JOURNAL OF BIOMEDICAL RESEARCH & CLINICAL PRACTICE

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Original Article

Optimisation of Biogas Production through Variation of PH, Detention Time and Ratio of Substrate to Water for Rural Utilization

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ABSTRACT

A response surface methodology (RSM) was utilized in this study for optimisation of biogas production process. The optimal values of process parameter capable of giving a high yield of biogas were established. A biodigester of 20 liters capacity capable of producing biogas from rural household domestic waste was designed, constructed and used in the study. Its major units are the anaerobic and gas collecting units. The process parameters investigated are the pH of the substrate, detention time and ratio of substrate to water while the yield of biogas was used as performance characteristics. The experiment was based on a central composite rotatable design (CCRD). The results revealed that the highest yield of biogas was obtained from a combination of detention time of 30 days, ratio of substrate to water of 1:1 and pH of 7, while the least yield of biogas of 11 cm3 was obtained from combination of detention time of 30 days, ratio of substrate to water of 1:3 and pH of 2. Numerical optimization carried out with the goal of maximizing the biogas of 771.77 cm3 with the desirability of 0.9850. The detention time had the highest significant effects on the yield of biogas. The results of this study provided standard input process variables capable of yielding the optimum yield of biogas for the rural community.

Keywords: Biogas, Domestic waste, Optimisation, Response surface methodology

INTRODUCTION

Energy plays an important role in the socio-economic development of many Countries. It is widely recognized that energy is linked in various ways in reducing poverty, improving human well-being and living standards. The demand of energy requirement is directly proportional to the development and population growth rate of a country.¹ Basically energy is available in the form of renewable and nonrenewable energy. The non-renewable energy is from sources that cannot be replenished. Most non-renewable energy sources are fossil fuels: coal, petroleum, and natural gas. Fossil fuels especially petroleum is the most used form of energy in most 2018 Journal Impact Factor: 1.10 Print ISSN: 2636-7378 | Online ISSN: 2651-5865

developing countries. The major concern about this source of energy are its limited nature and negative impacts on the environment, with a particular focus on the global climate change that is caused by increasing concentrations of greenhouses gases. The development of an alternative energy source has being in the forefront of research and renewable energy source was identified as one of them.² Renewable energy sources are energy sources that are constantly being replenished, such as sunlight, wind, water and biomass.

This form of energy has infinite sustainability. It is clean and produces little or no greenhouse and net carbon emissions. It does not deplete natural resources and have minimal, if any, adverse effect on the environment. It is reliable, cheaper and more economically sound than other sources of generated energy. In recent years, biogas a renewable source of energy has been receiving increasing attention as an alternative to fossil fuels in solving the problems of rising energy prices, waste management and creating a sustainable development.³ Biogas refers to a mixture of different gases produced by the breakdown of organic matter in the absence of oxygen. Biogas can be produced from raw materials such as agricultural waste, manure, municipal waste, plant material, sewage, green waste or food waste. Biogas technology plays an important role in producing energy from renewable energy.⁴ In the rural areas of Nigeria, fire wood is the form of energy source used for preparation of food. It is in the form of logs and branches from trees.

Firewood (fuel wood) is defined by the Food and Agriculture Organization of the United Nations (FAO) as "wood in the rough (from trunks and branches of trees) to be used as fuel for purposes such as cooking, heating or power production.⁵ The burning of firewood has a negative impact on health due to high emissions of gases, such as respiratory, heart diseases, lung cancer, and eye irritations.⁶ Therefore biogas technology was considered as an alternative source of renewable energy, capable of producing clean resources, in addition to its applicability in management of organic waste from the industry and household sectors.⁴ Furthermore, it is a flexible form of renewable energy that can produce heat, electricity and is commonly used for cooking, lighting and serves as fuel for vehicle.⁷ Therefore, this study focused on optimisation of biogas production through variation of pH, detention time and ratio of substrate to water, for rural utilization.

MATERIALS AND METHODS

Collection and Processing of Samples

The substrates used in this study were domestic household wastes which include: carbohydrate food wastes (yam peels and products, potato peels, cassava peels products, corn cobs and corn products), leafy vegetables and orange peels as well as fat and protein rich food wastes(beans and beans products, egg shells, fish crumps, ground nut shells). These were from Ndawangwa village in Lavun Local Government Area of Niger State, Nigeria. To collect the domestic household wastes ten (10) clean waste bags were distributed to ten (10) households for a period of one month. The waste bags were collected and emptied into two clean waste containers in the village. All the samples collected were transported to the laboratory and airdried at room temperature $(28 \pm 2^{\circ}C)$ for seven days, pounded using a clean mortar and pestle, kept in air-tight containers for further processing.

