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# Effect of hydraulic retention time and substrate-to-inoculum ratio on batch anaerobic digestion of goat manure and response surface methodology optimization

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**ABSTRACT**

Biogas production is one of the renewable energy alternatives to fossil fuel consumption amidst a global rise in energy demand. In this study, goat manure was used as the substrate in batch-process anaerobic digesters, and the inoculum used was obtained from an existing biogas plant. The aim was to develop an empirical biomethane potential (BMP) of goat manure, develop a predictive model, and establish optimum process parameters for its anaerobic digestion using a response surface methodology. Proximate analysis of the substrates and inoculum was carried out according to American Public Health Association standards. An empirical BMP study was conducted on the substrate using the anaerobic biodegradation, activity, and inhibition protocol, and the effects of the process parameters on biogas yield from anaerobic digestion were investigated according to the central composite design generated by Design Expert 11 software (Stat-Ease Inc.). The results showed that goat manure has a dry matter content of 205.60 ± 12.64 g/kg and organic matter of 688.78 ± 18.02 g/kg of dry matter. The BMP was 0.49 ± 0.002 $LCH_4$/gVS. Maximum biogas production of 650 mbar was recorded at a hydraulic retention time (HRT) of 60 days and a substrate-to-inoculum (S/I) ratio of 10:1. The significant mathematical model was linear, with a p-value < 0.0001. The optimum biogas yield was obtained at a S/I ratio of 0.5 and an HRT of 33.09 days at room temperature of 29 °C. The biogas composition was 58.53% $CH_4$ and 41.47% $CO_2$. The study established goat manure as a good substrate for biogas production. It also established a mathematical model to predict process parameters for optimum yield.

**Keywords:** anaerobic digestion, biogas production, hydraulic retention time, substrate-to-inoculum ratio, biogas process parameters optimization, biomethane potential

## INTRODUCTION

Goats are one of the most produced livestock globally, and they are mostly kept for their milk, meat, and skin, which have high nutritional and potential health benefits such as low levels of cholesterol, lower allergies, and higher energy contents when compared to products from other animal sources (Lima et al., 2018; Nayik et al., 2021). Goat rearing is predominantly done in Asia and Africa, with 90% of global goat production found in developing countries, where it is seen as a pathway out of poverty (Utaaker et al., 2021). In these countries, different systems of goat farming adopted, including open grazing, closed grazing, or even as part of a backyard farming arrangement, are known to be sources of goat manure (Mostafa Imeni et al., 2019). It has been reported that a goat has a manure production capacity of about 1.13 kg/day (Muatip et al., 2022). These manures, when disposed of openly in the environment, cause environmental nuisances through the reduction of air quality by the offensive odours and the release of methane, a highly potent greenhouse gas, from their degradation (Akporube et al., 2023; Paolini et al., 2018). In order to prevent this, the manure can be subjected to anaerobic digestion, and the methane ($CH_4$)produced will be captured and applied as a renewable, clean, green, and carbon-neutral energy (Fernández-Rodríguez et al., 2021; Obileke et al., 2021; Orangun et al., 2021; Samer et al., 2022).

Although the $CH_4$ and $CO_2$ produced from anaerobic digestion of organic matter are potent greenhouse gases, the production process occurs in anaerobic digesters. These digesters serve the dual purpose of treating the substrates and simultaneously capturing the biogas for desired end usage (Iweka et al., 2024). This is more successful when the anaerobic digester has limited to no chances for diffusive emissions. In light of this, biogas production from anaerobic digestion of organic matter is therefore viewed as a less polluting and ecologically friendly production process considered clean and appropriate to replace fossil fuels for numerous heat-generating applications (Odejobi et al., 2016). This will help in slowing down global warming and its effects, a global phenomenon resulting from the accumulation of greenhouse gases in the atmosphere (Sakthivel et al., 2018).

