BAJOPMAS JOURNAL 16(1): 58 – 69
Printed in Bayero University, Kano - Nigeria.

BIOGAS PRODUCTION AS A RENEWABLE SOURCE OF ENERGY FOR ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY

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ABSTRACT
This study investigates the potential of potato waste as a feedstock for biogas production through anaerobic digestion, aiming to promote environmental and economic sustainability. A 25-liter plastic digester was used, with potato waste processed into slurry for digestion. The physico-chemical analysis revealed significant changes in parameters such as Total Solids (TS), Volatile Solids (VS), Chemical Oxygen Demand (COD), and Volatile Fatty Acids (VFA) throughout the digestion process. TS decreased from 20.5% to 10.5%, VS reduced from 85.33% to 40.33%, and COD dropped from 1998 mg/L to 1845 mg/L, indicating effective degradation of organic matter. Biogas production started on day 6, peaking at 2550 m^3/day on day 36, with an average slurry temperature of 30.66°C and pH range of 7.7–8.6. The results demonstrate that potato waste is a viable substrate for biogas generation, achieving over 50% VS reduction and producing substantial biogas yields. This aligns with findings by Kafle and Kim (2013), confirming the efficiency of anaerobic digestion systems treating food waste. The study highlights the importance of optimizing operational conditions, such as temperature and pH, to enhance biogas output. Recommendations include feedstock pre-treatment to improve biodegradability and digestate utilization as biofertilizer, promoting circular economy principles. These findings support the viability of small-scale, low-cost biogas systems in addressing energy poverty and reducing greenhouse gas emissions, particularly in developing regions like Nigeria. This research underscores biogas technology's role in advancing sustainable development goals related to clean energy, climate action, and responsible consumption.

Keywords: Atmospheric Sustainable Development; Biogas; Biomass; Contaminations; Renewable Energy,

1.0 Introduction
Worldwide energy consumption and demand have grown significantly over the past 50 years [1]. Renewable energy resources and opportunities for energy efficiency exist across wide geographical areas, unlike other energy sources concentrated in a few countries [2]. The rapid deployment of renewables and energy efficiency, coupled with a diversification of energy sources, offers major energy security and economic benefits[3]. Additionally, this transition would reduce environmental pollution caused by fossil fuel combustion, improve public health, and reduce pollution-related premature mortality [4]. Biomass can be converted into usable energy forms like methane gas or transportation fuels such as ethanol and biodiesel. Agricultural and human waste release methane gas—also known as landfill gas or biogas [5].

Sustainable development is an approach that accounts for Earth's finite resources [6]. It emphasizes renewable energy and sustainable agriculture or forestry practices [7], and entails the responsible use of minerals. The core idea is to build systems that can endure indefinitely into the future. While often associated with environmental concerns, sustainable development also requires attention to economic and social sustainability. Current challenges include desertification, deforestation, soil erosion, population growth, industrialized livestock farming, ecological imbalance, and waste accumulation. Addressing these requires visionary leadership, effective policies, and global cooperation, particularly to support Developing Countries.

Anaerobic digestion in integrated resource recovery systems is crucial for tackling both ecological and economic problems in Developing Countries. Interest in biogas technology increased post-1973 energy crisis, highlighting the need to develop renewable energy alternatives to depleting fossil fuels. Biogas is now recognized as an efficient, non-polluting energy source [8]. Sustainable development, as defined by the Brundtland Commission, is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." It includes two key concepts: the essential needs of the world's poor, and the limitations of technology and social organization in meeting current and future needs. All definitions emphasize viewing the world as a connected system-spatially and temporally. Sustainable development envisions a future where human societies meet their needs without degrading natural systems. Sustainable energy, unlike fossil fuels, produces minimal or no pollution, offering a cleaner alternative for long-term environmental and societal well-being [9].

