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The Impact of Process Variables on the Quantity and Quality of Biogas Generated from Anaerobic Digestion of Food Waste and Rumen Contents

Afeez Oladeji Amoo[1,2*], Sabo Ahmed[2], Adamu Haruna[2,3]

[1]Department of Environmental Sciences, Federal University Dutse, P.M.B. 7156, Dutse, Jigawa State, Nigeria.
[2]Department of Environmental Management Technology, Abubakar Tafawa Balewa University, Yelwa Campus, Bauchi, 740272, Bauchi State, Nigeria.
[3]Department of Chemistry, Abubakar Tafawa Balewa University, Yelwa Campus, Bauchi, 740272, Bauchi State, Nigeria.

*Correspondence: afeezoladeji@fud.edu.ng; amooafeez415@gmail.com

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ABSTRACT: This research aimed to investigate how combining process variables affects biogas production from anaerobic digestion of food waste and rumen contents. A mixture design was used to evaluate the effects of temperature, pH, agitation frequency, and retention time on biogas quantity and quality. Anaerobic mono-digestion and co-digestion were performed using 2 liter single-stage plastic anaerobic digesters. Cumulative biogas volume and its composition, including carbon dioxide, hydrogen sulphide, moisture, and methane content, were estimated volumetrically. The highest biogas volume and quality were obtained under the following conditions: food waste (0.30 kg), rumen content (0.30 kg), water content (0.40 kg), temperature (34.0° C), pH (9.0), agitation frequency (4 times/day), and retention time (32 days). Combining process variables can significantly impact biogas quantity and quality, and optimal process parameters vary depending on the substrate and operational conditions. Anaerobic digestion can effectively manage organic waste, produce renewable energy, and mitigate greenhouse gases.

KEYWORDS: Anaerobic digestion; biogas production; food waste; process variables; rumen content.

1. Introduction

The utilization of anaerobic digestion technology for the treatment of organic waste has been acknowledged as an efficient method for waste management, renewable energy generation, and the mitigation of greenhouse gases [1]. The production of biogas is a natural process that entails the anaerobic digestion of organic materials by a consortium of microorganisms, usually under mesophilic or thermophilic conditions [2]. The process can be summarized by the following equation:

$$C_6H_{12}O_6 \text{ (glucose)} \rightarrow 3CO_2 + 3H_2 + CH_4 \text{ (biogas)}$$

In this equation, glucose ($C_6H_{12}O_6$) represents various organic materials, including food waste, rumen content, animal manure, and energy crops. During the process of anaerobic digestion, glucose is hydrolyzed by bacteria into simpler compounds, which are subsequently metabolized by other bacteria to produce organic acids, hydrogen, and CO_2. Methanogenic archaea then convert the organic acids, hydrogen, and carbon dioxide into methane (CH_4) and carbon dioxide (CO_2), which constitute the biogas. The methane content in biogas can range from 50% to 70%, depending on the substrate and the operational conditions [3–5].

The quality and quantity of biogas production from anaerobic digestion of organic matter depend on various process parameters. Temperature is a crucial process variable in anaerobic digestion. In a recent study by Lashari et al. [6], the highest biogas yield was observed at 50°C in the digestion of cattle manure and kitchen waste. Similarly, Wang et al. [7] reported that the optimal temperature for biogas production from food waste and cow dung was 50°C. Hydraulic retention time (HRT) is the time required for the substrate to remain in the digester and is an essential parameter that affects biogas production. In a study by Ng et al. [8], the optimal HRT for biogas production from food waste was 28 days, with a biogas yield of 0.70 m^3/kgVS. Likewise, Han et al. [9] reported that the highest biogas yield was achieved at an HRT of 20 days for the digestion of cow manure and kitchen waste.

The pH of the digester is a crucial parameter that affects biogas production, and it is influenced by both the nature of the substrate and the microbial activity in the digester. Cheng et al. [10] recently found that the optimal pH for biogas production from food waste is 7.5, while Lashari et al. [6] reported that the highest biogas yield was obtained at a pH of 7.0 in the digestion of cattle manure and kitchen waste. Organic loading rate (OLR) is another essential parameter that affects biogas production. A high OLR can cause digester failure by inhibiting microbial activity. Luo et al. [11] determined that the optimal OLR for biogas production from food waste is 2.5 kg VS/m^3·d, while Han et al. [9] discovered that the highest biogas yield for the digestion of cow manure and kitchen waste was obtained at an OLR of 3.5 kg VS/m^3·d.

