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Research Article

Effect of Biochar on Biogas Yield of Poultry Wastes

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Abstract: This study investigates the effect of biochar as an additive on the anaerobic digestion of poultry droppings from layers and broilers. Six digesters (A, B, C, D, E, and F) with dry weight content of 100% layer wastes (control), 100% broiler wastes (control), 95% layer wastes + 5% biochar, 90% layer wastes + 10% biochar, 95% broiler wastes + 5% biochar, and 90% broiler wastes + 10% biochar were used for 31 days. The respective cumulative biogas yields of layer and broiler waste digestion were 17.9 L, 17.7 L, 21.8 L, 22.6 L, 21.3 L, and 22.0 L. This study revealed that biochar addition of 10% increased the biogas yield of both wastes by 26% and 24%, respectively. The methane content was highest in the biogas from digester F (68.12%), producing the least amount of hydrogen sulphide (0.84%). Consequently, broiler waste is found to be the most suited for biogas generation, especially when spiked with 10% biochar.

***Keywords*:** biogas, waste-to-energy, broilers, layers, renewable energy, digester

1. Introduction

Environmental pollution is a severe problem globally, mainly caused by human activities. Al-Ghussain [1] stated that rampant economic development and profound consumption of natural resources are the reasons for global warming, acid rain, and ozone layer depletion. For instance, renewable energy accounts for 13% of the total electricity generated in Nigeria, predominantly from solar energy [2]. The incessant increase in the nation's population is predicted to surpass that of the United States by 2050 [3]. Such scenarios would cause a major surge in energy demand [4], which cannot be met by the dwindling petroleum resources and present inadequate energy infrastructure. Therefore, there is a need to explore other renewable energy sources.

Due to the enormous amount of waste generated in Nigeria and the ineffective and inadequate waste disposal infrastructure, environmental pollution has escalated in recent years, necessitating a suitable way of disposing or utilizing this waste [4]. Biodegradable biomass, which forms a large part of the waste generated in Nigeria, is potentially fuel for biogas plants. Using biogas as an alternative energy source will reduce the dependence on liquefied natural gas for cooking, transportation, and heating in homes [5]. Of the many substrates used in biogas production, animal and poultry wastes rank among the top base materials with the highest biogas yields [6].

In Nigeria, many households run a small-scale poultry farm, and their waste disposal is one of the major problems

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associated with the practice, along with infections, sickness, and malodour [7]. Poultry waste is organic and made up of biodegradable compounds like carbohydrates, proteins, and lipids. Figure 1 shows the pathway for the degradation of poultry waste into biogas and other products [8]. Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four stages of biogas production. Hydrolysis is the breaking of large compounds into small ones by water molecules. Insoluble components such as carbohydrates, fats, and proteins undergo hydrolysis at this stage. The products of acetogenesis (acetates, carbohydrates, carbon dioxide, and oxygen) are used to form methane (CH_4) in the methanogenesis stage [9].