Equipment

A 20 liters capacity biodigester capable of producing biogas from household domestic waste was designed and constructed using metallic chaka plate. The digester consists of anaerobic chamber and gas collecting chamber. In between the two chambers is a narrow passage which allows the flow of gas from anaerobic chamber to gas chamber. A short valve of 10 mm diameter conveyed the gas from gas chamber to element for burning. In between the burner and gas chamber was a knob which served to regulate the biogas flow as shown in Plate 1.^{8,9,10}



Plate 1: Biogas production design for rural communities

Experimental setup and plan

A Response Surface Methodology was employed in this study using central composite rotatable design (CCRD). It consisted of three factors which were varied at five levels (Gana et al. 2018). The CCRD consisted of 20 experimental runs (2k + 2k + m, where k is the number of factors and m the number of replicated centre points), comprised of eight factorial points (2k), six axial points (2k), and six replicated centre points (m = 6). The k is the number of independent variables and the axial points have $\alpha = 1.68$. Results from previous research were used to establish a centre point of the CCRD for each factor.^{11, 12}
 Table 1: Matrix Transformation of Five Level- Three Factors Central Composite

 Rotatable Design of the Experiment

| Standard Order | Run Order | Detention Time (day) | Ratio of Substrate to Water | рН | Yield of biogas |
|-------------------|--------------|-------------------------|-----------------------------------|----|--------------------|
| 10 | 1 | 47 | 1:3 | 7 | 642 |
| 17 | 2 | 30 | 1:3 | 7 | 654 |
| 19 | 3 | 30 | 1:3 | 7 | 482 |
| 16 | 4 | 30 | 1:3 | 7 | 570 |
| 11 | 5 | 30 | 1:1 | 7 | 783 |
| 18 | 6 | 30 | 1:3 | 7 | 511 |
| 20 | 7 | 30 | 1:3 | 7 | 510 |
| 4 | 8 | 40 | 1:4 | 4 | 212 |
| 7 | 9 | 20 | 1:4 | 10 | 148 |
| 9 | 10 | 13 | 1:3 | 7 | 218 |
| 6 | 11 | 40 | 1:2 | 10 | 512 |
| 15 | 12 | 30 | 1:3 | 7 | 412 |
| 14 | 13 | 30 | 1:3 | 12 | 34 |
| 2 | 14 | 40 | 1:2 | 4 | 571 |
| 5 | 15 | 20 | 1:2 | 10 | 143 |
| 13 | 16 | 30 | 1:3 | 2 | 11 |
| 1 | 17 | 20 | 1:2 | 4 | 254 |
| 3 | 18 | 20 | 4 | 4 | 112 |
| 8 | 19 | 40 | 4 | 10 | 243 |
| 12 | 20 | 30 | 1:5 | 7 | 242 |

Key: pH = *Hydrogen ion Concentration*

The three factors (process parameters) are detention time, ratio of substrate to water and pH of the substrate. The detention time was varied at 13, 20, 30, 40 and 47 days, ratio of substrate to water was varied at ratio of 1:1, 1:2, 1:3, 1:4 and 1:5. The pH was varied at2, 4, 7, 10 and 14 respectively. The experiment was conducted based on the design matrix shown in Table 1. The process parameters were the independent variables while the yield of biogas was the dependent variable (response).

Experimental procedure

The performance of digester and yield of gas was evaluated in accordance with standard method and procedure described by Nnabuchi *et al*¹³ and Theresia and Priadi.¹⁴ Twenty samples of ten kilograms (10 kg) of waste each were prepared. The samples were used to prepared slurry by adding specific amount of water as shown in Table 1. The pH of the samples was varied as in Table 1 with the help of 0.1 M sodium

hydroxide buffer solution. Each of the samples was loaded into the digester and seeded with three 3 kg portions of starter culture (digest of the laboratory digester). The retention time was also varied as in Table 1 and the experiment was carried out under room temperature (28.5 ± 2) . The biogas readings were taken using a sensitive hanging weighing balance. This was done by taking the difference between the weight of biodigester with the substrate and weight of the biodigester with substrate and biogas.

