Optimization of Operating Conditions for Enhanced Biogas Production with Substrates using Response Surface Methodology

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ABSTRACT

Biogas is produced when organic matter is broken down through bacteria in the absence of oxygen. However, the operating conditions can inhibit the growth of methanogenic bacteria needed for optimal biogas production if care is not taken. Therefore, this study optimized selected process conditions for enhanced biogas production using the Response Surface Methodology (RSM). The Central Composite Design (CCD) was used to determine the maximum and minimum cumulative biogas yield, and the selected independent variables (pH, temperature, retention time, total solids and volatile solids) were all fitted by a second order polynomial model, while the Analysis of variance (ANOVA) for the quadratic model was carried out on all the responses obtained from the CCD of all the operating conditions. For the biological pretreatment process with poultry dung, the recommended optimal conditions from the biological pretreatment process are; temperature (35^0C), pH (7.3), retention time (32 days), total solids (8.2 g/Kg) and volatile solids (9.6 g/Kg). For the chemical pretreatment process with poultry dung, the recommended optimal operating conditions are; temperature (35^0C), pH (8.15), retention time (32 days), total solids (4.16 g/Kg) and volatile solids (4 g/Kg). The operating conditions pH, temperature, total solids, volatile solids and retention time had significant cumulative effects on the eventual biogas yield for both the biological and chemical pretreatment processes.

KEYWORDS: Biogas, Poultry dung, Operating conditions, Optimization.

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1. INTRODUCTION

Biogas is produced when organic matter (animal and plant products) become broken down through bacteria in an environment devoid of oxygen, composed mostly of methane and some gases through the process of anaerobic digestion. Biogas systems make use of anaerobic digestion to treat the organic matter by transforming them into biogas, containing both valuable soil products (solids and liquids) and energy (gas) (Franco *et al.,* 2018) [1]. Anaerobic digestion occurs naturally in some livestock management systems and landfills, but may still be contained, controlled and optimized through an anaerobic digester. Ordinarily, biogas should contain nearly 30 – 40 percent carbon dioxide, 50 - 70 percent methane and other gases in trace amounts (McKennedy and Sherlock, 2015) [2]. However, in order to accomplish optimal biogas production, Oladejo *et al.,* (2020) [3] concluded bio-methanation which is a product of the interaction of different groups of microorganisms helps in the production of methane. This is because these microbes exist naturally and enter the digester with the introduction of raw materials and whenever the pre-digested raw material is introduced into the digester and the small quantity of water treatment plant sludge is added, the methane production will quickly increase.

This means that bio-methanation demands a huge quantity of starting bacteria and as such, the addition of seeding bacteria into the slurry reduces the retention time but also increases biogas production and methane yield. Generally, the co-digestion of various materials produces better output (Bala *et al.,* 2019) [4]. Furthermore, Degueurce *et al.,* (2016) [5] concluded that co-digestion usually generates more gas than is anticipated through gas production from the individual substrates. The reason for this is that a complex material is very likely to contain all the component parts that are critical for microbial growth. Also, substrates that are not too uniform and are complex enhance the growth of multiple types of microbes in the digester (Dahunsi *et al.,* 2017) [6]. However, if there is a continuous process that is fed for a long period with a substrate that is very uniform (a sugar-rich material), it may become difficult to digest fats and proteins in such a system. This is because most of the microbes with the capacity to break down proteins and fats would have been washed out of the process (Dahunsi, 2019a) [7] (Dahunsi *et al.,* 2019a) [8].

Therefore, a multiplicity of co-substrates is desirable because it increases the possibility of a robust and stable process. If a diverse microbial community is able to develop and grow by decaying many various types of components, the process will develop the ability to handle large future differences in co-substrates composition (Chuichulcherm *et al.,* 2017) [9]. Furthermore, Chen *et al.,* (2016) [10] argued that co-digestion enhances the chances of the process to manage substrates that contain harmful (toxic) components. In fact, if there are various microorganisms at the beginning which fulfill the same functions as the breaking down of sugars, the process will continue to perform as expected. Even when one or more of these microbes are removed due to harmful effects, as long as some exist, the process will still function optimally.

As such, Latha *et al.,* (2019) [11] concluded that to accomplish a stable digestion process and optimal biogas production with a variety of substrates, it is better if the mixing happens under controlled conditions in a digester. This is why digester operating conditions such as temperature, pH, carbon/nitrogen ratio, moisture content and retention time are essential parameters that must be monitored and maintained appropriately. According to Dahunsi, (2019b) [12], maintaining operating conditions in a digester is very important, but the optimization of the operating conditions is even more important. This is because optimization provides the optimal conditions that must be maintained in the digester in order to achieve sustainable and improved biogas production. This is why this study is justified.