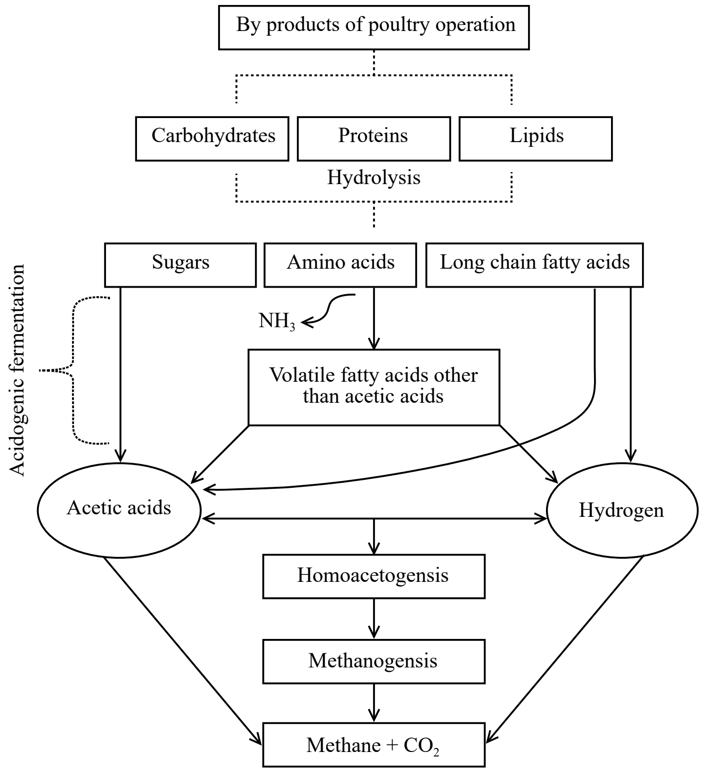

Figure 1. Pathway for degradation of poultry waste into biogas

Research has demonstrated that some additives can enhance biogas production via anaerobic digestion of organic and inorganic wastes [10]. Several additives have shown various degrees of success and failure [6, 11]. The current research shows the effect of biochar (pyrolyzed biomass) additive on biogas yield from poultry droppings. Biochar has been used as an additive to cow manure and is capable of increasing the biogas yield by 31% and CH_4 content by 27% for a retention period of 31 days [12, 13].

Regarding novelty, this study's uniqueness is that it aims to mimic real-life household digesters to determine the biogas prospect of poultry wastes from two bird species (as the primary substrate). The waste was doped with locally sourced biochar. Therefore, the following hypotheses have been proposed: (1) layers and broilers have different biogas yields; (2) adding biochar increases biogas yield in both substrates; and (3) adding biochar increases the biogas CH_4 content. This research will contribute to a greater understanding of waste valorisation using biogas as an alternative energy source.

2. Materials and methods

This study was carried out on the grounds of the Federal University of Technology, Akure, Ondo State, Southwestern Nigeria, with an average annual temperature of 25.1 ± 3.0 °C. Fresh poultry waste was collected from the university poultry farm at Malu Road. The droppings from the layer and broiler sections of the farm were collected on the same day without additional preparation.

The biochar was prepared by pyrolyzing sawdust and wood chips of a teak tree (hardwood) for 35 minutes at 50 °C in a furnace. The produced biochar was cooled to room temperature and pulverised to less than 5 µm, evincing a surface area of 125 m^2/g, capable of facilitating substrate degradation. The carbon and oxygen contents of the biochar were 70.25% and 25.72%, respectively. The high carbon content optimises biogas production [14].

Six black 12 L digesters, an analytical weighing balance, a gas chromatography analyser (Shimadzu GC-2014), a mercury-in-glass thermometer (range 0 °C to 100 °C), a pH meter, and a pressure gauge were utilised in the current study. The specifications and relative errors of the equipment are as shown in Table 1.

Table 1. Specifications and relative errors of the equipment used in this study

Equipment	Specification	Relative error
pH meter	Digital pH meter PH 02	± 0.01
Thermometer	Mercury-in-glass SL 206	± 0.02
Pressure gauge	Tianhu Y-60ZT	± 0.05
Digital weighing balance	Cammry 277HL16	± 0.01

2.1 *Preliminary analysis*

The moisture content (*MC*) of the substrate is the weight loss after 24 hours of heating at 105 °C (Equation 1). The total solid (*TS*) is the mass remaining after the *MC* has been removed (Equation 2). Meanwhile, the volatile solid matter (*VS*) is the weight loss after heating the remaining mass from Equation 2 for three hours at 550 °C in a closed crucible (Equation 3). The total carbon (*TC*) is the amount of carbon contained in a feedstock, calculated based on the *VS* content (Equation 4). All of the analyses followed the American Public Health Association - Standard Methods [15].

$$MC\ (\%) = \frac{w_s - w_a}{w_s} \times 100 \tag{1}$$

$$TS\ (\%) = \frac{w_a}{w_s} \times 10 \tag{2}$$

$$VS\ (\%) = \frac{w_a - w_b}{w_s} \times 1000 \tag{3}$$

$$TC\ (\%) = \frac{VS}{1.8} \tag{4}$$

where w_s is the total weight of substrate (g), w_a is the dried matter of the substrate (g), and w_b is the weight of the substrate after evaporation of *VS* (g).

