Covenant Journal of Engineering Technology (CJET) Vol.3 No.2, Dec. 2019
ISSN: p. 2682-5317 e. 2682-5325

An Open Access Journal Available Online

Optimization of Process Parameters Influencing Biogas Production from Rumen and municipal waste: Analytical Approach

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Received: 22.07.2019 Accepted: 06.11.2019
Date of Publication: December, 2019

***Abstract*:** Rumen waste with high carbohydrate, protein, and lipid content is considered as a suitable substrate for fermentation for methane gas**.** In this study, direct substrate and co-digestion of rumen waste (RW) and municipal waste (MW) were used. Samples (fresh cow rumen and food waste) were dried, grinded, and blended with water into a semi-solid to facilitate digestion. Central composite design (CCD) was applied to optimize parameters of co-digestion of RW and MW at a different temperature (29 – 33ºC), initial pH values, agitation time (AGT), and carbon-nitrogen ratio (C/N). A comparative analysis was done using RSM in a predictive model of the experimental data obtained in accordance with the CCD. The combined effects of temperature, pH, AGT, and C/N as methane production by fermentation of RW and MW were investigated. Optimization using RSM showed a good fit between the experimental and the predicted data as elucidated by the coefficient of determination with R^2 values of 0.9214. Quadratic RSM predicted the maximum yield to be 7764 mL CH_4/g volatile solid (VS) at optimal conditions of 31°C; pH 7.05; 6s and C/N ratio 20.33. The maximum methane yield was 8550 mL CH_4/g VS, at the optimal conditions for the experimental response obtained. The verification experiment successfully produced 8550 mL CH_4/g VS within 30 days of incubation. This experiment indicated that the developed model was successfully and can be used for methane production from animal and municipal waste.

Keywords**:** Biogas, Rumen waste, Municipal waste, Response Surface Methodology, Co-digestion**,** Methane.

1. Introduction

Biogas technology is the application of the method that is based on the bacterial fermentation of organic materials, in the absence of air, to produce a flammable gas that can be put to various end-uses. In practice, the organic materials commonly used include manure from animals (cattle, pigs, and poultry), household/market garbage, wastewaters, and wastes of crop or agro-industrial origin. These materials are usually subjected to anaerobic fermentation in a biogas plant, and the gas produced is known as biogas [1]. The benefits of biogas technology at the public level include the application of biogas for cooking, water heating, and illumination. Once produced in large quantities, biogas can also be used to produce electricity [2]

Additionally, the fermented manure residues from the biogas plant contain significant amounts of nitrogen, phosphorus, and potassium and can thus be used as organic fertilizer for a variety of crops.

Biogas mostly describes as gases released from the decay of organic matter [3]. Biogas manufacturing is through anaerobic breakdown of organic matter. Biogas production is usually viewed as a two-stage process: such as acid and methane forming stages [4]. Wastes create a primary environmental worry both in the industry and in the domestic aspect, since proper disposal facilities are not available within the industrial layout of most towns of Nigeria, and even where the disposal are available, they are costly to run. However, a simple conversion of waste into fuel can be tremendously useful as renewable fuel, especially for domestic and industrial use. Biogas is a combination of mostly methane gas and carbon dioxide gas. Natural gas contains about 90-95% methane, while biogas include mostly 50-75% methane [2]. The second element necessary for biogas production is micro-organisms. Biogas produced from animal waste at ambient temperature (27 – 40°C) yields about 55 % - 65 % CH_4 and 30 % - 35 % CO_2 and traces of other gases like H_2S and N_2 [5].

Animal Rumen is one of slaughterhouse wastes that is frequently disposed into the drainage system. This waste disposal system causes environmental nuisance, particularly pose a health hazard to humans due to its content of millions of microorganisms. However, the availability of rumen may be useful as an activator in producing biogas through anaerobic fermentation, since some of rumen microorganisms are cellulolytic and methanogenic bacteria. The rumen is part of digestion system in ruminant where the microbial fermentation occurs. This fermentation process is similar to that of the biogas digester principle [6].