The composition of the substrate is another critical factor that influences biogas production, biogas composition, and digestion stability. Studies have shown that co-digestion of different substrates can enhance biogas production and improve the quality of the biogas produced compared to mono-digestion [12, 13]. Inoculum type is also an important parameter that affects biogas production. The type and quality of the inoculum affect biogas production, digestion stability, and biogas composition. For instance, cow manure inoculum and chicken manure inoculum were demonstrated to enhance biogas production from food waste when compared to pig manure inoculum [14, 15].

Agitation is a crucial process variable in anaerobic digestion that can significantly affect the quantity and quality of biogas production. Wang et al. [7] discovered that appropriate agitation intensity significantly improved biogas production and substrate utilization efficiency during the anaerobic digestion of food waste. Similarly, Jeong et al. [16] reported an increase in methane yield of up to 18.5% when the digester was agitated at 100 rpm during the anaerobic digestion of rumen contents. However, excessive agitation can have a negative impact on biogas production, as [17] found that an agitation speed above 200 rpm resulted in a reduction in biogas production during the anaerobic digestion of food waste. The objective of this study is to determine the effect of combining process variables on the quantity and quality of biogas produced from the anaerobic digestion of food waste and rumen contents.

2. Materials and Methods

2.1. Collection of food waste and rumen content.

The source of the cow's rumen content (RC) used as the primary microbial inoculum for the anaerobic digestion process was the Dutse Central Abattoir in Dutse, Jigawa State of Nigeria. The RC was collected and immediately placed in a 60 L plastic container for transportation to the experimental site. The food waste used in the experiment was also collected from various sources within the Dutse metropolis, including cooked rice, cooked beans, Tuwo-Shinkafa (cooked rice powder meal), Tuwo-Masara (cooked corn powder meal), boiled yam, Akara (wasted bean cake), and Masa (wasted rice and corn cakes). The collected food waste was homogenized by blending together using an electric mixer, as described by Amoo et al. [18].

2.2. Physico-chemical characterization of the Food Waste and rumen content.

Samples of the rumen content and homogenized food waste were taken to the laboratory to evaluate their physicochemical properties using standard methods. Parameters including total dry solids (TS), water content (WC), volatile solids (VS), ash content (AC), total carbohydrate, crude protein, volatile fatty acid (VFA), ash-free acid detergent lignin (ADL), total nitrogen, total carbon, and crude lipid in the substrates were determined according to the methodology described by Amoo et al. [18].

2.3. Microbiological characterization of the food waste and rumen content.

The populations of facultative anaerobic bacteria (FAB), strict anaerobic bacteria (SAB), acetoclastic methanogens (AM), and hydrogenotrophic methanogens (HM) were determined in the samples of rumen content and homogenized food waste, as described by [19]. This is because the determination of these microorganism populations helps in predicting the efficiency and stability of the anaerobic digestion process, as well as the potential biogas yield of the substrate [20, 21].

2.4. Design of the experiment.

To assess the collective influence of temperature (28 – 45° C), pH (5 - 9), number of bio-digester agitation/day (0 – 6 times/day), and retention time (15 – 40 days) on the quantity and quality of biogas produced, anaerobic mono-digestion and co-digestion experiments were conducted on food waste (0 – 1 kg), rumen content (0 – 1 kg), and water (0 – 1 kg) using the mixture design (Combined I-optimal) in the Design Expert (version 13) software. A total of 100 experimental runs were generated to analyze the outcomes [18].

2.5. Design and set-up of the anaerobic digester.

The anaerobic digester was set up and designed precisely as described in Amoo et al. [18]. In each of the 100 experimental trials, a single-stage plastic anaerobic digester with a capacity of 2 liter, providing a useful volume of approximately 1.9 liter and a head space of around 0.1 liter, was used. The digester had an air-tight seal, a biogas outlet, feeding inlet, and digestate outlet. Additionally, a biogas cleaning system, which included units for removing carbon dioxide (CO_2), hydrogen sulphide (H_2S), and water vapor (H_2O), was connected to the biogas outlet of the bio-digester.

2.6. Operating the anaerobic digesters.

The operation of the bio-digesters followed the protocol described by Amoo et al. [18]. Each bio-digester was equipped with a temperature probe, and a digital thermostat (Inkbird ITC-308) was used to regulate the temperature, which was maintained by immersing the bio-digester in a water bath. The pH of the bio-digesters was monitored and adjusted using hydrochloric acid or potassium hydroxide with the aid of a digital pH meter with probe (Hanna Instruments HI98127 pH/EC/TDS) to maintain stability throughout the experiment. The contents of the bio-digesters were manually agitated by hand-shaking several times per day to enhance mixing and promote biogas production.

