Optimization of Process Parameters Influencing Biogas Production from Rumen and Municipal Waste: Analytical Approach

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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. Response surface methodology (RSM) and central composite design were applied to optimize parameters of co-digestion of RW and MW at different temperature, 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 central composite design. The combined effects of the independent variables (temperature, pH, AGT and C/N) as the most significant parameters of methane 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 CH4/g VS within 30 days of incubation. This experiment indicated that the developed model was successfully used to predict the fermentable methane production.

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

1.0 Introduction

Biogas technology is the application of the process 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 normally 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. The benefits of biogas technology at the community level include the utilization of biogas for cooking, water heating and lighting. When produced in large quantities, biogas can also be used to generate electricity (Teodorita *et al.*, 2008). 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 generally, describes gases released from decomposition of organic matter. Biogas production is through anaerobic decomposition of organic matter (Ward *et al.*, 2008). Biogas production is generally viewed as a two-stage process. Such as acid forming and Methane forming stages (Batstone *et al.*, 2002). Wastes raise a major environmental concern both industrially and domestically, since proper disposal facilities are not available within the industrial layout of most towns of Nigeria, and even where available, they are costly to run. However, a simple conversion of waste into a fuel can be tremendously useful as renewable fuel source especially for domestic and industrial use. Biogas is a mixture of mainly methane gas and carbon dioxide gas. Natural gas contains about 90-95% methane while biogas contain mostly 50-75% methane (Teodorita *et al.*, 2008). The second ingredient necessary for biogas production is bacteria. 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. Biogas is actually a mixture of gases, carbon dioxide and methane.

Rumen is one of slaughterhouse wastes that is frequently disposed into drainage system. This waste disposal system causes environmental nuisance, particularly pose health hazard to human due its content of millions of microorganisms. However, rumen may be useful as an activator in producing biogas through anaerobic fermentation. Since some of rumen microorganisms are cellulolitic and methanogenic bacteria. Rumen is part of digestion system in ruminant where the microbial fermentation occurs. This fermentation process is similar to that in biogas digester (Abdeshahian *et al.*, 2016).

2.0 Design of Experiment (DOE)

Response surface methodology (RSM) is considered a useful mathematical and statistical technique for analyzing several independent parameters, experimental design, and evaluation of factors, optimization of different conditions (Ward *et al.*, 2008). The optimization of different process parameters affecting biogas production is one of complex process with more number of interactive effects for controlling process parameters. The optimization is producing accurate results about interactive process parameters and which improves the production of biogas significantly (Ward *et al.*, 2008). The traditional "one or more variable at a time approach" for medium optimization disregards the complex between various components of the RSM. It is one of the analytically based experimental designs such as placket-burman design and Response Surface Methodology (RSM). Mainly used to study the effect of factors and estimating optimum levels of the experiments (Ward *et al.*, 2008). In the last seven years RSM has been used in so many industries to optimize and estimate the interactive effects of independent variables in chemical and biochemical processes involved in anaerobic digestion (Ward *et al.*, 2008). Generally, biochemical reaction mechanism is mainly for production of biogas from batch processed anaerobic digester (Ward *et al.*, 2008). The main aim of this study was to investigate the effects of temperature, pH, carbon nitrogen ratio, and agitation time as well as their interactive effects on biogas production

3.0 Statistical Analysis

Analysis of variance (ANOVA) was used in analysis of regression co-efficient, prediction equation, and case statistics. The experimental results of RSM were fitted using the following second order polynomial regression Equation:

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

Where Y is the measured response, β_o is the intercept term, β_{ii} are quadratic coefficient, β_{ij} are interaction coefficient, and X_i and X_j are coded independent variables. The following Equation was used for coding the actual experiment values of the factors in the range of (-1 to +1):

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

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

Where x_i is the dimensionless value of an independent variable, X_i is the real value of an independent variable, X0 is the value of X_i at the corner point and Δxi is the step change. Statistical analysis of the data was performed by design package using design expert v10 to evaluate the analysis of variance, to determine the significance of each term in the equations fitted and estimate the goodness of the fit in all cases. The polynomial or linear Equation was represented in three-*dimensional* response surface plots to indicate the interactive effects of variables. The optimal concentration of critical variables was obtained by analyzing 3D Plots. The experimental design was carried out based on central composite design (CCD) with response surface methodology (RSM). It was applied for four independent variables, each at two levels to fit second order polynomial model. The software design expert version 7.0 state-

Ease.inc was used. The independent variables of temperature, pH, carbon nitrogen ratio, agitation time were analyzed using optimization techniques. The full experimental plan with respect to their actual and coded forms is listed in Table 1.