2. Statistical Analysis

The experimental results were fitted using the following polynomial regression Equation (1): [7-9]

$$Y = \beta_o + \sum\beta_i X_i + \sum\beta_{ii} X_{i2} + \sum\beta_{ij} X_i X_j \quad (1)$$

However, Y is the measured response, β_o are the intercepts term, β_{ii} are quadratic coefficient, β_{ij} are the relationship coefficients, and X_i and X_j are the coded variables. Equation (2) was used for coding the actual experiment values of the factors in the range of (-1 to +1):

$$X_i = \frac{Xi - Xj}{\Delta Xi} \quad (2)$$

$$\Delta Xi,\ i = 1, 2, 3, ..k$$

Where x_i is the non-measurement value of an independent variable, X_i is the actual data of an independent variable, X_0 is the data of X_i at the angle point, and Δxi is the step-change. Numerical examination of the data was performed using design expert v10 to assess the investigation of the analysis of variance to determine the importance of each term in the equations and estimate the goodness of the fit in all stages. The new design was carried out based on central composite design (CCD). It was applied for four independent variables, each at two levels, to fit the second-order polynomial model. The software design expert version 7.0 was used. The independent variables of temperature, pH, carbon-nitrogen ratio, agitation time were investigated using optimization techniques. The full experimental plan concerning the actual and coded forms is listed in Table 1.

Table1: Experimental Plan with respect to Actual and Coded Values

Factors	Variables	Unit	Low Actual	High Actual
A	Temperature	°C	29.00	33.00
B	pH		5.80	8.90
C	Agitation Time	S	2.00	10.00
D	C/N Ratio		18.33	22.33

3. Experimental Procedure

Fresh cow rumen was collected from an abattoir with appropriate pre-treatment prior, storage, and transportation to the laboratory for analysis and anaerobic digestion. The collected rumen waste was milled and blended with water to facilitate digestion and ease of interpretation. The experimental studies were conducted in a batch bio-digester reactor of 30 litres capacity plastic. The reactor was coupled with an appropriate channel for feeding feedstock, stirring and mixing digested discharge, and biogas collection. The reactor was initially purged or evacuated of air after that, sealed (air-tight). Water was used as the scrubber to remove carbon dioxide [10]

4. Results and Discussion

Optimization of experimental variables was conducted using Design Expert Version 10 using central composite design (CCD) to generate matrix. Complete experimental plan and created matrix of central composite design for studying the effects of the four independent variables were also considered in Table 2. The design was carried out with six replicates facial centre and axial centres generating standard run of 30 days. The experimental matrix was used to investigate the effect of variables influencing the biogas yield.

Table 2: CCD Matrix for Four Variables with Actual Biogas Production

Run	A	B	C	D	Biogas Yield (ml)
1	29	5.9	2	18.33	4050
2	33	5.9	2	18.33	4200
3	29	8.2	2	18.33	4300
4	33	8.2	2	18.33	4400
5	39	5.9	10	18.33	4750
6	33	5.9	10	18.33	4800
7	31	8.2	10	18.33	4950
8	33	8.2	10	18.33	5000
9	29	8.2	2	20.33	5200
10	33	5.9	2	22.33	5250
11	29	8.2	2	20.33	5250
12	33	8.2	2	22.33	5300
13	29	5.9	10	22.33	5400
14	33	5.9	10	22.33	5600
15	29	8.2	10	22.33	5750
16	33	8.2	10	22.33	6000
17	29	7.05	6	20.33	6500
18	33	7.05	6	20.33	6550
19	31	5.9	6	20.33	6700
20	31	7.05	6	20.33	6850
21	31	7.05	2	20.33	6900
22	31	7.05	10	20.33	6950
23	31	7.05	6	18.33	7000
24	31	7.05	6	20.33	7250
25	31	7.05	6	20.33	7350
26	31	7.05	6	20.33	7400
27	31	7.05	6	20.33	7500

28	31	7.05	6	20.33	8000
29	31	7.05	6	20.33	8200
30	31	7.05	6	20.33	8550

The optimized parameters were explored using CCD, and calculation involves varying the parameter of choice, testing, and validating the design model obtained in analyzing the response. By applying multiple regression analysis and ANOVA on the experimental data, the second-order or quadratic model was generated to explain and represent the biogas yield from the three substrates. By employing multiple regression analysis on the experimental value, the polynomial Equations 3-5 were derived to describe the biogas production from the three substrates.

