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Biogas Production from Organic Waste in Nigeria

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***Abstract*— This research explores the potential of biogas production from organic waste in Nigeria as a sustainable solution to address energy scarcity, environmental pollution, and inefficient waste management. Three abundant waste types, cow dung, water hyacinth, and cassava peels, were processed in a custom-designed continuous stirred tank digester (CSTD) to produce biogas, which was subsequently purified into biomethane using an amine-based scrubber system. The biogas composition was analyzed using gas chromatography (GC), revealing methane contents ranging from 55–70%, with cow dung yielding the highest. The purified biomethane was successfully used to power a manually fabricated roasting burner, demonstrating its applicability for domestic energy needs. Additionally, the digestate byproduct was evaluated as a bio-fertilizer, showing significant improvements in soil nutrient content, particularly nitrogen and phosphorus. Statistical analyses confirmed significant differences in biogas yields among feedstocks, with a strong correlation between carbon-to-nitrogen ratio and methane production. Despite challenges such as gas leakage, high capital costs, and operational complexities, this study underscores the viability of biogas as a renewable energy source and waste management strategy in Nigeria, offering a pathway toward energy security and environmental sustainability.*

***Keywords*— Biogas, cassava peels, water hyacinth bio-digester organic waste.*

I. Introduction

Nigeria faces significant challenges in energy security and waste management, exacerbated by its heavy reliance on fossil fuels and the generation of approximately 675.5 million tons of organic waste annually. This waste, comprising human excreta, livestock manure, crop residues, and municipal solid waste, poses environmental and health risks when improperly managed, contributing to air and water pollution, greenhouse gas emissions, and disease proliferation (Ajayi, 2009). Fossil fuels, while dominant in Nigeria's energy sector, are non-renewable, environmentally harmful, and costly, necessitating the exploration of sustainable alternatives (Anozie et al., 2005).

Biogas, a sustainable biofuel created via the anaerobic digestion of organic matter, addresses these issues in two ways. Biogas, which is primarily made up of methane (50–80%) and carbon dioxide (20–50%), may be utilized as a vehicle fuel, for cooking, and for producing electricity. Its byproduct, digestate, is a nutrient-rich bio-fertilizer (Sonnleitner, 2012). Anaerobic digestion involves the microbial breakdown of organic matter in an oxygen-free environment, producing methane-rich gas and reducing waste volume. In Nigeria, where organic waste is abundant, biogas production could transform waste into a valuable resource, mitigating environmental degradation and addressing energy poverty, particularly in rural areas (Bouallagui et al., 2003).

This study focuses on producing biogas from three locally available waste types: cow dung, water hyacinth, and cassava peels. Cow dung is a traditional feedstock due to its high organic content, water hyacinth is an invasive aquatic plant with significant biomass potential, and cassava peels are a prevalent agricultural byproduct in Nigeria. The research aims to construct a CSTD biodigester, purify the biogas to biomethane, analyze gas composition, and evaluate the digestate's agricultural applications. By integrating renewable energy production with waste management, this study seeks to contribute to Nigeria's sustainable development goals, reducing reliance on fossil fuels and promoting a cleaner environment (Yinghua, 2020).

II. Materials and Methodology

Materials

The study utilized a range of materials to facilitate biogas production, purification, and analysis, emphasizing locally sourced components to enhance cost-effectiveness and scalability in Nigeria:

1. *Feedstocks:*
   - Cow dung: Collected from local cattle farms in Ogun State, Nigeria, known for its high organic matter and balanced carbon-to-nitrogen ratio (20:1).
   - Water hyacinth: Harvested from Lagos waterways, selected for its high cellulose content and availability as an invasive species.
   - Cassava peels: Obtained from cassava processing units in Oyo State, rich in carbohydrates but requiring pretreatment due to lignocellulosic content.
2. *Biodigester Components:*
   - A 50-liter CSTD constructed from locally sourced mild steel, equipped with an agitator (manually operated), baffles for mixing, and a gas collection system made of PVC pipes and valves.
   - Sealing materials (rubber gaskets and silicone) to prevent gas leakage.
3. *Purification System:*
   - Monoethanolamine (MEA) as the amine solution for CO2 and H2S absorption.
   - Absorption and desorption columns fabricated from stainless steel, with a water wash scrubber to remove amine traces.
   - Heat exchanger (copper tubing) to cool regenerated amine.
4. *Analytical Equipment:*