2.7. Determination of biogas production and its composition.

The cumulative volume of biogas produced, as well as its carbon dioxide, hydrogen sulphide, moisture, and methane contents, were estimated volumetrically by means of serially connected biogas-separating chambers. Each chamber was equipped with a gas measuring syringe and corresponding biogas separating solutions, such as potassium hydroxide solution, iron (II) oxide solution, and silica gel, as described by Dwivedi and Khanna [22]. The quality of biogas produced in each of the anaerobic digesters was determined using Equation 1 [23].

$$Biogas\ Quality\ (\%) = \frac{Volume\ of\ cumulative\ biogas}{Volume\ of\ bio\text{-}methane\ content}\ x\ 100\% \qquad (1)$$

3. Results and Discussion

3.1. Characteristics of the food waste and rumen content.

The physico-chemical and microbiological characteristics of the rumen content and homogenized food waste have been discussed in Amoo et al. [18]. The present study reports the results on the volume of cumulative biogas production and its carbon dioxide, hydrogen sulphide, moisture, and methane contents, as well as its quality in 100 bio-digesters under different operating conditions. The results are specific to this study and cannot be directly compared to other studies due to differences in the experimental setup, operating conditions, and feedstock. However, the results are consistent with previous research indicating that the type of feedstock, operating conditions, and retention time significantly affect biogas production in anaerobic digestion systems.

3.2. Volume of cumulative biogas.

he volume of cumulative biogas produced in each of the 100 bio-digesters ranged from 0 to 19.40 l, as shown in Figure 1. The highest volume of biogas was generated in bio-digester 57 (19.40 l), followed by bio-digester 73 (18.70 l), bio-digester 10 (18.60 l), bio-digester 46 (16.50 l), bio-digester 42 (15.70 l), bio-digester 60 (15.50 l), and bio-digester 58 (15.20 l). The optimal operating conditions that led to the highest biogas production in digester 57 consisted of a feedstock mixture of food waste (0.30 kg), rumen content (0.30 kg), and water (0.40 kg), a temperature of 34.0o C, a pH of 9.0, four agitations per day, and a retention time of 32 days.

A study conducted by Haque et al. [24] demonstrated that the highest biogas yield was achieved at a temperature of 35°C, a hydraulic retention time of 30 days, and an organic loading rate of 2.0 g VS/l/day. This finding is in line with the result of this study, which revealed that the greatest volume of biogas was obtained at a temperature of 34°C and a retention time of 32 days. Another study by de Araújo et al. [25] revealed that a mixture of pig manure, cassava peels, and water at a ratio of 3:1:2 resulted in the highest biogas yield. This result is also consistent with the finding of this study, which indicates that the operating condition that produced the highest volume of biogas in digester 57 included a combination of food waste, rumen content, and water at a ratio of approximately 1:1:1.7.

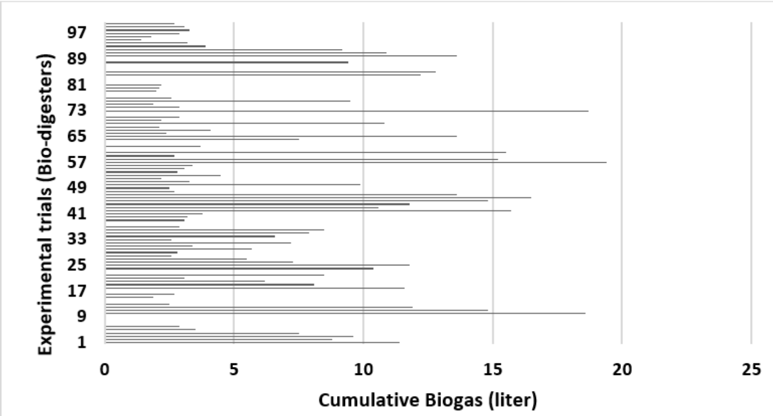

Figure 1. Volume of cumulative biogas produced between bio-digester 1 and bio-digester 100, which were operated under different conditions.