$$\boldsymbol{R} = 7670.18 + 52.78A + 102.78B + 241.67C + 419.44D + 12.50AC + 12.50AD + 37.50BC - 50CD - 982.02A^2 - 732.02B^2 - 582.02C^2 - 382.02D^2 \quad (3)$$

$$\boldsymbol{M} = 8697 + 69.44A + 127.78B + 211.11C + 522.22D - 25AB - 31.25AC - 25BC - 18.75BD - 75CD - 1186.4A^2 - 861.4B^2 - 461.4C^2 - 88.8D^2 \quad (4)$$

$$\boldsymbol{R} + \boldsymbol{M} = 7495.18 + 44.44A + 141.67B + 294.44C + 441.67D + 9.38AB - 3.12AC + 3.13AD + 53.13BC + 59.38BD - 53.12CD - 1132.02A^2 - 757.02B^2 - 332.02C^2 - 257.02D^2 \quad (5)$$

Therefore, A, B, C, and D are used as a coded symbol for temperature, pH, agitation time, and C/N ratio, respectively. Statistical significance and fitness of the polynomial Equation generated were checked and verified by f-test and analysis of variance (ANOVA). The models f-values implies the models are significant; the chance is that % model f-value this large could occur due to noise. A non –significance lack of error greater enough will be needed to support and confirm the usefulness and fitness of the model equation generated. As for the result obtained f < p for all the three models generated. Hence, these model equations showed a high level of significance. The linearity of these models, though p < 0.5, still showing excellent insignificance relationship with biogas yield.

For the cow rumen, the Model F-value was 25.30, indicates the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.050 indicate model terms are significant. In this case, C, D, A2, B2, C2 are significant terms.

Values greater than 0.100 implies that the parameters are not vital. When the elements are much that is insignificant, the model reduction process will be implemented to improve the mathematical models. The "Lack of Fit F-value" of 0.30 implies the Lack of Fit is not significant relative to the pure error [11]. There is a 94.92% chance that a "Lack of Fit F-value" this large could occur due to noise [12]. Figures 1 and 2 show the graphical relationship between variables and 3D format

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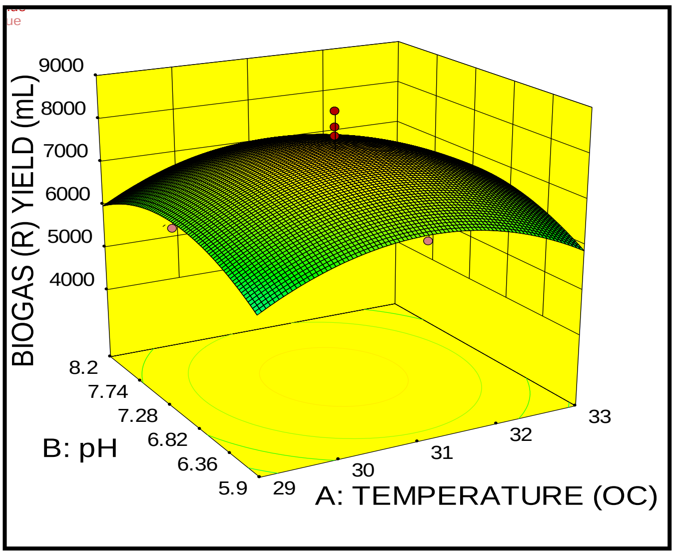

Figure 1: Three-dimensional response surface plot showing the interaction of pH and Temperature.

