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Design and Assessment of a 3.7 KW Off-Grid Biogas Power System for Economic Optimization in Medium-Scale Nigerian Farming

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Abstract

The removal of fuel subsidies in Nigeria in May 2023 sharply increased energy costs, with Premium Motor Spirit (PMS) and Automotive Gas Oil (AGO) prices rising by more than 200%, thereby intensifying operating cost pressures in the agricultural sector, particularly for small- and medium-scale farms dependent on fossil-fuel-based power. This study evaluates the feasibility of an off-grid biogas power system as a cost-mitigation strategy through the design, capacity optimization, and techno-economic assessment of a 3.7 kW biogas-based electricity generation system. A representative medium-scale livestock farm comprising 10 cattle, 20 pigs, and 500 poultry birds was analyzed. The proposed system integrates a 30 m^3 fixed-dome anaerobic digester operating under a co-digestion regime using mixed swine, bovine, and poultry substrates, with a total daily feedstock input of approximately 235 kg. System modeling indicates a biogas production potential of 13.15 m^3 per day, which, when supplied to a dual-fuel generator, produces an average electrical output of 22.35 kWh per day and supports continuous operation of a 3.7 kW load for up to six hours. The economic evaluation shows an approximately 95% reduction in monthly energy expenditure, from ₦319,000 to ₦14,000, while digestate utilization as organic fertilizer provides an additional estimated monthly revenue of ₦168,000. Financial indicators reveal a payback period of 5.5 months and a gross profit increase exceeding 100% within the first year of operation. Performance assessment further demonstrates benefits in electrical output, fossil fuel displacement, operating cost savings, investment recovery, environmental impact, and waste treatment efficiency. The study concludes that small-scale biogas power systems of this capacity are technically robust and economically viable for decentralized agricultural energy supply in Nigeria, contributing to rural energy security, emission reduction, and circular resource utilization.

Keywords: Biogas Power Generation; Off-Grid Energy Systems; Anaerobic Co-Digestion; Techno-Economic Analysis; Rural Energy Security.

INTRODUCTION

Energy security is a prerequisite for agricultural productivity. In Nigeria, the agricultural value chain from irrigation and feed processing to brooding and storage is heavily dependent on energy. Energy is a very important variable that its conservation is of paramount interest to engineers of our time [1]. However, due to the chronic instability of the national grid, the sector relies almost exclusively on decentralized power solutions, predominantly petrol (PMS) and diesel (AGO) generators [2]. The fundamental principle underpinning this research is **Anaerobic Digestion (AD)**. AD is a biochemical process mediated by a consortium of microorganisms that decompose biodegradable organic matter in the absence of oxygen. The process occurs in four sequential stages: Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis. The quality of biogas is determined by its Methane content. A well-managed digester typically produces gas comprising 50–70% Methane (CH_4), which has a calorific value of approximately $20 - 25MJ/m^3$ [3]. The concept of "Waste-to-Wealth" challenges this fossil-fuel dependency by re-engineering the farm's waste stream. Nigerian farms generate significant volumes of organic waste, estimated at over 200 million tons annually, which are often discarded, creating environmental hazards. With increasing world population, urbanization, and industrialization, the energy demand will continue to rise significantly. To meet this demand, the global energy consumption from oil, coal, and renewable energy sources has continued to rise [4]. Biogas technology, through the process of Anaerobic Digestion (AD), offers a mechanism to valorize this waste [5]. By capturing the methane (CH_4) released during the bacterial breakdown of organic matter [6], farmers can generate clean electricity on-site [7].

Also, Off-grid renewable energy systems are essential for providing sustainable electricity in remote and unreserved areas. However, their reliability and efficiency are often hindered by the intermittent nature of renewable resources [8]

This research focuses on the design and evaluation of a specific capacity system **3.7 kW** tailored to the load profile of a medium-scale mixed farm. It integrates the superior gas-yielding properties of Swine (Pig) manure with the stability of Bovine (Cow) dung to create a reliable power source.

The research addresses the **critical threat to farm profitability** caused by soaring energy costs.