Several studies have examined the process variables and how they affect biogas production from different substrates. The effects of organic loading rates (OLR) and hydraulic retention time (HRT) on anaerobic digestion of food waste in a continuously stirred tank reactor were assessed in the study by Liu et al. (2018). The results of the investigation demonstrated that the maximum amount of methane was produced at a constant HRT and an optimum OLR of 2.25 $g \cdot L^{-1} \cdot d^{-1}$. Similar to this, Ma et al. (2019) investigated the methane generation performance resulting from the co-digestion of rape straw and dairy manure at different substrate-to-inoculum (S/I) ratios. The best biogas yield was found with a S/I ratio of 2:3, according to the data. Using tomato and rumen as co-substrates, Alharbi et al. (2023) also investigated biogas production from the co-digestion of sheep and camel faces. According to the study, adding rumen and tomatoes as co-substrates significantly increased the efficiency of biogas generation. The sample that contained rumen and tomatoes as co-substrates had the highest methane concentration, at roughly 69.30%.

Additionally, several published research have examined the anaerobic digestion of goat manure to produce biogas. Zhang et al. (2013) studied the production of biogas by the co-digestion of goat dung with three crop residues: rice straw, wheat straw, and corn stalks, all at varying mixing ratios. The findings demonstrated the effectiveness of the anaerobic co-digestions of goat manure with corn stalks and rice straw, which increased cumulative biogas production by lowering substrate C/N ratios. Furthermore, Mohamed and Morsy, (2018) investigated the impacts of batch anaerobic digestion of goat dung by temperature, type of fermentation, and HRT optimization to get the most biogas generation at the lowest production costs in a lab setting. The entire cost of biogas per litre under various circumstances was computed in the study using a predetermined cost equation. At the maximum cumulative output of 128.74 liters at 60 °C for dry fermentation, the lowest biogas production cost of 4.09 LE/liter was reached.

Similar to these, Opurum et al. (2019) used cow rumen fluid as the inoculum in a kinetic study of the anaerobic digestion of goat dung with poultry droppings and plantain peels for the production of biogas over 47 days at a pH range of 6.80-7.80 and an ambient temperature of 25-36 °C. The biodigester containing goat manure had the highest cumulative yield (23.36 $dm^3$) across all the treatments, as indicated by the Duncan test, which revealed a significant difference ($p \leq 0.05$) in cumulative biogas yield. The study concluded that the modified Gompertz model equation, with correlation coefficients more than 0.97, adequately suited the experimental results in terms of estimating biogas production rate, biogas production potential, and the lag phase length.

Furthermore, Kaur and Kommalapati (2021) used mathematical modeling approach and the biochemical biomethane potential (BMP) test to optimize the anaerobic co-digestion of goat dung and cotton gin waste. The biomethane output from goat dung mono-digestions was not increased by adding cotton gin trash, but the values found were within the range reported by other researchers following the pretreatment of cotton residues. In like manner, the formation of biogas by the co-digestion of watermelon peels and goat dung under anaerobic digestion was examined by Mitiku and Kifle (2023) with emphasis on the physicochemical characteristics of the slurry. Batch fermentation was used to experiment in a mesophilic environment (38 °C) and the investigation demonstrated that, in contrast to the substrates, the digestate's pH rose.

Although several studies have investigated the effect of process parameters on anaerobic digestion of different substrates, there is a knowledge gap on the standard optimization of S/I ratio and HRT in anaerobic digestion of goat manure for biogas production using response surface methodology (RSM). There is a need for process parameters such as HRT and substrate-inoculum ratio to be optimized to achieve maximum benefits from a batch-process biogas plant. This is because, long HRT can lead to the accumulation of digestate, and too short HRT can lead to incomplete conversion of substrates, thereby negatively impacting biogas yield (Parajuli et al., 2022). Also, a high S/I ratio can lead to residue accumulation in the digester. This study therefore seeks to investigate these parameters for the optimum generation of biogas from goat manure for application as fuel in heat engines and for cooking in homes.