2. MATERIALS AND METHODS

2.1 Selection of Independent Variables and Operating Conditions as Responses

The substrate (poultry dung) used for digestion was initially subjected to the processes of biological and chemical pretreatment in order to enhance biogas production. During the process of biogas production, particular attention was paid to digester operating conditions such as temperature and pH because according to Oladejo *et al.,* (2020) [3], these are parameters which often determine the survival of microorganisms required for biogas production. Subsequently, the values of temperature and pH obtained in the digester (35.0^0C and 7.3) were used to carry out the process of optimization respectively. The RSM was adopted according to Dahunsi (2019a) [7] for this work in order to evaluate the available optimal levels of the operating conditions for statistical optimization and the values obtained were subsequently used for the evaluation of the maximum production of methane.

Furthermore, the CCD was adopted for the determination of the maximum and minimum cumulative biogas yield, minimum and maximum hydraulic retention time, minimum and maximum temperature, minimum and maximum pH, minimum and maximum total solids and minimum and maximum volume of solids. Subsequently, the cumulative biogas yield (kg) was selected according to Dahunsi *et al.,* (2016) [13] as the response for the combination of five independent variables (pH, temperature, retention time, total solids content and volatile solids) and which were all fitted by a second order polynomial model. The second order polynomial model into which the independent variables were all fitted into Equation 1 accordingly;

$$Y = \beta_O + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j \tag{1}$$

2.2 Optimization of Selected Process Conditions

The optimization process included the design factors information for the RSM, the design responses information, the design layout, the Analysis of Variance (ANOVA) values for quadratic model and the responses, the final equation in terms of coded factors and the 3D design curvatures optimization for design factors. Consequently, Y served as the predicted response, Xi Xj were the independent parameters, βo served as the intercept term, βi was the linear coefficient, βii was the quadratic coefficient, while βij served as the coefficient of interaction in this polynomial relationship. Furthermore, model graphs and diagnostics were obtained in order to carry out the analysis of the effects of the operating conditions separately and their relationships for the determination of their optimal levels. Also, the model F and P values were obtained with such accuracy that even the values were checked for their significance in conjunction with the model terms.

Similarly, the point prediction approach was adopted for the optimization of the optimal levels of each operating condition for maximum response. The statistical model adopted was also validated with respect to all the five operating conditions within the design space. This is because values greater than 0.1000 often mean that the model terms are not significant and if there are many insignificant model terms, model reduction may be used to improve the model. This was done for both the biological and chemical digestion pretreatment processes with poultry dung samples. Furthermore, the equation in terms of the coded factors was used to make predictions about the response for given levels of each factor. By default, the high levels of the factors were coded as +1 and the low levels were coded as -1. The coded equation was also used for identifying the relative impacts of the factors through the comparison of the factor coefficients.

3. RESULTS AND DISCUSSION

3.1 Optimization of Results from Biological Pretreatment with Poultry Dung Samples

The results obtained from the entire process for the biological pretreatment with poultry dung samples which covered the design factors information for the RSM, the design layout, the ANOVA values for quadratic model and the responses, the final equation in terms of coded factors and the 3D design curvatures optimization for design factors are all presented in Tables 1, 2 and 3, and Figures 1 to Figure 10 accordingly. From the results obtained, the Model F-value of 38.50 showed that the model is significant and that there is only a 0.58% chance that an F-value this large could occur due to noise.

Table 1: Design factors information for design expert for biological pretreatment with poultry dung substrates

Factor	Name	Units	Type	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Temp	Degree	Numeric	35.00	35.10	-1 ↔ 35.00	+1 ↔ 35.10	35.06	0.0413
B	pH		Numeric	7.30	7.54	-1 ↔ 7.30	+1 ↔ 7.54	7.42	0.0992
C	Retention Time	Days	Numeric	30.00	32.00	-1 ↔ 30.00	+1 ↔ 32.00	31.04	0.8244
D	Tot. solids	g/Kg	Numeric	4.00	12.00	-1 ↔ 4.00	+1 ↔ 12.00	7.74	3.40
E	Vol. Solids	g/Kg	Numeric	4.00	12.00	-1 ↔ 4.00	+1 ↔ 12.00	7.91	3.30

Table 2: Design layout for design expert for biological pretreatment with poultry dung substrates

