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Article

Effect of Biochar Application on Biogas Production From Cattle Paunch Content

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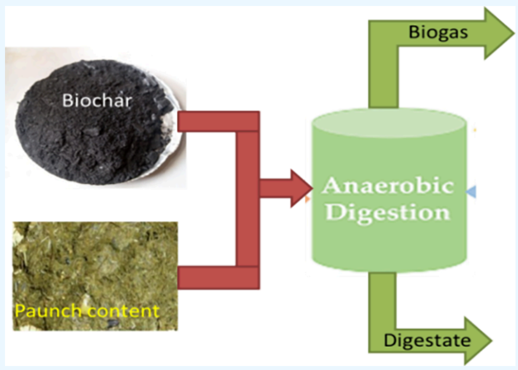
ABSTRACT: Indiscriminate disposal of cattle paunch content by meat processing factories (abattoirs) to the surrounding environments as a result of poor regulation has constituted serious environmental pollution. To address this issue, this study employs the use of sorghum stalk biochar application for anaerobic digestion of paunch content. This research study was therefore designed to determine the effects of one-time addition and periodic addition of sorghum stalk biochar to the paunch content for enhanced biogas production. The design used was 5 g of one-time biochar addition to a digester, 1 g of biochar addition to a digester periodically at four day intervals, and a control digester. The digestion was carried out in a 1000 mL digester bottle with replicates. The biogas yields were 22.79 mL/g V S, 13.83 mL/g V S, and 11.67 mL/g V S for 5 g of one-time biochar addition, 1 g of periodic biochar addition, and control, respectively. Thus, the 5 g one-time biochar addition gives a better yield than the other two treatments. The test for significant difference between pairs of treatments shows that there is a significant difference between 5 g one-time biochar addition and 1 g periodic addition of biochar, and 5 g one-time biochar addition and control at the 5% level of significance. There was no significant difference between 1 g of periodic addition of biochar and the control. The experimental data of the three treatments were fitted to the Gompertz model, which shows adequate fit with R^2 values of 0.991, 0.969, and 0.990 for 5 g one-time biochar addition, 1 g periodic biochar addition, and control, respectively.



1. INTRODUCTION

Energy is a fundamental concept that underpins all physical processes and human activities.[1] In human civilization, energy is crucial for powering homes, industries, transportation, and technology.[2−4] Traditionally, fossil fuels such as coal and natural gas have been the primary sources of energy.[5]

The destructive impact, along with the depletion of these nonrenewable resources, has led to serious concern. This has driven an increased global shift toward incorporating renewable and green energy sources to combat climate change and reduce greenhouse gas emissions.[6−8] Therefore, alternative energy sources that are renewable and environmentally friendly have become imperative. These sources add value to wastes, improving economic returns and the viability of processes.[6] Wastes from abattoirs are potential resources for renewable energy.[9]

Abattoirs are meant to maximize consumption-extracted consumable parts from the processing procedure of meat for human consumption. However, large quantities of waste, which comprise both organic and inorganic solids that are not suitable for further consumption, are inevitable in the process.[9] The massive generation of waste and poor management have made abattoir waste, particularly paunch content, one of the major environmental nuisances.[10,11]

Paunch content (PC) contains partially digested cattle feed, primarily consisting of grass and grains. Roser[12] reported that 19 million tons of PC is generated globally per year. In addition, the PC is an underutilized waste, resulting in an annual energy loss of 23,216,548,750 to 27,804,250,000 MJ, and a financial loss of approximately 800,000,000 Euros.[13] Saverettiar et al.[14] reported that it cost 17 dollars per ton for its disposal. Therefore, it is necessary to convert the PC to energy such as biogas. However, to convert the PC to biogas, it is important to add a stabilizer, like the biochar for optimum biogas yield.