Biogas originates from bacterial degradation of organic materials under anaerobic conditions, a vital part of the carbon cycle. Methanogens are the final agents in this process, producing biogas as a renewable energy source. Biogas can generate electricity or serve as automotive fuel, and can substitute for Compressed Natural Gas (CNG) [10]. With a calorific value of about 6 kWh/m^3, equivalent to half a litre of diesel, biogas's net calorific value depends on burner efficiency. Methane is its most valuable component when used as a fuel. Energy is a key driver of socio-environmental development. Biogas contributes to environmental sustainability [11] by reducing greenhouse gas emissions and conserving forests. It improves health and sanitation by offering clean, smokeless energy, positively impacting women and children. A healthy environment, combined with clean energy, supports better enterprise integration [11]. Biogas composition varies by substrate—typically 55% methane and 45% CO_2 for carbohydrate-based feeds, and up to 75% methane for fat-based feeds [11]. Pure methane has a calorific value of 9,100 kcal/m^3; biogas ranges between 4,800 and 6,900 kcal/m^3. In energy terms, 1.33–1.87 m^3 of biogas equals one litre of gasoline; 1.5–2.1 m^3 equals one litre of diesel. Biogas has a specific gravity of 0.86 and a low flame speed factor (11.1), requiring appropriately designed burners to prevent unstable flames.

Biogas technology is gaining momentum in Developing Countries due to its potential to address:

i. Dependence on imported energy;
ii. Deforestation and resulting soil erosion, affecting agricultural productivity;
iii. The need for inexpensive fertilizers to boost food production;
iv. Sanitary waste disposal, crucial for public health;
v. Industrial waste disposal, which contributes to water pollution.

Anaerobic fermentation has evolved into a robust method of biomass conversion. Efficient biogas systems provide wide-ranging benefits for individuals, society, and the environment [12].

Biogas offers energy in the form of heat, light, and electricity, and converts organic waste into high-quality fertilizer. This reduces pathogens, worm eggs, and flies, improving hygiene and reducing the workload of women involved in firewood collection and cooking.

Environmentally, biogas conserves soil, water, air, and woody vegetation. Economically, it substitutes energy and fertilizers, generates income, and boosts productivity in agriculture and animal husbandry. Decentralized biogas systems reduce dependency on imported energy while promoting environmental sustainability. Biogas technology also mitigates climate change by reducing greenhouse gases. However, the systems require substantial initial investment, and technical limitations must be addressed to ensure long-term sustainability.

Biogas fights climate change by reducing CO_2 emissions in two major ways: replacing fossil fuels in cooking, heating, and electricity, and lowering the demand for synthetic fertilizers, which are significant CO_2 contributors. Biogas use also reduces deforestation and soil degradation while supporting forest carbon sinks. Though methane is a potent greenhouse gas, burning biogas releases CO_2 previously absorbed by plants, creating a closed carbon cycle, unlike fossil fuel emissions.

Biogas becomes highly combustible when its methane content exceeds 50%, producing a blue flame ideal for cooking and heating. Feedstocks include agricultural waste (e.g., maize, rice), food processing waste, sugar industry by-products, industrial waste, and organic kitchen and hotel waste. Biogas can be refined into high-purity methane, compressed, and used as CNG for vehicles [13]. The residue from biogas plants digestate can be processed into liquid fertilizer rich in nitrogen and solid compost for further conversion into nutrient-rich fertilizer. In China, anaerobic digestion has proven beneficial for energy generation, environmental protection, and ecological restoration [14]

Economically, small-scale biogas plants must be evaluated based on the value of fertilizer and fuel outputs relative to construction, operation, and maintenance costs. They also generate indirect benefits such as improved sanitation, better rural health, and access to electricity enhancing education and quality of life. Increased organic manure use improves soil health and crop yields while reducing reliance on chemical fertilizers [15].
Despite the evident advantages of biogas as a clean and renewable energy source, several challenges hinder its widespread adoption, particularly in Developing Countries. These include:

i. Limited awareness and technical know-how among rural populations, which restricts the understanding and acceptance of biogas technology [16]
ii. High initial costs of constructing and installing biogas digesters, making them unaffordable for many low-income households [13];
iii. Inconsistent government policies and lack of financial incentives, which discourage private investments and large-scale implementation [17];
iv. Inadequate research into locally available feedstocks, leading to inefficient use of potential biogas resources [18]
v. Poor maintenance culture and lack of trained personnel for troubleshooting, resulting in frequent breakdowns and abandonment of systems [19]