Run	Factor 1 A:Temp Degree	Factor 2 B:pH	Factor 3 C:Retention Time Days	Factor 4 D:Tot. solids g/Kg	Factor 5 E:Vol. Solids g/Kg	Response 1 Biogas yield L/Kg VS
1	35.0205	7.48	32	10.2	4	0.78144
2	35.1	7.3	32	12	4	0.79772
3	35.075	7.348	30	4	12	0.814
4	35.04	7.45	30	9.6	12	0.83028
5	35.1	7.4656	32	8.16	9.68	0.84656
6	35.1	7.3	31.24	12	12	0.86284
7	35.1	7.3	30.98	4.04	8.12	0.86284
8	35	7.3	30	4	12	0.87912
9	35.1	7.4608	30.5748	8.12	4	0.87912
10	35	7.54	32	12	12	0.78144
11	35	7.3732	30.94	12	8.2	0.79772
12	35.043	7.4356	31.47	4	12	0.814
13	35.033	7.3	30.6	8.2	4	0.83028
14	35	7.54	30.92	6.28	8.36	0.84656
15	35.069	7.54	31.0019	12	7.92	0.86284
16	35.085	7.54	32	4	4	0.87912
17	35	7.54	30	12	4	0.87912
18	35	7.324	32	4	4	0.78144
19	35.1	7.54	30	4	12	0.79772
20	35.0825	7.3864	32	7.06041	4	0.814
21	35.0418	7.4356	30	4	6.28	0.83028
22	35.1	7.3	30	12	7.04	0.86284
23	35.1	7.5328	31.19	4	8.68	0.86284
24	35.0335	7.3	32	8.2	9.6	0.87912

Table 3: Response 1: Biogas yield on biological pretreatment with poultry dung substrates of the ANOVA for quadratic model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0279	20	0.0014	38.50	0.0058	Significant
A-Temp	0.0023	1	0.0023	63.75	0.0041	

B-pH	0.0000	1	0.0000	0.5589	0.5090
C-Retention Time	0.0018	1	0.0018	48.42	0.0061
D-Tot. solids	0.0003	1	0.0003	7.21	0.0747
E-Vol. Solids	0.0000	1	0.0000	1.33	0.3328
AB	0.0005	1	0.0005	14.15	0.0328
AC	0.0004	1	0.0004	10.38	0.0485
AD	0.0003	1	0.0003	7.30	0.0737
AE	0.0014	1	0.0014	37.81	0.0087
BC	0.0003	1	0.0003	7.40	0.0725
BD	0.0002	1	0.0002	5.56	0.0996
BE	0.0060	1	0.0060	165.57	0.0010
CD	0.0012	1	0.0012	32.55	0.0107
CE	0.0016	1	0.0016	43.06	0.0072
DE	0.0001	1	0.0001	1.85	0.2673
A^2	4.602E-06	1	4.602E-06	0.1271	0.7451
B^2	0.0040	1	0.0040	110.46	0.0018
C^2	9.552E-06	1	9.552E-06	0.2637	0.6430
D^2	0.0013	1	0.0013	36.16	0.0092
E^2	0.0004	1	0.0004	11.43	0.0431
Residual	0.0001	3	0.0000		
Cor Total	0.0280	23			

Furthermore, P-values as seen in Table 3 is less than 0.0500 indicated that model terms are significant and in this case, A, C, AB, AC, AE, BE, CD, CE, B^2, D^2, E^2 are significant model terms. This is because values greater than 0.1000 often mean that the model terms are not significant and if there are many insignificant model terms, model reduction may be used to improve the model.

The following is a description of the fit model statistics and the values obtained;

Fit Statistics

Standard. Deviation	0.0060	R^2	0.9961
Mean	0.8364	Adjusted R^2	0.9702
C.V. %	0.7195	Predicted R^2	0.7927
		Adequate Precision	18.2130

Similarly, the predicted R^2 of 0.7927 was very close to the adjusted R^2 of 0.9702 as normally expected because the difference is not more than 0.2. This therefore indicated that there was not a large block effect with the model and/or data. Also, the adequate precision is used to measure the signal to noise ratio and usually, a ratio greater than 4 is always desirable. Therefore, the ratio of 18.213 of this study indicated that the signal is an adequate signal and this means the model is fit enough for the navigation of the design space.

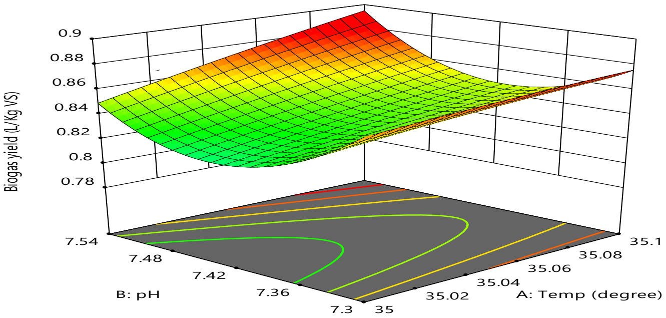

Figure 1: The curvatures' nature of 3D surfaces plots for pH and temperature in the biological pretreatment process