## MATERIALS AND METHODS

### Materials

The materials used in this study include ceramic crucibles, 256 ml sets of batch biodigesters, 5 ml capacity vacuum sample bottles, and goat manure substrate obtained from residential areas in Oyo Town, Nigeria. The inoculum used was obtained from an active anaerobic digester treating food waste in Oyo Town, Nigeria. The chemical used was analytical-grade sodium hydroxide (NaOH). The instruments employed include a pH meter, a Greinsinger GMH 3151 electronic digital pressure meter, a capper and decapper, needles and syringes, an American Ohaus Cp214 210 g 0.1 mg laboratory electronic analytical balance, a furnace, an oven, and a two-way valve.

### Methods

#### *Preparation of feedstock and inoculum*

A sufficient quantity of feedstock was gathered for use as substrate and stored at 4 °C inside a refrigerator to retard the rate of degradation by microorganisms. The feedstock was thoroughly mixed to be well homogenized. Samples of homogenized feedstocks were then characterized using dry and organic matter as indices. This procedure was repeated for the inoculum.

### *Preliminary evaluation of substrate and inoculum*

The evaluation at this stage involved the proximate and empirical BMP analyses of the substrate and inoculum using standard methods.

**Proximate analysis:** Samples of homogenized feedstock (substrate) and inoculum were characterized using American Public Health Association (APHA) 2540 B for total solids and E for volatile solids (APHA, 2000) (Fernández-Rodríguez et al., 2023; Ngulde & Mustapha, 2018). Aliquots of samples and inoculum were weighed and dried at 105 °C to drive off moisture and the residue was cooled in a desiccator to obtain the dry matter. The dry matter was heat-treated in the furnace at 550 °C to obtain ash. The dry and organic matter were estimated using Eq. (1) and q. (2), respectively (Fajobi et al., 2022).

$$Dry\ matter\ (g/kg) = \frac{Dry\ weight\ of\ sample\ at\ 105\ ^{o}C}{Wet\ wight\ of\ sample} \times 1000. \quad (1)$$

$$Organic\ matter\ (g/kg) = \frac{Weight\ of\ sample\ at\ 105\ ^{o}C - Weight\ of\ sample\ at\ 550\ ^{o}C}{Wet\ wight\ of\ sample} \times 1{,}000. \quad (2)$$

**Empirical biomethane potential analysis:** The BMP test was carried out in nine airtight serum bottles of 256 ml capacity, divided into three sets, each containing substrate-inoculum mixture, inoculum alone, and blanks (water). The initial pH of the substrate-inoculum mixture group after preparation was 7.32 while the inoculum alone group has a pH of 7.54. The batch digestion was carried out at an average room temperature of 29 ± 2 °C and the pressure in the serum bottles was measured at a 12-hour interval with a Greinsinger electronic digital pressure meter until relatively constant pressure was observed for each of the samples, which indicates the end of the anaerobic digestion. The BMP was then estimated according to standard protocol by the task group for anaerobic biodegradation, activity, and inhibition (Zhang et al., 2021) and the specific biogas and methane production (L/gVS) of the substrate were estimated.

### *Experimental design and anaerobic digestion process*

Design Expert 11 software (Stat-Ease Inc.) was used in this study to generate the required experimental runs for evaluating the anaerobic digestion of the goat manure substrate and to optimize the process parameters. The experimental design employed was a central composite design (CCD) in the RSM. Thirteen experimental runs generated are shown in **Table 1**, while the process variable coding for the parameters is shown in **Table 2**. HRT and S/I ratio (volatile solid basis) were selected as independent factors, while biogas yield was the dependent factor (response). The process variables were coded as -1 and +1 for the minimum and maximum values, respectively. The input minimum and maximum values range are 10-60 days HRT, and 0.5-10 for the solvent-to-solute ratio. The OLR for the corresponding S/I ratio was estimated using Eq. (3). Daily biogas production was estimated using the barometric method with the aid of a Greinsinger electronic digital pressure meter.