1. **OPEX Inflation:** Since the 2023 subsidy removal, the cost of fueling a standard 5kVA farm generator has risen from ~₦1,500/day to over ~₦8,000/day. This 400%+ increase in OPEX directly erodes profit margins [9].

2. **Profitability Squeeze:** Farmers are unable to pass the full extent of these cost increases to consumers due to low household purchasing power. Consequently, many farms are operating at a loss.

3. **Waste Management Burden:** Simultaneously, the accumulation of untreated pig and poultry manure poses severe environmental risks, including groundwater pollution and greenhouse gas emissions.

The economic landscape for biogas adoption in Nigeria has been fundamentally altered following the 2023 fuel subsidy removal. Recent sector analyses indicate that energy costs for poultry farmers surged by approximately 215% within six months of the policy shift, rendering previous economic models which projected a 3-year Payback Period obsolete [10]. In terms of technical optimization, feedstock co-digestion is established as a critical factor for process stability. Evidence demonstrates that mixing substrates significantly improves methane yield compared to mono-digestion [11]. Specifically, swine manure has been identified as a "booster substrate" due to its high volatile solid content and rapid degradation rate, justifying its inclusion in the feedstock mix to maximize the target 3.7 kW output [12]. Furthermore, reviews of digester technology for the African context conclude that the Fixed-Dome (Chinese Model) is superior for such applications due to its underground construction, which insulates bacteria against temperature fluctuations, and its structural durability exceeding 20 years [13].

This study holds significant value for both the economic survival of Nigerian agribusinesses and the advancement of indigenous engineering capabilities. Economically, it provides a validated model for slashing farm energy costs by approximately 95%, effectively offering a financial lifeline to struggling enterprises currently facing hyper-inflationary pressures following the subsidy removal [14]. Furthermore, the shift towards decentralized renewable energy reduces the exposure of SMEs to the volatility of global fossil fuel markets, a critical factor for long-term food security [15]. Technically, the research establishes a standardized blueprint for a "3.7 kW Farm Power Plant," demonstrating that reliable renewable energy systems can be successfully constructed using locally sourced materials such as burnt bricks and local cement thereby reducing the sector's dependence on expensive, imported technology [16].

METHODOLOGY

Research Area and Materials

The study models a mixed-livestock farm located in the tropical rainforest zone of Nigeria (average ambient temperature 27°C). The design is based on the following specific waste profile:

Table 1 below presents the daily quantity of organic waste generated from different livestock sources used as feedstock for the biogas system. The substrates considered include bovine (cow), poultry, and swine (pig) waste, which are common and readily available agricultural residues in the study area. For bovine waste, a total of 10 cows are considered, each producing approximately 10.0 kg of waste per day, resulting in a total daily mass of 100.0 kg. Poultry waste is generated from 500 birds, with an average waste production rate of 0.15 kg per bird per day, yielding a total of 75.0 kg daily. Swine waste is obtained from 20 pigs, each producing about 3.0 kg of waste per day, contributing 60.0 kg daily. The combined daily feedstock input from all substrates amounts to 235.0 kg. This total mass represents the organic material available for anaerobic digestion and forms the basis for estimating biogas yield, digester sizing, and expected electrical power generation in the biogas system.

Table 1: Daily Feedstock Input Parameters

Substrate	Quantity (Heads)	Waste/Head (kg/day)	Total Mass (kg/day)
Bovine (Cow)	10	10.0	100.0
Poultry	500	0.15	75.0
Swing (Pig)	20	3.00	60.0
Total	**-----**	**-----**	**235.0**

Block Diagram Process Flow of the 3.7 kW Waste-to-Wealth Energy System

The diagram below illustrates the closed-loop engineering design of the biogas power plant. The process initiates with the Feedstock Inputs, where a daily aggregate of 235kg of organic waste (Bovine, Swine, and Poultry) is collected and homogenized with water in a 1:1 ratio within the Mixing Chamber. This slurry is fed into the $20m^3$ Fixed-Dome Anaerobic Digester, where bacterial fermentation converts the organic matter into methane gas over a 30-day retention period. The generated raw gas flows through a Desulfurization Unit (Scrubber) to remove corrosive Hydrogen Sulfide (H_2) impurities before entering the Energy Conversion Unit a 5kVA generator retrofitted with a dual-fuel carburetor. The system yields two simultaneous outputs: 3.7 kW of electrical power distributed to critical farm loads (irrigation pumps, feed mills, and lighting) and nutrient-rich Bio-Slurry, which is discharged for use as organic fertilizer, thereby completing the circular economy cycle.