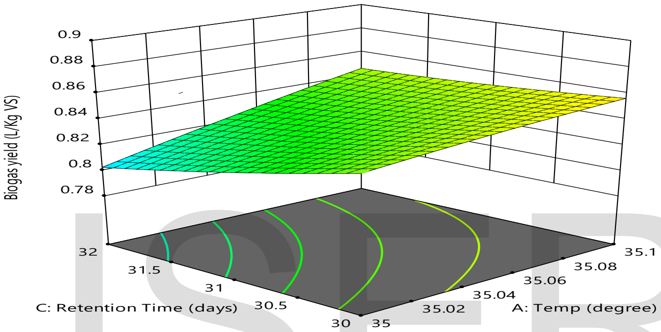

Figure 2: The curvatures' nature of 3D surfaces plots for retention time and temperature for biological pretreatment process

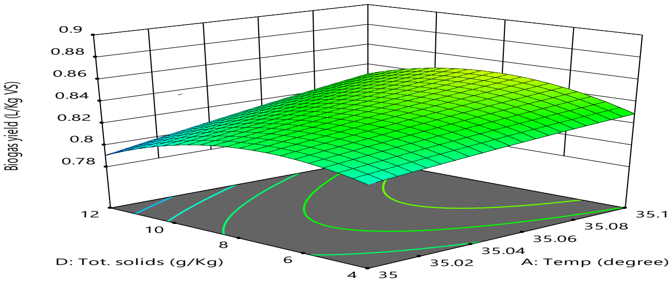

Figure 3: The curvatures' nature of 3D surfaces plots for total solids and temperature for biological pretreatment process

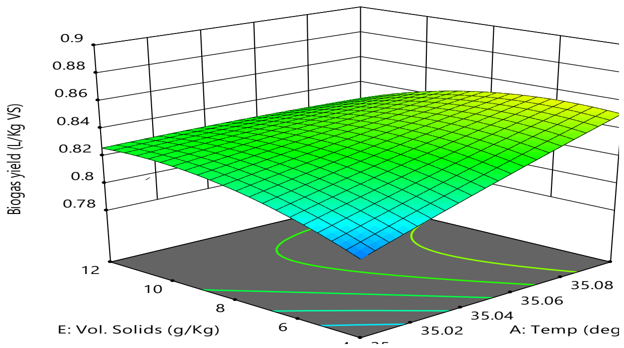

Figure 4: The curvatures' nature of 3D surfaces plots for volatile solids and temperature for biological pretreatment process

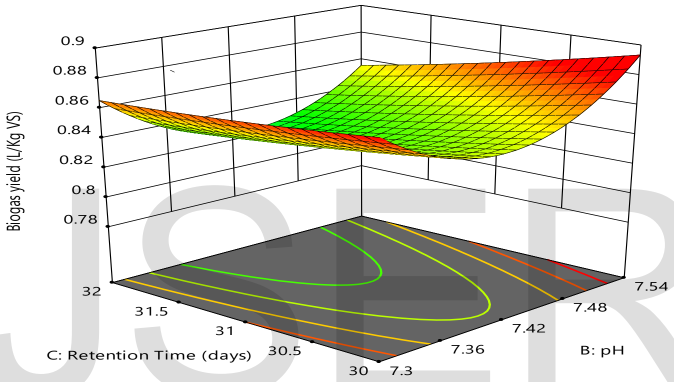

Figure 5: The curvatures' nature of 3D surfaces plots for retention time and pH for biological pretreatment process

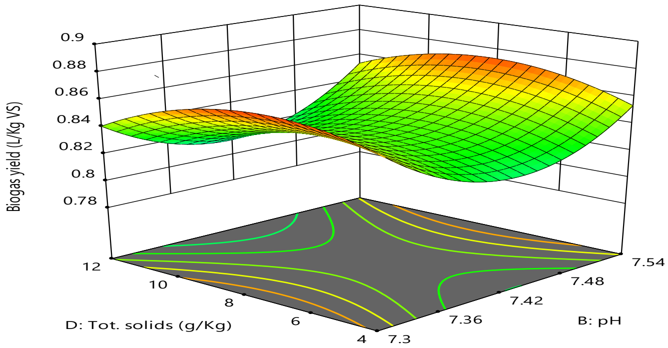

Figure 6: The curvatures' nature of 3D surfaces plots for total solids and pH for biological pretreatment process

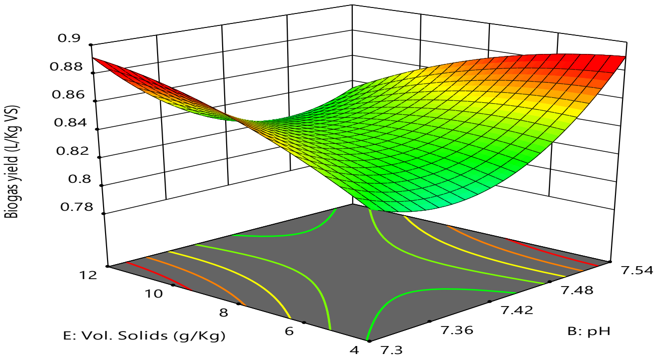

Figure 7: The curvatures' nature of 3D surfaces plots for volatile solids and pH for biological pretreatment process

