Optimization of Biogas Production from Municipal Solid Waste Using Response Surface Methodology

[1]Onah, O. Thomas, [2]Nwankwo M. Azubuike [3]Aka C. Christian
[13]Mechanical Engineering Department, Enugu State University of Science and Technology, Enugu
[2]Works and Engineering Services Department, Federal Polytechnic, Oko, Anambra

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ABSTRACT: *This study investigated the development and simulation of CSTR for biogas production from municipal solid waste. The factors affecting biogas production studied were pH, retention time and organic loading rate. Optimization of the parameters were done using Minitab and desirability optimization function shows that percentage error between predicted optimal responses and actual optimal responses is less than 2%, making the desirability function adequate in optimizing the factors affecting the yield of biogas from MSW. Under the process of continuous stirring of the Bio-digester tank and optimization of the process conditions, the digestion of the substrates subjected at different process parameters with these conditions averagely gave biogas yield of 67.588mL biogas/mg. This showed an increase in the production of Bio-gas.*

KEYWORDS: optimization, biogas production, response surface methodology, municipal solid waste, continuous stir tank reactor

INTRODUCTION

A bioreactor refers to any manufactured or engineered device or system that supports a biologically active environment, (James et al, 2000). It is also a vessel in which a chemical digestion or degradation process is carried out, involving organisms or biochemically active substances derived from such organisms. Many factors affect the biodegradation of organic matter. These include, but not limited to, the microbial concentration, organic content of the substrate, operating temperature, pH, mode and degree of substrate agitation, mixing/flow regimes. (Rakib, et al, 2022), When these factors are under control as in bioreactors, degradation or digestion of organic matter, it can bring about beneficial effects and products. For example, under controlled conditions, biogas and waste organic fertilizer by-products can be produced by the biological breakdown of organic matter.

The poor performance of bioreactors may be attributed to inappropriate or non-existent slurry flow dynamics. It could be implied that its effects have never been considered at the bioreactor design stage. These attendant problems of bioreactor failure and poor performance calls for further research in order to understand more clearly some of the mitigating factors with a view to proffering solutions and developing high-yield biogas plants. It is expected that the incorporation of appropriate flow regimes in the bioreactors will provide the basis for effective digestion of organic waste thereby avoiding putrefaction due to inadequate slurry mixing during digestion. Thus the operation of such bioreactors in any environment would not produce polluting effects.

However, (S. Achinas et al, 2020), report that bioreactor operating and process conditions can well be established by experimental work but with an attendant delay in project launch. He identified fluid mechanic effects as one of the critical limiting factors in the design of large-scale bioreactors. In furtherance of his study on the prediction of flow characteristics in bioreactors, he employed computer simulations using Computational Fluid Dynamics (CFD) modelling. Also, (Ogunbiyi, 2001) have shown has fluid flow and mixing in bioreactors have a significant effect on the overall performance of the systems. In their study of fluid mixing in a roller bottle bioreactor, they identified the problem of limited mixing, especially, in the axial direction and verified same computationally and experimentally. Such mixing limitations were readily overcome by introducing a small amplitude vertical rocking motion that disrupted both fluid symmetry and recirculation, leading to much faster and complete axial mixing which is a critical parameter in the performance of reactor.

Admittedly, one of the single most important limitations to high quality biogas yield is the application of appropriate flow regimes in bioreactors. Hence, purpose of this research what affects the production of biogas in a continuous stir tank.

Biogas production

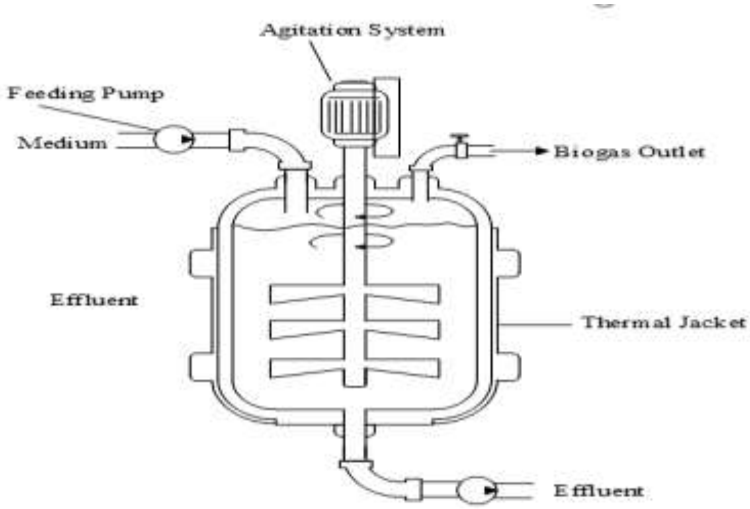

Fig. 1: Continuous Stirred Tank Reactor (CSTR)