**Table 1.** CCD experimental runs for anaerobic digestion of goat manure substrate

| Experimental run | A: HRT | B: S/I ratio |
|---|---|---|
| 1 | 35 | 5.25 |
| 2 | 35 | 5.25 |
| 3 | 10 | 0.50 |
| 4 | 35 | 5.25 |
| 5 | 35 | 0.50 |
| 6 | 10 | 5.25 |
| 7 | 10 | 10.00 |
| 8 | 60 | 10.00 |
| 9 | 35 | 10.00 |
| 10 | 60 | 0.50 |
| 11 | 60 | 5.25 |
| 12 | 35 | 5.25 |
| 13 | 35 | 5.25 |

$$OLR = \frac{C_{VS}}{HRT}, \quad (3)$$

where $C_{VS}$ is concentration of volatile solids (gVS/L), HRT is hydraulic retention time (days), and OLR is organic loading rate.

### *Statistical analysis, model generation, and optimization*

Statistical analysis was carried out on the experimental data obtained from the 13 experimental runs. The F test, $R^2$ and values of model coefficients were accessed for reliability, the import of each experimental variable, and to obtain mathematical models for the process. A mathematical model depicting the relationship between biogas yield and the process parameters as well as a statistical analysis of the model were generated in Design Expert 11 software (Stat-Ease Inc.). Regression analysis was applied in fitting the modelled equation followed by numerical optimization in the software (Oladunni et al., 2021, 2023). The constraints set for the optimization were to minimize the HRT and S/I ratio while maximizing the biogas yield. The predicted optimum point was then validated in the laboratory by carrying out experiments at the predicted points in triplicate and compared to the predicted result.

### *Characterization of biogas*

Biogas samples obtained at optimum process parameters were characterized using established alkaline absorption method (Domingues et al., 2017; Lohani et al., 2020; Nwaezeapu & Agbozu, 2023). A NaOH solution of 5 M concentration was prepared by dissolving 40 g of anhydrous NaOH pellets in 200 ml of distilled water for the absorption of $CO_2$ in biogas. A known volume (2 ml) of the biogas sample (V1) was syringed out and injected into an empty, airtight serum bottle. 5 ml of the 5 M NaOH solution was then introduced into the airtight serum bottle and shaken for about

**Table 2.** Process variable coding for anaerobic digestion of goat manure substrate

| Factor | Name | Units | Type | Minimum | Maximum | Coded low | Coded high | Mean | Standard deviation |
|---|---|---|---|---|---|---|---|---|---|
| A | HRT | days | Numeric | 10.00 | 60.00 | -1 ↔ 10.00 | +1 ↔ 60.00 | 35.00 | 17.68 |
| B | S/I ratio | | Numeric | 0.50 | 10.00 | -1 ↔ 0.50 | +1 ↔ 10.00 | 5.25 | 3.36 |

**Table 3.** Preliminary analyses of goat manure substrate and inoculum

| Parameter | Goat manure substrate | Inoculum |
|---|---|---|
| Dry matter (g/kg) | 298.95 | 0.24 |
| Organic matter (g/kg) of wet | 205.60 | 0.11 |
| Organic matter (g/kg of dry matter) | 688.78 | 422.10 |
| Biogas Potential(L/gVS) | 0.83 ± 0.003 | |
| BMP ($LCH_4$/gVS) | 0.49 ± 0.002 | |

10 minutes to completely absorb the $CO_2$. This method assumes methane $CH_4$, and carbon (IV) oxide $CO_2$ are the major constituents of the biogas produced, with other gases assumed to be present in trace quantities. The room temperature was taken, and the number of moles of methane in the biogas was estimated by calculating the difference between the number of moles of biogas introduced and that of $CO_2$ consumed using the Ideal gas equation shown in Eq. (4) (Odejobi et al., 2017).

$$PV = nRT, \tag{4}$$

where $P$ is the pressure of the biogas, $V$ is the volume of the biogas, $n$ is the number of moles of the biogas, $R$ is the molar gas constant (8.314 J mol$^{-1}$ K$^{-1}$), and $T$ is the temperature.