The incorporation of biochar, a carbon-dense substance obtained through the thermal decomposition of biomass via

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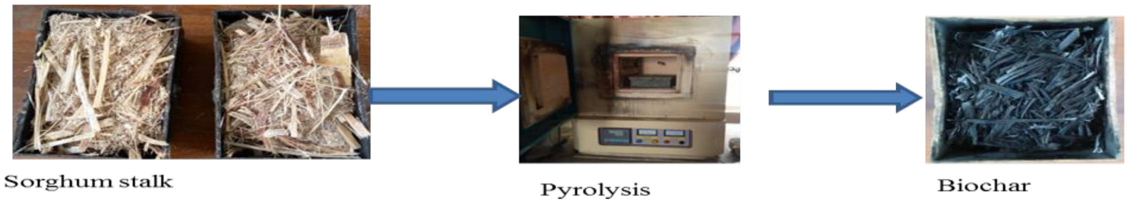

Figure 1. Biochar production process.

pyrolysis, into the anaerobic digestion (AD) process has shown a promising potential in improving biogas production.[15,16] It is expected to realize an overall performance improvement because of the multifunctional promotion effects of biochar.[17] Buffering effect, direct interspecies electron transfer (DIET), microbial immobilization, and disinhibition effect all play significant roles in improving anaerobic digestion performance when adding biochar to anaerobic digestion.[16]

2. EXPERIMENTAL SECTION

2.1. Substrates and Sorghum Stalk Sources. In Nigeria, paunch content is generated in abattoirs (slaughterhouses) and littered in the surrounding environment. In this study, the paunch content was collected from Tayi village abattoir Minna, Niger State, Nigeria. The sorghum stalk was collected from a local farm at the Albishiri area one, Minna, Niger State, Nigeria.

2.2. Biochar Production. The sorghum stalk was crushed, placed in a crucible, and tightly covered (Figure 1). The crucible was placed in a muffle furnace (HSX-2−6−13 model). The furnace temperature was set at 500 °C for 2 h in order to carbonize the sample. After carbonization, the crucibles were left in the furnace overnight to allow them to cool to room temperature.

2.3. Substrate Characteristics. Moisture content (MC), total solids (TS), volatile solids (VS), and ash content were determined according to the standard method.[18] A pH meter (model: ZMW 837) was used to determine the pH, and the open reflux method (5220D) was used to determine the chemical oxygen demand (COD) of the substrate.[19] Carbon (C) and nitrogen (N) contents were determined using eqs 1−3.

$$\mathrm{C\%} = 0.97\mathrm{FC} + 0.7(\mathrm{VM} - 0.1\mathrm{A}) - \mathrm{MC}(0.6 - 0.01\mathrm{M}) \quad (1)$$

$$\mathrm{FC\%} = 100 - (\mathrm{MC} + \mathrm{A} + \mathrm{VM}) \quad (2)$$

$$\mathrm{N\%} = (2.10 - 0.020 \times \mathrm{VM}) \quad (3)$$

where C% = percentage carbon, FC% = fixed carbon, VM% = volatile matter, A% = ash content, and MC% = moisture content.

2.4. Biochar Characterization. The ash content of the biochar was determined using the ASTM E-1755−01 standard.[20] The surface area of the sample was assessed using Brunauer−Emmett−Teller (BET). A pH meter (model: ZMW 837) was used to determine the pH value. Suspension of the biochar was produced using distilled water. The pH meter was immersed in the suspension, and the pH value on the meter was taken.

2.5. Experimental Design. There were three experimental treatments, each with three replicates: 5 g of biochar addition, 1 g of periodic biochar addition, and the control, as presented in Table 1. There were nine digesters, with three allocated to a

Table 1. Experimental Design

digesters	substrate	quantity
digester one, two, and three	paunch content (%)	100
digester four, five, and six	paunch content (%)	100
	biochar (g)	5
digester seven, eight, and nine	paunch content (%)	100
	biochar (g)	1 g/4 days

group to form three groups. Digesters one, two, and three contain only paunch content (control). Digesters four, five, and six contain paunch content. After the 4th day, 5 g of biochar was added when gas depletion was observed in the system. Digesters seven, eight, and nine contain paunch content, and 1 g of biochar was added after the 4th day. The additions of 1 g continue consecutively after every 4 days to the 24th day. Figure 2 shows the water displacement experimental setup for the digestion process. The reactors (1000 mL DURAN bottles) contain the biochar and the substrate that was digested. The biogas produced from the reactors moves through 8 mm diameter silicon tubing to the gas collection bottle, where it displaces the water in it, to the water collection bottle. The quantity of water displaced was measured on a daily basis, which is equivalent to the daily biogas produced.