Continuous stir tank reactor (CSTR) can be considered a closed tank reactor, usually of cylindrical configuration, with a stirring mechanism such as an impeller as shown in fig. 1 above. (Nathenial et al, 2019), in the study of boiling stirred tank reactors used multiple impeller configurations which consist of six flat blade disk turbines and six-concave blade disk turbines. (Ondiba, et al, 2017), reported that various mixing forms such as axial, radial or mixed flows can be produced by impellers. (Oyinola, 2001), reported that agitation in CSTR increases the rate of mass and heat transfer operations and provides the required degree of mixing of the reactor contents. Insufficient agitation leads to limitations in the transfer operations and appearance of regions of insufficient nutrient content or inadequate temperature or pH. As a result, the overall productivity of the reactor declines. CSTR is usually baffled in order to improve mixing. (Sinnott, 2005), reported some applications of the CSTR in waste water treatment. In his study of diary waste water treatment, the chemical oxygen demand COD removal efficiency was 60% and methane composition in the generated biogas was in the range of 22.5-76.9%. Some other successful studies have been carried out for the treatment of palm oil mill effluent POME using CSTR, (Marylee et al, 2018). In the study, CSTR registered 90% reduction in COD, with a hydraulic retention time HRT of 6days and 64% methane in the produced biogas.

Biogas is derived from the microbial degradation of organic waste stored in the absence of air; a process called anaerobic digestion and variously defined as “a biological decomposition of organic waste done in the absence of air (Agbede ete al, 2019). This is why (Shahzad et al, 2020) says anaerobic digestion is “a bioreactor in which organic matter is progressively degraded in the absence of oxygen by a process known as methanogenesis”. (Juan et al, 2014), (Bailet et al, 1986). (Spyridon et al, 2018) Explains that recently anaerobic digestion is also being applied to the treatment of municipal solid waste (MSW) and thus offers a more holistic definition when he says that anaerobic digestion is “the use of microbial organisms in the absence of oxygen, for the stabilization of organic materials by conversion to methane and inorganic products, including carbon dioxide”.

A myriad of factors affects the performance of bioreactors. A careful study and control of these factors is imperative for efficient operation of bioreactors. Some of the major factors commonly reported in literature include the following: pH (Oluka, 2001) and (Olaoye, 2001) reported that methanogenesis decreased when pH for microbial growth is between 6.8 and 7.2. pH lower than 4 or higher than 9.5 are not tolerable. Temperature is an important factor in bioreactor processing of organic materials. Microbial activities thrive in the mesophillic i.e. 30-50^{0}C or in the thermophilic i.e. 50-60^{0}C temperature ranges. (Aguwamba, 2001) and (Eze, 2004) said failure to control temperature increase can result to biomass washout and therefore bioreactor failure. Carbon/Nitrogen Ratio **(C:N Ratio)** measures the relative amounts of carbon and nitrogen in the substrate. In the absence of carbon, bacteria tend to die and deficiency of Nitrogen leaves them no means of rebuilding new cell structure, Organic Loading Rate (Olr**)** for same substrate composition and volume, the measure of chemical oxygen demand (COD) reduction by bioreactors denote the efficiency and extent of the organic material degradation process. Some studies have shown that higher OLR will reduce COD removal efficiency in waste water treatment system, (S. Achinas et al, 2020). Flow/Mixing Requirements is a very important factor in bioreactor performance. Mixing provides the needed contact between microbes and substrate, reduces resistance to mass transfer,

minimizes the build-up of inhibitory intermediate reactants and stabilizes bioreactor environment, (Ondiba, et al, 2017).
The breakdown of carbohydrates, nitrogenous compounds and fats can simply be expressed using chemical formula as follows:

$$C_6H_{12}O_6 + 2H_2O \longrightarrow 2C_2H_4O_2 + 2CO_2 + 4H_2 \quad (1)$$

From the acetic acid and hydrogen products of the above reaction, methane would be produced thus.