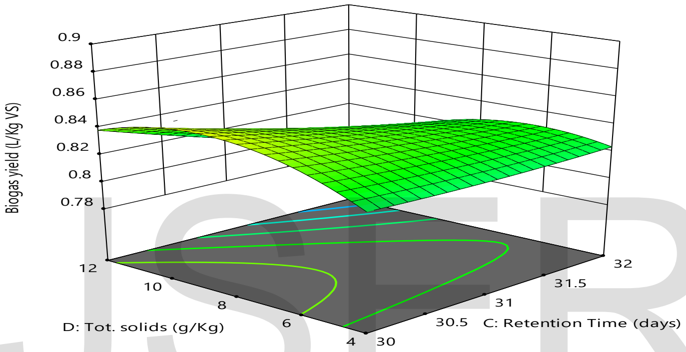

Figure 8: The curvatures' nature of 3D surfaces plots for total solids and retention time for biological pretreatment process

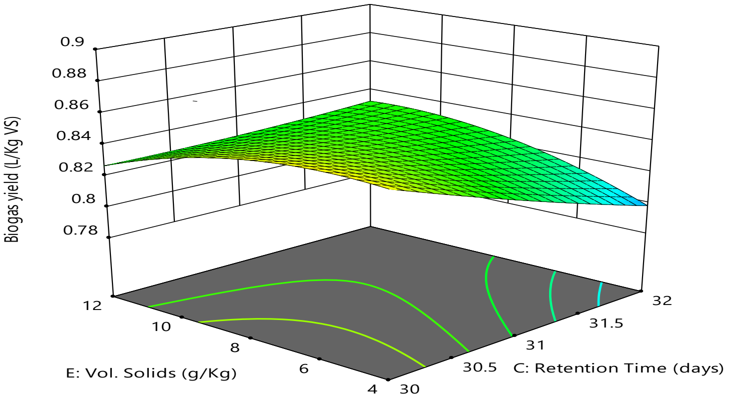

Figure 9: The curvatures' nature of 3D surfaces plots for volatile solids and retention time for biological pretreatment process

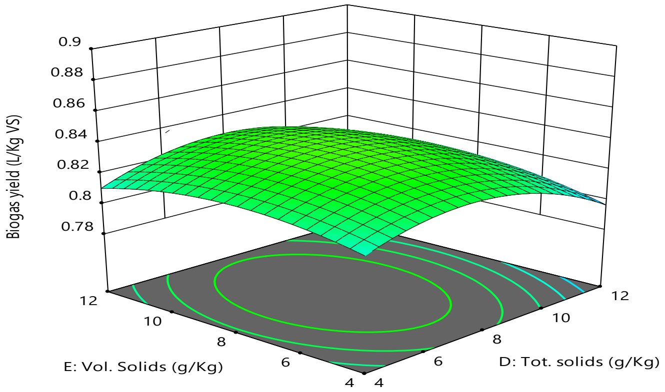

Figure 10: The curvatures' nature of 3D surfaces plots for volatile solids and total solids for biological pretreatment process

The equation in terms of the coded factors was used to make predictions about the response for given levels of each factor. By default, the high levels of the factors were coded as +1 and the low levels were coded as -1. The coded equation was also used for identifying the relative impacts of the factors through the comparison of the factor coefficients. From the results obtained as shown in Table 2, the recommended optimal conditions from the biological pretreatment process from this study are; temperature (35^0C), pH (7.3), retention time (32 days), total solids (8.2 g/Kg) and volatile solids (9.6 g/Kg), because these conditions all produced 0.87912 L/KgVS of biogas yield as the highest quantity of biogas generated from the process.

3.2 Optimization of Results from Chemical Pretreatment with Poultry Dung Samples

The optimization results obtained from the chemical pretreatment with poultry dung samples are all presented in Tables 4, 5 and 6, and Figure 11 to Figure 20 accordingly. From the results obtained, the Model F-value of 7.92 showed that the model is significant and that there is only a 0.03% chance that an F-value this large could occur due to noise. Also, P-values less than 0.0500 indicated that model terms are significant and in this case, A, D and E are the significant model terms. This is because values greater than 0.1000 often mean that the model terms are not significant and if there are many insignificant model terms, model reduction may be used to improve the model.

