTAINABILITY OF HOUSEHOLD BIOGAS SYSTEMS IN RURAL NORTHERN NIGERIA: A CASE STUDY OF BOMO COMMUNITY, KADUNA STATE

[1]Paul-Jazom, Felicia Friday[1] and Ifeanyichukwu Edeh[2]
[1]Energy Technology Institute, Faculty of Engineering, University of Port Harcourt
[2]Department of Chemical Engineering, University of Port Harcourt, Nigeria

Abstract: Biogas is frequently presented as a technically viable and economically attractive clean cooking alternative in rural sub-Saharan Africa. However, techno-economic assessments often overlook financial feasibility, substrate competition, and structural livestock management practices that condition long-term sustainability. This study evaluates the technical performance, economic viability, and financial feasibility of household-scale biogas systems in Bomo community, Sabon-Gari LGA, Kaduna State, Nigeria. Methane generation from cow dung and rice husk co-digestion was simulated using Aspen Plus v14 under thermophilic conditions (55 °C, 1 atm), while household energy demand modeling, cost–benefit analysis, affordability assessment, and regression modeling of adoption likelihood were conducted using primary field data. Simulation results indicate methane yield of 0.0623 kg CH_4/kg feedstock at 15 kg/day substrate input, sufficient to offset approximately 20 kg of weekly firewood consumption under controlled feedstock availability. Economic analysis reveals a positive Net Present Value (₦2,921,699) and Benefit–Cost Ratio of 3.29 over project lifespan, suggesting theoretical profitability. However, the initial capital cost (~₦391,500) exceeds three times the annual affordability threshold of most households (≤₦120,000), and 97 % of respondents express unwillingness to adopt loan financing. Moreover, open grazing systems, competition for cow dung as cooking fuel and fertilizer, and persistent energy stacking behaviors significantly undermine substrate reliability and sustained adoption. The study concludes that while biogas systems are technically feasible and economically viable, they are financially inaccessible and structurally constrained under prevailing rural conditions. Sustainable deployment, therefore requires institutional restructuring, livestock management reform, and capital subsidy mechanisms.

Keywords: Biogas; Techno-economic analysis; Clean cooking; Aspen Plus; Rural energy; Financial feasibility; Energy stacking

1.0 Introduction

Access to clean and sustainable cooking energy remains a critical challenge in many developing countries, particularly in sub-Saharan Africa. Globally, about 2.4 billion people still rely on traditional biomass such as firewood, charcoal, and crop residues for cooking, with over 1.5 million premature deaths annually attributed to indoor air pollution from inefficient combustion (Ezzati et al., 2004; Smith et al., 2004; WHO, 2009). Cooking with biomass fuels also contributes significantly to climate change, with household cooking emissions estimated at 3.2 billion tons of CO_2 equivalent annually, including about 18 % of global black carbon emissions (Jun-Jun-Jia et al., 2022; Bond and Sun, 2005). These health, environmental, and socio-economic impacts underscore the importance of advancing clean cooking solutions in line with Sustainable Development Goals (SDGs) 3 (health), 5 (gender equality), 7 (clean energy), 11 (sustainable communities), and 13 (climate action) (Mazorra et al., 2020). Nigeria, the most populous country in Africa with over 200 million people (World Bank, 2020), faces one of the continent's largest energy access deficits. More than 80 million Nigerians lack access to modern energy services (IEA, 2020), and over 90 % of rural households still depend on firewood and kerosene for cooking. This dependence drives deforestation, greenhouse gas emissions, and exposes millions, particularly women and children, to health hazards from smoke inhalation (Smith et al., 2021). Despite government efforts through the National Renewable Energy and Energy Efficiency Policy (MNRE, 2015), the adoption of clean cooking alternatives such as biogas remains limited, constrained by high upfront costs, poor awareness, limited financing, and weak technical support (Oyedepo, 2012; Gbadeyan et al., 2024).