2.2 *Fabrication of the anaerobic digester*

The six anaerobic digesters used for this research were constructed locally using 12 L black plastic kegs as the digestion chambers. The anaerobic digesters were designed such that each digester has an inlet for feeding the substrate into the digestion chamber and a drip bag connected to it for daily biogas collection and storage. The thermometer and pressure gauge were inserted into the digester to measure the temperature and pressure of the digestion chamber, respectively (Figure 2).

Figure 2. Designed digester system

2.3 *Loading the digesters*

The digester has a total volume of 12 L, but the substrate should not occupy more than 80% of this amount to allow for the production of biogas. Thus, the volume of the substrate was 9.6 L. Using a mix ratio of 1:2, one component of waste was combined with about two parts of water. After mixing the substrates, they were fed into the six fabricated anaerobic digesters (A, B, C, D, E, and F), which were connected to the plastic gas collection system to generate biogas for a period of 31 days. In digesters C and E, finely pulverised biochar replaced 5% of the total volume of the substrate, whereas in digesters D and F, 10% of the biochar was used. Digesters A and B served as the control setups for the experiment (Table 2).

Table 2. Individual digesters and content

Digester	Content
A	Layer wastes only
B	Broiler wastes only
C	Layer wastes + 5% of total biochar volume
D	Layer wastes + 10% of total biochar volume
E	Broiler wastes + 5% of total biochar volume
F	Broiler wastes + 10% of total biochar volume

2.4 *Experimental procedure*

The temperature and gas yield were measured and recorded daily for 31 days using a thermometer and a digital weighing balance, respectively. The volume of biogas produced per day was determined using Equation 5:

$$Biogas\ volume = \frac{Mass\ of\ gas}{Density\ of\ gas} \tag{5}$$

where the average density of biogas is 1.15 kg/m^3 [16].

Also, the pH of the slurry was measured daily using a digital pH meter through the base outlet of the digester, while the pressure was monitored using the pressure gauge installed in the digester.

Finally, the highest biogas yields from the three setups on the 10th, 20th, and 30th days of the retention period were collected, and the constituents' properties were determined.

3. Results and discussion

The analyses of the poultry waste and their mixtures with biochar in different ratios were carried out in the laboratory to determine their physicochemical properties. Table 3 shows the *MC*, *VS*, and *TS* concentrations and the different constituents of the wastes, such as ash, fat, crude protein, carbon, and nitrogen content.

Biochar is predominantly carbon, with minor compositions of hydrogen, oxygen, nitrogen, and sulphur [17]. The carbon to nitrogen ratio (C:N) is also a critical factor contributing immensely to the quality of biogas produced, based on the percentage of the CH_4 yield [18]. Usually, the optimum C:N ranges from 10 to 25 [19]. From Table 3, the *MC* observed in the feedstock without biochar was lower than that with biochar, probably due to the hygroscopic nature of biochar. The *TS* and *VS* contents of samples C and D were lower than those of A. Meanwhile, the *TS* and *VS* contents of samples E and F were also lower than those of sample B. The carbon content of D was the highest, resulting in its exhibiting the highest C:N value. In addition, samples containing biochar (C, D, E, and F) exhibited higher initial pH than samples devoid of biochar (A and B) [20].

Table 3. Physicochemical properties of the fresh poultry waste

Parameters	Digesters					
	A	B	C	D	E	F
Moisture (%)	71.2	55.3	68.4	65.25	52.4	50.06
Fat (%)	4.3	6.7	4.8	3.9	6.54	6.32
Ash (%)	3.05	2.6	3.9	4.2	2.4	2.2
Fibre (%)	1.03	1.5	1.2	1.37	1.59	1.65
Crude protien (%)	10.25	12.25	10.23	10.3	12.4	13.1
Nitrogen (%)	1.84	2.5	1.75	2.25	1.85	1.9
TS (%)	32.3	29.2	29.67	28.45	26.4	27.3
Temperature (°C)	30	30	29.5	29	30	29.5
TC (%)	19.87	25.62	21.35	32.22	29.34	29.9
Carbohydrate (%)	9.6	8.9	8.69	8.74	9.2	9.05
C:N	10.8	10.25	12.2	14.32	15.86	15.74
pH	7.2	6.9	7.8	7.7	7.3	7.6
VS (%)	27.75	28.5	28.24	27.59	25.85	25.7
Phosphorus (%)	1.1	1.5	1.12	1.11	1.45	1.56
Calcium (%)	0.97	2.5	0.94	0.93	1.8	1.94
Potassium (%)	0.78	0.9	0.77	0.75	0.85	0.89
Magnesium (%)	0.35	0.32	0.31	0.32	0.3	0.37
Sodium (%)	0.2	0.25	0.26	0.23	0.23	0.26