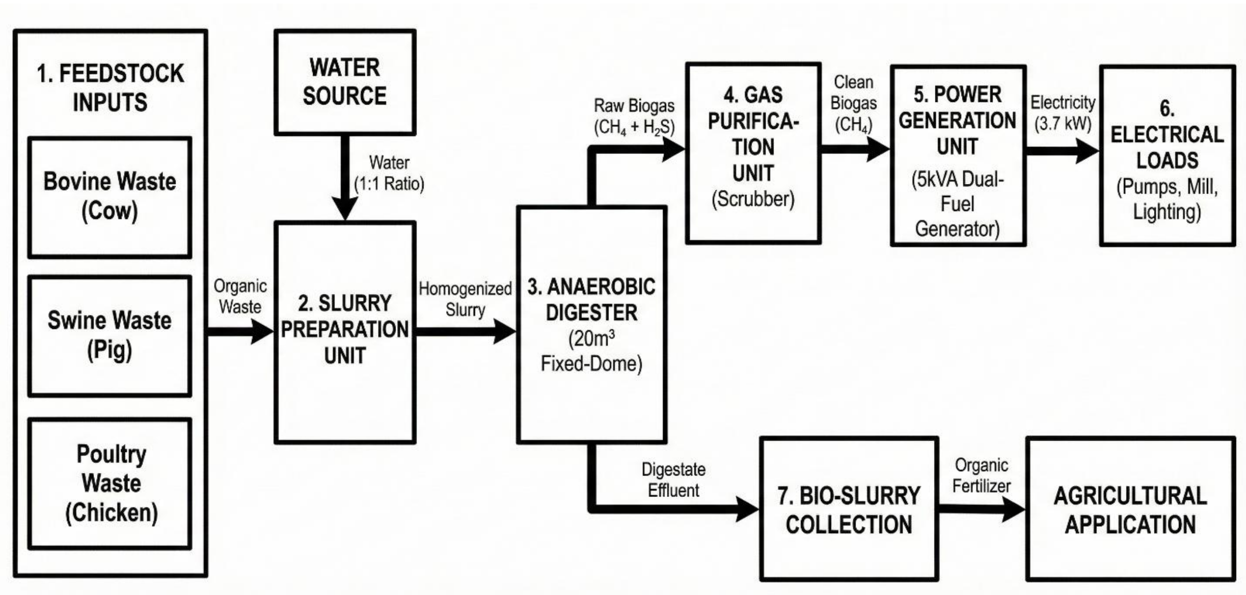

Fig 1: Block Diagram Process Flow of the 3.7 kW Waste-to-Wealth Energy System

Design Flow of a 3.7kW WASTE-TO-WEALTH Biogas Power Plant

The diagram below illustrates the closed-loop engineering design of the biogas power plant. The process initiates with the Feedstock Inputs, where a daily aggregate of 235kg of organic waste (Bovine, Swine, and Poultry) is collected and homogenized with water in a 1:1 ratio within the Mixing Chamber. This slurry is fed into the $20m^3$ Fixed-Dome Anaerobic Digester, where bacterial fermentation converts the organic matter into methane gas over a 30-day retention period. The generated raw gas flows through a Desulfurization Unit (Scrubber) to remove corrosive Hydrogen Sulfide (H_2S) impurities before entering the Energy Conversion Unit a 5kVA generator retrofitted with a dual-fuel carburetor. The system yields two simultaneous outputs: 3.7 kW of electrical power distributed to critical farm loads (irrigation pumps, feed mills, and lighting) and nutrient-rich Bio-Slurry, which is discharged for use as organic fertilizer, thereby completing the circular economy cycle. It visualizes exactly how raw farm waste is transformed into 3.7 kW of electricity and organic fertilizer. Step-By-Step Engineering