Table 1: 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

4.0 Experimental Procedure

Fresh cow rumen was source and collected from Minna abattoir with appropriate pretreatment prior, storage and transportation to laboratory for analysis and anaerobic digestion. Necessary sampling and analysis was done before and after complete digestion. The collected rumen waste was grinded and blended with water to facilitate digestion and ease of analysis. The experimental studies were all conducted in batch bio-digester reactor of 30 liters capacity of compact water plastic material at an ambient environmental condition. The reactor was coupled with appropriate channel for feeding feedstock, stirring and mixing, digestate discharge and biogas collection. The reactor was seal such that it was air tight and also purge or evacuated of air. Absorption/scrubbing was used to remove carbon dioxide precisely but alongside CO_2 removal water has the ability to remove impurities such as hydrogen phosphide, chlorinated hydrocarbons, ammonia, hydrogen sulphide and other traces of impurities (Grande and Rodrigues, 2007). Gas volume measurement was performed using a well calibrated gas bag as storage facility.

5.0 Results and Discussion

Optimization of experimental variables was conducted using Design Expert Version 10 combining Response Surface Methodology, 2^4 factorials, box benken and central composite design to generate experimental plan to yield the experimental matrix. Complete experimental plan and generated matrix of central composite design for studying the effects of the four independent variables were also considered (Table 2). The design was done with 6 replicates facial centre with other facial and axial centres generating standard run of 30 days. Experimental matrix was used to investigate effect of variables influencing the biogas yield, the parameters are temperature, pH, agitation time and carbon nitrogen ratio.

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

Run	A	B	C	D	Biogas
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 of these variables were explored using CCD and calculation involve varying the parameter of choice and testing and validating the design model obtained in analyzing the responses outcome. By applying multiple regression analysis and ANOVA on the experimental data, a second order or quadratic model was generated to explain and represent the biogas yield from the three substrates. By applying multiple regression analysis on the experimental data, the second order polynomial Equations 1, 2 and 3 was derived to explain the biogas production from the three substrates.

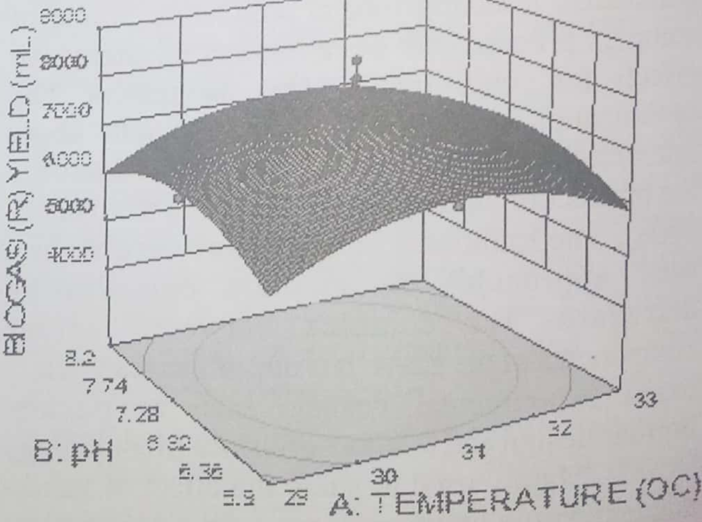

Figure 1: Three-dimensional response surface plot showing the interactive effects of pH and Temperature

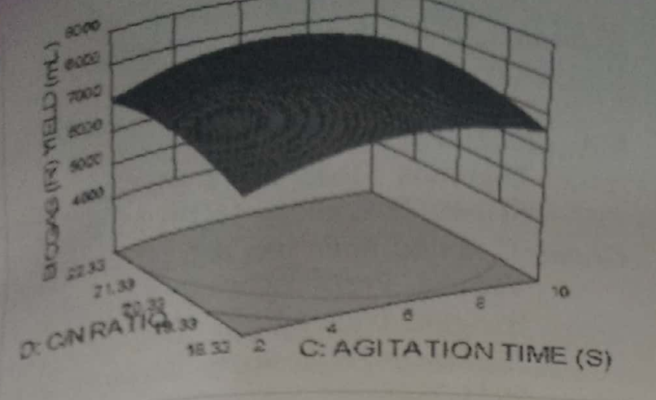

Figure 2: Three-dimensional response surface plot showing the interactive effects of C/N ratio and agitation time

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" measures the signal to noise ratio. A ratio greater than 4 is desirable. Ratio of 13.843 indicates an adequate signal. With standard deviation (359.57), mean (6063.33) and coefficient of variance (5.93%). This model can be used to navigate the design space.

For municipal substrate the Model F-value of 17.28 implies 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.

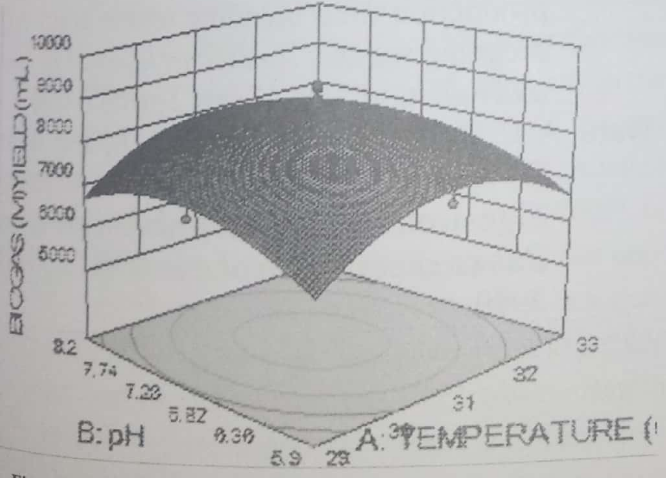

Figure 3: Three-dimensional response surface plot showing the interactive effects pH and temperature