3.1 *Biogas yield*

Figures 3 (a) and (b) show the plots of the daily and cumulative biogas yields of the six digesters. The cumulative biogas yield for digesters A, B, C, D, E, and F was 18.0 L, 17.7 L, 21.8 L, 22.6 L, 21.3 L, and 20.0 L, respectively. The different peaks and troughs shown in Figure 3 can be attributed to varying environmental and biological conditions of the different digesters, such as temperature, pH, and physicochemical properties of the substrates.

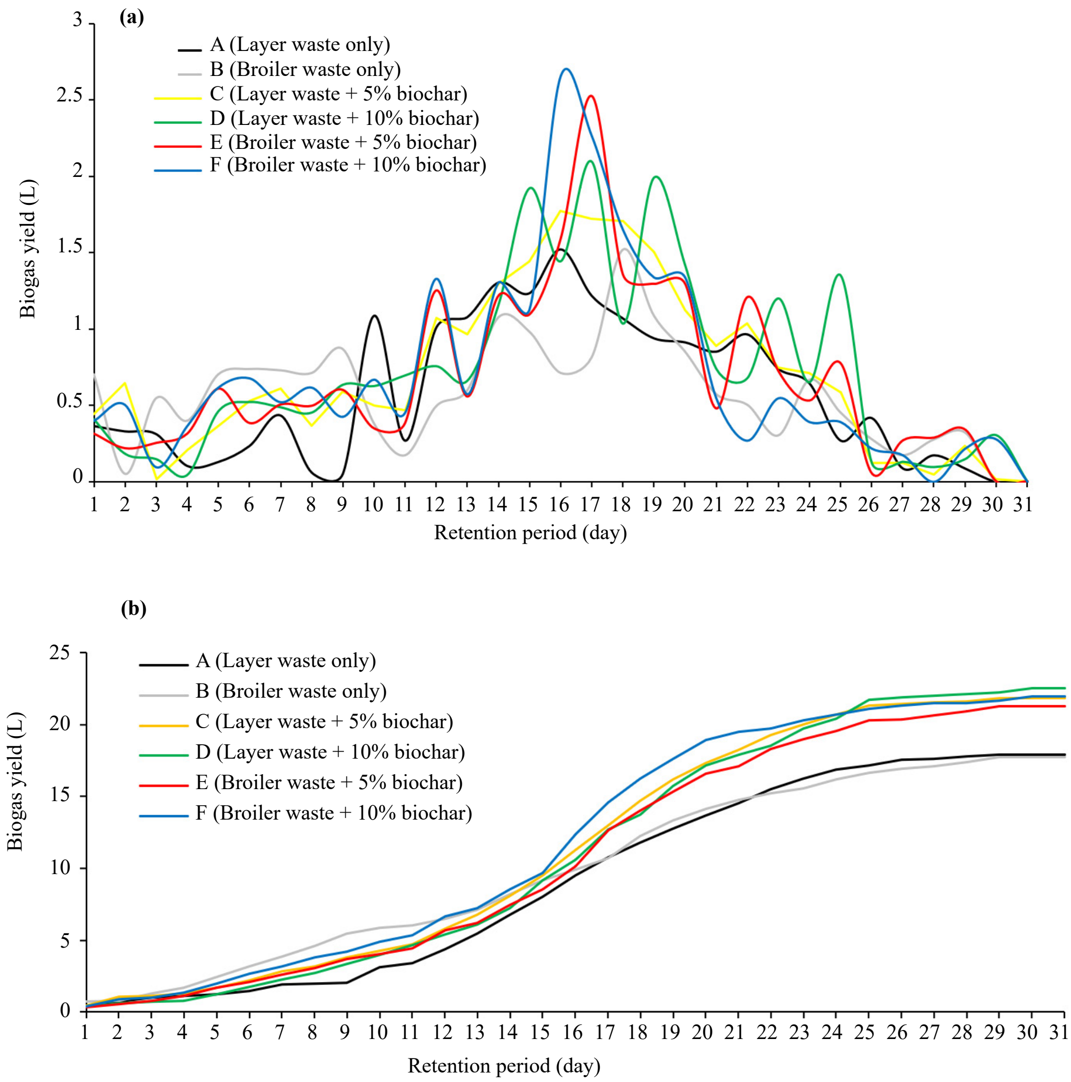

Figure 3. (a) Daily and (b) cumulative biogas yields of the digesters

As shown in Figure 3, digester A produced a higher yield than digester B due to the higher C:N of 10.8 in the former than 10.25 in the latter (for the broiler wastes). The results of the preliminary tests (Table 3) on the feedstocks were aligned with previous findings [19]. It was noticed that there was a steady increase in daily biogas yield until the third week before the biogas yield started to dwindle due to the microorganisms in the digester using up the bio-degradable part of the feedstock. Therefore, the population of the microorganisms starts reducing alongside the biogas yield [21].

The highest biogas yields were recorded for the digesters containing biochar [22]. The digesters D and F had the highest yields for both wastes. Meanwhile, there was a 5% increase in the gas yield for every 5% increment in the addition of biochar. This increase is negligible for a small setup, but becomes noticeable on a larger scale. As biodegradation occurs, ammonia is developed in the digesters, reducing the biogas potential of the substrate [23]. Biochar, a carbon-rich additive, can suppress the formation of ammonia in the digester [20]. This phenomenon is why the digesters containing biochar had a higher biogas yield. The pH was observed to increase in alkalinity as the experiment progressed. This condition was more noticeable in the digesters containing biochar than in those devoid of biochar. This is due to methanogenesis, which is responsible for CH_4 production in biogas [24].

The cumulative yield of digesters C and D was 21% and 26% higher than that of digester A's. Similarly, the cumulative yield of digesters E and F was 20% and 24% more than that of digester B [23].