Table 4: Design factors information for design expert for chemical pretreatment with poultry dung substrates

Factor	Name	Units	Type	Minimum	Maximum	Coded Low	Coded High	Mean	Std. Dev.
A	Temp	degree	Numeric	35.00	35.10	-1 ↔ 35.00	+1 ↔ 35.10	35.05	0.0447

B	pH		Numeric	8.15	8.19	-1 ↔ 8.15	+1 ↔ 8.19	8.17	0.0171
C	Retention Time	Days	Numeric	30.00	32.00	-1 ↔ 30.00	+1 ↔ 32.00	30.99	0.8748
D	Tot. Solids	g/Kg	Numeric	4.00	12.00	-1 ↔ 4.00	+1 ↔ 12.00	8.40	3.52
E	Vol. Solids	g/Kg	Numeric	4.00	12.00	-1 ↔ 4.00	+1 ↔ 12.00	8.14	3.49

Table 5: Design layout information for design expert for chemical pretreatment with poultry dung substrates

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Response 1
Run	A:Temp	B:pH	C:Retention Time	D: Tot. Solids	E:Vol. Solids	Biogas Yield
	degree		Days	g/Kg	g/Kg	L/KgTS
1	35.011	8.19	30.4251	12	5.6	0.71632
2	35	8.15	30.1	6.07607	12	0.74888
3	35	8.19	30.4873	12	12	0.78144
4	35.0425	8.15	31.14	10.4	7.44	0.814
5	35.095	8.19	32	4	6	0.84656
6	35.1	8.173	31.01	8.56	8.56	0.87912
7	35.0493	8.173	30	8.64	8.6	0.91168
8	35	8.15	30	4.24	4.2	0.92796
9	35.1	8.19	30	4	12	0.94424
10	35	8.152	32	4.44	4.52	0.96052
11	35.0955	8.1598	32	12	4	0.9768
12	35	8.19	32	12	6.4	0.71632
13	35	8.1626	32	12	12	0.74888
14	35	8.19	32	6.4405	12	0.78144
15	35.1	8.16	31.8	12	12	0.814
16	35.076	8.19	32	12	12	0.84656
17	35.095	8.15	32	6	12	0.87912

18	35.1	8.19	30	12	4	0.91168
19	35.0435	8.1818	31.15	7.44	4	0.92796
20	35.0425	8.167	31.12	4	10.4	0.94424
21	35.1	8.15	30	4	4	0.96052
22	35.1	8.151	32	4.16	4	0.9768
23	35.012	8.1588	30.36	12	11.88	0.71632
24	35	8.16	30.1	12	4	0.74888
25	35.1	8.15	30	12	12	0.78144
26	35	8.19	30.0982	4	5.94287	0.814

Table 6: Response 1: Biogas yield on chemical pretreatment with poultry dung substrates of the ANOVA for linear model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.1316	5	0.0263	7.92	0.0003	Significant
A-Temp	0.0451	1	0.0451	13.58	0.0015	
B-pH	0.0011	1	0.0011	0.3363	0.5685	
C-Retention Time	0.0007	1	0.0007	0.2091	0.6524	
D-Tot. Solids	0.0392	1	0.0392	11.80	0.0026	
E-Vol. Solids	0.0193	1	0.0193	5.80	0.0258	
Residual	0.0665	20	0.0033			
Cor Total	0.1981	25				

Furthermore, the predicted R^2 of 0.4153 as shown in Table 7 was in reasonable agreement with the adjusted R^2 of 0.5806; meaning that the difference was less than 0.2. Also, the adequate precision is used to measure the signal to noise ratio and in practice, a ratio greater than 4 is desirable. Therefore, the ratio of 9.986 obtained indicated an adequate signal and as such, this model is acceptable for the navigation of the design space. The equation in terms of the coded factors was used to make predictions about the response for given levels of each factor. By default, the high levels of the factors were coded as +1 and the low levels were coded as -1.

Table 7: Adjusted and predicted values of values
Fit Statistics

Std. Dev.	0.0576	R^2	0.6645
Mean	0.8491	Adjusted R^2	0.5806
C.V. %	6.79	Predicted R^2	0.4153
		Adequate Precision	9.9861

Also, the coded equation was also used for identifying the relative impacts of the factors through the comparison of the factor coefficients. Therefore, the recommended optimal operating conditions from this study as shown in 5 for the chemical pretreatment process are; temperature (35^0C), pH (8.15), retention time (32 days), total solids (4.16 g/Kg) and volatile solids (4 g/Kg), because the conditions all produced 0.9768 L/KgTS, which happened to be the highest quantity of biogas generated from the process.