Given these challenges, this work aims to:

i. Assess the potential of biogas as a sustainable energy source addressing environmental, economic, and health concerns;
ii. Highlight its role in promoting sustainable development, energy independence, and improved agricultural productivity;
iii. Identify key challenges and provide policy and technical strategies for wider adoption in Nigeria and similar contexts;
iv. Support climate change mitigation through low-emission energy alternatives;

v. Encourage the integration of waste-to-energy solutions in national and local development plans.

Ultimately, the study underscores the importance of biogas in achieving energy security and environmental sustainability in developing regions.

Method

Potato waste is an excellent feedstock for biogas production due to its high starch content, which can be effectively converted into biogas through anaerobic digestion. The following methods were used in carrying out the research. This includes digester construction, preparation of the sample, the physico-chemical analysis and collection of the data,

2.1 Digester Construction

A plastic can of 25 Litres capacity was used as the digester. A hole was made at the top of the container and a rubber tube was inserted and fixed which serves as the gas outlet. The gas produced leaves the digesters by means of the delivery tubes connected into a measuring cylinder which was used as the gas measuring device. The delivery tubes were fitted with a tap for regulating the gas flow. The tube then ran through a bucket containing water and hence into an upturned measuring cylinder inside the bucket. The water in the bucket acts as a seal preventing air from entering the digester and allowing the gas produced to flow through the delivery tubes (Figure 1). The gas then flows into an upturned measuring cylinder inside the bucket. This measuring cylinder allows for the accurate measurement of the gas produced during the digestion process.

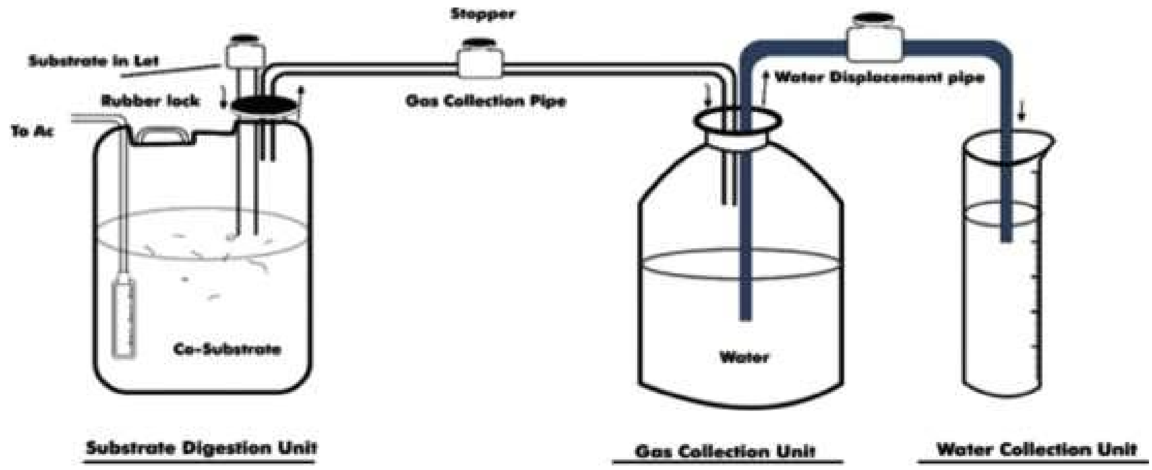

Figure 1: Schematic Diagram of the Measurement of Biogas Production
by Water Displacement Method.

2.2 Collection and Preparation of Potato Waste

Before the anaerobic digestion process begins, potato waste is collected, sorted, and prepared to ensure it is suitable for digestion and optimized for maximum biogas production. Potato waste can originate from various sources, including food processing plants, kitchen scraps such as potato peels, spoiled potatoes, and agricultural residues from potato farming. To enhance microbial activity, the waste undergoes size reduction through chopping or grinding, increasing the surface area. The waste is then mixed with water to form a slurry, making it easier to process during the digestion process.