The effects of biogas production parameters such as detention time, ratio of substrate to water and pH of the substrate on yield of biogas were investigated. The results of the experiment were analysed and optimum production parameters capable of yielding maximum biogas were established.

Optimisation Analysis

Optimisation is the process of finding the best substrate and production parameters for a system or operation. The main purpose of optimisation is to achieve optimum conditions for the operation of a system or biodigester plant in producing biogas. In this study, the optimisation analysis of the independent variables and the dependent variable were carried out using the numerical technique in Design expert software as reported by Aworanti *et al.*¹⁵ and Gana *et al.*¹⁶ who studied the development and testing of an automated grain drink processing machine.

Statistical analysis

Design expert software package (version 7.0.0) was used for the regression and graphical analysis. A quadratic polynomial equation was developed to predict the response as a function of independent variables and their interaction. In general, the response for the quadratic polynomials is described below as reported by Aworanti *et al.*¹⁵

$$Y = f (D, R, P)$$
(1)

$$Y = \beta_o + \beta_1 D + \beta_2 R + \beta_3 P$$
(2)

Where $\beta_{0,} \beta_{1,} \beta_{2,} \beta_{3}$ are the coefficients to be estimated, D, R and P, are the constraints or independent variables and Y are the objective functions (dependent variables). Analysis of variance (ANOVA) was carried out to estimate the effects of main variables and their potential interaction effects on the yield of the biogas.

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RESULTS

Effects of production Parameters on Biogas Yield

The digester production parameters investigated in this study were detention time, ratio of substrate to water and pH of the substrate. The relationship between the independent variables; detention time, ratio of substrate to water, pH of the substrate with the yield of the biogas is presented in Table 1. The results revealed that the yield of biogas ranged between 11 cm³ and 783cm³. The highest value of 783cm³ was obtained from combination of detention time of 30days, ratio of substrate to water of 1:1 and pH of 7, while the least yield of biogas of 11 cm³ was obtained from combination of detention time of 30days, ratio of substrate to water of 1:3 and pH of 2.

The result of the statistical analysis of variance (ANOVA) of the experiment (Table 2) showed that the model terms were significant. The significant model terms were identified at 95% significance level. The Quadratic regression model equation developed to predict the yield of biogas with respect to process parameters (independent variables) is shown in equations3 and 4. The results of the data ANOVA analysis in Table 2 showed the model equation was significant ($P \le 0.0001$) implied that there were only 0.01 possibilities that a big Model F value of 17.97 might occur as result of noise. The results further indicated that the detention time and ratio of substrate to water were significant Model terms (P < 0.05). It can be clearly observed that A (detention time) has the highest significant effects on the yield of biogas with value of coefficient of estimate of 116.72. Also, the lack of fit F-value of 0.64 means that it is insignificant relative to pure error. There was 68.16% possibility that F-value was unfit. This big value might occur as a result of noise. Insignificant of unfit value is good because if it is significant then the model equation will not be able to predict the response.^{15, 16}

The coefficient of determination R value of 0.9705 indicated that the Model equation was capable of predicting about 97.05% of the differences between the predicted and experimental values. Therefore, the Model was not capable to account for only 2.95% of the variation. The coefficient of correlation R – Square value of 0.9418 was high very close to 1 as recommended by Xin and Saka.¹⁷ But the author further reported that large value of R² does not always suggest that regression model equation is a good one because it will

increase when a variable is added even though the new variable is of significant or otherwise.

Table 2: Regressional Analysis of Response of Biogas Yield

| | Coefficien | Standard | F | p-value | R-Squar | red |
|-------------|------------|----------|---------|----------|---------|-----------------|
| Source | Estimate | Error | Value | Prob F | Value | |
| Model | 524.5844 | 30.3183 | 17.97 | <.0001 | 0.9418 | Significant |
| A-DT | 116.7238 | 20.1155 | 33.6710 | 0.0002 | | |
| B-AS | -122.638 | 20.1155 | 37.1696 | 0.0001 | | |
| C-pH | -10.867 | 20.1155 | 0.2918 | 0.6009 | | |
| AB | -61.375 | 26.2821 | 5.4533 | 0.0417 | | |
| AC | 5.875 | 26.2821 | 0.0499 | 0.8276 | | |
| BC | 29.625 | 26.2821 | 1.2705 | 0.2860 | | |
| A^2 | -42.2049 | 19.5819 | 4.6453 | 0.0566 | | |
| B^2 | -13.0368 | 19.5819 | 0.4432 | 0.5206 | | |
| C^2 | -177.439 | 19.5819 | 82.1086 | < 0.0001 | | |
| Lack of Fit | | | 0.6405 | 0.6816 | | not significant |