## RESULTS AND DISCUSSION

### Preliminary Analysis

The data obtained from the preliminary analyses of the substrate and inoculum are presented in **Table 3**, and the details of the discussion are as follows:

#### *Proximate analysis of substrate and inoculum*

As presented in **Table 3**, the goat manure substrate contained dry matter (298.95 g/kg of wet sample) and organic matter (688.78 g/kg of dry matter). The inoculum, on the other hand, contained dry matter (0.24 g/kg of wet sample) and organic matter (422.10 g/kg of dry matter). The dry matter content showed that the substrate has about 70.10% moisture and 29.90% dry matter, and the organic fraction of the wet sample available for bio digestion is about 20.56%. However, when organic matter is considered a fraction of dry matter, there is about 68.88% of the dry matter that is available for bio digestion. This implies a high tendency for the substrate to be converted to biogas through anaerobic digestion. The inoculum, on the other hand, contains about 0.02% dry matter, and the organic fraction of 42.21% shows that it still contains some organic matter that can produce biogas, though in small quantities during the anaerobic digestion. These values are consistent with those of typical animal manure used in anaerobic digestion, as reported for pig, dairy, beef, and broiler manure (Shen et al., 2015).

#### *Empirical biomethane potential analysis*

The results for the biogas and BMP of the samples are also presented in **Table 3**. Goat manure showed a potential to produce 0.83 ± 0.003 L of biogas from its volatile solid of 1 g, with a methane potential of 0.49 ± 0.002 $LCH_4$/gVS. The results obtained are similar to those of other studies. The biogas

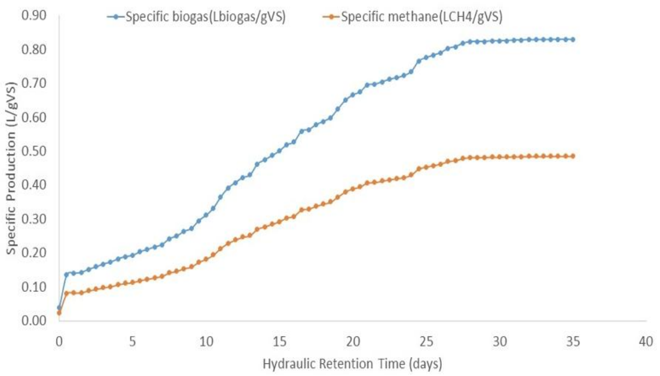


**Figure 1.** Plots of specific biogas and biomethane productions from goat manure substrate (Source: Authors' own elaboration)

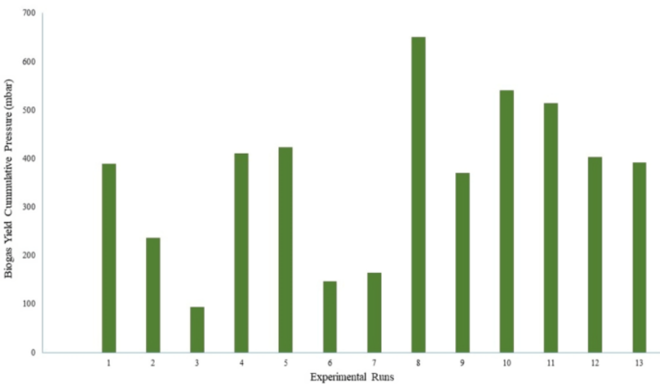


**Figure 2.** Biogas yields from batch anaerobic digestion of goat manure substrate using CCD (Source: Authors' own elaboration)

potential is higher than the experimental results obtained by Lohani et al. (2020), who obtained 0.109 L/gVS using a substrate comprising food waste, goat and poultry manure in a batch-process anaerobic digestion system, and that obtained by Kafle and Chen (2015) who got 0.242 L/gVS for only goat manure. The differences in these values can be attributed to the uniqueness of the manure source and variations in other process parameters such as temperature and time (Ogundola et al., 2023). The plots of the specific biogas and biomethane productions from the goat manure substrate are shown in **Figure 1**. The specific biogas production ranged from 0.04 L/gVS on day 1 to 0.83 L/gVS on day 35. The corresponding specific methane production, on the other hand, ranged from 0.02 to 0.49 $LCH_4$/gVS.