2.6. Kinetic Modeling. The Gompertz model (eq 4) was employed to quantitatively simulate the cumulative biogas produced. This model is widely recognized as the most commonly used kinetic expression for describing biogas production during AD. It is particularly suitable when biogas production follows a pattern similar to microbial growth.[21] The parameters and the model were coded in Python with initial guesses as $a = 25$, $b = 0.1$, and $c = 15$ for all three treatments.

$$y = a\exp^{(-\exp^{(b-ct)})} \quad (4)$$

where y = biogas production accumulation, a = biogas production potential, b = a constant, the lag phase period (minimum time to produce biogas), c = a constant, the maximum biogas production rate, and t = time (day) over the digestion period.

2.7. One-Way ANOVA. A one-way ANOVA test to ascertain the significant difference in biogas produced. The treatments were 5 g of Biochar vs 1 g of Biochar, 5 g of Biochar vs control, and 1 g of Biochar vs control at a significant level of 5%. The ANOVA was obtained using the Python code.

2.8. Flame Test. The flame test for biogas involves testing the combustion characteristics and performance of biogas produced from organic materials through processes like anaerobic digestion. The flame test was conducted in a well-ventilated environment (Agricultural and Bioresource Engineering Laboratory) for safety purposes. The test provides visual and measurable insight into the quality and characteristics of the gas, particularly its methane content. A blue flame

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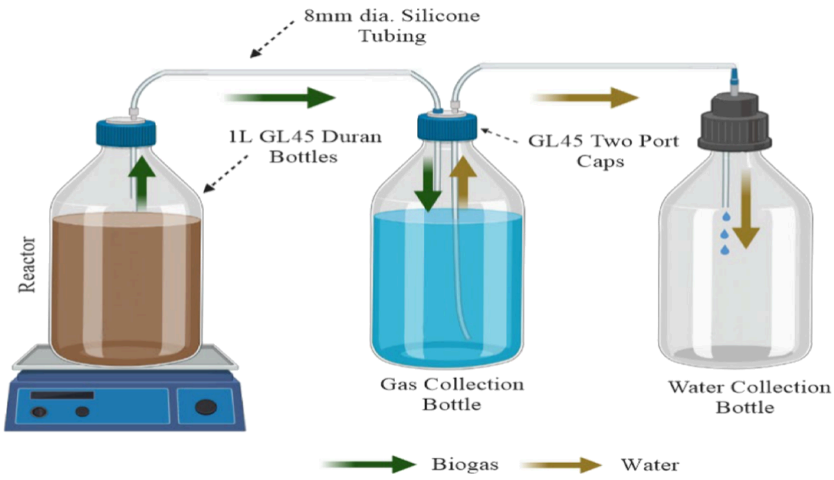

Figure 2. Experimental setup.

generally indicates a high methane concentration, suggesting efficient and complete combustion, while a yellow or orange flame may indicate incomplete combustion or the presence of contaminants like carbon dioxide.[22] The materials used for the test were lighter (for ignition), rubber tubing, a gas flow control valve, safety goggles, and a burner. The gas valve was slowly opened to allow the gas to flow toward the burner. The flow rate was adjusted to a moderate level. The lighter was used to create a small flame. The flame was brought close to the outlet point (a needle) where the biogas was released.[22]

3. RESULTS AND DISCUSSION

3.1. Characterization of the Substrate. The characteristics of the substrate are presented in Table 2. A volatile

Table 2. Physiochemical Properties of Substrate

properties	values
moisture content (%wb)	91.38
total solid content (%db)	8.62
volatile solid (%)	53.78
COD (mg/L)	23,800
pH	6.56
C (%)	37.13
N (%)	1.02
C:N	36.25
ash content (%)	6.39

content of 53.78% was obtained, which shows that the paunch content is a fairly good substrate for biogas production. Studies on various substrates like red grape pomace, cattle dung, tofu waste, and manure from different animals show that biogas yield peaks at specific volatile solid concentrations, ranging from 60 to 90%.[23] The total solid content of 8.62% categorizes the AD process as a wet process. This is because TS is less than 15% of the total substrate content.[24] The COD of 23800 mg/L indicates high organic matter in the substrate. This shows the extent of degradation occurring within the anaerobic digester.[25] The pH value of 6.56 was obtained from the substrate before digestion. This value is less than recommended by various research findings on maintaining a pH value from 7.3 to 6.8 to enable digester stability.[26]