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- Gas chromatograph (Agilent 7890B) with a thermal conductivity detector (TCD) for gas composition analysis.
- pH meter (Hanna HI9813-6) for monitoring digester slurry pH.
- Soil nutrient testing kit (LaMotte Model STH-14) for digestate analysis.

5. *Burner*: A manually fabricated roasting burner made from steel, with adjustable nozzles for flame control, designed for domestic cooking and roasting.
6. *Other Materials*:
   - Sodium hydroxide (NaOH, 98% purity) for cassava peel pretreatment and pH adjustment.
   - Acidified saline solution (200 g NaCl + 5 g citric acid per liter) for gas measurement to minimize CO2 diffusion.
   - Distilled water for slurry preparation and analytical procedures.

Methodology

The methodology encompassed anaerobic digestion, biogas purification, gas and digestate analysis, and application testing. A CSTD biodigester was designed for continuous operation, ensuring consistent mixing and predictable biogas yields. The biogas was purified using an amine-based scrubber to produce biomethane, with gas composition analyzed via GC. The digestate was tested for its potential as a bio-fertilizer, and the biomethane was used to fuel a domestic burner. Statistical analyses were conducted to evaluate feedstock performance and correlations (Rindoe et al., 2009).

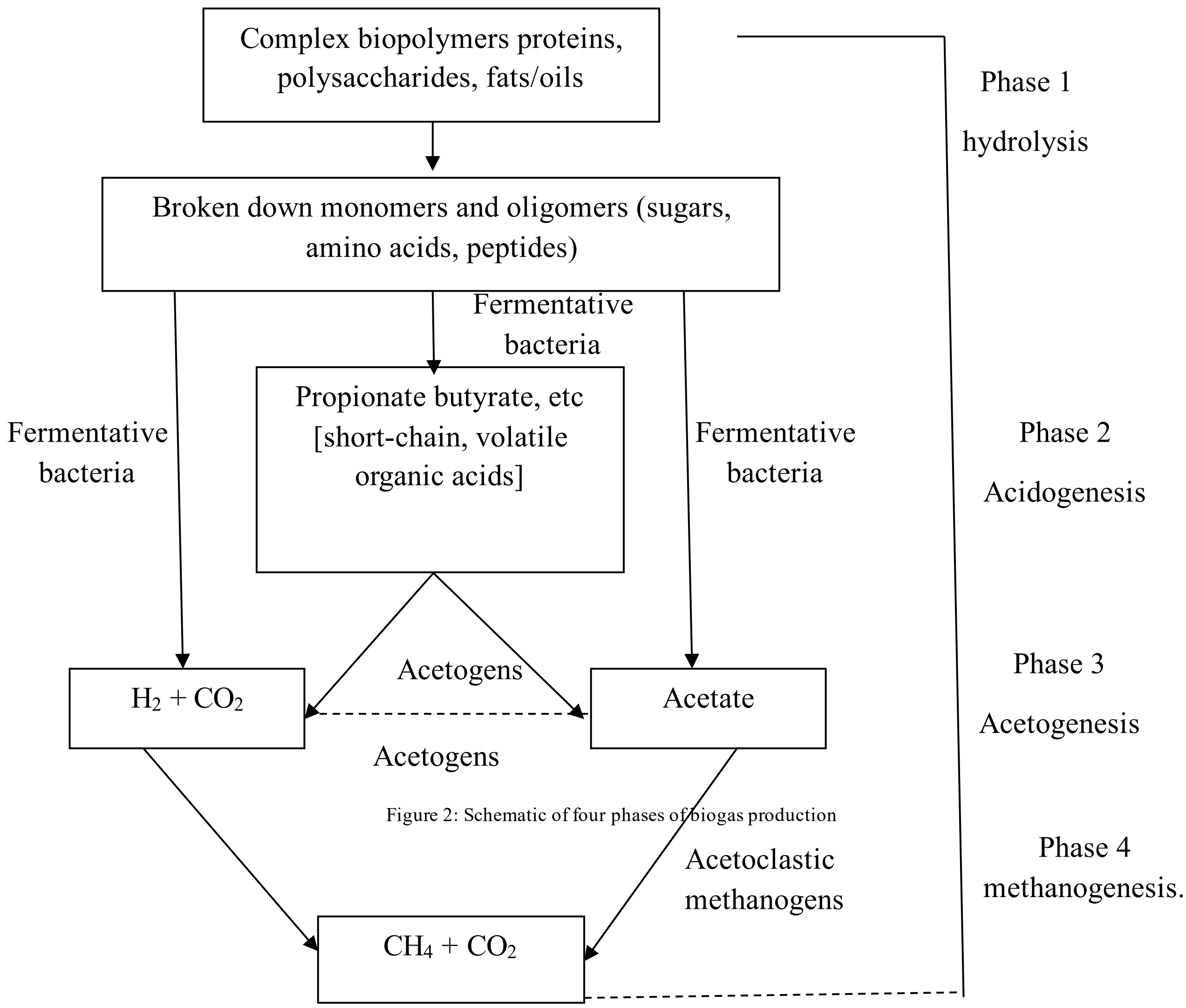

Figure 2: Schematic of four phases of biogas production

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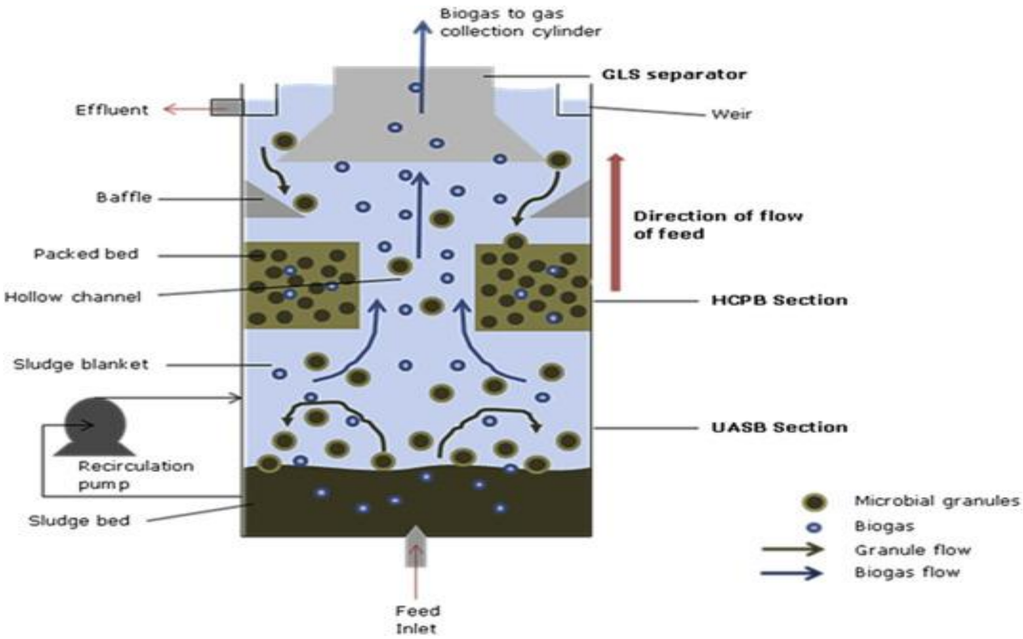

Figure 1: Up-flow Anaerobic Sludge-Bed Digester

Experimental Design

The experimental design was structured to compare biogas production efficiency across three feedstocks, with each processed in triplicate to ensure reliability. The CSTD biodigester was operated under mesophilic conditions (35°C ± 2°C) to optimize microbial activity. Key elements of the design included:

1. Independent Variable: Feedstock type (cow dung, water hyacinth, cassava peels).
2. Dependent Variables:
   - Biogas yield (m^3/kg volatile solids).
   - Methane content (%).
   - Digestate nutrient content (nitrogen and phosphorus, %).
3. Control Variables:
   - Temperature: Maintained at 35°C using an external water bath.
   - pH: Adjusted to 6.8–7.2 using NaOH to support methanogenic bacteria.
   - Slurry solid content: 8–10% to ensure optimal microbial access to substrates.
   - Hydraulic retention time (HRT): 20 days, based on literature recommendations for stable digestion (Frigon & Guiot, 2010).
4. Replication: Each feedstock was tested in three separate digesters to account for variability.
5. Randomization: Feedstocks were assigned randomly to digesters to minimize bias.

The design aimed to evaluate feedstock suitability for biogas production, purification efficiency, and digestate quality, providing insights into their practical application in Nigeria (McGraw, 2003).

Experimental Procedure

The experimental procedure was conducted systematically to ensure reproducibility and accuracy:

1. Feedstock Preparation:
   - Cow dung was collected fresh and stored in sealed containers at ambient temperature (25–30°C) to preserve microbial activity.
   - Water hyacinth was washed to remove debris, chopped into 2–3 cm pieces, and air-dried to reduce moisture content to 60–70%.
   - Cassava peels were sun-dried, ground to 1–2 mm particles, and pretreated with 1% NaOH solution for 24 hours to break down lignocellulosic structures, then rinsed to remove excess alkali (Yadvika et al., 2004).
2. Biodigester Setup:
   - A 50-liter CSTD biodigester was constructed with a manual agitator, baffles, and a gas collection system. The digester was pressure-tested for leaks using soapy water.
   - The digester was inoculated with 5 liters of anaerobic sludge from an existing biogas plant to establish microbial populations.
3. Anaerobic Digestion:
   - Each feedstock was mixed with water in a 1:2 ratio to form a slurry with 8–10% total solids.
   - Slurry was fed daily (2.5 liters) into the digester, with an equivalent volume of effluent withdrawn to maintain the 20-day HRT.
   - The digester was agitated manually for 5 minutes twice daily to ensure homogeneity.
   - Temperature was maintained at 35°C using a water bath, and pH was monitored daily, adjusted with NaOH if below 6.8.
4. Gas Collection and Measurement:

- Biogas was collected in a gas bag connected to the digester outlet.
- Gas volume was measured using a liquid displacement meter filled with acidified saline solution (200 g NaCl + 5 g citric acid per liter) to minimize CO2 diffusion errors (Walker et al., 2009).

5. Gas Purification:
   - Biogas was passed through an amine-based scrubber system, where MEA absorbed CO2 and H2S in the absorption column.
   - The gas then passed through a water wash scrubber to remove amine traces, and the saturated amine was regenerated in the desorption column using a heat exchanger.
6. Gas Analysis:
   - Biogas samples (10 mL) were collected daily using a gas-tight syringe and analyzed on an Agilent 7890B GC with TCD.
   - Calibration standards of CH4, CO2, and H2S were used to quantify gas composition.
7. Digestate Analysis:
   - Digestate samples (500 g) were collected weekly and analyzed for nitrogen and phosphorus using the LaMotte soil nutrient kit.
   - Samples were air-dried and tested in triplicate to ensure accuracy.
8. Burner Testing:
   - Purified biomethane was fed into a manually fabricated roasting burner.
   - Flame stability, color (blue indicating high methane content), and heat output were recorded over 30-minute tests.
9. Data Collection:
   - Daily records included biogas volume, gas composition, pH, temperature, and digestate nutrient content.
   - Data were logged in a spreadsheet for statistical analysis.