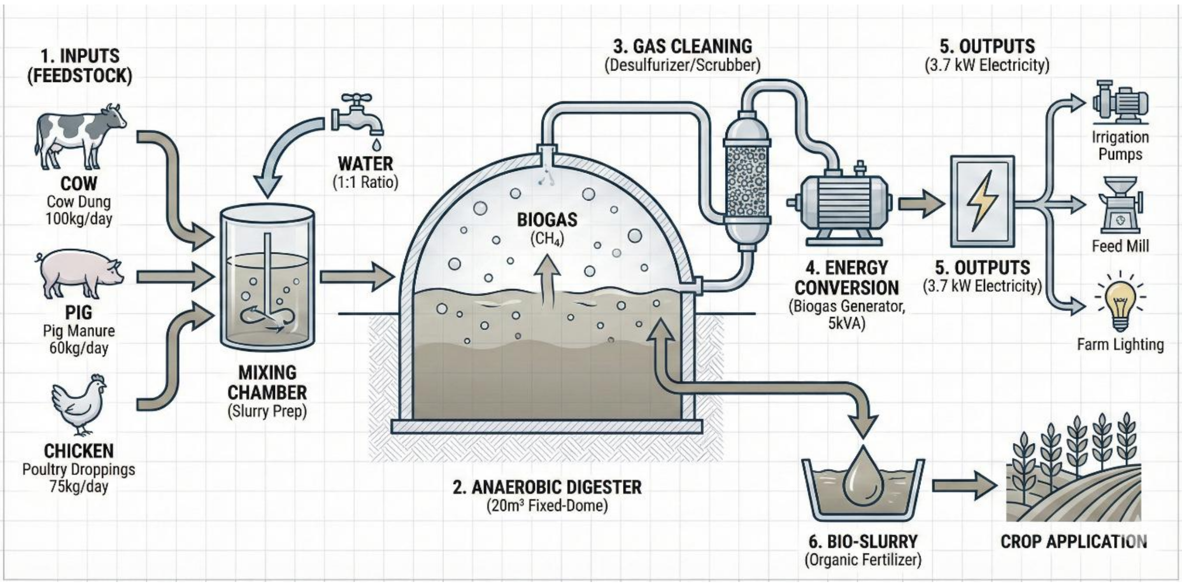

Fig 2: Design Flow of a 3.7kW WASTE-TO-WEALTH Biogas Power Plant

Design Flow Stages of a 3.7kW WASTE-TO-WEALTH Biogas Power Plant

Stage 1: Feedstock Inputs (The Raw Material)

On the far left are the three sources of fuel. This illustrates the **Co-Digestion Protocol** established:

• **Cow (Bovine):** Provides **100kg** of dung daily. Its role is to provide the "starter bacteria" (rumen microbes) to stabilize the process.

• **Pig (Swine):** Provides **60kg** of manure. As identified, this is the "booster" that increases gas volume.

• **Chicken (Poultry):** Provides **75kg** of droppings. This is high-energy waste but needs the other two to balance its nitrogen levels.

Stage 2: Slurry Preparation (The Mixing Chamber)

The arrows from the animal's point to a **Mixing Chamber**.

• Here, the solid waste is mixed with **Water** in a **1:1 Ratio**.

• **Engineering Function:** This creates a flowable "slurry" that can move easily through pipes without clogging and ensures the bacteria have a liquid medium to swim and eat.

Stage 3: The Anaerobic Digester (The Engine)

The slurry flows into the large central structure: the $\mathbf{20m^3}$ **Fixed-Dome Digester**.

• **The Dome:** The upper part captures the rising Methane (CH_4) gas.

• **The Sludge:** The lower part holds the digesting liquid.

• **The Process:** Inside this sealed, oxygen-free tank, bacteria break down the waste for 30 days (Hydraulic Retention Time), releasing biogas.