The carbon−nitrogen (C/N) ratio of 36.25 was obtained. This was above the recommended ratio by various research outputs.[27] Carbon and nitrogen are crucial for the growth and survival of anaerobic bacteria. An optimal C/N ratio of 20−30:1 is usually recommended.[27] Moisture content of 91.38% was obtained. Different studies highlight the varying impacts of the moisture content on methane production and process stability. Higher moisture content can lead to improved methane yield and biogas production kinetics, as seen in studies on solid-state NaOH pretreatment and codigestion with pig manure.[28] Conversely, dry anaerobic digestion may result in a lower final methane yield compared to wet conditions. This emphasizes the importance of water in promoting substrate hydrolysis and facilitating nutrient transfer to bacterial sites.[29] The ash content obtained from the substrate is 6.39%. Studies have shown that dried rumen content from different animals like cattle, camel, sheep, and goat shows varying ash content levels, with cattle having the highest at 14.23%.[30]

3.2. Produced Biochar and Its Characterization. Figure 3 shows the produced biochar from the sorghum stalk. The

Figure 3. Produced biochar.

sorghum stalk changes to a dark color, indicating high-density carbon.[31] Some of the biochar characteristics of the sorghum stalk are presented in Table 3. These characteristics, surface area, ash content, and pH value, can affect the anaerobic digestion process. The biochar produced has a surface area of 217.20 m^2/g. Studies have shown that biochar with a larger specific surface area tends to exhibit enhanced performance in terms of biogas production.[32,33] Biochars with a specific surface area greater than 150 m^2/g have been identified as beneficial

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Table 3. Biochar Characteristics

properties	values
surface area (m^2/g)	217.20
ash content (%)	32.36
pH	9.07

for anaerobic digestion, with particle size also playing a role in their effectiveness.[34,35] Larger surface areas allow for more interactions between the biochar and the microbial community, promoting processes like Cu immobilization and enhancing biogas production rates.[36]

The pH value of the sorghum stalk biochar produced was 9.07. In the study by Song et al.,[37] the pH of the finer fraction of wood waste biochar was 9.08. Additionally, biochars produced from Vietnamese biomass had alkaline pH values around 10.[38] The ash content obtained from the sorghum biochar was 32.36%. Studies have shown that ash content plays a significant role in the sorption characteristics of biochars.[39] The ash content of sorghum biochar can vary based on different factors. There are indications that the ash content of biochars produced from sweet sorghum bagasse can be influenced by the pyrolysis temperature, with higher temperatures leading to increased ash content.[40] Studies also indicate that biochar containing elevated ash levels, usually exceeding 20%, can notably improve and speed up the generation of biomethane in anaerobic digestion procedures.[41]

3.3. Biogas Production. The biogas yield in mL/g V S was plotted against the number of days as shown in Figure 4. The quantity of the biogas produced on day two was the highest production obtained across all nine digesters. This observation could be attributed to the conversion of easily degradable materials within the Anaerobic Digestion media by methanogens.[15] On day four, there was a decline in the daily production of biogas. The decrease is due to substrate limitation, which could be explained by the partial degradation of easily degradable materials into volatile fatty acids through hydrolytic acidification. This is usually a result of the inhibition of methanogens.[42] The production was recovered on the 5th day for all of the digester. It is possible that the increase occurred because more recalcitrant materials were now able to degrade, resulting in more biogas production.[43]

However, as other digesters continue to experience a decline in biogas production after the 5th day. The digester that was treated with 5 g of biochar on the 4th day continues to have fluctuating increase throughout the 23rd day of the digestion. The observed increase might be due to the buffering effect of alkaline biochar, which could have alleviated the inhibition caused by the earlier accumulation of volatile fatty acids (VFAs) as noted by Wang et al.[44] Additionally, biochar could have offered surface area for improved growth and activity of methanogens, as suggested by Wang et al.[44] After day six, the digester to which 1 g of periodic biochar was added stabilized and remained relatively consistent, hovering around 0.5 to 1.0 mL/g V S. This consistent fluctuation is similar to the digester with 5 g of biochar addition, though it has a relatively low yield. The low yield could be due to the low dosage (1 g) of biochar added periodically.[45] The digester that served as the control was the one that failed first on day 15; this is a result of the inhibition of methanogens due to the lack of biochar compared to other digesters.[42]