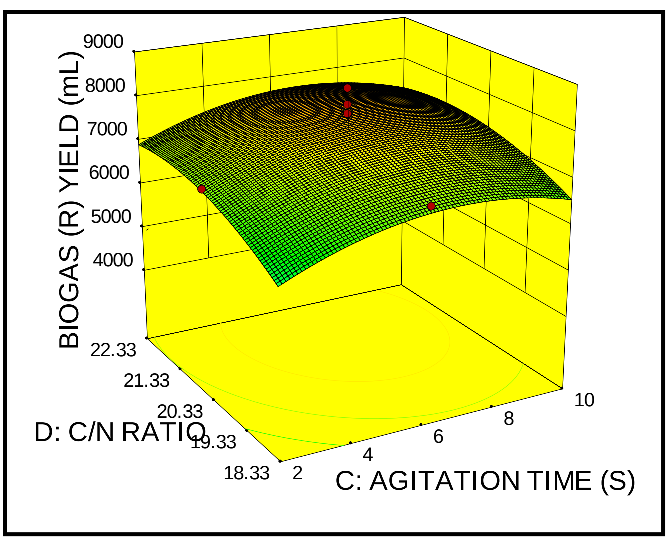

Figure 2: Three-dimensional response surface plot showing the interaction of C/N ratio and agitation time

The "Predicted R-Squared" of 0.9108 is in reasonable agreement with the "Adjusted R-Squared" of 0.9214, i.e., the difference is less than 0.2. "Adequate Precision" evaluate the signal to noise ratio. A ratio greater than 4 is desirable. The value 13.843 indicates an adequate signal, with standard deviation (359.57), mean (6063.33), and coefficient of variance (5.93%). This developed model can be used to predict the design space.

For municipal waste, the Model F-value of 17.28 depicted that the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. There is a 14.00% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Predicted R-Squared" of 0.8294 is in reasonable agreement with the "Adjusted R-Squared" of 0.8871, i.e., the difference is less than 0.2. Figures 3 and 4 show the graphical relationship between variables and 3D format.

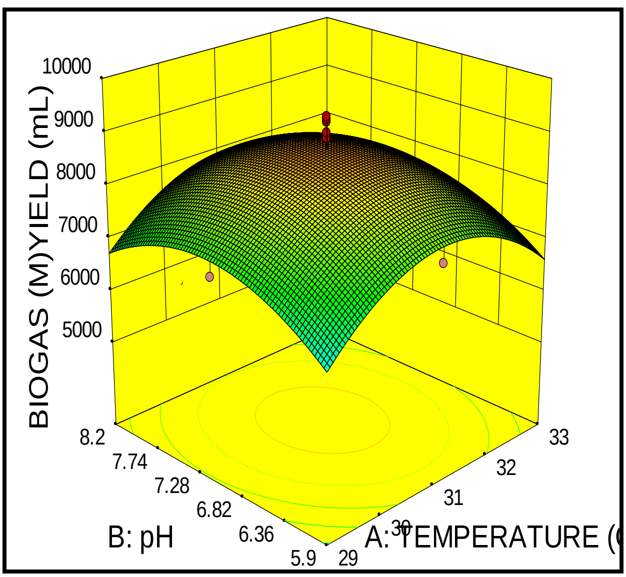

Figure 3: Three-dimensional response surface plot showing the interaction of pH and temperature

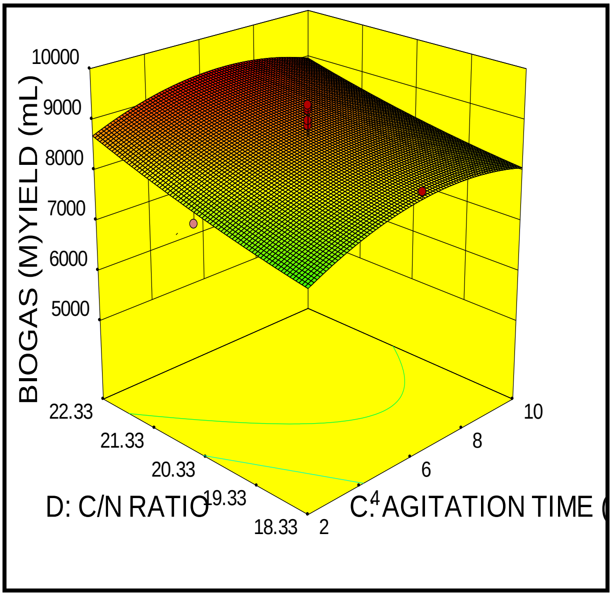

Figure 4. Three-dimensional response surface showing the interaction of C/N ratio and agitation time