$$2C_2H_4O_2 \longrightarrow 2CH_4 + 2CO_2 \quad (2)$$

$$4H_2 + CO_2 \longrightarrow CH_4 + 2H_2O \quad (3)$$

When these expressions are combined, the generalized equation for the anaerobic digestion process is obtained as follows

$$\text{Organic matter} + \text{Combined water} \xrightarrow[\text{microbes}]{\text{Anaerobic}} \text{New cells} + \text{Energy for cells} + CH_4 + CO_2 + \text{Other end products}$$

Waste Defined

Generally, waste is regarded as a useless material that is unwanted and therefore discarded. This explains that waste is “anything or anyone rejected as useless, worthless, or in excess of what is required”. Hence municipal solid waste (MSW) is defined as “all waste collected by private and public authorities from domestic, commercial and some industrial (non-hazardous) sources” (Spyridon et al, 2018) and (Agbede ete al, 2019) say MSW comprises small and moderately sized solid waste items from houses, businesses, and institutions. Management of Municipal Solid Waste **l**ike many other cities in Nigeria (Ekenta, 2001), large volumes of refuse are generated on a daily basis in Port Harcourt and also improperly discarded by residents. Energy Potential of Municipal Solid Waste (Oyinola, 2001) cites the 1997 appraisal report of the Urban Development Bank of Nigeria Plc; and states that the estimated average per capita waste generation for the country is 0.45kg/day, and that for Port Harcourt metropolis is 0.33kg/day. This paper deals with the flow regime of the parameters that affects the production of bio-gas using CSTR

METHODS

Production of biogas involves use of municipal solid waste; hence this research aims at utilizing the solid wastes in Enugu east local government area of Enugu state Nigeria for the biogas. The municipal solid waste (MSW) was collected from the entire waste bins located at various strategic points in Enugu East metropolis and the chemical reagents were purchased from certified vendors in Enugu state. The laboratory work and reactor experimentation was done in Energy Research Center Nsukka, in the University of Nigeria Nsukka.

One (1) container-waste-load of total volume 0.098m^3 was collected from each waste receptacle, for designated 10 sites randomly selected throughout the Enugu East metropolis, given a total of ten (10) container-waste-loads of total volume 0.98m^3.

When the wastes were collected with the bin, they were weighed in their composite form as-discarded, and then the same mass of waste was compacted with manual compactor until the change in volume became constant. The measured wastes were then sorted into individual components on the bases of their organic and inorganic character. After the sorting, both the organic and inorganic components were measured by volume and weight, both 'as-discarded' and 'as-compacted'. The results were used in the determination of the 'as-discarded' and 'as-compacted' densities, and the "ratio of the 'as-compacted' density (ρ_c) to the 'as-discarded' density (ρ_d)) is the compaction ratio (r) (Nathenial et al, 2019), which was employed in the design of the digester for the waste.

$$r = \frac{\rho_c}{\rho_d} \tag{4}$$

About 5.00g of sample was weighed and dried in an oven at a regulated temperature of 105^{0}C. The drying sample was constantly reweighed every 10 mins interval until a constant weight was obtained. The crucible and its content was retrieved and cooled in desiccators. The difference in weight was recorded and the moisture content calculated as using equ. 5 below

$$\%\, Moisture = \frac{wt\ of\ wet\ \ sample - wt\ of\ oven\ dry\ \ sample}{wt\ of\ oven\ dry\ shell\ sample} \times \frac{100}{1} \tag{5}$$

The volatile matter content was obtained by heating 10g of moisture free sample in a muffle furnace at 900°C for one hour. Heating in the absence of air at high temperature removes the volatile matter only, its percentage was obtained using equ. 6 below.

$$\%\, Volatile\ matter\ = \frac{weight\ loss}{weight\ of\ moisture\ free\ sample} \times \frac{100}{1} \tag{6}$$

The crude fibre content was determined using equation 7 and the result was shown in Table 1

$$\%\, Crude\ fiber = \frac{Loss\ in\ weight\ on\ ignition\ (W_2 - W_1) - (W_3 - W_1)}{Weight\ of\ shell\ sample} \times \frac{100}{1} \tag{7}$$

The sample was exhaustively extracted of its lipid for 3hrs by heating the flask on an electric hot plate at a temperature of 50^{o}C. After 3hrs, the extranctant (petroleum ether) was distilled off while the flask and its content were cooled in a desiccator before reweighing. (AOAC, 1995)
The percentage lipid was calculated using equ. 8

$$\% \, Lipid(or \, fat) = \frac{weight \, of \, lipid}{weight \, of \, sample} \times \frac{100}{1} \tag{8}$$