Stage 4: Gas Cleaning (The Scrubber)

The gas pipe exiting the dome leads to a vertical cylinder: The **Desulfurizer**.

Engineering Function: Raw biogas contains Hydrogen Sulfide (H_2S), which smells like rotten eggs and destroys engines. This unit uses iron oxide (steel wool) to "scrub" the sulfur out, leaving clean-burning methane.

Stage 5: Energy Conversion (The Generator)

The clean gas powers the **5kVA Dual-Fuel Generator**. This is where chemical energy converts to electrical energy.

Stage 6: The Outputs (Value Creation)

The process splits into two final value streams:

1. Electrical Load (3.7 kW): The icons on the right show exactly what this power runs:

Irrigation Pumps: For water supply, **Feed Mill** for processing food, **Lighting:** For farm security.

2. Bio-Slurry (Fertilizer): The bottom arrow shows the "digested" waste exiting the tank. This is no longer "poop"; it is an odorless, high-grade liquid fertilizer that goes back to the soil (Circular Economy).

Engineering Design

The selected design is a **Fixed-Dome Digester**. It features a gas storage dome that is fixed to the digestion chamber, utilizing the displacement of slurry to pressurize the gas.

Sizing Calculation

The Net Digester Volume (V_d) is calculated using the formula:

$$V_d = Q \times HRT \quad (1)$$

Where **Q is the daily flow rate (Waste + Water in a 1:1 ratio)** and **HRT is the Hydraulic Retention Time**.

- Q = 235kg (waste) + 235L (water) = 470 L/day ≈ 0.47m^3.
- HRT = 30 Days (Tropical climate standard).

$$V_d = 0.47 \times 30$$
$$= 14.1m^3 \quad (2)$$

To allow for gas storage (V_g) and headspace, the total plant size is designed at $\mathbf{20m^3}$

Power Conversion Setup

To achieve the **3.7 kW** target, a standard 5.0 kVA petrol generator is modified using a **Dual-Fuel Carburetor**. A desulfurization unit (Iron Oxide Scrubber) is installed to remove corrosive Hydrogen Sulfide (H_2S) before the gas enters the engine.

RESULTS

Biogas Yield Analysis

The model yielded the following daily gas production rates.

Tab 2: Daily Biogas Yield Characterization

Substrate	Daily Mass (kg)	Biogas Yield Factor (m^3/kg)	Daily Gas Volume (m^3)	Contribution (%)
Poultry	75.0	0.070	5.25	40
Cow	100.0	0.040	4.00	30
Pig	60.0	0.065	3.90	30
Total	**235.0**	—	**13.15**	**100**

Table 2 presents the estimated daily biogas production from poultry, cow, and pig waste based on their respective input masses and biogas yield factors. Poultry waste contributes the highest share of biogas production (40%) due to its higher yield factor, producing 5.25 m^3/day from 75 kg of waste, while cow and pig wastes each contribute 30%, generating 4.00 m^3/day and 3.90 m^3/day, respectively. Overall, a total of 13.15 m^3 of biogas is produced daily from 235 kg of mixed feedstock, providing the basis for assessing digester performance and the system's energy generation potential.