Note: A-DT = Detention Time (Days), AS = Ratio of substrate to water, pH = pH of the substrate

Hence, adjusted and predicted R^2 were suggested to be used to test the model adequacy. Based on that it was observed that the predicted R – square and Adjusted R – square values were in logical conformity with each other, the value of 0.7759 and 0.8894 respectively.

This means that experimental data were well fitted. All these pointed out that the model is adequately well fitted and thus, might predict the effects of the independent variables on the yield of biogas up to nearly 97%. Model precision measures the ratio of signal to noise and minimum value of 4 was reported by Salam *et al.*¹⁸ as desirable value. The value model precision of 13.12 obtained means adequate signal, thus the model equation can be employed to navigate the design area.

The Quadratic regression model and fitted model equations developed to predict the yield of biogas with respect to biogas production parameters (independent variables) were given as shown in equations 3 and 4.

$$\begin{split} Y_B &= 524.58 + 116.72A - 122.64B - 10.87C - 61.37AB + 5.88AC + \\ 29.63BC - 42.20A^2 - 13.04B^2 - 177.44C^2 \quad (3) \end{split}$$

 Y_B = the Yield of Biogas (cm³), A= Detention Time (Days), B = Ratio of substrate to water, C= pH of the substrate. The developed equations contain both significant and insignificant terms. Model terms with p – value greater than 0.5000 were not

significant model terms (that is C, AC, BC, A^2 , B^2 were not significant) and since these terms were insignificant.

The fitted model is presented in equation 2 as reported by Gana *et al.*¹⁸

$$Y_{\rm B} = 524.58 + 116.72A - 122.64B - 61.37AB - 177.44C^2$$
 (4)

It is important to add that the variable A(detention time) in the fitted model has positive co-efficient implying a direct proportionality, while B (ratio of substrate to water) has negative co-efficient implying an indirect proportionality. That is independent increase in A increase the biogas yield while in B decreased the biogas yield.

The Response Surface and Contour Plot for the Yield of Biogas with respect to Detention Time and pH of the Substrate

The response surface and contour plot for yield of biogas with respect to detention time and pH of the substrate are presented in Figures 1 and 2 respectively. The yield of biogas increased significantly (P \leq 0.05) from 150 cm³ to 497 cm³ as the detention time increased from 20 days to 40 days at the pH 2. Also, at pH 7, the yield of the biogas increased significantly (P ≤ 0.05) from 345 cm³ to 610 cm³ with increase in detention time from 20 days to 40 days. This indicated increase in biogas yield with increase in detention time. On the other hand, at the 20 days detention time the yield increased significantly (P \leq 0.05) from 187 to 345 cm^3 with increase in pH from 4 (acidic) to 7 (neutral) and then further decreased to 182 cm³ with further increase in the pH up to pH 10. In addition, at the detention time of 40 days, the yield increased from 400 cm³ to 600 cm³ with increase in pH from 4 to 7 and then decreased with further increase in pH.

This contrasted the study conducted by Rabah *et al.*²⁰ and Otun *et al.*²¹ who observed a decrease in pH but increase in detention time which is in conformity with the present study. The gradual reduction in pH might be attributable to gradual change of state of generation of biogas, from hydrolysis to acidogenesis in which the slurry becomes more acidic and forms substrate that was acted on by methanogenic bacteria to produce biogas. The present findings conform to the report of Gerardi²² which recommended that the pH of anaerobic digester should be maintained between 6 and 8; otherwise, the growth of methanogenes will be seriously inhibited. The longer period of inactivity might also be due to inability of the substrate to

decompose faster due to lignocellulosic substances which implies low biogas yield.²³ The significant increase in biogas yield ($p \le 0.05$) with increase in detention time agrees with the report of Sambo *et al.*²⁴