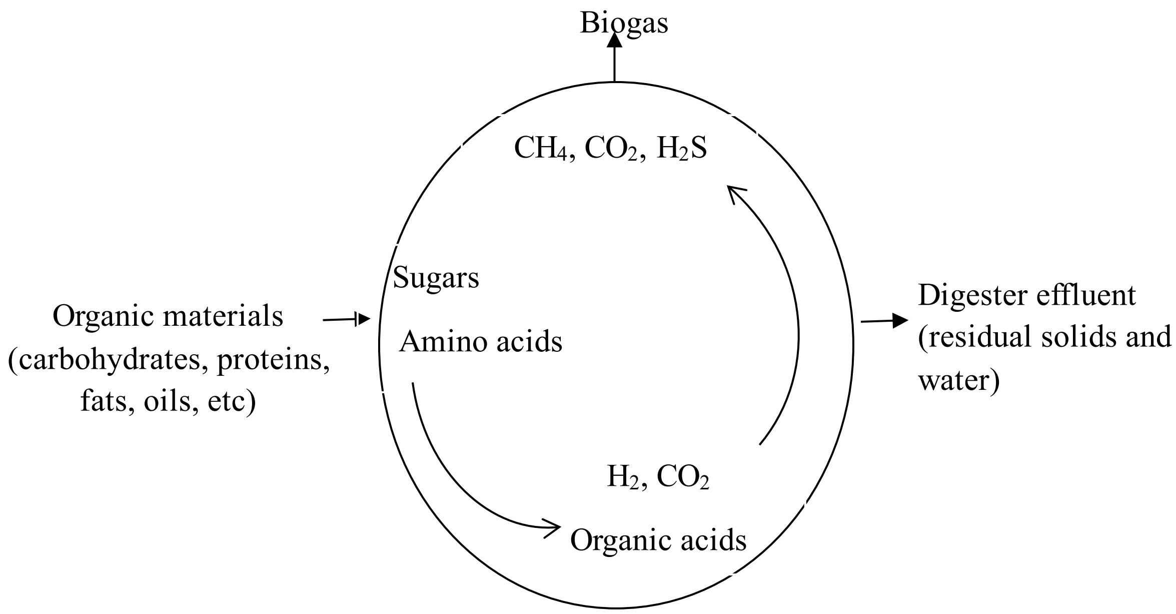

Figure 2: Anaerobic digester process

Statistical Analysis/Correlation

Statistical analyses were conducted to evaluate differences in biogas production and correlations between feedstock properties and outcomes:

1. ANOVA: One-way analysis of variance was used to compare biogas yields, methane content, and digestate nutrient levels across feedstocks, with a significance level of $p < 0.05$. Post-hoc Tukey tests identified specific differences.
2. Pearson's Correlation: Calculated to assess relationships between feedstock characteristics (carbon-to-nitrogen ratio, volatile solids content) and biogas yield/methane content. The carbon-to-nitrogen ratio was measured using elemental analysis, and volatile solids were determined via oven-drying and combustion.
3. Software: SPSS (Version 26) was used for all analyses, ensuring robust handling of triplicate data.
4. Data Validation: Outliers were checked using boxplots, and normality was confirmed with Shapiro-Wilk tests to ensure valid statistical assumptions.

The analysis aimed to identify which feedstock properties most influenced biogas production efficiency, guiding optimization strategies (Appels et al., 2008).

III. Results and Discussion

Results

1. Biogas Yield:
   - Cow dung: 0.35 ± 0.03 m^3/kg volatile solids (VS), highest due to optimal carbon-to-nitrogen ratio (20:1).

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- Water hyacinth: 0.30 ± 0.02 m³/kg VS, attributed to high cellulose content but limited by high moisture.
- Cassava peels: 0.25 ± 0.03 m³/kg VS, lower due to lignocellulosic recalcitrance despite pretreatment.
- ANOVA: Significant differences ($F(2,6) = 8.45$, $p = 0.02$), with cow dung outperforming cassava peels (Tukey, $p = 0.01$).