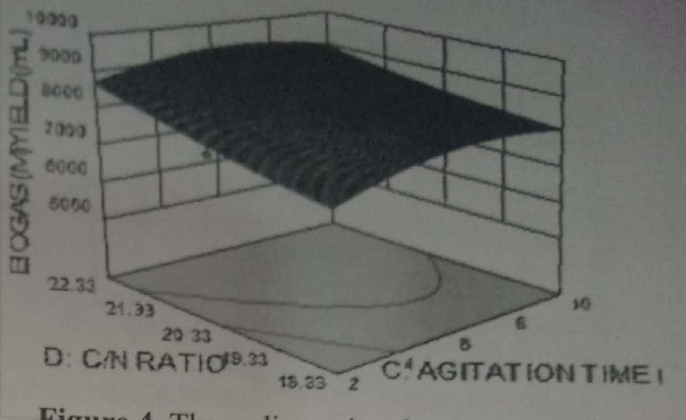

Figure 4. Three-dimensional response surface showing the interactive effects of **C/N ratio and agitation time**

"Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Ratio of 14.136 indicates an adequate signal. This model can be used to navigate the design space. For the co-digested blend substrate the Model F-value of 58.33 implies 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 0.0500 indicate 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; i.e. the difference is less than 0.2. "Adequate Precision" measures the signal to noise ratio. Figures 5 and 6 show the graphical relationship between variables and 3D format.

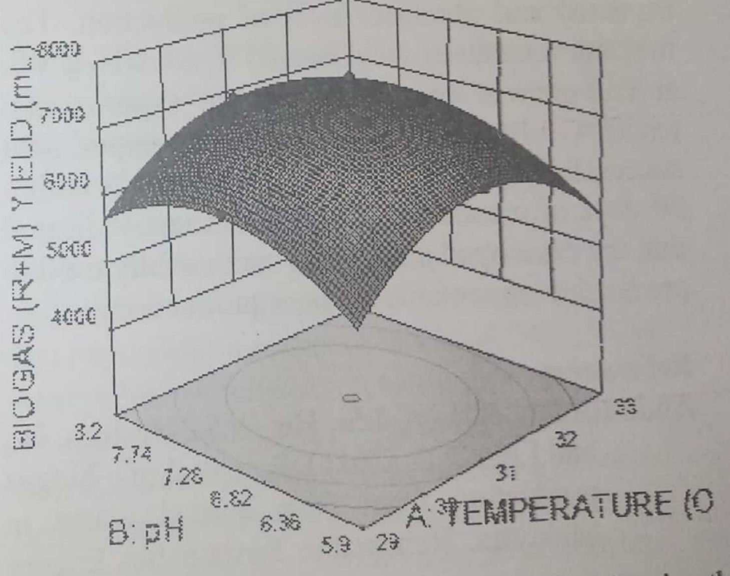

Figure 5. Three-dimensional response surface showing the interactive effects of pH and temperature

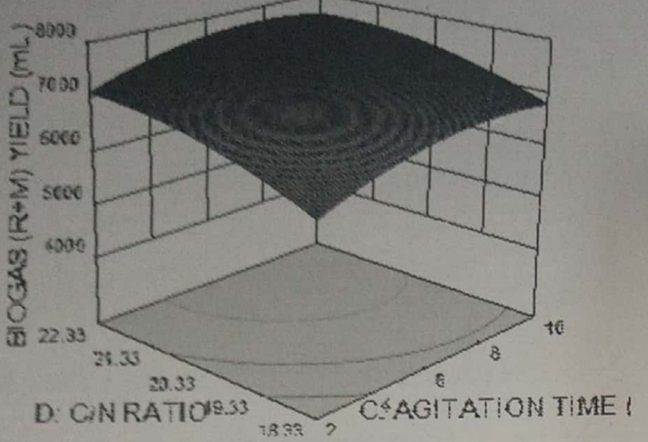

Figure 6. Three-dimensional response surface showing the interactive effects of agitation time and C/N ratio

A ratio greater than 4 is desirable. Ratio of 22.028 indicates an adequate signal. This model can be used to navigate the design space. The obtained optimal values for the operating parameter were computed using design expert calculation by simulating the developed model from 0 – 100 iterations to achieved best working condition yielding maximum biogas (Uzodinma *et al.*, 2011).

6.0 Conclusion

This research work was designed, using design expert v10. The optimal experimental values were obtained as temperature (30.82°C), pH (7.367), agitation time (7.019s) and C/N ratio (21.523) using RSM, CCD and most significant variables which significantly 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 obtained. The verification experiment successfully produced 8550 mL $CH4$/g VS within 30 days of incubation. This experiment indicated that the developed model was successfully used to predict the fermentable methane production.

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