2.3 Physico-Chemical Analysis

The Moisture Content (MC), Chemical Oxygen Demand (COD), Volatile Fatty Acids (VFA), Carbon Content (CC), Total Solids (TS), and Total Volatile Solids (VS) of the waste sample were analysed prior to digestion. A small sample of the slurry was collected, properly labelled, and transported to the Ministry of Environment laboratory for analysis. All analyses were conducted following standard protocols, including the APHA guidelines for monitoring COD, TS, and VS throughout the study period. The Moisture Content of the raw material was determined in accordance with procedures outlined in the ASTM Standard [20]. Below is a summary of the methods, basic principles, and formulas (Equations 1– 5) used [21]:

Moisture Content (MC): Moisture content is determined by the weight difference before and after drying the sample.

$$MC(\%) = \frac{Initial\ weight - Dry\ weight}{Initial\ weight} \times 100 \qquad (1)$$

Chemical Oxygen Demand (COD): COD is determined by oxidizing organic matter in the sample using a strong oxidant like potassium dichromate under acidic conditions, followed by back titration with ferrous ammonium sulphate.

$$COD(mg/L) = \frac{(V_b - V_s) \times N \times 8000}{Volume\ of\ sample\ (mL)} \qquad (2)$$

Where V_bVolume of titrant for blank is, V_s is Volume of titrant for sample and N is Normality of ferrous ammonium sulphate.

Volatile Fatty Acids (VFA): VFAs are determined using gas chromatography or titration methods to quantify the short-chain fatty acids in the slurry. Acidify the sample, distil it, and analyze the distillate using chromatography or titration.

Carbon Content (CC): Carbon content is estimated using a Carbon-Hydrogen-Nitrogen (CHN) analyser or via combustion, measuring the CO_2 released.

$$CC(\%) = \frac{Mass\ of\ Carbon\ in\ the\ sample}{Mass\ of\ the\ sample} \times 100 \qquad (3)$$

Total Solids (TS): TS is determined by evaporating all water from the sample and weighing the residue.

$$TS(\%) = \frac{Weight\ of\ dry\ residue}{Weight\ of\ wet\ sample} \times 100 \qquad (5)$$

Volatile Solids (VS): VS is determined by burning the total solids in a muffle furnace at 550°C to remove organic matter, and weighing the residue.

$$VS(\%) = \frac{Weight\ loss\ on\ ignition}{Weight\ of\ total\ solids} \times 100 \qquad (6)$$

2.4 Anaerobic Digestion Process

Anaerobic digestion is the primary method used to convert potato waste into biogas. This process involves the breakdown of organic matter by microorganisms in an oxygen-free environment. As the microorganisms decompose the waste, they produce biogas, which is primarily composed of methane, and digestate, a nutrient-rich by-product.

2.5 Single-Stage Anaerobic Digestion

In a single-stage anaerobic digestion process, all the biochemical reactions (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) occur in a single reactor. This is the simplest and most common method used for biogas production.

The Processes of the anaerobic digestion includes:

i. Hydrolysis: The complex carbohydrates (starch) in potato waste are broken down into simpler sugars.
ii. Acidogenesis: These sugars are then converted into volatile fatty acids, alcohols, and other intermediates by acidogenic bacteria.
iii. Acetogenesis: The intermediates are further converted into acetic acid, hydrogen, and carbon dioxide.
iv. Methanogenesis: Finally, methanogenic archaea convert acetic acid and hydrogen into methane and carbon dioxide, forming biogas.