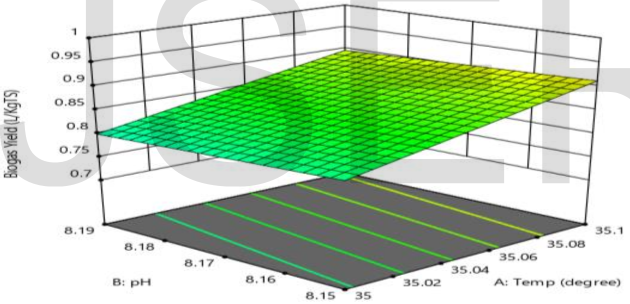

Figure 11: The curvatures' nature of 3D surfaces plots for pH and temperature for chemical pretreatment process

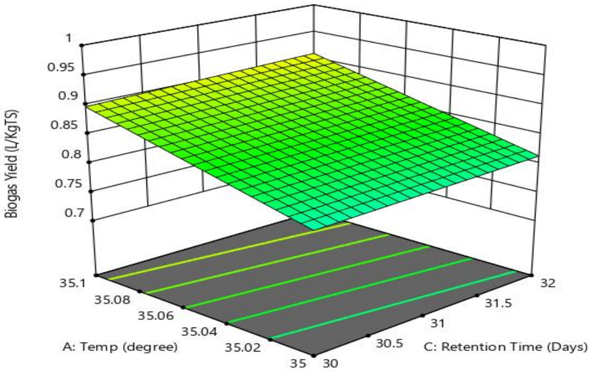

Figure 12: The curvatures' nature of 3D surfaces plots for temperature and retention time for chemical pretreatment process

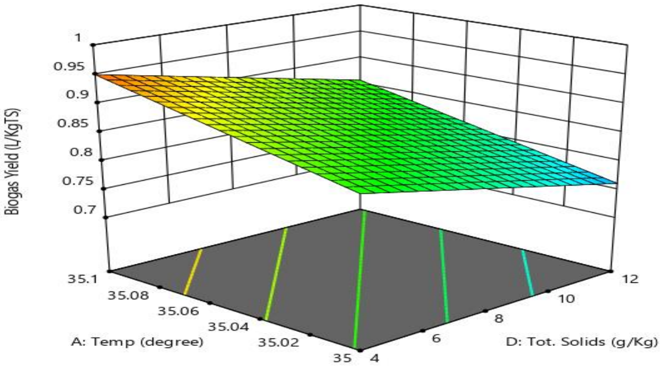

Figure 13: The curvatures' nature of 3D surfaces plots for temperature and total solids for chemical pretreatment process

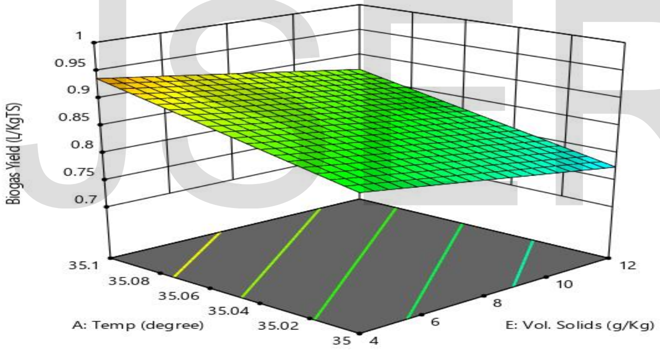

Figure 14: The curvatures' nature of 3D surfaces plots for temperature and volatile solids for chemical pretreatment process

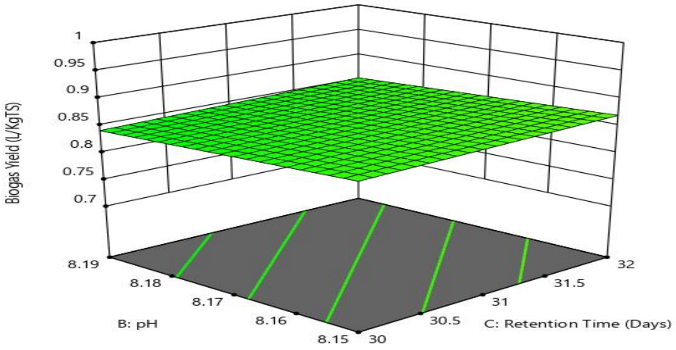

Figure 15: The curvatures' nature of 3D surfaces plots for pH and retention time for chemical pretreatment process

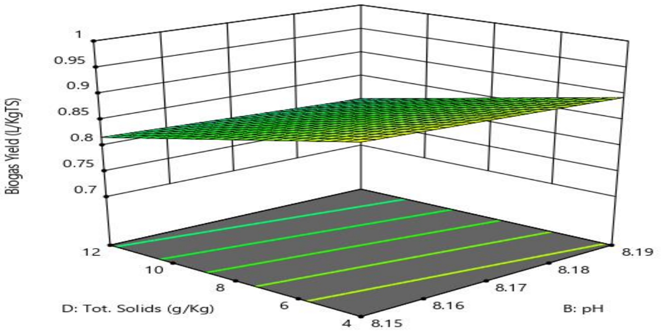

Figure 16: The curvatures' nature of 3D surfaces plots for total solids and pH for chemical pretreatment process