3.4. Cumulative Biogas Production. The plot of the cumulative yield is presented in Figure 5. The digester with 5 g of biochar addition has a cumulative biogas yield that increases steadily over time. This indicates that the addition of 5 g of biochar consistently enhances biogas production. This suggests that the presence of 5 g of biochar has a positive impact on biogas yield throughout the experiment.[46]

The digester that has 1 g of biochar added has cumulative biogas yield in an increasing trend over time but with lower yield. This contribute to overall biogas production, even though with lower variability when compare with the digester with 5 g of biochar treatment.[20,47]

The controlled digester maintained a relatively constant cumulative biogas yield throughout the study. This indicates that without the addition of biochar, the biogas production remains stable but at a lower level compared to those with biochar treatments.[48]

The cumulative biogas yield for the 5 g biochar treatment was generally higher than that of the 1 g biochar treatment. This suggests that a higher initial dosage of biochar 5 g has a more consistent and effective impact on biogas production compared to periodic additions of a lower dosage 1 g.[20,47] Comparing 5 g and 1 g treatment with the control, the two

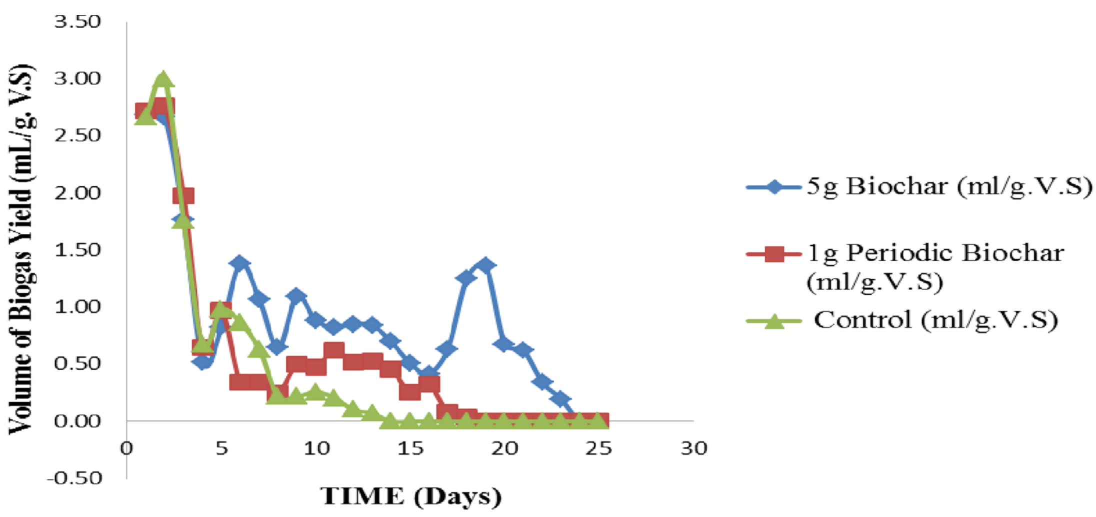

Figure 4. Daily biogas yield.

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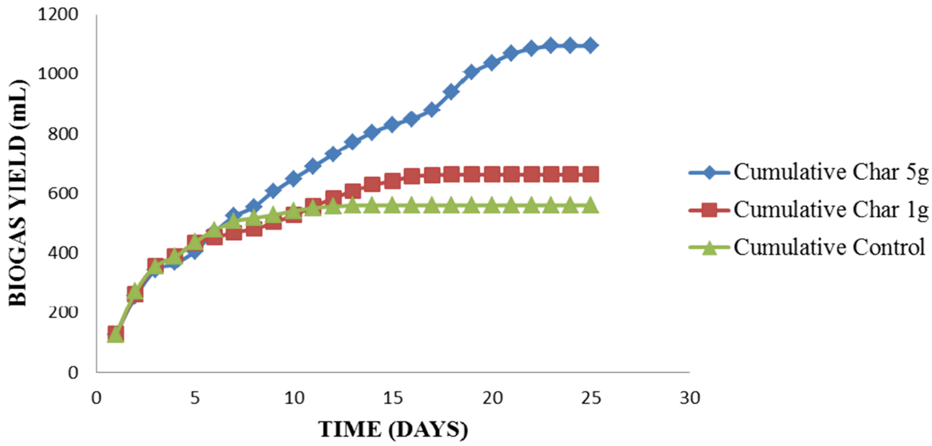

Figure 5. Cumulative biogas yield for the period of digestion.