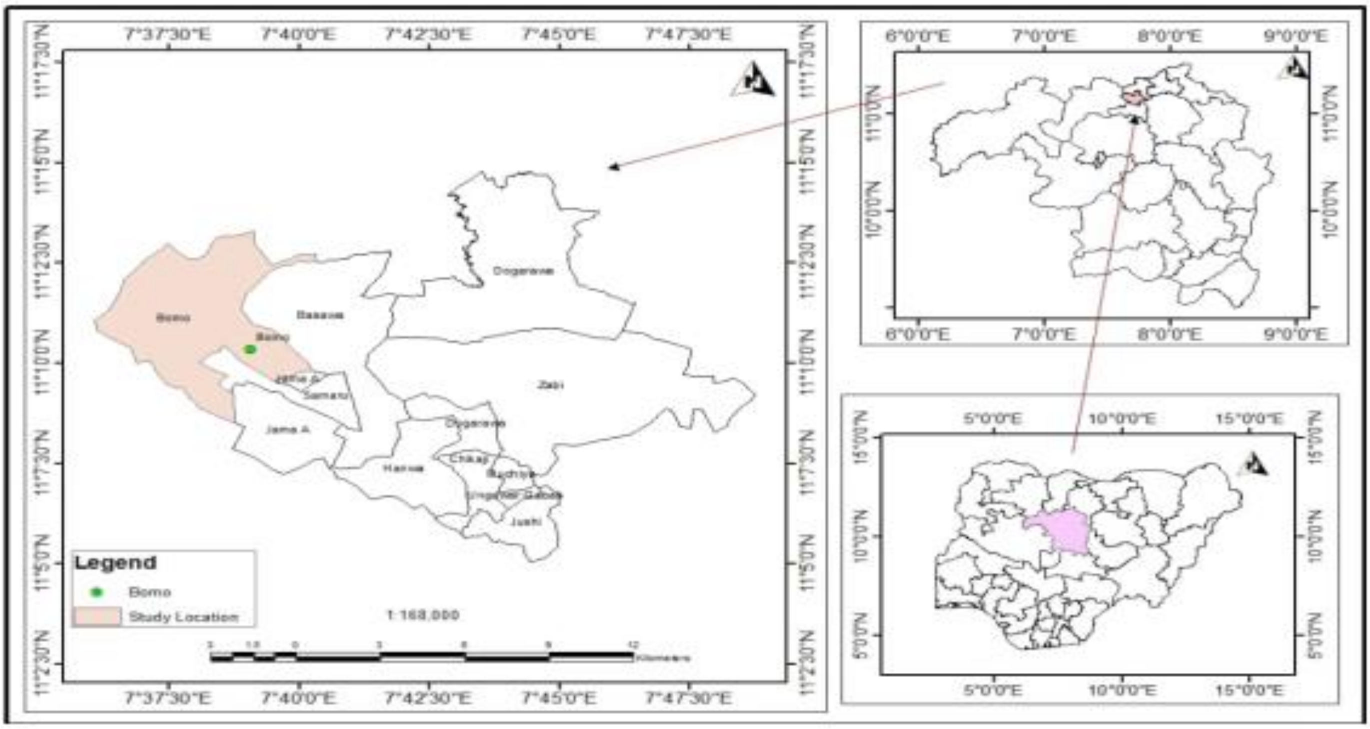
Researches have been carried out on suitable substrates for biogas generation and optimization. Iyagba et al. (2009) experimentally studied the co-digestion of cow dung and rice husk at room temperature conditions for 52 days and found that a 50:50 ratio yielded the highest gas output of 161 mL/day. Aguilar et al. (2012) used Aspen Plus simulations to analyze anaerobic co-digestion of food waste and primary sludge under mesophilic and thermophilic conditions, showing higher yields under mesophilic digestion at a 1:2 ratio. Dai et al. (2014) conducted an economic and ecological sustainability analysis of household biogas systems in rural China, reporting significant environmental benefits and annual household savings. Nevertheless, the study concluded that household-sized digesters offered limited economic benefits compared to community-scale systems, raising questions about affordability and scalability for rural Nigerian households. These researches reveal the need for localized, simulation-based, and sustainability-focused assessments tailored to Nigerian rural communities such as Bomo.he current work provides empirical evidence on the feasibility of biogas in the Bomo community, a previously unassessed rural area, while demonstrating the usefulness of Aspen Plus v14 in improving the accuracy of methane yield predictions from cow dung, rice husk, and their co-digestion. It combines household-level data with simulation results to generate new insights on the environmental and economic benefits of biogas, showing its potential to reduce deforestation and carbon emissions while offering a cost-effective cooking alternative. Furthermore, the analysis offers clear policy recommendations, emphasizing the importance of incentives and rural energy strategies to support large-scale adoption of biogas. These contributions strengthen the evidence base for advancing biogas as a viable clean cooking technology in rural Nigeria. Kaduna State exemplifies this challenge. While it is one of Nigeria's leading producers of rice, maize, sugarcane, cassava, and livestock (Kaduna State Bureau of Statistics, 2020), rural communities remain energy-poor. In Sabon-Gari Local Government Area (LGA), the Bomo community depends almost entirely on firewood and dried cow dung for cooking despite abundant agricultural and livestock waste. This paradox highlights the potential of biogas as a decentralized, renewable, and affordable solution for rural households. Yet, its adoption in Bomo and similar communities remains slow due to limited awareness, economic barriers, and the absence of locally grounded sustainability assessments (Surendra et al., 2014).

This paper, therefore, conducts a technical sustainability analysis of biogas as a clean cooking technology in rural Nigeria, focusing on Bomo community. It assesses the technical feasibility of biogas production from cow dung and rice husks, simulating methane yield using Aspen Plus. It further evaluates the economic viability of household-level biogas adoption through affordability and cost-benefit analysis, and analyzes the environmental and health impacts of current cooking methods compared to biogas adoption. Nigeria's abundant livestock and crop residues present a major opportunity for biogas adoption. However, existing research largely emphasizes urban or peri-urban contexts, overlooking rural households that bear the greatest health, environmental, and economic burdens of biomass cooking (Capuno et al., 2018; Liu et al., 2018). By addressing technical, economic, social, and environmental dimensions, this study fills a critical gap in understanding the role of biogas in clean cooking transitions in rural Nigeria. The findings provide practical benefits to Bomo residents by offering cleaner and healthier cooking alternatives, support policymakers with data for designing effective subsidy and incentive frameworks, guide renewable energy entrepreneurs with business insights for rural deployment, and supply development agencies and researchers with evidence to advance sustainable energy access.