3.3. Volume of cumulative carbon dioxide.

The cumulative volume of carbon dioxide (CO_2) generated in bio-digesters 1 to 100 ranged from 0 to 7.60 l, as shown in Figure 2. Bio-digester 58 produced the highest volume of CO_2 (7.60 l), followed by bio-digesters 11 (7.20 l), 65 (7.10 l), 60 (6.80 l), 73 (6.70 l), 85 (6.60 l), 10 (6.50 l), and 47 (6.50 l). The operating conditions that generated the highest volume of cumulative CO_2 in bio-digester 58 consisted of a mixture of food waste (0.25 kg), rumen content (0.25 kg), and water (0.50 kg), a temperature of 28.0°C, pH of 5.0, 3 times per day agitation frequency, and a retention time of 30 days.

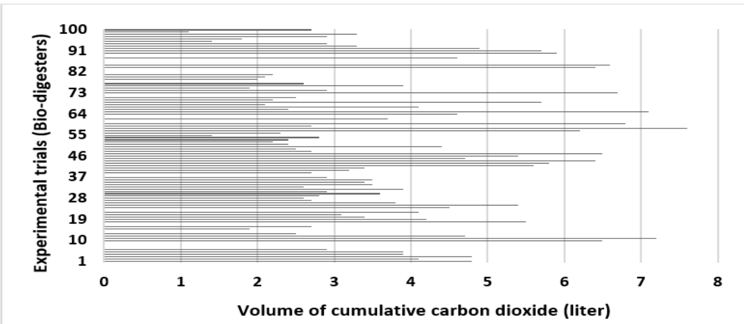

Figure 2. Volume of cumulative CO_2 content of the biogas generated between bio-digester 1 and bio-digester 100, which were operated under different conditions.

A study conducted by Bressani et al. [26] showed that the highest yield of carbon dioxide was obtained at a temperature of 30°C, a hydraulic retention time of 15 days, and an organic loading rate of 3.3 g COD/l. This result is consistent with the finding from this study, which shows that the highest volume of carbon dioxide was produced at a temperature of 28°C and a retention time of 30 days. Another study conducted by Cuetos et al. [27] found that the production of carbon dioxide was influenced by the type and proportion of feedstock used. This result is also in line with the finding from this study, which shows that the highest volume of carbon dioxide in bio-digester 58 was generated using a combination of food waste and rumen content.

3.4. Volume of cumulative hydrogen sulphide.

The volume of cumulative hydrogen sulphide (H_2S) produced between bio-digester 1 and bio-digester 100 ranged from 0 to 0.90 l (Figure 3). The highest volume of hydrogen sulphide (0.90 l) was recorded in bio-digester 51, followed by bio-digester 93 (0.60 l), bio-digester 31 (0.50 l), bio-digester 55 (0.50 l), bio-digester 71 (0.50 l), bio-digester 1 (0.40 l), bio-digester 39 (0.40 l), bio-digester 44 (0.40 l), bio-digester 69 (0.40 l), and bio-digester 91 (0.40 l). The operating condition that generated the highest volume of cumulative H_2S in digester 51 was set at a combination of food waste (0.50 kg), rumen content (0.50 kg), water content (0 kg), temperature (45.0°C), pH (5.0), number of bio-digester agitation per day (4 times/day), and retention time (32 days).

The results of this study indicate that there is variability in the volume of cumulative hydrogen sulphide (H_2S) produced across different bio-digesters. In a study by [28], it was found that the optimal operating conditions for biogas production resulted in a relatively low concentration of H_2S in the biogas. This suggests that there is a trade-off between biogas yield and H_2S production, as evidenced by the highest volume of hydrogen sulphide in bio-digester 51 and the highest volume and quality of biogas in bio-digester 57 (section 3.2).

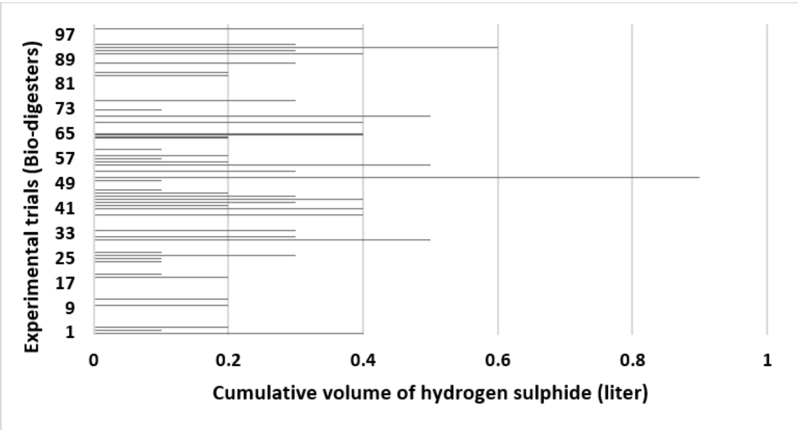

Figure 3. Volume of cumulative H_2S content of the biogas generated between bio-digester 1 and bio-digester 100, which were operated under different conditions.