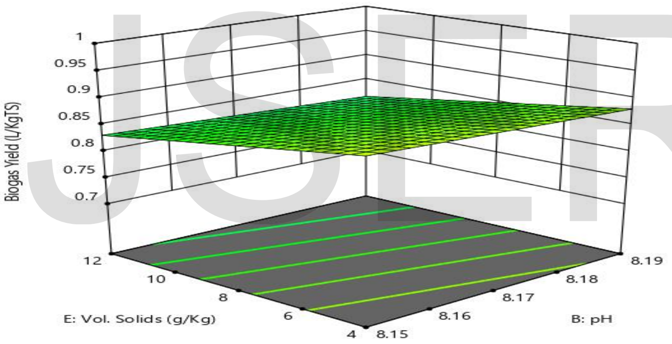

Figure 17: The curvatures' nature of 3D surfaces plots for volatile solids and pH for chemical pretreatment process

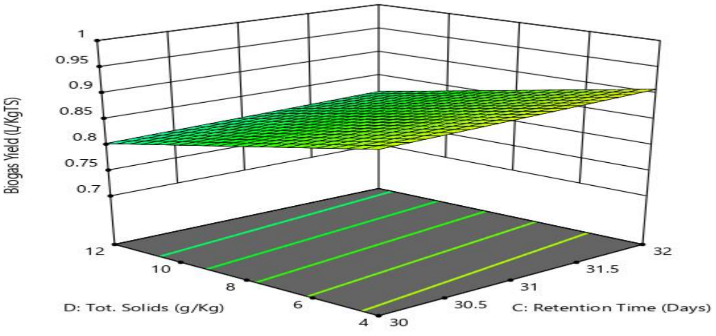

Figure 18: The curvatures' nature of 3D surfaces plots for total solids and retention time for chemical pretreatment process

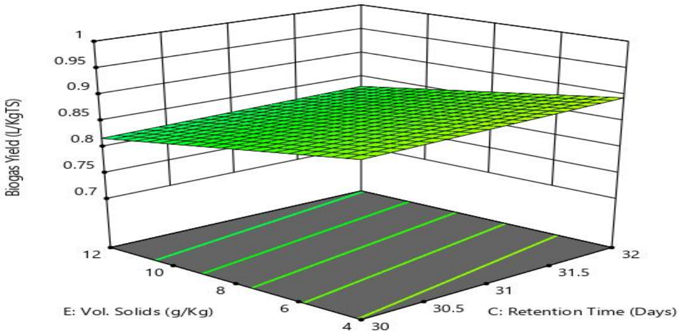

Figure 19: The curvatures' nature of 3D surfaces plots for volatile solids and retention time for chemical pretreatment process

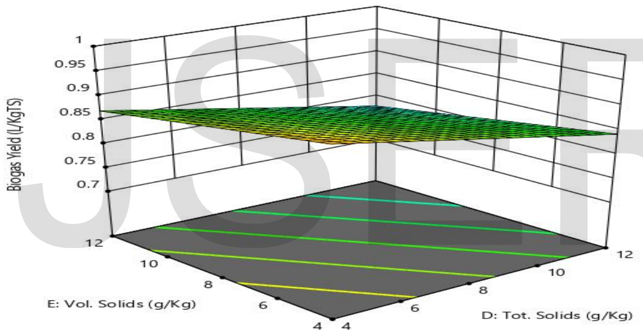

Figure 20: The curvatures' nature of 3D surfaces plots for volatile solids and total solids for chemical pretreatment process

Furthermore, the coded equation was also used for identifying the relative impacts of the factors through the comparison of the factor coefficients. Therefore, the recommended optimal operating conditions from this study as shown in 5 for the chemical pretreatment process are; temperature (35^0C), pH (8.15), retention time (32 days), total solids (4.16 g/Kg) and volatile solids (4 g/Kg), because the conditions all produced 0.9768 L/KgTS, which happened to be the highest quantity of biogas generated from the process.

4. CONCLUSIONS

The selected operating conditions such as pH, temperature, total solids, volatile solids and retention time had significant cumulative effects on the eventual biogas yield for both the biological and chemical pretreatment processes. Also, the biogas yield was significant because of the model F-value of 38.50 and that the P-values was less than 0.0500 for A, C, AB, AC, AE, BE, CD, CE, B^2, D^2, E^2 respectively for the biological pretreatment process. Again, for the chemical pretreatment process, the biogas yield was significant because of the model F-value of 7.92 and that the P-values was less than 0.0500 for A, D, E respectively. Further work should consider the use of other locally sourced organic materials as substrates which can also enhance bacteria and microbial growth, while ultimately improving biogas production. Also, further work should consider investigating the costs-benefits analysis of biogas production in developing countries, in comparison with the conventional liquefied petroleum gas.

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