2.0 Materials and Methods

2.1 Study Area

The Bomo community is located in Sabon-Gari Local Government Area of Kaduna State (Figure 1). The community is characterized by mixed crop–livestock farming systems (Kaduna State Bureau of Statistics, 2020). Households depend heavily on biomass fuels, with firewood constituting the dominant cooking fuel, supplemented by charcoal and dried cow dung cake. Livestock management follows predominantly open grazing patterns, where cattle roam freely during the day and return intermittently to communal or household enclosures.



2.1 Feedstock Characterization

The high volatile matter fraction indicates strong biodegradability potential, particularly for cow dung, while rice husk contributes structural carbon but slightly higher lignocellulose resistance. The primary substrates used in the simulation were cow dung (CD) and rice husk (RH), reflecting locally available biomass in Bomo community. The substrates were analysed to obtain data on the substrate property which was used to simulate biogas production in Aspen Plus v14.

2.1.1 Biochemical Analysis

This was done to determine lignin, cellulose, and hemicellulose percentage composition.

1) **Cellulose Determination**

A 1.0 g of dried and ground sample (cow dung) was put in a 100 mL beaker, and hydrolyzed with 72 % sulfuric acid while stirring for 1 hr to degrade the cellulose structure at room temperature. The resulting mixture was then diluted to a 3 % acid concentration by the addition of 84 mL of distilled water, transferred to a 250 mL beaker, and heated at 100 °C for 1 hr. The hydrolysate was filtered through a pre-weighed crucible containing filter paper, and the residue was washed with hot distilled water until the washing water was neutral to pH paper. The residue was dried in an oven at 105 °C to constant weight and cooled in a desiccator. It was then weighed, and cellulose content was determined as shown in Equation 1. The process was repeated using the rice husk sample.

$$\text{Cellulose (\%)} = \frac{\text{weight of residue (g)} \times 100}{\text{weight of sample (g)}} \qquad (1)$$

2) **Hemicellulose Determination**

A 1.0 g of dried, ground cow dung was put into a 100 mL beaker, and treated with a neutral detergent solution to remove soluble components, such as proteins, sugars, and lipids. This helped to ensure that the desired material remained on structural polysaccharides. The resulting residue was filtered and washed thoroughly with hot distilled water for preliminary lignocellulose extraction. The residue was then transferred to a 250 mL beaker, and 5 mL of 4 % NaOH solution was added. The mixture was heated in a water bath for 2 hr at 80 °C with occasional stirring to release hemicellulose, and was then filtered through a filter paper to separate the alkali-soluble hemicellulose fraction from the residue. The filtrate was neutralized with acetic acid drop wise until the pH was between 6 - 7. The hemicellulose was precipitated by adding three volumes of ethanol, filtered, and collected. The recovered hemicellulose was dried in an oven at 105 °C until a constant weight was achieved, after which it was cooled in a desiccator and weighed to determine the hemicellulose content. The percentage of hemicellulose was calculated using Equation 2. The entire process was repeated using the rice husk sample.

$$\text{Hemicellulose (\%)} = \frac{\text{weight of hemicellulose (g)} \times 100}{\text{weight of sample (g)}} \qquad (2)$$

3) Lignin Determination

A 1.0 g of the dried and ground cow dung was put into a 100 mL beaker, and 72 % sulfuric acid was added and allowed to stand for 1 hr while stirring intermittently to facilitate polysaccharide breakdown, after which the acid concentration was diluted to 3 % by adding 84 mL of distilled water. The mixture was transferred to a 250 mL beaker and heated at 100 °C for 1 hr. The mixture was filtered with a sintered glass to collect the acid-insoluble residue (ash and lignin). The residue was washed with hot distilled water until all the acid was removed from the filtrate. The remaining residue was placed in a muffle furnace at 575 °C for 4 hr to burn off organic matter, leaving only ash. Acid-insoluble lignin percentage was calculated using Equation 3, and the entire process was repeated using the rice husk sample.

$$\text{Lignin (\%)} = \frac{\text{weight of residue (g)} \times \text{weight of ash} \times 100}{\text{weight of sample (g)}} \qquad (3)$$

2.1.2 Proximate Analysis

This was done to determine the moisture, ash, volatile, and fixed content.

(i). Moisture Content Determination

A 1.0 g of cow dung was put into a crucible, and dried at 105 °C for 24 h, before cooling in a desiccator. The moisture content was then calculated using Equation 4. The entire process was repeated using the rice husk sample.

$$\text{Moisture content (\%)} = \frac{\text{Weight of dried cow dung after drying}}{\text{Weight of cow dung before drying}} \times 100 \qquad (4)$$

(ii). Volatile Matter Determination

The dried sample from moisture analysis was placed in a pre-weighed crucible with a lid and heated at 550 ± °C for 10 min in a muffle furnace. Afterward, it was cooled in a desiccator and weighed. The volatile matter was calculated using Equation 5. The entire process was repeated using the rice husk sample.

$$\text{Volatile matter (\%)} = \frac{\text{Weight of cow dung after heating at 550 } ^{O}\text{C}}{\text{Weight of cow dung after drying at 105 } ^{O}\text{C}} \times 100 \qquad (5)$$

(iii). Ash Content Determination

The residue from volatile matter was heated in a muffle furnace at 750 ºC for 2 h, it was then cooled in a desiccator and weighed. The ash content was calculated using Equation 6. The entire process was repeated using the rice husk sample.

$$\text{Ash content (\%)} = \frac{\text{Weight of cow dung after heating at 750 } ^{O}\text{C}}{\text{Weight of cow dung after drying at 550 } ^{O}\text{C}} \times 100 \qquad (6)$$

(iv). Fixed Carbon Content

This was determined using Equation (7).