2.6 Data Collection

During the research, several parameters were measured daily, including ambient temperature, slurry temperature, pH, mass, and volume of gas produced. Data collection was performed at 4-hour intervals between 9:00 am and 5:00 pm, aligned with periods of significant solar radiation. Three readings were taken daily at these intervals. The ambient temperature and slurry temperature were measured using a thermometer. For slurry temperature, the thermometer was dipped into the slurry, and readings were taken once they stabilized. The pH of the slurry was measured using a pH meter, which was standardized with phosphate buffer solutions before use. The electrode of the pH meter was immersed in the slurry, and readings were recorded once stabilized. The average ambient temperature and average slurry temperature were calculated from these readings to provide diverse observations. The biogas production rate was also analysed across various temperature ranges, with the measured parameters offering valuable insights into the relationship between temperature, pH, and biogas production under different conditions.

3.0 Results and Discussions

Table 1 presents a summary of the physico-chemical properties of the waste sample analysed at three distinct stages: before digestion, during digestion, and after digestion. The measured parameters include Total Solids (TS), Carbon Content (CC), Moisture Content (MC), Volatile Solids (VS), Organic Carbon (OC), Volatile Fatty Acids (VFA), and Chemical Oxygen Demand (COD). These values offer insights into the biochemical transformations and degradation processes that occur throughout the digestion period, emphasizing the reduction in organic matter and moisture content, along with variations in key chemical indicators over time.

Table 1. Physic-chemical properties of potato waste for biogas production.

Physico-Chemical Properties	Before Production	During Production	After Production
TS (%)	20.50	19.10	10.50
CC (%)	69.00	55.00	48.00
MC(%)	80.00	65.00	35.00
VS (%)	85.33	70.58	40.33
OC(%)	22.40	21.4	20.50
VFA(mg/l)	2625.00	2035.00	1993.05
COD(mg/l)	1998.0	1900.00	1845.00