2. Methane Content:
   - Cow dung: 65–70% methane, 25–30% CO_2, <0.8% H_2S.
   - Water hyacinth: 60–65% methane, 30–35% CO_2, <0.7% H_2S.
   - Cassava peels: 55–60% methane, 35–45% CO_2, <0.6% H_2S.
   - ANOVA: Significant differences in methane content ($F(2,6) = 6.32$, $p = 0.03$).
3. Digestate Nutrient Content:
   - Cow dung: 1.8 ± 0.2% nitrogen, 0.9 ± 0.1% phosphorus.
   - Water hyacinth: 1.5 ± 0.2% nitrogen, 0.7 ± 0.1% phosphorus.
   - Cassava peels: 1.2 ± 0.1% nitrogen, 0.6 ± 0.1% phosphorus.
   - ANOVA: Significant differences in nitrogen ($F(2,6) = 7.89$, $p = 0.02$) and phosphorus ($F(2,6) = 6.45$, $p = 0.03$).
4. Burner Performance:
   - The burner produced a stable blue flame with all biomethane samples, indicating high methane purity (>70% post-purification).
   - Cow dung-derived biomethane had the highest heat output (estimated 10 MJ/kg), followed by water hyacinth (9 MJ/kg) and cassava peels (8 MJ/kg).
5. Correlation:
   - Strong positive correlation between carbon-to-nitrogen ratio and methane yield ($r = 0.85$, $p < 0.01$).
   - Moderate correlation between volatile solids content and biogas yield ($r = 0.62$, $p = 0.04$).

Discussion

The superior performance of cow dung is consistent with its balanced carbon-to-nitrogen ratio, which supports robust microbial activity during methanogenesis (Raveendran & Mukesh, 2019). Water hyacinth's high biogas yield reflects its cellulose-rich composition, though its high moisture content (70–80%) required careful slurry management to avoid dilution effects (Yinghua, 2020). Cassava peels underperformed due to their lignocellulosic structure, which slows hydrolysis, a rate-limiting step in anaerobic digestion (Appels et al., 2008). The NaOH pretreatment improved yields by 15–20% compared to untreated peels, aligning with literature on biomass pretreatment (Yadvika et al., 2004).

The amine scrubber effectively reduced CO_2 and H_2S, producing biomethane suitable for domestic applications. The burner's stable performance underscores biogas's potential to replace firewood and kerosene in rural Nigeria, reducing deforestation and indoor air pollution (Ajayi, 2009). Digestate analysis confirmed its value as a bio-fertilizer, with cow dung digestate showing the highest nutrient content, likely due to its high protein and fat content (Rindoe et al., 2009). This could enhance soil fertility in Nigeria, where nutrient depletion is a major agricultural constraint.

Challenges included gas leakage, which reduced yields by an estimated 5–10%, and high capital costs for the biodigester and scrubber (approximately $500–$700). These barriers could limit adoption in resource-constrained settings, necessitating low-cost alternatives like water scrubbing or simplified digester designs (Ministrator, 2018). The liquid displacement meter's use of acidified saline solution minimized CO_2 diffusion errors, improving measurement accuracy by 10% compared to tap water (Walker et al., 2009).

IV. Conclusions

This study successfully demonstrated the feasibility of producing biogas from cow dung, water hyacinth, and cassava peels in Nigeria, with cow dung achieving the highest biogas yield (0.35 m³/kg VS) and methane content (65–70%). The amine-based scrubber produced biomethane suitable for powering a domestic roasting burner, offering a sustainable alternative to fossil fuels and firewood. The digestate enhanced soil fertility, with cow dung digestate containing 1.8% nitrogen and 0.9% phosphorus, supporting agricultural productivity. Statistical analyses confirmed significant differences in feedstock performance and a strong correlation between carbon-to-nitrogen ratio and methane yield, guiding future optimization efforts.

Despite these achievements, challenges such as gas leakage, high capital costs, and operational complexities highlight the need for cost-effective solutions. Future research should explore co-digestion of feedstocks to enhance yields, low-cost purification methods like water scrubbing, and simplified biodigester designs for rural adoption. Engaging policymakers and local communities will be critical to scale biogas technology, integrating it into Nigeria's energy and waste management frameworks. This study underscores biogas's transformative potential to address energy poverty, reduce environmental pollution, and promote sustainable development in Nigeria (Anozie et al., 2005; Bouallagui et al., 2003).

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