Fixed Content (%) = 100 – (moisture content (%) + volatile mater (%) + ash content (%))

2.1.3 Ultimate Analysis

This was carried out to determine the elemental composition of the cow dung and rice husk samples using a portion of the dried and heated sample from the proximate analysis. A 2 mg of the sample was put into a combustion capsule (made of tin), sealed, and loaded into the Carbon, Hydrogen, Nitrogen, Sulfur, and Oxygen (CHNS/O) analyzer combustion chamber, heated at 950 °C in the presence of oxygen. The elements were converted to gaseous products which were passed through a catalytic reactor containing Copper Oxide to achieve complete oxidation, while removing the interfering gases using NaOH solution. The CHNS analyzer calculated the percentage of each element based on gas detection. Oxygen was calculated by indirect calculation using Equation 7

$$\text{Oxygen}\ (\%)=100-(C+H+N+S+Ash) \qquad (7)$$

2.2 Process Simulation and Technical Assessment

The modeling of biogas production under anaerobic digestion conditions was carried out using Aspen Plus. The feedstocks used for the simulation were cow dung and rice husk. The system was operated under varying operational conditions to determine the optimal biogas production. The rice husk was co-digested with cow dung, and the hydraulic retention time (HRT) was varied between 25 and 40 days. The system was operated under thermophilic temperature (55 °C), which is recommended for the solid-state anaerobic digestion (Li et al., 2011). The pressure was 1 atm, and the digester capacity was 5000 L/day (determined by Aspen Plus). The Non-Random Two Liquid (NRTL) method was used; cow dung and rice husk were defined under Biocomponents, while the rest used were defined under conventional. The input mode was a steady state, the stream class was conventional, the flow basis was the mole, and the valid phases were vapor-liquid. It operated under no free water, the operational year was 8766 h. The Global unit set was user-defined (METCBAR). Four blocks were used, B1 (mixer), B2 (RStoic for Hydrolysis), B3 (RCSTR for the remaining three reactions), and B4 (separator). Rstoic handled the stoichiometric reaction while RCSTR handled the kinetic reactions. The substrate's mass concentration was 15 kg, and the feedstock-to-water ratio was 1:2. The substrate was varied in percentage 50:50, 60:40, 70:30, 80:20, 9, and 0:10. The substrates were fed CD: RH, 7.5:7.5, 9:6, 10.5:4.5, 12:3, 13.5:1.5, and 15:0. The software defined other parameters in the simulation. The cost was computed in US dollars and divided into capital cost and utilities.

The Aspen Plus v14 flowsheet consisted of: FEED stream (CD + RH + Water); MIXER block (slurry preparation); HEATER block (temperature adjustment to 55 °C); RStoic reactor (anaerobic digestion); FLASH separator (biogas-liquid separation); Gas outlet stream ($CH_4 + CO_2$); and Slurry outlet stream (biofertilizer)

2.3 Economic Evaluation Framework

The economic viability was assessed through standard discounted cash flow analysis. The capital costs included digester construction, piping, stove installation, and auxiliary components.

2.3.1 Detailed Biodigester Cost Structure

A realistic cost breakdown based on local fabrication and materials is presented in Table 1

Table 1 - Capital Cost Breakdown of 6 m^3 Fixed-Dome Biodigester

S/N	Material	Quantity	Amount(₦)
1	Digester tank	$11m^2$ (15,000)	82500
2	Floating drum (hdpe)	1	20000
3	Feeding inlet pipe	3m (6500)	19500
4	Gas collector outlet		5000
5	Slurry outlet	1	12000
6	Hose	1	24000
7	Thermometer	1	4500

8	Ball valve	5(4500)	22500
9	Adapter and fittings		16000
10	Gas regulator		8500
11	Adhesives and sealant		15000
12	Stove		32000
13	Labour		80000
14	Miscellaneous		20000
15	Total		361500

The annual maintenance is estimated at ₦12,000 – ₦18,000.

2.4 Energy Demand Modeling

Assumptions:

Dual stove capacity: 0.44 m^3/hr (FAO, 1996)

~0.5 m^3 gas/person/day (Iftikhar et al., 2017)

1 m^3 gas ≈ 4 kg firewood (Iftikhar et al., 2017)

Weekly baseline consumption in Bomo:
Firewood: ~20 kg/week
Charcoal: ~25 kg/week
Dried cow dung cake: ~20 kg/week

Firewood worth for 1-week consumption is an average of 20 kg in weight (based on market survey in Bomo)

½ bag of charcoal (~25 kg) consumed in a week (from Focus Group Discussion (FGD))

A bag of cow dung is ~ 20 kg (from FGD)

Quantity of cow dung used in biogas production per = 15 kg of cow dung/day

Considering the methane yield of 0.0623 kg CH_4/kg feedstock (from the methane yield table)