3.5. Volume of cumulative water vapour.

The volume of cumulative water vapour (H_2O) generated between bio-digester 1 and bio-digester 100 ranged from 0 to 1.60 l (Figure 4). Bio-digester 32 and bio-digester 45 recorded the highest volume of water vapour (1.60 l), followed by bio-digester 73 (1.50 l), bio-digester

42 (1.30 l), bio-digester 57 (1.30 l), bio-digester 58 (1.30 l), bio-digester 92 (1.30 l), bio-digester 10 (1.20 l), and bio-digester 34 (1.20 l). The operating condition that generated the highest volume of cumulative H_2O vapour in digester 32 was set at food waste (1.0 kg), rumen content (0 kg), water content (0 kg), temperature (38.2°C), pH (5.0), no agitation per day, and retention time (19 days).

The results presented in this study provide information on the volume of moisture content (H_2O) in the biogas generated across bio-digesters 1 to 100, with the highest volume recorded in bio-digesters 32 and 45. Zhang et al. [29] investigated the effect of temperature on biogas production from cattle manure and found that higher temperatures led to higher moisture content in the biogas. This finding is consistent with the results from this study, which show that the highest volume of biogas moisture content was recorded at a temperature of 38.2°C.

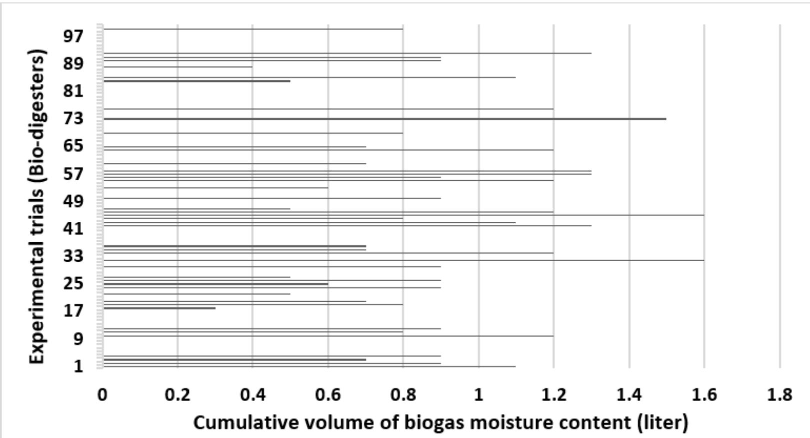

Figure 4. Volume of cumulative moisture (H_2O) content of the biogas generated between bio-digester 1 and bio-digester 100, which were operated under different conditions.

3.6. Volume of cumulative methane.

The study presents information on the cumulative volume of methane (CH_4) generated across bio-digesters 1 to 100, with the highest volume recorded in bio-digester 57. This is followed by bio-digesters 10, 73, 46, 42, 45, 60, 90 and 11. The operating condition that led to the highest volume of methane in bio-digester 57 included food waste (0.30 kg), rumen content (0.30 kg), water content (0.40 kg), temperature (34.0°C), pH (9.0), agitation frequency (4 times/day) and retention time (32 days) (Figure 5).

Previous studies have shown that co-digestion of food waste with different types of manure can enhance biogas production and methane yield. For instance, a study reported that the highest methane yield was obtained at a ratio of 1:1 for food waste and cow manure [30]. Another study also found that co-digestion of food waste and swine manure increased biogas yield and methane content, with the highest methane yield observed at a ratio of 1:1 for food waste to swine manure [31]. These results are consistent with the findings of this study, which demonstrate that the highest volume of methane in bio-digester 57 was obtained with a combination of food waste and rumen content in a ratio of 1:1:1.7.