The maximum biogas yield of digesters A, B, C, D, E, and F was 1.52 L, 1.52 L, 1.78 L, 2.10 L, 2.53 L, and 2.66 L, while the number of days required to reach the maximum yield was 16, 18, 16, 17, 17, and 16, respectively.

3.2 *Operating parameters*

All analyses were done using the STATA 12 software and Microsoft Excel 2016. Table 4 shows the correlation between the biogas yield and the pressure, which is positively correlated.

Table 4. Correlation between pressure and biogas yield of digesters

	Pressure (mmHg)					
Digester	A	B	C	D	E	F
A	0.53	0.48	0.67	0.64	0.69	0.50
B	0.61	0.61	0.55	0.62	0.62	0.61
C	0.64	0.58	0.74	0.72	0.77	0.67
D	0.47	0.42	0.53	0.53	0.56	0.51
E	0.65	0.48	0.64	0.61	0.66	0.58
F	0.66	0.47	0.54	0.50	0.57	0.50

Regression analysis was carried out to predict the cumulative biogas yield with the independent variables, which include waste type, duration, percentage addition of biochar, temperature, pressure, and pH. There were 186 observations, and the regression had a coefficient of determination (R^2) value of 0.967.

From Table 5, the cumulative yield was reduced by 1.369 units for every change in the categorical variable waste type (i.e., for every change from layer waste to broiler waste). The most significant variables from Table 5 were waste type, duration, pH, and the constant (y-intercept), as their P-values were less than 0.05.

Table 5. Estimates of multiple regression analysis

Cumulative yield	Coefficient	Standard error	t-statistic	P-value	95% Confidence interval	
Waste type	-1.369	0.390.	-3.51	0.001	-2.139	-0.599
Duration (day)	0.674	0.042	16.21	0	0.592	0.756
Biochar added (%)	2.012	5.740	0.35	0.026	-9.311	13.336
Temperature (°C)	-0.264	0.150	1.76	0.08	-0.559	0.032
Pressure (mmHg)	0	0.010	0.04	0.966	-0.019	0.02
pH	3.432	0.887	3.87	0	1.682	5.181
Constant	-14.877	6.669	2.23	0.027	-28.038	-1.716

The relationship between the response and predictor variables is as described in Equation 6:

$$Cumulative\ yield = 0.674t + 2.012B - 0.264T - 14.877 \quad (6)$$

where t is the duration (minute), B is the percentage of biochar added, and T is the temperature (°C).