Amount of biogas produced per day = 0.0623 × 15 = 0.9345 $kg\ CH_4/day$

The cost of fertilizer is ₦40,000 per bag (amount obtained from FGD)
The average quantity of fertilizer used in a year is 4 Bags
Annual savings from fertilizer on an average is ₦160,000
Annual savings from medicals on an average is ₦30,000
The benefit of adopting biogas in this community based on the result obtained from the Focus Group Discussion amounted to ₦570,590.00 per year

Energy Output Equivalence
Biogas calorific value assumed: 20–23 MJ/m^3
Energy equivalence:
Weekly production sufficient to displace ~20 kg firewood under stable operation

Energy equivalence analysis evaluated potential biomass displacement

Economic sustainability assessed through:

Key cost components

1. Initial investment cost: Bio-digester construction, stove purchase, piping, and labor
2. Operational Costs: Feedstock collection, water usage, and labor
3. Maintenance cost: throughout the lifespan of the digester

Key benefits components

The benefits identified included:

1. Cost savings in terms of reduced spending on using firewood
2. Time saved from not having to collect firewood

Health Benefit: Reduced respiratory illnesses from indoor air pollution as a result of using dirty cooking fuels like firewood, cow dung, and kerosene (2012)

3. $NPV = \sum_{t=1}^{T} \frac{(B_t-C_t)}{(1+r)^t}$
4. Environmental Benefit: Reduced deforestation and better waste management
5. Agricultural Benefit: Bio-slurry (digestate) is used as an organic fertilizer.

Maintenance cost = estimated at 10 % of capital cost/year (Singh & Kalamdhad, 2022)
Cost–Benefit Analysis (CBA)
Cost side calculations:
Net Present Value (NPV)

Net Present Value (NPV) was determined using Equation 8 according to Smith (8)

NPV = PV Benefit – PV Cost (Smith, 2012)

Where:

B_t = Benefits in year t

C_t = Cost in year t

r = discount rate (18 %)

T = project lifetime (10 years, typical for floating drum household digester)

T= number of time periods

The Benefit–Cost Ratio (BCR) was determined using Equation 9

$$BCR = \sum_{t=1}^{T} \frac{\frac{(B_t)}{(1+r)^t}}{\sum_{t=1}^{T} \frac{C_t}{(1+r)^t}} \qquad (9)$$

Benefit – Cost Ratio = PV Benefit ÷ PV Cost (Smith, 2012)

Where,

C = capital cost (digester construction, gas system, and installation)

r = discount rate = 6 % (Smith, 2012)

T = digester life span (10 years) (FAO, 1996)

Payback Period (PBP) was calculated using Equation 10

$$\text{payback period} = \frac{\textit{fixed cost}}{\textit{annual net cash}} \qquad (10)$$

Benefits were calculated as avoided expenditures on firewood, charcoal, and dung cake, alongside valuation of bio-slurry as organic fertilizer substitute. A project lifespan consistent with small-scale fixed-dome digesters was assumed.

Net Present Value (NPV), Benefit–Cost Ratio (BCR), and Payback Period (PBP) were calculated under realistic discount rate assumptions, Ayodele et al (2018).

3.0 Results and Discussions

3.1 Technical Analysis – Feed stock characterization

The substrate chosen for biogas generation was determined by carrying out a survey in the study area. The result showed availability of cow dung and rice husk in commercial quantity consistently, and this informed the feed stock choices. The summary of the survey result is presented in Tables 1 and 2.

Table 1. Organic waste availability

Feedstock type	Frequency (N)	Percentage (%)
Kitchen waste	250	73.32
Cow dung	167	48.96
Crop residues	101	29.63

Field findings revealed that livestock are managed primarily through open grazing systems. Under such arrangements, dung is dispersed across grazing lands, complicating systematic collection. Unlike zero-grazing or ranch-based systems where manure is centrally accumulated, open grazing reduces predictability of feedstock availability. Moreover, cow dung already functions as an established cooking fuel in the form of dung cake. Households often dry collected dung for direct combustion, particularly when firewood becomes scarce or regulated. Diverting dung from this traditional pathway into digesters introduces opportunity cost considerations rarely captured in techno-economic

Table 2. Manure production

Weekly Production (kg)	Frequency (N)	Percentage (%)
< 5	234	68.61
5 - 10	70	20.53
11 - 15	16	4.69

models. Additionally, rising chemical fertilizer prices have increased the value of raw manure for soil amendment, creating a competing agricultural demand. Thus, substrate competition is not hypothetical but embedded in rural livelihood strategies. These structural realities significantly weaken the assumption of reliable, surplus feed stock necessary for sustained biogas production.

3.1.1 Biochemical Analysis

The biochemical analysis carried out to determine the cellulose, hemicellulose, and lignin content in the chosen substrates has the results presented in Table 3. The results show that the composition of cellulose in cow dung and rice husk were 32.88 and 38.68 %, respectively with the later having the highest percent. This was followed by the hemiscellulos with 23.24 % and 26.85 %, for cow dung and rice husk, respectively. From the table, cellulose is predominant compared to other components of the biomass (cow dung and rice husk). The high amount of cellulose and hemiscellulose in the biomass shows that cow dung and rice husk have a great potential to be used as feedstocks for biogas production.

Table 3. Biochemical Analysis Results

Sample	Cellulose (%)	Hemiscellulose (%)	Lignin (%)
Cow dung (Cd)	32.88	23.24	18.48
Rice husk(Rh)	38.69	26.85	20.57

The Biochemical analysis results aligned with results obtained by Zulkifil et al (2009) with slight variations in moisture content for cow dung owing to handling issues however the results obtained during simulations showed negligible variations.