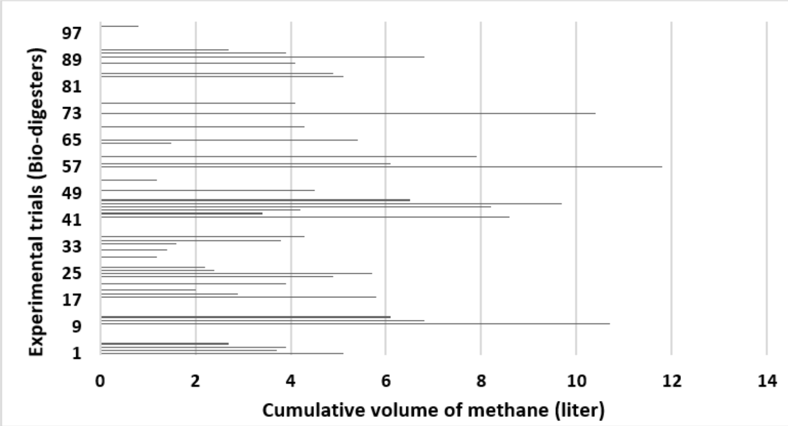

Figure 5. Volume of cumulative CH_4 content of the biogas generated between bio-digester 1 and bio-digester 100, which were operated under different conditions.

3.7. Quality of biogas production.

The study presented information on the quality of biogas production between bio-digester 1 and bio-digester 100, ranging from 0 – 60.82 % (Figure 6). The highest quality of biogas production (60.82 %) was recorded in bio-digester 57 followed by bio-digester 46 (58.80 %), bio-digester 45 (55.40 %), bio-digester 42 (54.80 %), bio-digester 12 (51.26 %), bio-digester 60 (50.97 %), bio-digester 36 (50.60 %) and bio-digester 18 (50.00 %). The operating condition which generated the highest quality of biogas production in digester 57 was set at a combination of food waste (0.30 kg), rumen content (0.30 kg), water content (0.40 kg), temperature (34.0° C), pH (9.0), number of bio-digester agitation per day (4 times/day), and retention time (32 days).

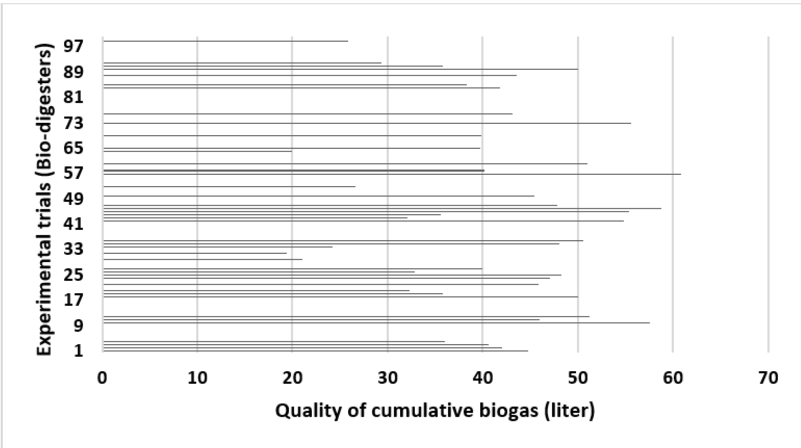

Figure 6. Quality of the biogas generated between bio-digester 1 and bio-digester 100, which were operated under different conditions.

Finally, the study result suggests that biogas quality can vary significantly between different bio-digesters, with bio-digester 57 producing the highest quality of biogas as demonstrated in this study. This finding is consistent with other studies that have identified various factors such as the feedstock used, temperature, pH, retention time, and organic loading rate that can influence the quality of biogas production [28]. Additionally, a study found that the use of cow dung and corn stover as co-substrates resulted in higher methane content in biogas compared to the use of cow dung alone [32]. Another study also found that the use of rumen content as an inoculum source resulted in higher biogas quality [33]. These results are in agreement with the findings in this study, highlighting the importance of using suitable substrates such as rumen content and co-substrates like food waste to enhance biogas quality.

5. Conclusion

This study aimed to investigate the impact of process variables on the quantity and quality of biogas generated from the anaerobic digestion of food waste and rumen contents. The results demonstrated that a combination of process variables such as temperature, pH, number of bio-digester agitation per day, and retention time can significantly affect the quantity and quality of biogas produced. The highest volume and quality of biogas were recorded in bio-digester 57, which was generated from food waste (0.30 kg), rumen content (0.30 kg), water content (0.40 kg), temperature (34.0° C), pH (9.0), number of bio-digester agitation per day (4 times/day), and retention time (32 days). These findings offer valuable insights for the optimization of anaerobic digestion processes. Future studies should aim to scale up the process to commercial levels and investigate the economic feasibility of biogas production from food waste and rumen contents. In conclusion, anaerobic digestion can contribute to sustainable waste management, energy production, and climate change mitigation.

Competing Interest

We, authors of this article, solemnly declare that we have no competing interest.

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