### Effect of Varying HRT and S/I Ratio on Biogas Yield from Goat Manure Substrate

Biogas yields from the goat manure substrate, measured as a daily cumulative pressure inside airtight anaerobic digesters, are presented in **Figure 2**. The result showed that the cumulative pressure of the biogas yield ranged from the lowest value of 93.3 mbar in experimental run 3 to 650 mbar in experimental run 8. Experimental run 3 is the sample with an HRT of 10 days and a S/I ratio of 0.5. The results revealed that biogas yield cumulative pressure increases with an increase in the S/I ratio. Considering the HRT of 10 days, it can be observed that the pressure increased from 93.3 mbar in run 3

**Table 4.** Fit summary for anaerobic digestion of goat manure substrate

| Item | Value | | | | |
|---|---|---|---|---|---|
| Linear | < 0.0001 | 0.8056 | 0.8638 | 0.8266 | Suggested |
| 2FI | 0.7668 | 0.7379 | 0.8502 | 0.7684 | |
| Quadratic | 0.6278 | 0.6309 | 0.8314 | 0.5798 | |
| Cubic | 0.3780 | 0.9965 | 0.8400 | 0.9026 | Aliased |

**Table 5.** ANOVA for a linear model for biogas yield from goat manure

| Source | SS | df | MS | F-value | p-value | |
|---|---|---|---|---|---|---|
| Model | 2.844E+05 | 2 | 1.422E+05 | 39.0400 | < 0.0001 | Significant |
| A-HRT | 2.817E+05 | 1 | 2.817E+05 | 77.3400 | < 0.0001 | |
| B-SI ratio | 2,688.17 | 1 | 2,688.17 | 0.7380 | 0.4104 | |
| Residual | 36,423.62 | 10 | 3,642.36 | | | |
| Lack of fit | 15,038.53 | 6 | 2,506.42 | 0.4688 | 0.8056 | NS |
| Pure error | 21,385.09 | 4 | 5,346.27 | | | |
| Cor total | 3.208E+05 | 12 | | | | |

Note. SS: Sum of squares; MS: Mean square; & NS: Not significant

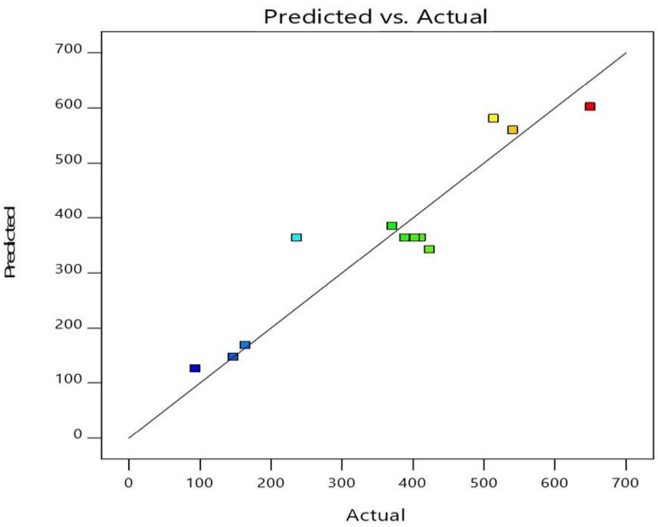


**Figure 3.** Plot of predicted and actual values of biogas yield from goat manure substrate (Source: Authors' own elaboration)