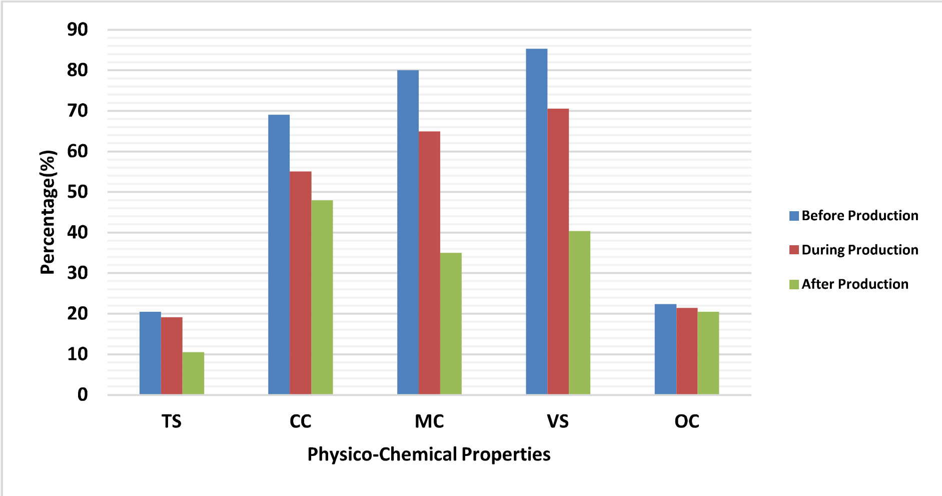

Figure 2: Changes in TS, CC, MC, VS, and OC at different stages of production

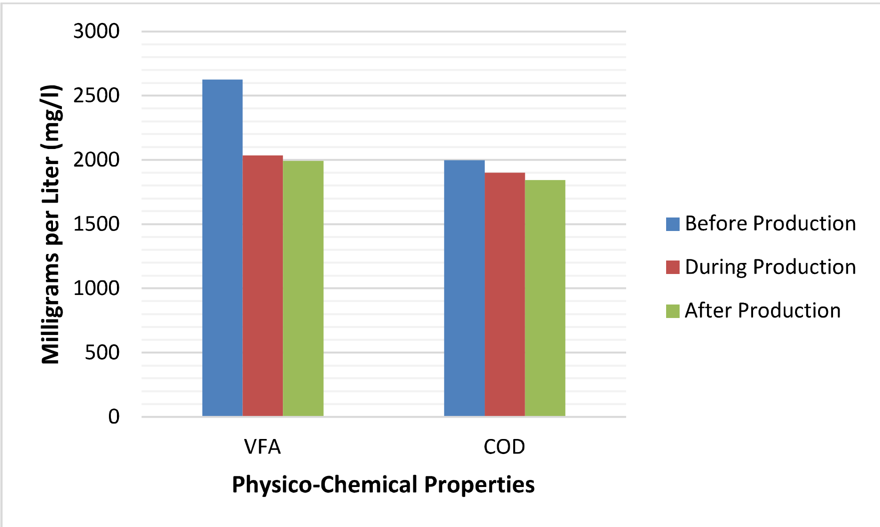

Figure 3 Changes in VFA and COD at different stages of production

From figures 2 and 3, there is a significant reduction in total solids over the course of the process, this is expected, as solids like organic matter are broken down, leaving behind less dense residuals. The reduction in TS suggests effective degradation of the organic material. The marked reduction in total solids (TS) observed in this study indicates effective degradation of organic material, aligning with findings by Kafle and Kim, who reported that TS reduction serves as a reliable indicator of successful biodegradation in anaerobic digestion systems. While the extent of reduction may vary based on the type of feedstock used, efficient systems typically exhibit TS decreases ranging from 40% to 60% [22].

The steady decline in carbon content is a clear indicator of microbial activity. During anaerobic digestion (AD), microbes consume organic carbon as an energy source, producing biogas; primarily methane and CO_2. The lower final carbon content suggests that most of the easily degradable organic material was utilized. [23] also observed a continuous drop in carbon content as organic matter was progressively converted into biogas. This trend is typical of an effective AD process, where organic carbon is steadily consumed by microbes.

VFA concentrations decreased over time. These acids are key intermediates in the breakdown of organic matter during AD. Their reduction signals that methanogenesis; the final stage of AD is occurring efficiently. Towards the end of the process, the decline in VFAs was moderate, indicating a stable digestion phase. [23] Noted that VFAs are vital intermediates, and their conversion into methane reflects active methanogenic activity. Their reduction reflects effective activity by methanogens in converting these intermediates into methane [23]. This transition from acidogenesis to methanogenesis is characteristic of a well-functioning biogas system.

Moisture content dropped substantially during the process. Initially, high moisture levels support microbial activity by enhancing contact between microbes and substrates. As digestion progresses, moisture is either used in microbial processes or lost through evaporation. A final moisture level of 35% likely marks the end of active digestion, with remaining material becoming drier and more stable. [24] emphasized the importance of moisture for microbial dynamics in AD. The observed reduction aligns with expectations and literature.

Chemical oxygen demand (COD), which reflects the organic load of a system, showed a slight reduction over time. This implies that organic materials were partially broken down and converted into biogas. However, the modest decrease suggests incomplete digestion or the presence of complex, recalcitrant compounds. According to [25], efficient AD systems typically show COD reductions between 40–60%. The limited reduction in this case may be due to the persistence of resistant organic matter.

Volatile solids, comprising biodegradable organics, dropped by over 50% by the end of digestion. This indicates substantial degradation of the feedstock material. VS reduction is a standard metric for AD performance. [1] reported VS reductions of 40–60% in well-operated systems, aligning with the results observed here.

The remaining carbon content at the end of the process likely represents recalcitrant materials. These are organic compounds, such as lignin, that resist microbial breakdown. [26] highlighted the challenge of degrading complex organics during AD. Such residual carbon is commonly observed in systems dealing with fibrous or lignin-rich feedstocks.

Overall, the data shows progressive degradation of organic matter, including reductions in total solids, VS, carbon content, and VFAs. While some resistant organics remain, the significant decrease in biodegradable components points to a successful digestion process. These trends are consistent with literature on biogas production [24]. The substantial reduction in key parameters indicates that the system performed effectively in converting organic matter into biogas.