A clean empty specific gravity bottle was weighed on an electronic balance and the mass (W_1) noted. It was then filled with the sample at the required temperature and its mass (W_2) and volume noted. The mass of sample (W_s) was the difference between W_2 and W_1. The density, ρ, was calculated using the equation:

$$Density = \frac{Mass}{Volume} \tag{9}$$

The bottle was washed, dried and filled with equal volume of water at the required temperature and the mass (W_3) was noted. The mass of water (W_w) was the difference between W_3 and W_1. The specific gravity of the sample was determined using the equation:

$$Specific \, gravity = \frac{Weight \, of \, sample}{Weight \, of \, equal \, volume \, of \, water} \tag{10}$$

That is:

$$Specific \, gravity = \frac{W_2 - W_1}{W_3 - W_1} \tag{11}$$

The energy content of the waste was determined using the equation for the estimation of the energy content of MSW, presented by (Spyridon et al, 2018) as:

$$EC = 0.051[F + 3.6(CP)] + 0.352(PLR) \tag{12}$$

Where: Ec - Energy content of MSW, MJ/kg
F - % of food by weight
CP - % of cardboard and paper by weight
PLR - % of plastic and rubber by weight

Reactor Experimentation was done at **e**nergy Research Center Nsukka laboratory. Five batch-wise anaerobic digesters each of 5 liters' volume were set up for this experiment. The schematic of the experimental design layout is as shown in Fig 2 below:

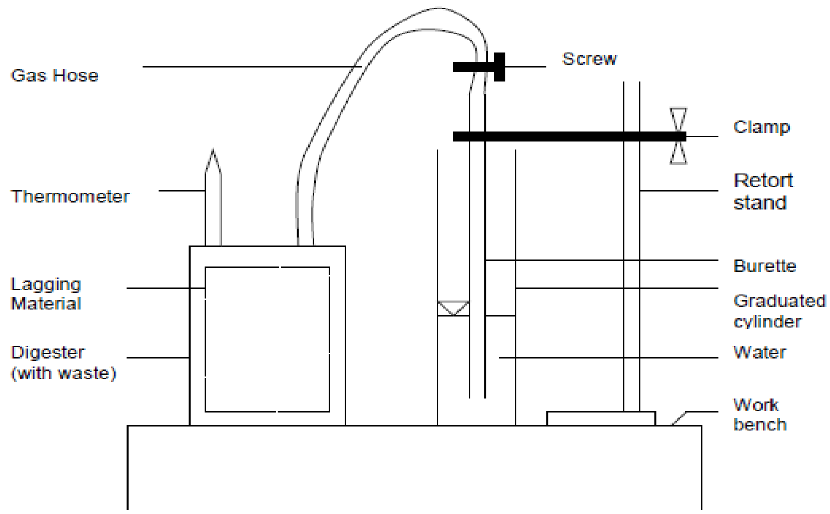

Fig. 2: Schematic of Reactor Experimentation Design Layout (Igoni et al, 2007)

Optimization of Biogas Production using Response Surface Methodology

Minitab software (version 19) two-level-three factor full factorial design, including 20 experiments was used. pH, retention time and organic loading rate were selected as independent factors for the optimization study. The response chosen was the biogas production yield obtained from anaerobic fermentation of MSW. Six replications of center points were used in order to predict a good estimation of errors and experiments were performed in a randomized order. The actual and coded levels of each factor are shown in Table 1. The coded values were designated by −1 (minimum), 0 (centre), +1 (maximum), −α and +α. Alpha is defined as a distance from the centre point which can be either inside or outside the range, with the maximum value of 2n/4, where n is the number of factors. Hereby the value of alpha is set at 0.5. It is noteworthy to point out that the software uses the concept of the coded values for the investigation of the significant terms, thus equation in coded values is used to study the effect of the variables on the response. The empirical equation is represented as shown below:

$$Y = \beta_o + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j \quad (13)$$

Selection of levels for each factor was based on the experiments performed to study the effects of process variables on the anaerobic fermentation of the substrates. The lower level of pH is 6.0 and the upper level of pH is 8.0. The levels of retention time were selected between 20 and 50 and organic loading rate was limited between 9 and 13kg respectively.

Table 1: Studied range of each factor in actual and coded form.