3.1.2 Proximate analysis of the cow dung and rice husk biomass

The proximate analysis was carried out to determine the composition of moisture, volatile matter, fixed carbon and ash in the biomass (cow dung and rice husk). The values of these components of the biomass were required as simulation input data used in modeling the biogas production in the Aspen Plus component definition. The results obtained are presented in Table 4. The high volatile matter in cow dung (62.40 %), and rice husk (68.10 %) show that the biomass will support the production of a high quality biogas that can ignite easily, and have an improved flame stability (Zuhal, 2019).

Table 4. Proximate Analysis of the cow dung and rice husk biomass

Parameter	Cow dung (%)	Rice husk (%)
Moisture Content	18.50	9.20
Volatile Matter	62.40	68.10
Fixed Carbon	11.30	14.50
Ash Content	7.80	8.20

3.1.3 Ultimate analysis of the cow dung and rice husk biomass

This was conducted using CHNS analyzer to determine the elemental composition such as carbon, hydrogen, oxygen, nitrogen, sulfur and ash of the cow dung and rice husk biomass. The results obtained are presented in Table 5, and the values of these elements carbon, hydrogen, oxygen, nitrogen, sulfur and ash were incorporated into Aspen Plus elemental input for stoichiometric balancing. The high carbon content of cow dung (38.90 %) and rice husk (41.50 %) shows that the biomass can contribute to the biogas energy content and combustibility (Zuhal, 2019). The oxygen content of the cow dung (32.40 %) and rice husk (34.60 %) is within the prescribed range 31-52 % in literature, and as such might not reduce the methane content, lower the heating value or increase the production of carbon dioxide (Zuhal, 2019).

Table 5. Ultimate analysis of the cow dung and rice husk biomass

Element	Cow Dung (%)	Rice Husk (%)
Carbon (C)	38.90	41.50
Hydrogen (H)	5.20	5.80
Oxygen (O)	32.40	34.60
Nitrogen (N)	2.10	0.70
Sulfur (S)	0.40	0.20
Ash	7.80	8.20

3.1.4 Biogas Simulation

The simulation was carried out using Aspen plus v14 with a co-digestion of cow dung and rice husk. The process flow diagram is presented in Figure 2, and the result show that the biogas (methane) yield from the separator was 52.67 % obtained using cow dung:rice husk ratio (90:10) after 40 days. Other products obtained included 38 % of CO_2, and traces of H_2, H_2S, NH_3, and water vapor (9.33%). From Table 6, the highest yield of methane was 0.0623 kg CH4/kg feedstock obtained using cow dung:rice husk ratio (90;10) at a residence time of 40 day. The results show that the yield of methane gas was dependent on the residence time and the cow dung:rice husk ratio.

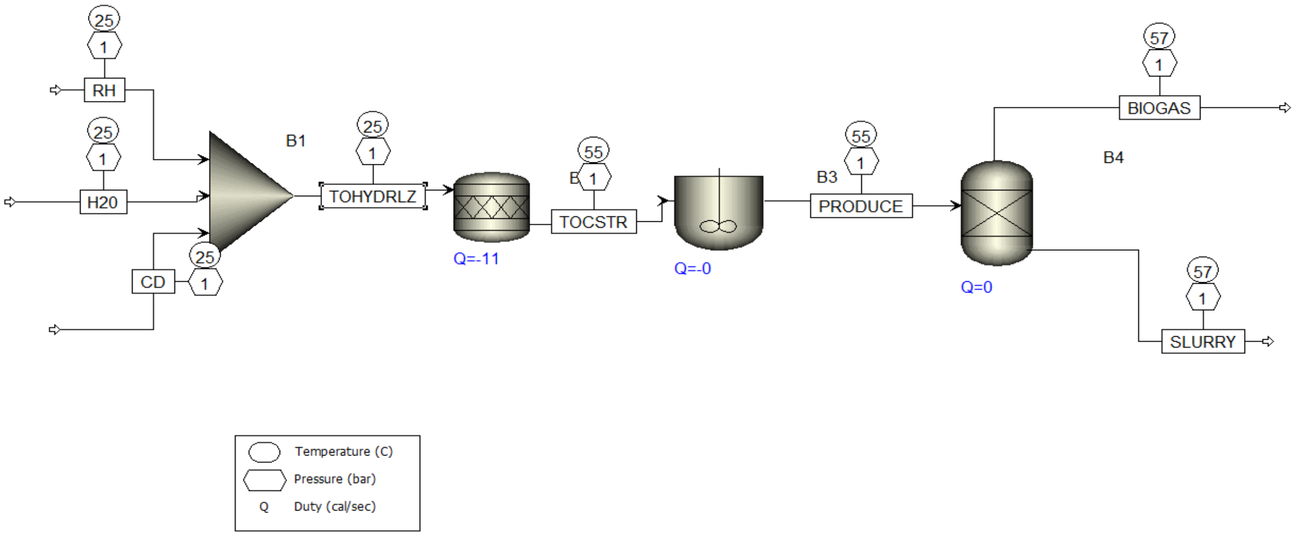


Figure 2. Biogas production using a co-digestion of cow dung and rice husk simulated with aspen plus v14