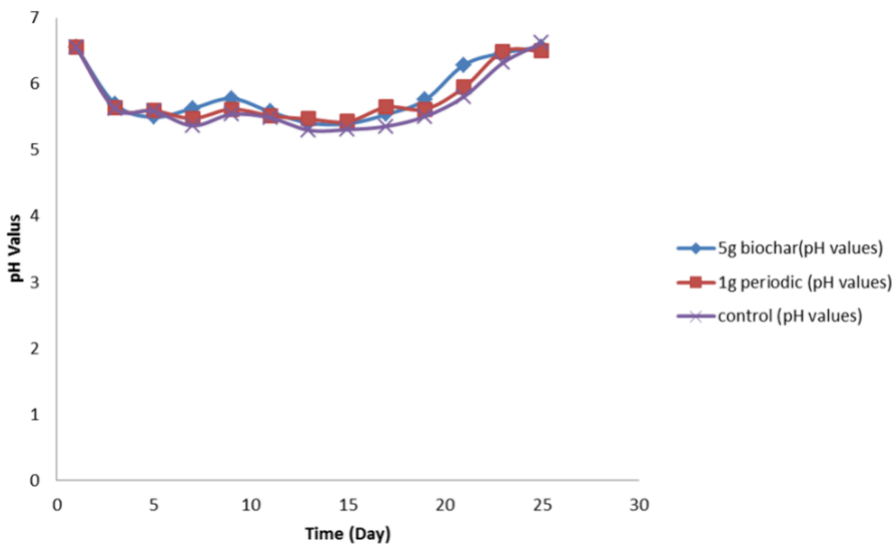

Figure 6. pH Variation at 2 days of interval.

treated with biochar consistently yield more biogas compared to the control throughout the study. This highlights the effectiveness of adding biochar in enhancing biogas production.[48]

The control shows a stable cumulative biogas yield up to day 13. This suggests that without any additional intervention, the biogas production reaches a plateau, maintaining a relatively constant level, and the AD process fails as a result of the inhibition of methanogens due to the lack of biochar compared to other digesters with biochar treatment.[42]

The two treatments (5 g of biochar and 1 g of periodic biochar) also reach their plateau in cumulative biogas yield after day 19. This indicates that there is a limit to the enhancement of biogas production achievable through the addition of biochar, beyond which the yield remains relatively constant.[42]

3.5. pH Variation throughout the Period of Digestion. The pH values were taken at 2 day intervals for the period of study. The pH values for all treatments fluctuate over time as shown in Figure 6. The value of the pH on day one was 6.56 for all treatments. The pH for all the treatments continues to decrease from 6.56 to 5.63, 5.48, and 5.37 for 5 g of biochar addition, 1 g of periodic biochar addition, and control, respectively, to day seven. The pH decrease can be attributed to the rapid acid formation during bacterial metabolic processes, leading to the inhibition of methane-producing bacteria, thus limiting the digestion process.[49] The pH of the treated digesters with biochar has a little higher value than the control digester; this could be a result of biochar addition on the 4th day. A study has found biochar to stabilize pH at 6.0 in processes contaminated with ammonium, showcasing its pH-regulating capabilities during anaerobic digestion.[50]

Generally, it was observed that the pH of all the digesters started to increase from day 17. This scenario was observed even for the control digesters that had stopped biogas production on day 15. This could be due to alkaline compound accumulation, such as sodium hydroxide (NaOH), calcium oxide (CaO), and alkaline hydrogen peroxide (AHP).[51] Biogas production often involves the generation of acidic compounds, such as volatile fatty acids (VFAs). When biogas production stops, these acids may no longer be produced or consumed at the same rate. This cessation of acid production can lead to a relative increase in alkaline compounds or a decrease in acidic compounds, resulting in a rise in pH.[52]

Biochar's ability to regulate pH is attributed to its chemical composition and ash content, rather than its inherent pH level, like other traditional methods of stabilization.[53] Lime ($Ca(OH)_2$) can be used to raise pH, but its effectiveness is