Factor	Units	Low level	High level	-α	+α	0 level
pH (A) x_1		6(-1)	8(+1)	5(-2)	9(+2)	7
Organic loading rate (B) x_2	kg	9(-1)	13(+1)	8(-2)	15(+2)	11
Retention time (C) x_3	days	20(-1)	50(+1)	5(-2)	65(+2)	35

The actual and coded level of each factors are shown in the table 2 below for number of runs PH values, organic loading rate and retention time for each of the levels.

Table 2: Experimental design matrix for Anaerobic Fermentation of

Run order	pH (X_1)		Organic loading rate (kg) (X_2)		Retention time (X_3)	
	Coded	Real	Coded	Real	Coded	Real
1	-1	6	-1	9	-1	20
2	+1	8	-1	9	-1	20
3	-1	6	+1	13	-1	20
4	+1	8	+1	13	-1	20
5	-1	6	-1	9	+1	50
6	+1	8	-1	9	+1	50
7	-1	6	+1	13	+1	50
8	+1	8	+1	13	+1	50
9	-2	5	0	11	0	35
10	+2	9	0	11	0	35
11	0	7	-2	8	0	35
12	0	7	+2	13	0	35
13	0	7	0	11	-2	5
14	0	7	0	11	+2	65
15	0	7	0	11	0	35
16	0	7	0	11	0	35
17	0	7	0	11	0	35
18	0	7	0	11	0	35
19	0	7	0	11	0	35
20	0	7	0	11	0	35

RESULTS AND DISCUSSION

The response surface models developed for determining the optimal value of the factors affecting the yield of biogas from MSW were optimized using graphical methods and the optimization tools of MINITAB 17, to ensure accuracy. The optimization tools of Minitab used is the data tips of contour and three dimensional (3D) surface graphs of the developed models.

Optimization using the contour and surface plots was used to estimate the optimal relationship between the response (biogas yield) and any combination of the factors as presented in Figs 3 – 5. Only statistically significant terms were considered in the plots and the topography of each plot indicates the effect each factor pair has on the response with other factors kept constant.

The effects of pH, retention time (days) and organic loading rate (kg) on biogas yield were investigated and discussed with response surface modeling and optimization technique. Both statistical analysis and experimental results revealed that the response surface models Equation (13) developed were reasonably accurate within the limits of the factors investigated.

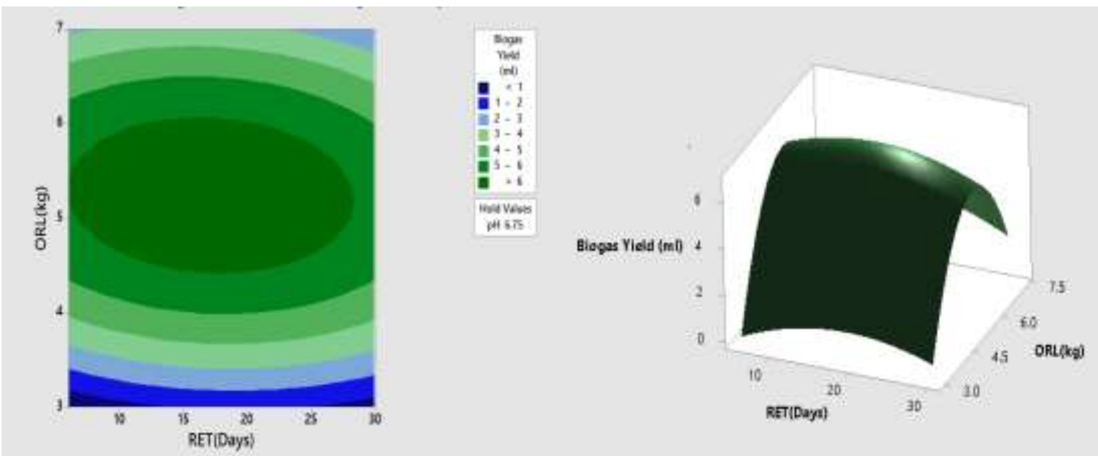

Fig 3: Response surface plot of biogas yield from MSW against RET (days) and OLR (kg)

Fig 3 shows the effect of retention time in days and organic loading rate (kg) on biogas yield from BSG. It could be observed that biogas yield increased as both retention time and organic loading rate increase but they decreased beyond 20days retention time and 5kg organic loading rate. This decrease could be attributed to near complete degradation of substrates in the digester as the retention time increases. (Igoni et al, 2007) Reported that generally, HRT varies between 20 and 120 days, depending on the design and operating temperature of the digester.