The value of 14.136 indicates an adequate signal. For the co-digested blend substrate, the Model F-value of 58.33 shows that the model is significant. There is only a 0.01% chance that an F-value this huge might arise due to noise. The values of "Prob > F" less than 0.0500 shows that the model terms are significant. In this case B, C, D, A^2, B^2, C^2 are significant model terms. The "Predicted R-Squared" of 0.9225 is in reasonable agreement with the "Adjusted R-Squared" of 0.9651; that is, the difference is less than 0.2. Figures 5 and 6 present the graphical relationship between variables using the 3D format.

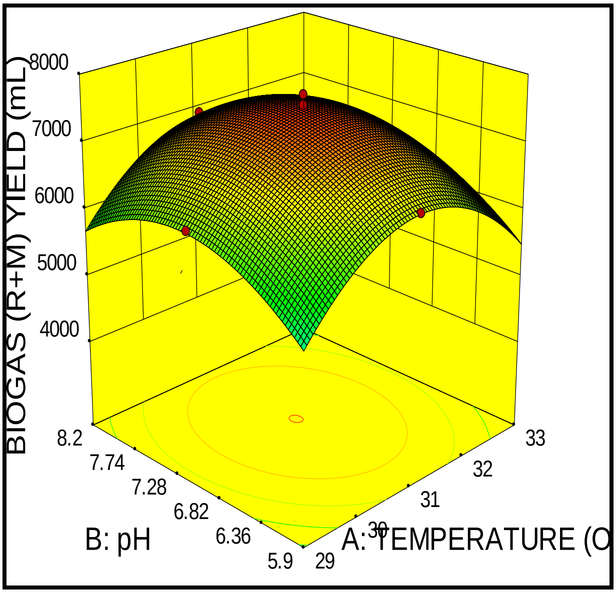

Figure 5. Three-dimensional response surface showing the interaction of pH and temperature

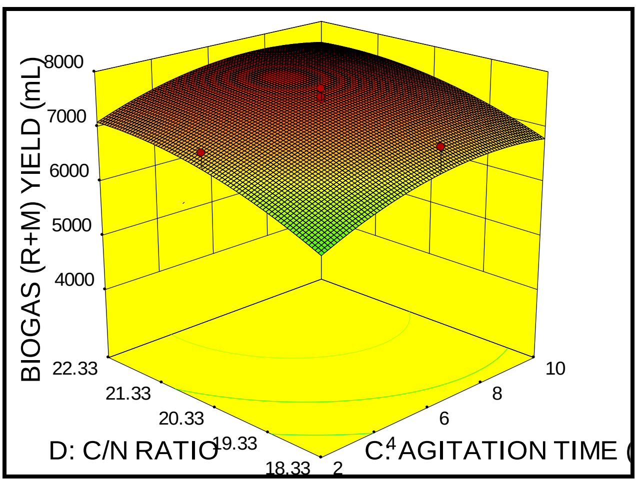

Figure 6. Three-dimensional response surface showing the interactive effects of agitation time and C/N ratio

A ratio greater than 4 is desirable. Value of 22.028 indicates an adequate signal. However, the mathematical models developed in this study can be used to predict the experimental values. The attained optimal values for the processing of the parameter were calculated using a design expert by simulating the developed model from 0 – 100 iterations. In order to achieve the best working condition yielding maximum biogas.

5. Conclusion

The optimal experimental values; 84.08, 51.521, and 95.518% methane composition were achieved at a temperature of 30.82 ºC, pH of 7.367, agitation time of 7.019s, and C/N ratio of 21.523 using CCD with the significant variables that enhanced the biogas yield. The result shows a close agreement between the expected and obtained level of production. The maximum methane yield was 8550 mL CH_4/g VS, at the optimal conditions for the experimental response achieved. The verification experiment successfully produced 8550 mL CH4/g VS within 30 days of incubation. This experiment showed that the developed model was successfully and can be used to predict the percentage of methane production from animal and municipal waste. Interestingly, water as a solvent was successfully demonstrated from this work as a potential purifier of biogas up to 80 – 90% methane.

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