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Table 4. Kinetic Parameters and Model Goodness Fit

conditions	A	B	C	SSE	R^2	adj. R^2	RMSE
5 g of biochar	26.886	0.105	6.512	8.396	0.991	0.9897	0.5795
1 g of biochar	14.096	0.203	1.845	6.747	0.969	0.9664	0.5195
control	11.653	0.434	1.526	1.202	0.990	0.9893	0.2193

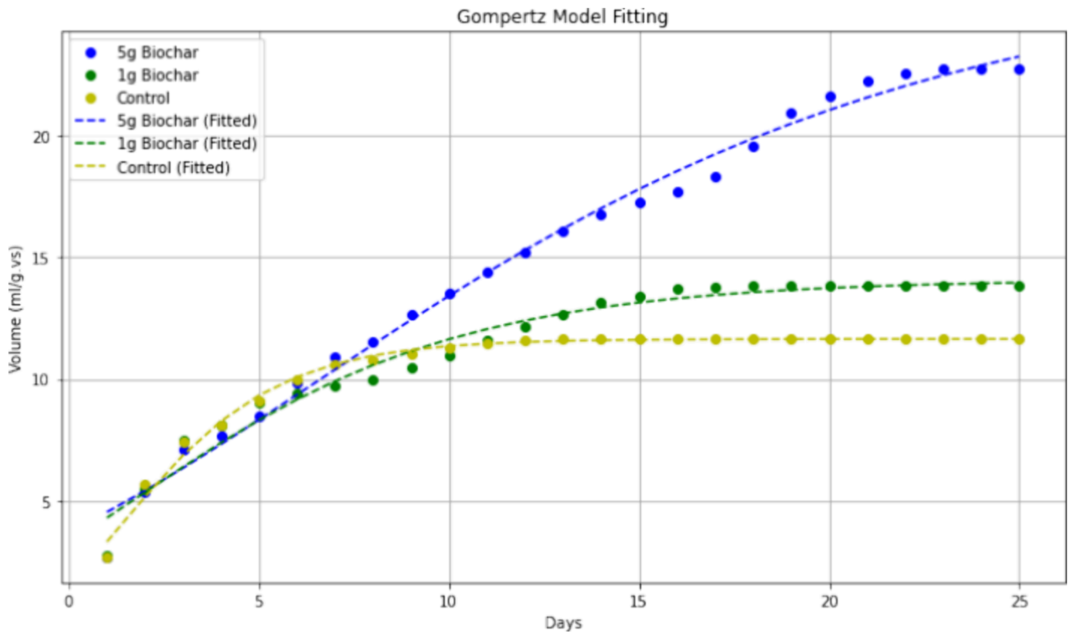

Figure 7. Fitting of parameters of Gopertz equation for biogas production.

limited.[54] When combined with persulfate, biochar accelerates the stabilization of animal waste digestate, improves nitrogen stability, and enhances microbial inactivation.[55] The unique physicochemical properties of biochar, including conductivity, pore adsorption, surface functional groups, and cation exchange capacity, contribute to its effectiveness in AD.[56] These properties allow biochar to alleviate inhibitions, improve process stability, and increase methanogenic efficiency.[56]

4.6. Kinetic Data Analysis. Table 4 shows the parameters acquired during the optimization process and illustrates a satisfactory fit using the Gompertz model. The biogas yield potential (a) was overpredicted with 26.886 and 14.096 mL/g V S for a digester that has 5 g of biochar added and 1 g of periodic biochar, respectively. The control was perfectly predicted with 11.653 mL/gVS. The lag times for digestion were predicted as 0.105, 0.203, and 0.434 days for 5 g of biochar, 1 g of periodic biochar, and control, respectively. However, this might not be of interest as all the digesters were having the same treatment on the first 4 days. The model also predicted 6.512, 1.845, and 1.526 mL/g V S per day as the rate of biogas production for 5 g of biochar, 1 g of periodic biochar, and control, respectively. This shows a higher rate of production with the digesters treated with biochar compared with the control.

Table 4 also includes the statistical metrics utilized to evaluate the prediction accuracy of the Gompertz model. The R-squared values were 0.991, 0.969, and 0.990, which means that the Gompertz model will be able to explain over 99% of the total variation in the experimental data. The sum of square error (SSE) that measures the total deviation of the response values from the fit was the lowest for the digester that has the control substrate, with a value of 1.202.