(0.5 S/I) to 147.1 mbar and 164 mbar in run 6 (S/I = 5.25) and run 7 (S/I = 10), respectively. A similar trend was observed for an HRT of 60 days, as seen in experimental runs 8, 10, and 11. However, there was a slight variation in this trend at HRT of 35 days. The results indicate that there was a decrease in biogas cumulative pressure from 423.7 mbar in run 5 at S/I of 0.5 to 410.8 mbar at S/I of 5.25. The results obtained at HRT of 35 days agree with those obtained from the literature (Baâti et al., 2018; Haider et al., 2015). This also suggests that too-short or too-long HRT can lead to desirable abnormal behavior in biogas production. Investigating further the impact of HRT on biogas yield by keeping S/I constant showed that there is an increase in biogas yield cumulative pressure with corresponding increase in HRT. Considering an S/I of 0.5, the cumulative pressure increased from 93.3 mbar in experimental run 3 at an HRT of 10 days to 540.7 mbar in experimental run 10 at an HRT of 60 days. A similar trend was observed when the S/I was 5.25. The cumulative pressure increased from 147.1 mbar in experimental run 6 at HRT of 10 days to 513.7 mbar in experimental run 11 at HRT of 60 days. The increase in biogas yield cumulative pressure due to the increase in HRT is because the substrate decomposes more with time, thereby producing more gas. However, a high S/I ratio causes low production at short HRT and excessively long HRT. This is due to the accumulation of undigested slurry in the case of short HRT and digestate in the case of long HRT (Haider et al., 2015; Orangun et al., 2021).

### Statistical Analysis and Model Evaluation

Statistical analyses of the results obtained from the experimental runs for biogas yield from goat manure are presented in **Table 4** and **Table 5**. As shown in **Table 5**, the linear model is the most suitable model to explain biogas yield from goat manure because it is the only model that is significant with a p-value < 0.0001 out of the four models tested for the process. The predicted $R^2$ of 0.8266 is in reasonable agreement with the adjusted $R^2$ of 0.8638, with a difference less than 0.2. This is supported by the relationship between experimental and predicted biogas yields displayed in **Figure 3**. An excellent correlation between the independent variables is justified by a higher value of the correlation coefficient for response (Ghani et al., 2011; Safian et al., 2011)

The analysis of variance (ANOVA) result for the result evaluation shows the model's F-value to be 39.04, which implies a significant model, and there is only a 0.01% chance that an F-value this large could occur due to a lack of fit. The lack of fit F-value of 0.47 implies insignificance relative to the pure error, and there is an 80.56% chance that a lack of fit F-value this large could occur due to noise. Hence, the non-significant lack of fit is good and also implies the model fits.

The complete regression model for goat manure is shown in Eq. (5), as coded values. The model can predict the response at the specified amounts of each component.

$$Biogas\ yield\ from\ goat = 364.07 + 216.68A + 21.17B. \tag{5}$$

In this model, the significant terms are those with high F values and p-values less than 0.05, while insignificant model terms have p-values greater than 0.05, as presented in **Table 5**. As a result, the model term B is not statistically significant; hence, there is no discernible impact on the biogas yield. Eq. (5) therefore becomes Eq. (6) when the non-significant model variable is removed from the regression model.

$$Biogas\ yield\ from\ goat = 364.07 + 216.68A. \tag{6}$$

The equations depict the relative impact of the factors by comparing the factor coefficients. The intercept of 364.07 in Eq. (6) is the average response of all the experimental runs for biogas production from goat manure. A unit increase in HRT (A) gives a positive increase of 216.68 in biogas production when other factors are held constant.

### Optimization Analysis

The outcome from the numerical optimization showed that the anaerobic digestion of goat manure must be carried out at an HRT of 33.09 days and an S/I ratio of 0.5, according to the numerical optimization result to yield 326.32 mbar shown in **Figure 4**, which was obtained based on 60.90% desirability.