Table 6. Production of biogas from co-digestion of cow dung and rice husk

Cow dung: rice husk	CH_4 yield (kg CH_4/kg feedstock) Residence Time				
	20	25	30	35	40
50:50	0.032	0.042	0.046	0.048	0.0577
60:40	0.038	0.039	0.046	0.048	0.0593
70:30	0.038	0.039	0.047	0.049	0.0562
80:20	0.042	0.048	0.045	0.052	0.061
90:10	0.043	0.051	0.055	0.057	0.0623

The simulation generated a methane yield of 0.0623 kg CH_4 per kg of feedstock under steady-state assumptions. This yield was converted into volumetric gas production and compared against modeled household cooking energy demand derived from field surveys. The energy equivalence was established using conversion factors linking 1 m^3 of biogas to approximately 4 kg of firewood. Weekly household firewood consumption averaged approximately 20 kg, enabling assessment of biomass displacement potential. The anaerobic digestion was modeled through simplified stoichiometric reactions representing hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The representative glucose-based stoichiometric equation used:

$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$

Simulation results confirm that methane production at the modeled feedstock rate is sufficient to offset a significant portion of current firewood consumption. A 6 m^3 digester operating under steady-state conditions could theoretically meet daily cooking requirements for an average household of ten individuals. However, this technical feasibility presupposes consistent daily feed stock supply on assumption that does not fully align with observed livestock management practices.

3.2 Economic Evaluation

This was carried out to determine the profitability of the investing money in the production of biogas (methane). The methods used have been presented earlier in section 2 and the results obtained are presented in Table 7. The result shows that the cost of the project throughout its life span is one million, six hundred and thirty seven thousand naira (₦ 1,637,000, and that it will require a sum of three hundred and sixty one thousand, five hundred naira (₦ 361,500) to construct a 6 m^3 fixed-dome bio-digester. The net present value (NPV) was ₦ 2,921.699 and it shows a positive financial outcome. This means that the projected cash inflows from the investment is greater than the initial cash outflows by ₦ 2,921.699. Thus, the investment is envisaged to be profitable. The payback period was approximately 11 months and this shows that the money invested in the production of biogas would be recovered within the eleven months of operating the business. This is considered to be fast, favourable and highly attractive. The benefit cost ratio (BCR) was 3.29 and this shows that for every ₦1 invested in the biogas business, ₦3.29 would be generated in return. Since the BCR is greater than 1.0, the total discounted benefits are greater than the total discounted costs.

Table 7. cost analysis

S/N	Parameter	Value	Unit
1.	Fixed capital cost breakdown of 6 m^3 fixed-dome bio-digester	361,500	₦
2.	Net Present Value	2,921.699	₦
3.	Present value annuity factor (PVAF)	7.3601	
4.	Annual net cost (operation and maintenance cost)	124,550	₦

5.	Payback period	~11	months
6.	Benefit cost ratio	3.29	
7.	Cost of the project throughout its life span	1,637,000	₦

3.2.1 Benefit Analysis

The benefit analysis was carried out to estimate the reductions and profitability accrued from the use of biogas. The benefits accounted for included reduction in fuel cost (firewood), reduction in medical bills, reduction in fertilizer cost. The method used for determining the benefits were presented in section 2, and the results obtained are shown in Table 8.

Table 8. Benefit Analysis Results from Survey Data

Savings Area	Frequency (N)	Percentage (%)
Reduced Firewood Collection	258	75.66
Reduced Fuel Costs	212	62.17
Improved Farm Productivity	150	43.99
Health Cost Savings	140	41.06

The cost savings were estimated from the responses of the survey (Table 8) and they included reduced firewood collection (75.66 %) and fuel costs (62.17 %). This demonstrates the financial benefits of transitioning to cleaner energy, and improved farm productivity through the use of bio-slurry fertilizer (43.99%) and reduced health costs (41.06%).

3.2.3 Financial Feasibility and Adoption Modeling

An affordability and willingness to pay survey was carried and the result is presented in Figure 3
Affordability thresholds were derived from household income data collected during field surveys.