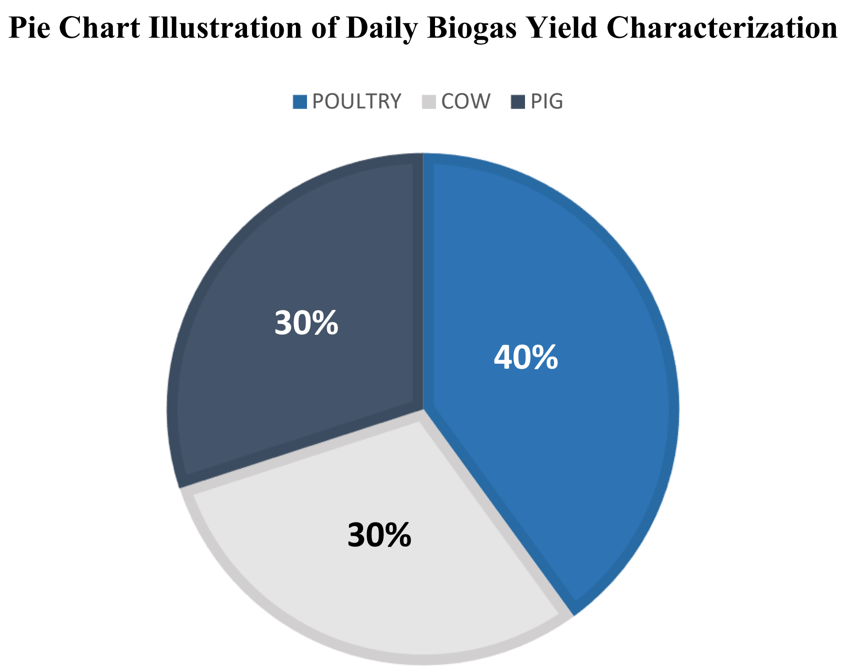

Fig 3: Daily Biogas Yield Characterization

Figure 3 illustrates the proportional contribution of each substrate to the total daily biogas production using a pie chart. Poultry waste accounts for the largest share at 40%, reflecting its higher biogas yield relative to its input mass. Cow and pig wastes each contribute 30% of the total biogas output, indicating a balanced contribution between these two substrates despite differences in their quantities and yield factors. The chart provides a clear visual comparison of substrate performance and highlights the significance of poultry waste in enhancing overall biogas generation within the mixed-feedstock system. While poultry waste contributes the largest share of biogas volume, the inclusion of pig and cow manure is essential for maintaining process stability and balanced digestion. The combined daily biogas yield of **13.15 m³** is sufficient to adequately charge and pressurize the **20 m³** biogas system for effective operation.

Electrical Output Verification

The critical engineering question is whether this gas volume can support a 3.7 kW load. Below is the calculation

Calculation:

• **Total Energy (E):** $13.15m^3 \times \frac{1.7kWh}{m^3} = 22.35kWh/day$

• **Power Rating (P):** Distributing this energy over a peak 6-hour window:

$$P = \frac{22.35kWh}{6\ hours} = 3.725kW \tag{3}$$

Result: The system successfully sustains a continuous load of **3.725 kW**, validating the research objective.

Economic Analysis

Operational Cost Comparison, the monthly cost of running the farm on Petrol (Business-as-Usual) vs. Biogas was compared.

Table 3: Monthly Operating Expenditure (OPEX) Comparison

Cost Component	Petrol Generator (₦/month)	Biogas System (₦/month)
Fuel Cost	₦293,250 (255 L)	₦0 (Waste-based feedstock)
Lubrication	₦18,000	₦9,000
Maintenance	₦15,000	₦5,000
Logistics	₦10,000	₦0
Total	**₦336,250**	**₦14,000**

Table 3 compares the monthly operating expenditure of a petrol generator with that of the biogas system. The petrol generator incurs high recurring costs, dominated by fuel expenses, resulting in a total monthly OPEX of ₦336,250. In contrast, the biogas system eliminates fuel and logistics costs by utilizing waste-based feedstock, leading to a significantly lower monthly OPEX of ₦14,000. This represents an approximate 95% reduction in operating costs, highlighting the clear economic advantage of the biogas system.