Figure 1: Response Surface and Contour Plot for the Yield of Biogas with respect to Detention Time and pH of the Substrate



Figure 2: Contour Plot for Yield of Biogas with respect to Detention Time and pH of the Substrate

The Response Surface and Contour Plot for the Yield of Biogas with respect to Ratio of substrate to water and pH

The response surface and contour plot for yield of biogas with respect to ratio of substrate to water and pH of the substrate are presented in Figures 3 and 4 respectively. The yield of biogas decreased significantly ($P \le 0.05$) from 410 cm³ to 220 cm³ as the ratio of water increased from 2 to 4. On the other hand, the yield increased significantly ($P \le 0.05$) from 400 cm³ to 605 cm³ as the pH increased from 4 to 7 and then decreased to 410 cm³ with further increase in pH up to pH 10. This is in lined with the findings of Iyagba *et al.*²³ The water content for each sample should be determined using the recommendation that

total solid is 8% in the fermentation slurry. This was the basis for the determination of the amount of water to be added to any given mass of total solid.²³The present study contrasts that of Chomini *et al.*²⁵ in the aspect of ratio of substrate to water in their work where ratio of 1:3 w/v was used against the ratio of 1:1 w/v.



Figure 3: Response Surface and Contour Plot for the Yield of Biogas with respect to Ratio of Substrate to Water used and pH of the Substrate



Figure 4: Contour Plot for the Yield of Biogas with respect to Ratio of Substrate to water used and pH of the Substrate.

The Response Surface and Contour Plot for the Yield of Biogas with respect to Ratio of substrate to water and Detention Time

The response surface and contour plot for yield of biogas with respect to ratio of substrate to water and detention time is presented in Figures 5 and 6 respectively. The yield of biogas decreased significantly ($P \le 0.05$) from 400 cm³ to 280 cm³ as the ratio of water increased from 2 to 4. On the other hand the yield increased significantly ($P \le 0.05$) from 400 cm³ to 750 cm³ as the detention time increased from 20 days to 40 days.

This agrees with the report of Asikong *et al.*¹⁹ and Rabah *et al.*²⁰



Figure 5: Response surface and Contour Plot for Yield of Biogas with respect to Detention Time and Ratio of Water used



Figure 6: Contour Plot for the Yield of Biogas with respect to detention time and Ratio of Water used

Optimisation of Biodigester Performance and Biogas Yield parameters

Numerical optimisation was performed to maximise the yield of biogas. By employing the desirability function method in RSM, 8 solutions were obtained for the best covering criteria with desirability value close to 1. In this case, first solution was selected as good desirability for maximum yield of gas with desirability of 0.9850 which was closest to 1 as shown in Figure 7



Figure 7: Bar Graph for Optimisation Desirability

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Ramp for the Optimization

The ramp for the optimisation is shown in Figure 8; it gave the optimum values of detention time of 40 days, ratio of substrate to water used; 1:2 and pH of 6.71 for biogas yield of 771.77 cm^3 and desirability of 0.9850.



Desirability = 0.9850

Figure 8: Ramp for Optimisation of biodigester Performance and biogas yield Parameters

CONCLUSION

The effects of process parameters of biogas production on biogas yield were studied and major conclusion were as follows: the yield of biogas increased from 150 cm^3 to 497 cm^3 as the detention time increased from 20 days to 40 days at the pH 2. The yield of biogas decreased from 410 cm^3 to 220 cm^3 as the ratio of water increased from 2 to 4. Also the yield increased from 400 cm^3 to 605 cm^3 as the pH increased from 4 to 7 and then decreased to 410 cm^3 with further increase in pH up to pH 10.Optimum values of values of detention time of 40 days, ratio of substrate to water used; 1:2 and pH of 6.71 for biogas yield of 771.77 cm^3 with a desirability of 0.9850.

RECOMMENDATIONS

We recommend that other household domestic waste not used in this study should be harnessed for biogas production, government and other relevant bodies should embark on and encourage more researches in rural biogas technology, adopt and commercialize small scale digesters to serve as means of producing and providing cooking gas for rural dwellers. This will go a long way to reduce the demand for wood from the forest and the impact of green house gas emission in Nigeria. Biogas production should be optimised through other variables or physicochemical parameters not used in this research.

Conflict of Interest

None declared

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