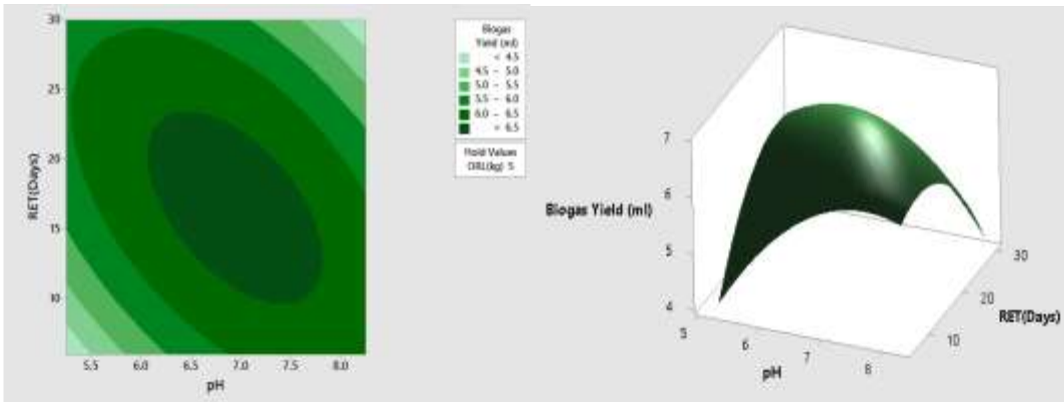

Fig 4: Response surface plot of biogas yield from MSW against RET (days) and pH

Fig 4 shows the effect of retention time in days and pH on biogas yield from MSW. It could be observed that biogas yield increased as both retention time and pH increase but they decreased beyond 20days retention time and pH of 7.5. This decrease could be attributed to complete degradation of substrates in the digester as the retention time increases and increase in pH value of the slurry due to increase in volatile fatty acid level in the digester . (Juan et al, 2014) Reported that an increase of VAFs does not only decrease the pH of the digester but also leads to a decrease in methane production.

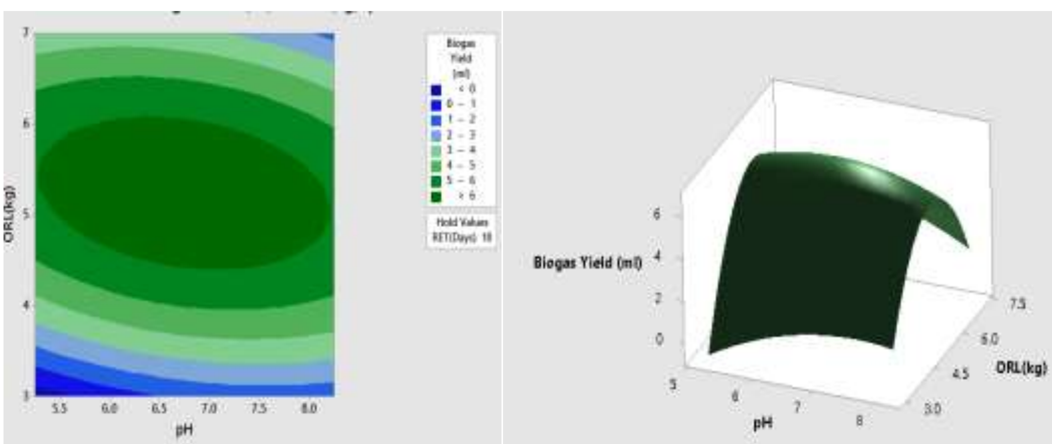

Fig 5: Response surface plot of biogas yield from MSW against pH and OLR (kg)

Fig 5 shows the effect of organic loading rate and pH on biogas yield from MSW. It could be observed that biogas yield increased as both organic loading rate and pH increases. Hence, beyond organic loading rate of 6kg and pH of 8 the yield of biogas started to decrease. This decrease could be attributed to digester over load and increase in alkalinity of the slurry.

Thus it can lead to multiplicity of optimal settings established for one response. Inspection of the contour and surface graphs revealed that for a particular response, some factor pairs are in the maximum region while others indicate minimum optimal region. The indeterminate tendency of this approach gave rise to the need to adopt a more suitable optimization approach which can define the optimal settings of the operational parameters for all the responses.