Figure 7 shows the plot of the Gompertz model fitted to the experimental data, affirming that the Gompertz equation accurately describes the cumulative biogas production over time.

3.7. One-Way ANOVA. Table 5 presents the result of the one-way ANOVA test to ascertain the significant difference in

Table 5. Pairwise One-Way ANOVA Results

	comparison	F-statistic	P-value
0	5 g of biochar vs 1 g of biochar	8.077470	0.006562
1	5 g of biochar vs control	13.626375	0.000570
2	1 g of biochar vs control	1.513866	0.224546

biogas produced between each treatment at a significant level of 5%. The F-statistic between group 5 g of biochar vs 1 g of biochar is 8.077470. It indicates a relatively high difference between these two groups, suggesting that there was a significant effect of the biochar dosage (5 g vs 1 g). The low p-value of 0.006562 further supports this, indicating that this difference is statistically significant at the typical significance level of 0.05. The F-statistic between 5 g of biochar vs control is 13.626375. The high value suggests a strong difference between the groups: 5 g of biochar and the control. The very low p-value of 0.000570 indicates a highly significant difference, providing strong evidence to reject the null hypothesis and indicating a significant effect of using 5 g of biochar compared to the control. Study indicates that adding biochar at a concentration of 5 g/L resulted in a substantial increase in biogas production and methane yield, enhancing the anaerobic digestion process.[20,47] In contrast, lower biochar dosages, such as 1 g, may not have the same impact on

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methane production and process stability. Studies have shown that higher biochar dosages, such as 25% based on substrate volatile solids, significantly increased cumulative methane production and process stability under severe conditions of high substrate overload.[43] Therefore, the data suggest that a dosage of 5 g of biochar can have a more pronounced effect on anaerobic digestion compared to a lower dosage, like 1 g. Thereby, the Null hypothesis was rejected.

The F-statistic between 1 g of biochar and the control is 1.513866. It is relatively low, suggesting a smaller difference between the group using 1 g of biochar and the control group. The p-value of 0.224546 is notably higher than 0.05, indicating that this difference is not statistically significant at the typical significance level.

3.8. Flame Test. The flame test result is represented in Figure 8. The flame was dominated by red color at the top and dominated by blue flame at the bottom. The red color at the top of the flame is due to the presence of CO_2, while the blue color at the bottom signifies the dominance of methane gas. This color variation is observed due to the different combustion characteristics of CO_2 and CH_4.[57−59] The presence of CO_2 in the biogas composition affects the flame color and temperature, influencing the combustion process and emissions.[60] Additionally, the flame test results can be influenced by factors like turbulence intensity and methane percentage in the biogas surrogate.[61] Overall, the red and blue flame colors in the biogas flame test provide insights into the gas composition and combustion behavior.

Figure 8. Flame test.

4. CONCLUSIONS

In this study, biochar from sorghum stalk was produced, characterized, and used as an enhancer for biogas production using paunch content as substrate. The produced biochar was found to be capable of improving biogas generation, holding a high surface area of 217.20 m^2/g and a moderately high pH value (9.07). The biogases from the paunch content in three treatments were found to be 22.79, 13.83, and 11.67 mL/gV.S for 5 g of biochar, 1 g of periodic biochar addition, and control, respectively, for 25 days of digestion. The 5 g one-time biochar addition gave a better yield for the total period of digestion.

Hence, the study contributes to improving waste management in abattoirs by demonstrating how the addition of sorghum stalk biochar enhances biogas production from cattle paunch content, reducing environmental pollution. The findings highlight that a one-time 5 g biochar addition yields significantly more biogas than periodic additions or no treatment, offering a more effective waste-to-energy conversion method.

The Gompertz model was fitted to the cumulative biogas yield. The model was found to be a good fit for the biogas produced for the 25 days of production with R^2 values of 0.991, 0.969, and 0.990 for 5 g of biochar, 1 g of periodic biochar addition, and control, respectively. The pairwise one-way ANOVA analysis indicates that there is a significant difference between the digester treatment with 5 g of biochar and 1 g of periodic biochar addition at a 5% level of significance. There was also a significant difference between 5 g of biochar and the control.

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Notes

The authors declare no competing financial interest.

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