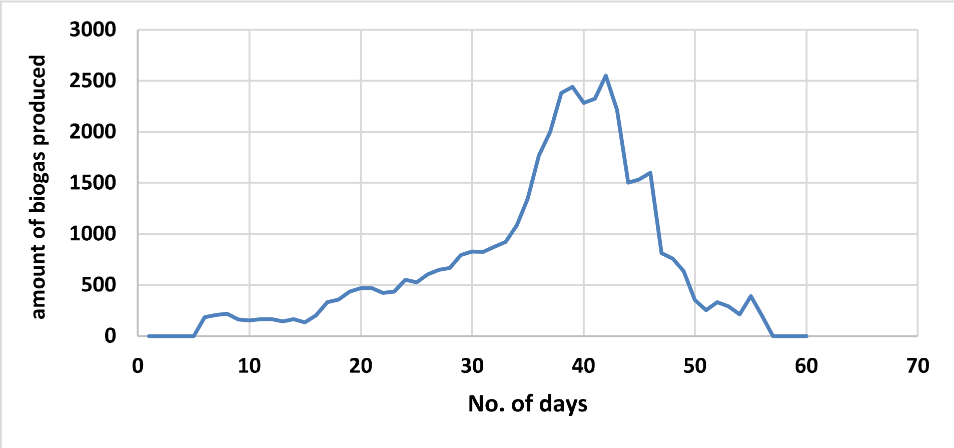

Figure 5: The Average Amount of Biogas Production from Potato Waste in variation to days.

From figure 4, Biogas production starts with very low volumes (days 1–5) and begins to rise sharply from day 6 onward. From days 20 to 40, there is a sustained high output, peaking around day 34 at 1083.33 m^3/day, followed by an even higher peak of 1766.66 m^3/day on day 36. After day 40, production starts to drop off, possibly due to nutrient depletion, microbial inhibition, or pH shifts. A similar lag phase is commonly reported in AD processes. [25] noted that during the first few days, microbial communities, especially methanogens, take time to acclimate to the environment and substrate. This can explain the zero-biogas production in the system during the first 5 days. The peak biogas production in the data occurs around days 30-40, consistent with the literature. [10] reported that under stable conditions (in terms of temperature and pH), the microbial community achieves maximum biogas yield in this time frame. A gradual decline in production after the peak could be due to substrate depletion or an accumulation of inhibitory by-products such as ammonia or volatile fatty acids. [1] observed similar patterns, where biogas production declines after a peak, often due to nutrient exhaustion or changes in system conditions (e.g., pH).

The biogas production curve is typical of a well-functioning anaerobic digester. The slow start, rapid increase, peak, and eventual decline match what is commonly reported in similar studies. However, maintaining high production for nearly 40 days suggests that the substrate had a good balance of readily and slowly degradable compounds.

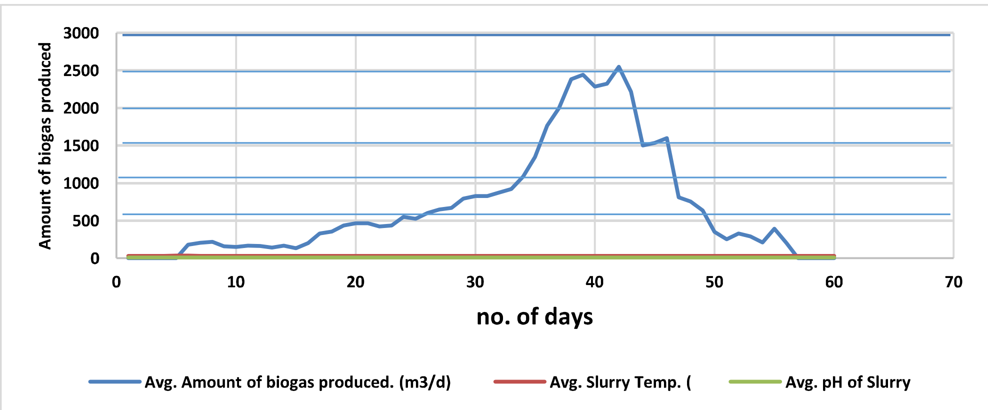

Figure 6: Variation of the Average Amount of Biogas Production from Potato Waste against the Temperature and pH of the Slurry.