Table 6 suggests that the P-value is less than 0.05, indicating a statistical difference exists among the groups. The different percentage additions of biochar cause a significant difference in the daily gas yields from the different digesters.

Table 6. Analysis of variance for different percentages of biochar addition

Groups	Count	Sum	Average	Variance		
Percentage addition	186	9.30	0.050	0.002		
Daily yield of biogas	186	123.2	0.663	0.278		
ANOVA						
Source of variation	Sum of squares	Degree of freedom	Mean square	F-value	P-value	F critical value
Between groups	34.92	1	34.93	249.45	2.57E-43	3.87
Within groups	51.79	370	0.14			
Total	86.70	371				

Table 7 shows that the P-value is less than 0.05, indicating a statistical difference among the groups and between the waste types used (layer and broiler wastes), which causes a significant difference in the daily gas yields from the digesters.

Table 7. Analysis of variance for different waste types (broiler and layer wastes)

Groups	Count	Sum	Average	Variance		
Daily yield	186	123.27	0.66	0.28		
Waste type	186	279	1.5	0.25		
ANOVA						
Source of variation	Sum of squares	Degree of freedom	Mean square	F-value	P-value	F critical value
Between groups	65.19	1	65.19	246.19	6.85E-43	3.867
Within groups	97.98	370	0.26			
Total	163.1	371				

3.3 *Biogas chemical composition*

Table 8 shows the major constituents of the biogas produced from the setups on different days within the retention period.

Table 8. Biogas constituents derived from poultry waste-biochar mixtures

Digester	Duration (day)	Gas composition (%)			
		CH_4	CO_2	N_2	H_2S
C	10	59.67	35.65	3.26	1.42
	20	62.31	33.33	3.08	1.28
	30	36.3	32.94	2.67	1.06

D	10	55.26	40.24	3.17	1.33
	20	63.52	32.19	3.11	1.18
	30	65.19	31.08	2.78	0.95
F	10	59.22	36.31	3.22	1.25
	20	65.76	30.10	3.02	1.12
	30	68.12	28.48	2.56	0.84

From Table 8, the gas sample collected on the 10th day contained a lesser amount of CH_4 than on the 20th day. In turn, the sample collected on the 20th day contained less CH_4 than on the 30th day, suggesting that the CH_4 content of the biogas increases with time [25]. The only toxic gas observed from the gas chromatography analysis was hydrogen sulphide (H_2S), which, according to Wellinger et al. [5], causes corrosion and mechanical wear in industrial anaerobic digesters, significantly increasing the cost. In addition, H_2S and sulphur dioxide (SO_2) emissions pose occupational health risks [26]. The decrease in the H_2S gas reduced the odour of the feedstock with time [27]. However, most of the H_2S was produced in the first two weeks. The biochar addition of 5% reduced the H_2S concentration of layer waste by 9.85% in the 20 days and 25.35% in the 30 days while also causing H_2S reduction of 11.28% and 28.57% in the 20 and 30 days in broiler waste. The addition of 5% biochar reduced the H_2S concentration of layer waste by 9.85% in 20 days and by 25.35% in 30 days. It also reduced the H_2S concentration of broiler waste by 11.28% in 20 days and by 28.57% in 30 days. The highest H_2S reduction was recorded in the digester F, which showed a 32.8% decrease in H_2S. The results prove the feasibility of adding biochar directly to the feedstock to reduce the H_2S concentration in biogas [28].

While this research has focused on the biogas yield, the CH_4 content of the biogas could be further improved by finding a way to feedback the biogas produced in the first few days into the digester and studying the effect on the CH_4 content of the resulting gases.

The relationships between the biogas yields from the digesters C, D, and F and the percentage composition of its constituents (CH_4 and H_2S) are represented in Figures 3, 4, and 5. From Figure 4, the correlation between the daily yield and the CH_4 and H_2S contents is 0.992 and -0.917, respectively [24].