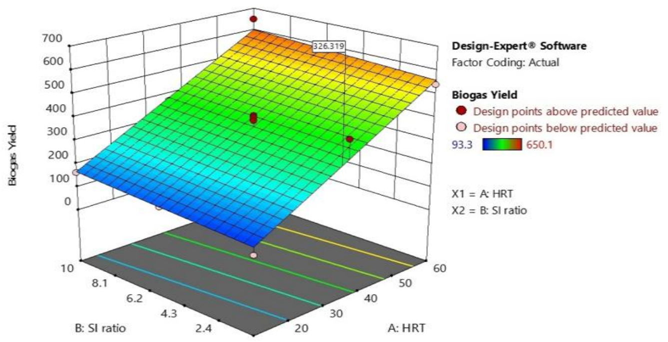


**Figure 4.** Response surface plots for optimization of biogas yield from goat manure substrate (Source: Authors' own elaboration)

**Table 6.** Confirmation and validation of predicted biogas production from goat manure substrate

| BS | PM | PMD | SD | n | SEP | 95% PIL | DM | 95% PIH |
|---|---|---|---|---|---|---|---|---|
| Goat | 364.069 | 364.069 | 60.352 | 3 | 38.656 | 277.938 | 361.66 | 450.20 |

Note. BS: Biogas source; PM: Predicted mean; PMD: Predicted median; SD: Standard deviation; SEP: Standard error predicted; PIL: Predicted interval low; DM: Data mean; & PIH: Predicted interval high

**Table 7.** Methane composition of biogas produced from goat manure substrate

| Sample | $\%CH_4$ | $\%CO_2$ and other gases |
|---|---|---|
| Goat manure | 58.53 | 41.47 |

**Table 6** displays the outcome of the optimized model's solution and validation.

The projected biogas yield for goat manure was 364.07 mbar, whereas the mean experimental biogas yield was 361.667 mbar. The experimental result is within the 95% expected high and low ranges. As a result, under ideal circumstances, there is high agreement between experimental and anticipated results, and the regression model produced through process optimization could accurately estimate the biogas yield for the combination of HRT and S/I ratio. The findings of the study align with those of Fernández-Rodríguez et al. (2023) as well as Kaur and Kommalapati (2021) who posited that a low S/I ratio or a high inoculum-to-substrate ratio is required for optimum biogas production in anaerobic batch processes.

### Characterization of Biogas at Optimum Yield

The result for the estimated biogas composition using the alkaline absorption method is shown in **Table 7**. The biogas sampled for evaluation was taken from the homogeneous mixture of the biogas from triplicate batch digesters used for optimization validation. The goat manure substrate had a biogas composition of 58.53% $CH_4$ and 41.47% $CO_2$. This result is comparable to that reported by Odejobi et al. (2017) for biogas produced from anaerobic digestion of kitchen wastewater, which yielded 58% $CH_4$ and 42% $CO_2$, as well as that of Ruihong et al. (2005), who reported 54.7% $CH_4$ and 45.3% $CO_2$ for biogas produced from green waste.

## CONCLUSION

The study established goat manure as a good substrate for biogas production. It also revealed that cumulative biogas yield from anaerobic digestion of goat manure varied with different S/I ratio and HRT. It established that too-short or too-long HRT can lead to desirable abnormal behaviour in the biogas production and that a high S/I ratio causes low production at short HRT and excessively long HRT. The HRT is a statistically significant process parameter, while S/I ratio is insignificant in biogas production from goat manure substrate. The optimized process conditions are HRT of 33.09 days and S/I ratio of 0.5. The CCD model generated can predict future biogas production from goat manure with 82.66% accuracy. Methane of approximately 58.53% was present in biogas generated from the goat manure.

**Author contributions: AAO:** designed and supervised the study; **ODO:** conducted the laboratory research and did the draft of the manuscript; & **TAO:** did the formatting and further discussion of the results. All authors agree with the results and conclusions.

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**Declaration of interest:** No conflict of interest is declared by the authors.

**Data sharing statement:** Data supporting the findings and conclusions are available upon request from the corresponding author.

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