From figure 5: the Ambient temperatures ranged from 25.66°C to 34.66°C, while slurry temperatures fluctuated between 27.66°C and 30.66°C. Initial days show low biogas production at these temperatures (days 1–5), but a significant increase starts on day 6, coinciding with slurry temperatures stabilizing around 30.66°C. Peak biogas production occurs between days 30 and 40, when slurry temperatures average around 30.66°C.

Temperature is a critical factor in anaerobic digestion. According to [10], temperatures between 30 °C and 40 °C promote microbial activity, especially during methanogenesis. In this study, the slurry temperature ranged between 30–31 °C, which falls within the mesophilic range. This likely explains the gradual rise in biogas production over time. Research by [22] further supports this, showing that microbial activity slows down significantly at temperatures below 25 °C. Thus, the minimal gas output observed in the initial few days can be attributed to suboptimal ambient temperatures. As the temperature rose and stabilized above 30 °C, methane production increased accordingly.

The pH during the process ranged between 7.70 and 8.60. In the early days (1–6), pH fluctuated and biogas output was minimal. As pH stabilized between 8.00 and 8.40, biogas production became more substantial, peaking around days 30 to 40. The optimal pH for methanogenesis typically lies between 6.8 and 7.5 [25]. Values above 8.0 can inhibit methanogenic bacteria and disrupt the microbial balance [23]. However, in this case, high biogas yields were still recorded, suggesting microbial adaptation or resilience of the feedstock. Some substrates, particularly those with high ammonia content, may tolerate alkaline conditions without adversely affecting methane output [26]. The elevated pH may be due to the presence of alkaline compounds in the substrate.

4.0 Conclusion

This study assessed the performance of an anaerobic digestion system treating food waste, focusing on Total Solids (TS), Volatile Solids (VS), Chemical Oxygen Demand (COD) reduction, and biogas production. The system achieved notable TS reductions (40–50% for potato waste; 30–55% for municipal solid waste), indicating effective solid waste minimization. VS reduction exceeded 50%, confirming efficient degradation of organic matter and the system's capacity for biogas-driven resource recovery.

Although COD reduction was lower than ideal, it remained within common operational ranges (30–70%), suggesting the presence of recalcitrant compounds. This points to the potential benefit of pre-treatment methods such as thermal hydrolysis or extended retention times to enhance biodegradability and energy output.

Biogas production was steady, with peak methane yields around day 40—highlighting the system's potential for renewable energy generation and its contribution to fossil fuel substitution and greenhouse gas mitigation. These results align with findings from comparable studies, reinforcing the feasibility of anaerobic digestion for both waste treatment and clean energy production.

To further improve efficiency, pre-treatment of feedstock is recommended to boost COD degradation and biogas yield. Utilizing the resulting digestate as biofertilizer can support circular economy practices by returning nutrients to the soil. Additionally, continuous emissions monitoring is advised to optimize energy capture and reduce environmental impact.

In conclusion, biogas production from food and agricultural waste presents a sustainable solution to energy and waste management challenges. This study offers a solid foundation for implementing small-scale, low-cost biogas systems—particularly in regions aiming to enhance environmental sustainability through climate change mitigation and circular economy strategies.

Recommendations

To further enhance both system efficiency and environmental sustainability:

i. Feedstock Pre-treatment; Pre-treatment methods like thermal hydrolysis could improve the breakdown of recalcitrant compounds, leading to greater COD reduction and increased biogas yield, thereby maximizing the system's sustainability potential.
ii. Circular Economy Integration; Utilizing the digestate as a biofertilizer supports circular economy principles by recycling nutrients back into the soil, reducing waste and enhancing resource efficiency.
iii. Emissions Monitoring; Continuous monitoring of methane and CO_2 emissions can optimize energy capture and minimize greenhouse gas release, further supporting climate change mitigation efforts.

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