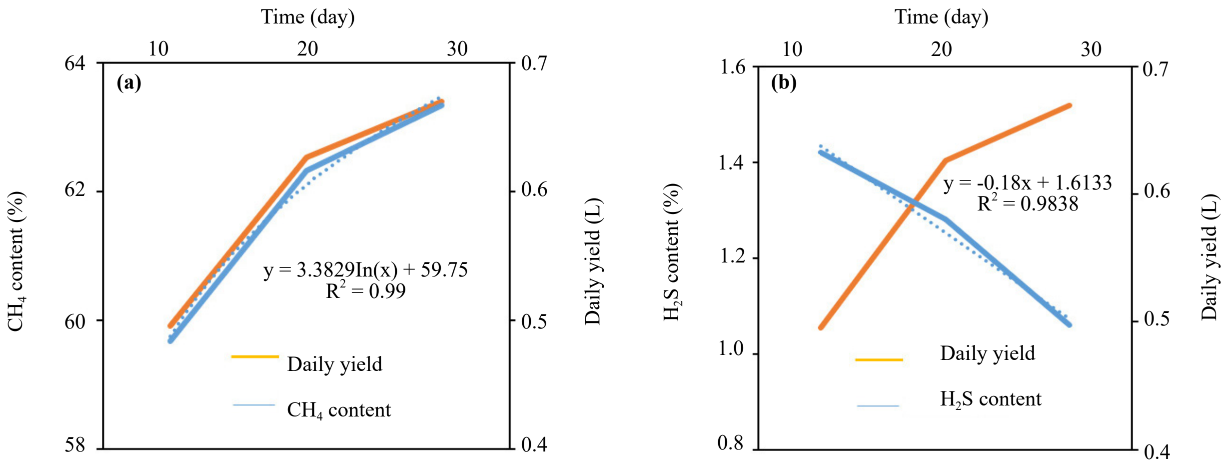

Figure 4. Comparison of daily yield with (a) CH_4 and (b) H_2S contents of digester C

As shown in Figure 5, the correlation between the daily yield and the CH_4 content is 0.913, while the correlation between the daily yield and H_2S content is -0.883, which is comparable to previous study [24].

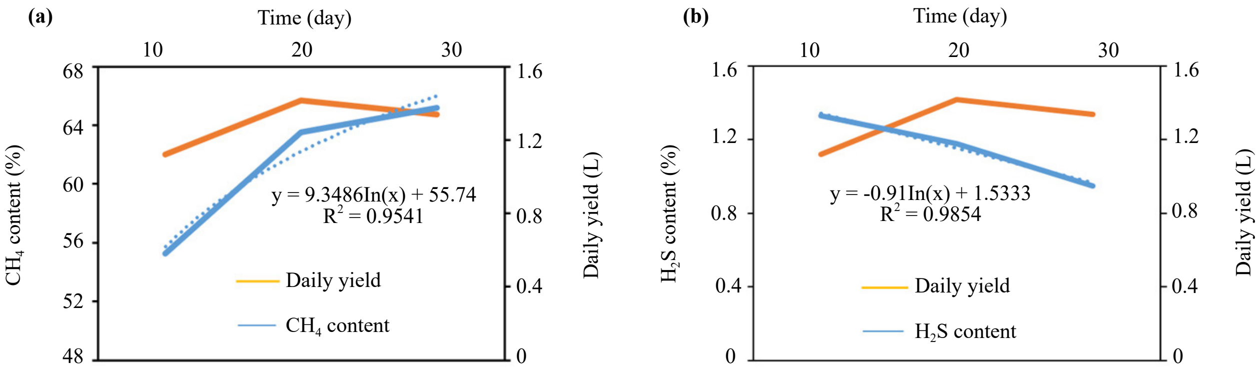

Figure 5. Comparison of daily yield with (a) CH_4 and (b) H_2S contents of digester D

Meanwhile, from Figure 6, the correlation between the daily yield and CH_4 and H_2S contents is 0.942 and -0.686, respectively, which is similar to what was recorded by Ajiboye et al. [24].