Desirability function approach eliminates the rigor associated with most other optimization techniques such as the optimization using contour and surface plots. The purpose of this research is to determine the optimum values of the factors required to maximize yield of biogas from MSW. The response optimizer capability of MINITAB 17.1 was employed for this purpose and the optimization plot is given in Fig 6.

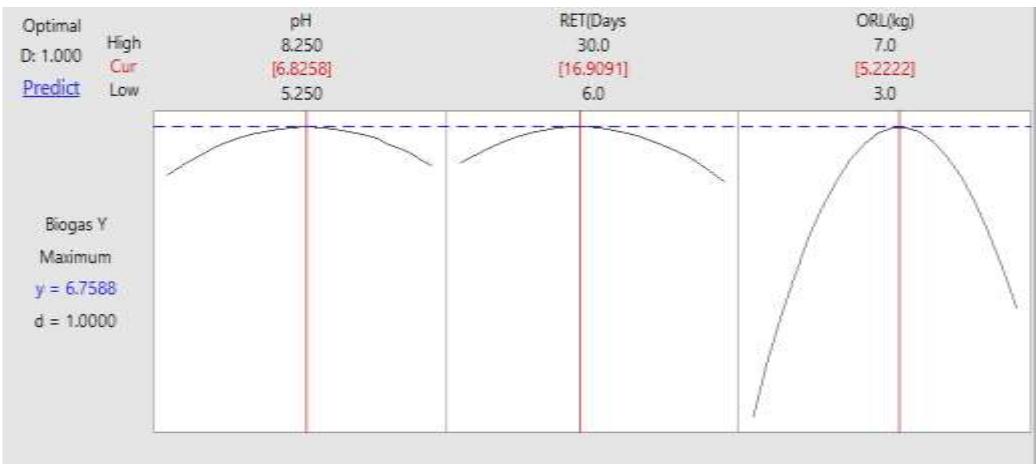

Fig 6: Desirability optimization plot of the biogas yield from MSW parameters.

The value of individual desirability and the desirability respectively approximate to 1 which signifies that the optimization result is highly desirable. Therefore, it is seen that the brewer spent grains had optimally biogas yield at the factor settings of 6.8258, 16.9091 and 5.2222 for pH, RET (days) and OLR (kg) respectively. The optimal response obtained is biogas yield of 67.588ml.

The optimal factor conditions were used to produce biogas from MSW to confirm and validate of the result as shown in Table 3. From the table, it could be observed that percentage error between predicted optimal responses and actual optimal responses is less than 2%. This shows that the desirability function was adequate in optimizing the factors affecting the yield of biogas from MSW.

Table 3: Confirmatory/validation of optimal responses

S/N	Response	Predicted optimal response	Actual optimal response	Percentage error
1	Biogas yield (ml)	67.588	62.342	±0.2588

The rate of substrate conversion to biogas is directly proportional to the substrate concentration in the anaerobic digestion process, according to a first order kinetic model. Let the substrate concentration represented as Y. The following are the kinetic equations:

$$\frac{dY}{dt} = -KY \quad (14)$$

For a batch reactor, the substrate remaining in the digester is given by integrating Eq. (14),

$$\boldsymbol{Y = Y_o e^{-k(t-t_o)}; t > t_o} \quad (15)$$

Rearranging equation (15), we have that;

$$Y/_{Y_o} = e^{-k(t-t_o)}; t > t_o \quad (\mathbf{16})$$

Rearranging by taking natural logarithm gives,

$$\ln\left(Y/_{Y_o}\right) = -kt + kt_o \quad (17)$$

Where Y is the final substrate concentration (g/l), Y_0 is the initial substrate concentration (g/l), k is the rate constant, t is the time (days) and t_o is the lag time in (days). This model describes the behaviour of an average reactor with a longer retention time.