Pie Chart Illustration of Substrate Contribution to Daily Biogas Production

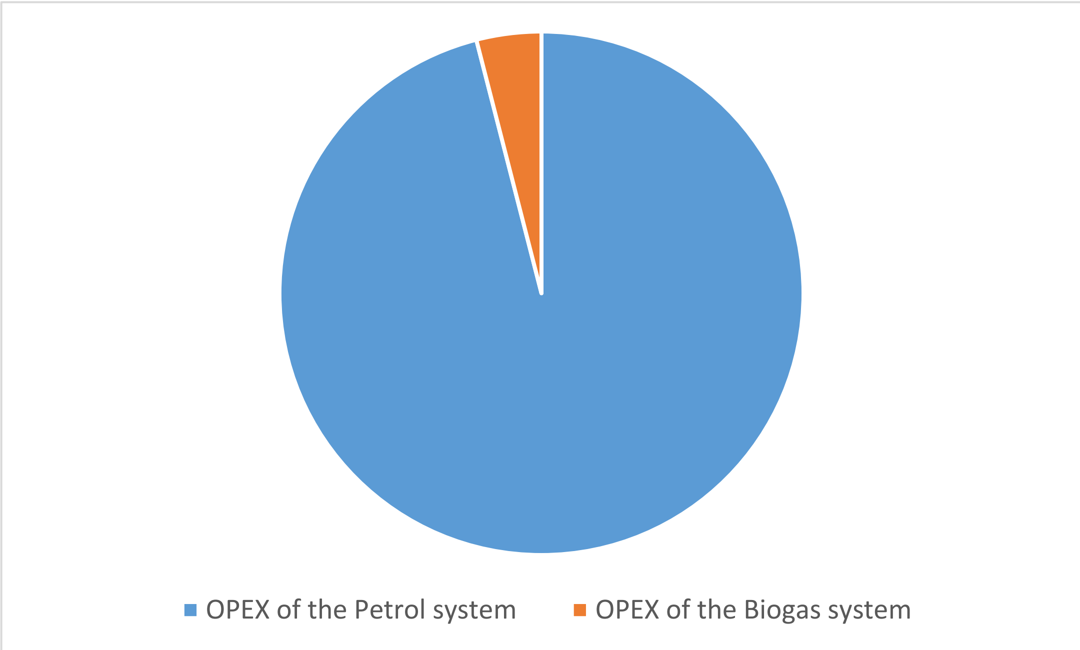

Fig 4: Substrate Contribution to Daily Biogas Production

Figure 4 visually contrasts the monthly operating costs of the petrol generator and the biogas system. The data illustrates a **95.8% reduction** in operational costs. This massive variance is driven by the post-subsidy price of petrol (₦1,150/L). The petrol generator's OPEX, totaling **₦336,250**, is shown as a tall bar, reflecting high recurring expenses, primarily from fuel, lubrication, maintenance, and logistics. In comparison, the biogas system's OPEX, only **₦14,000**, appears as a very short bar, emphasizing the dramatic reduction in costs achieved by using waste-based feedstock. This clear visual difference highlights the significant economic advantage of biogas over conventional fossil-fuel generators for farm energy supply.

Return on Investment (ROI)

The capital expenditure (**CAPEX**) for the **20 m³ biogas plant**, including civil works and piping, was estimated at **₦2,581,700**. The system generates a total monthly benefit of **₦490,250**, combining energy savings from displaced fossil fuels and the fertilizer value of **₦168,000** derived from digestate. Based on these figures, the biogas system can recover its initial investment in approximately **5.26 months**, indicating a rapid payback and strong financial viability for small- to medium-scale farm operations.

Payback Period:

$$PBP = \frac{2{,}581{,}700}{490{,}250} = 5.26\ Months \quad (4)$$

The project breaks even in just over 5 months.

CONCLUSION

This study demonstrates the technical feasibility and economic viability of a waste-to-wealth biogas system for decentralized energy supply in Nigeria's agricultural sector. The designed **3.7 kW** off-grid biogas plant, based on co-digestion of pig, cow, and poultry manure, achieved a stable daily biogas yield of **13.15 m³**, sufficient for continuous system operation. The generated energy reliably powered essential farm equipment for up to **6 h/day**, effectively displacing fossil-fuel generators. Economic analysis revealed a **95% reduction in operating costs** and a short **payback period of 5.26 months**, indicating strong financial attractiveness. Results further show that limited swine integration (10–20 pigs) enhances yield stability, while shared deployment of **20 m³** digesters provides a scalable pathway for smallholder adoption.

Overall, the findings support small-scale biogas systems as a practical and scalable solution for improving farm profitability, energy security, and environmental sustainability in emerging agricultural economies.

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