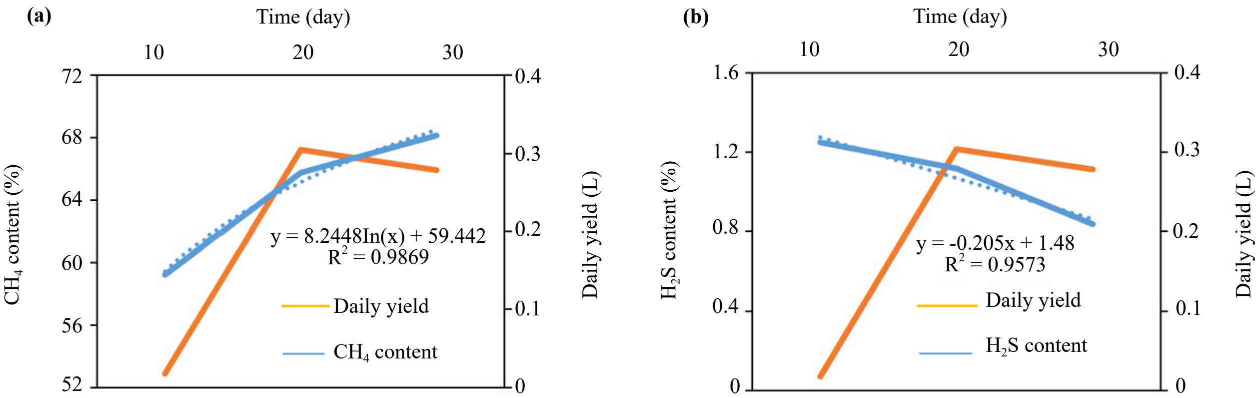

Figure 6. Comparison of daily yield with (a) CH_4 and (b) H_2S contents of digester F

3.4 *Economic analysis*

Droppings are produced in large quantities by layer and broiler birds. The prospect of making use of them has already been recommended. Poultry waste being combined with biochar for energy is seen as a cost-effective and environmentally friendly option. The resulting digestate can be used as fertiliser since it contains valuable nutrients. When greenhouse gases are compared to their global warming potentials, it is established that CH_4 and N_2O have 23 and 296 times the greenhouse impact of CO_2, respectively [29]. A 10% reduction in N_2O emissions can be observed due to anaerobic waste treatment. In addition, 1 m^3 of biogas is equivalent to 0.5 kg of petroleum, and CO_2 emissions are reduced by 2.6 kg when biogas is chosen over petroleum [30].

The unit cost of producing the digester used in this study was 10,000 Nigerian naira. The average total cost per kg of gas produced by digesters without biochar was 559 Nigerian naira, while it was 467 Nigerian naira for digesters containing biochar. This indicates that using biochar reduces biogas production costs by 92 Nigerian naira. As of 2021, the price of liquefied gas per kg was 650 Nigerian naira. The daily biogas used for cooking is 0.227 m^3 [31]. 1 m^3 of biogas is the same as 0.43 kg of liquefied petroleum gas. The cost of using biogas from poultry waste is 40% higher based on the digester size used in this study, although this cost will reduce as the production scale increases.

4. Conclusion

This study revealed that the amount of biogas that is produced from the two species of poultry waste (layer and broiler wastes) is increased by adding biochar at different proportions according to factors affecting the production of biogas.

Layer wastes + 5% of biochar by dry mass produced 21% more biogas than layer wastes alone, and layer wastes + 10% of biochar by dry mass produced 26% more than layer wastes alone, which is the control setup. Broiler wastes + 5% of biochar by dry mass produced 20% more biogas than digester broiler wastes alone, while broiler wastes + 10% of biochar by dry mass produced 24% more biogas than digester broiler wastes alone. This leads to the deduction that adding 5% and 10% of biochar leads to a significant increase in the biogas yield of poultry wastes, either from layers or broilers. The addition of 10% biochar by dry mass of the substrate produced the highest and most significant increase from the control setups, making it the optimum biochar concentration. Across the three highest biogas producing digesters, the broiler wastes + 10% biochar produced the highest amount of CH_4 and the least toxic gas, i.e., H_2S, making it the optimum substrate. The resulting slurry was also found to be odour-free due to the reduction in H_2S and nitrogen gas as the retention time increased, which is good for the environment.

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Conflict of interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this research.

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