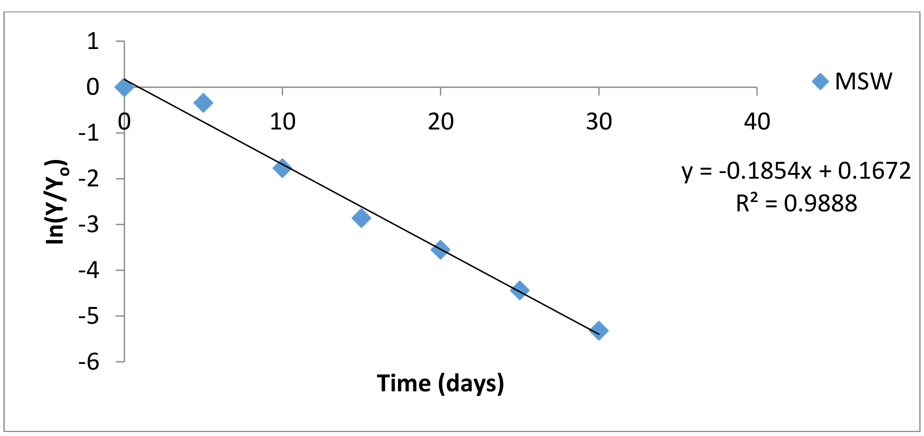

Fig 7: A plot of the natural logarithm of the ratio of initial to final substrate concentration against time, (days)

Fig 7 shows a graphical analysis of the kinetic models for data from bio-reactors including substrate of varied sizes, with $\ln\left(Y/_{Y_o}\right)$ against time plotted for each of the four reactors. Eq. 16 was used to get the rate constant and lag time. From the slope of kt and the intercept of kt_o, the rate constant and lag time can be determined from the kinetic analysis of the bio-reactors with each substrate of four different sizes. Table 4 shows the rate constant and lag time for various initial VS concentrations.

Table 4: Rate constant, correlation coefficient, predicted and observed lag time for various reactors

Feedstock	Rate Constant K	Correlation Coefficient (R^2)	Lag time t_o ((days) (Predicted)	Lag time t_o ((days) (Observed)
MSW	0.190	0.969	1.5	1.0

Fig 7 shows the result of linearizing Equ. (14) The maximum rate of utilization of the substrate is represented by the slope of the curve (k). A statistical examination of the curve using Microsoft chart editor yielded the equation explaining the curve. The values of the rate constant k for various sizes of substrate are shown in Table 4. It was discovered that as the particle size of the substrate decreases, the rate of substrate digestion by anaerobic microorganisms rises. This could be due to the substrate increased surface area for methanogenic bacteria attack. These values of k are strictly for the batch processing, and suggests that a relatively low amount of the organic matter is consumed in relation to the growth of microbes. This tends to corroborate the earlier assertion that the system was indeed self-generating in microbial content; hence only little amount of the substrate was used in the course of the digestion. It is also believed here that the large particle sizes of the control experiments, would have contributed to the low level of degradation of the waste and high value of the lag time recorded in these reactors. Therefore, in this regard, feedstock particle size reduction is likely to result in a higher 'k' value and reduction in lag time.

CONCLUSIONS

This study investigated the development and simulation of CSTR for biogas production from municipal solid waste and also presented the effect of process parameters, performance characteristics of the anaerobic digestion in batches. The stirring effect gave higher yield and this may be attributed to the distribution anaerobic microbes and temperature of the reactor of which resulted in availability of higher volatile solid for digestion. Under the optimize conditions, the digestion of the substrates subjected at different process parameters conditions averagely gave biogas yield of 67.588mL biogas/mg. Therefore, it is discovered that with the continuous stirring of the wastes in the bio- digester more gas is to be produced.

List of Abbreviations

CSTR –Continuous Stir Tank Reactor
MSW – Municipal Solid Waste
CFD – Computational Fluid Dynamics
COD – Chemical Oxygen Demand
HRT – hydraulic Retention Time
OLR – Organic Loading Rate
EC – Energy Content

CP – Cardboard and Paper
PLR – Plastics and Rubber
BSG – Biogas Yield
VAFs – Volatile Fatty Acid
RET – Retention Time

Declarations

Availability of data and materials
The datasets supporting the conclusions of this article are included within the article

Competing interests
The authors declare that they have no competing interest

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No funding was obtained for this study.

Authors' contributions
OS wrote up the manuscript **OE** and **OS** conducted the laboratory experiments. **TO** supervised the laboratory experiment and structured, edited, read, and approved the final manuscript. All authors read and approved the final manuscript.

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Authors' information
OS is currently a post graduate student, Department of Mechanical Engineering Enugu state university of science and technology, Enugu state. **TO** a lecturer, Department of Mechanical and production Engineering, Enugu state university of science and technology, Enugu state. **OE** is currently a lecturer, Department of Mechanical and production Engineering, Enugu state university of science and technology, Enugu state

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