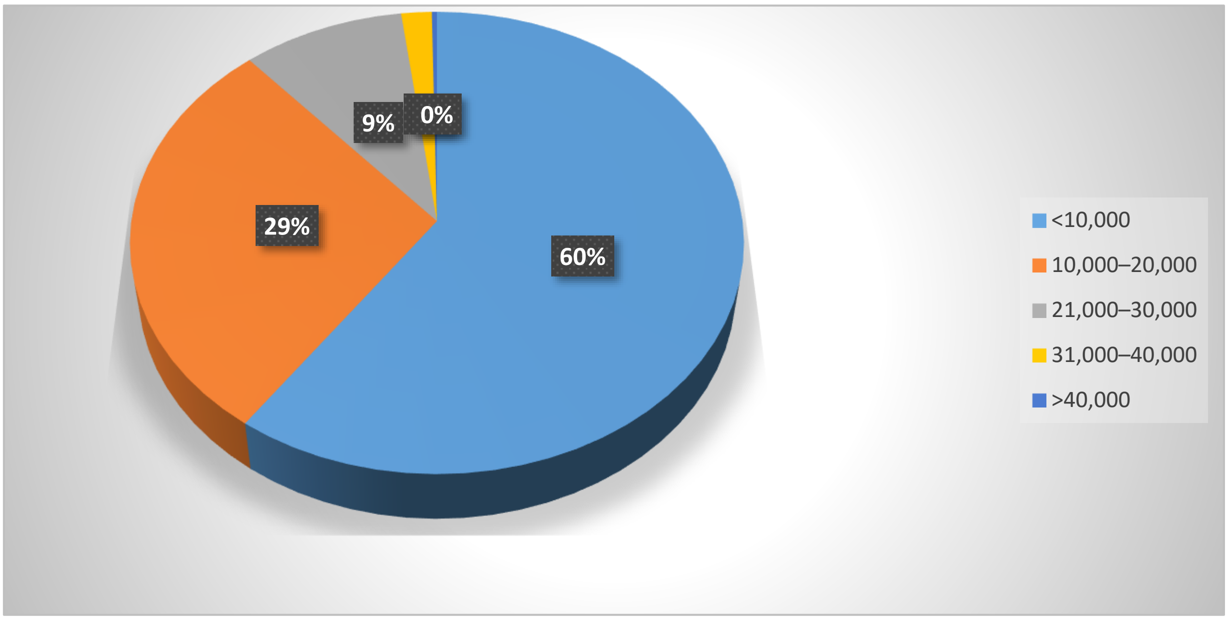


Figure 3. Willingness to pay

The majority of households reported capacity to allocate no more than ₦10,000 per month toward energy investments. In addition to affordability assessment, regression analysis was conducted to determine predictors of adoption likelihood. Independent variables included household income, education level, household size, and current fuel expenditure. Discounted cash flow analysis yields a positive NPV of ₦2,921,699 and a BCR of 3.29 over the system's lifespan. The calculated payback period of approximately eleven months suggests strong economic attractiveness under idealized utilization. Yet this profitability masks a fundamental financial barrier: the upfront capital cost represents more than three times the annual affordability threshold of most households. The survey results indicate overwhelming reluctance (97 %) to engage in loan-based financing, reflecting distrust of formal credit systems and income instability.

Energy stacking behavior remains prevalent within the community. Even if biogas were adopted, households are unlikely to abandon firewood entirely due to reliability concerns, seasonal variability, and cooking preferences for certain foods requiring high heat intensity. Energy stacking reduces projected cost savings and emission reductions, extending effective payback periods and weakening economic projections based on full fuel substitution assumptions. Thus, although the system generates long-term savings, its initial cost structure renders it inaccessible without subsidy or external financing support.

4. Conclusion

This study demonstrates that household-scale biogas systems in the Bomo community are technically feasible and economically viable under modeled conditions. However, they are financially inaccessible to most households and structurally constrained by open grazing practices, substrate competition, and persistent energy stacking behavior. Biogas sustainability in rural northern Nigeria is therefore conditional rather than inherent. Its successful deployment requires integrated interventions encompassing capital subsidies, livestock management reform, institutional financing innovation, and community-level support structures.

The findings expose a critical tension between theoretical sustainability and contextual feasibility. While process simulation confirms that biogas production is technically achievable, and economic modeling demonstrates long-term profitability, financial limitations and structural constraints undermine practical sustainability. The dominant open grazing system fundamentally shapes feedstock accessibility, highlighting the interdependence between livestock management policy and rural energy transitions. Without shifts toward semi-intensive or ranch-based systems, manure aggregation remains unreliable.

Furthermore, substrate competition illustrates that biomass is not an unclaimed resource awaiting technological conversion; it is already embedded in existing energy and agricultural systems. Ignoring these competing uses risks overestimating available feed stock.

The affordability gap reveals that positive NPV does not equate to adoption potential. Financial feasibility must be evaluated separately from economic profitability, particularly in low-income rural settings.

Without these enabling mechanisms, biogas will remain a theoretically attractive but practically limited clean cooking solution. Biogas technology is widely promoted as a technically viable and economically sustainable clean cooking alternative in rural sub-Saharan Africa. However, sustainability claims often overlook substrate competition, livestock management systems, and financial feasibility constraints.

This study evaluated the techno-economic sustainability of household-scale biogas systems in Bomo community, Kaduna State, Nigeria, integrating Aspen Plus v14 simulation, biochemical characterization of feedstock, detailed cost structure analysis, and field-based affordability assessment. Methane production was modeled under thermophilic anaerobic digestion (55 °C, 1 atm) using cow dung and rice husk co-digestion at 15 kg/day feed stock input. Simulation yielded 0.0623 kg CH_4/kg substrate, sufficient to offset approximately 20 kg of weekly firewood consumption. Economic evaluation indicates a positive Net Present Value (₦2,921,699) and Benefit–Cost Ratio of 3.29. However, the initial capital cost (~₦391,500) exceeds household affordability thresholds, and open grazing practices, substrate competition with dung cake fuel and fertilizer use, and energy stacking behavior significantly undermine long-term sustainability. The findings demonstrate that while technically feasible and economically profitable, household biogas remains financially inaccessible and structurally constrained under prevailing rural conditions. Despite technical sufficiency, open grazing limits manure collection consistency. Cow dung is already used as: Dung cake cooking fuel, organic fertilizer. Diverting manure to digesters introduces livelihood trade-offs not captured in basic techno-economic models.

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