Optimization of Biogas Production in a Batch Laboratory Digester Using Total Solids, Substrate Retention Time, and Mesophilic Temperature

Barasa H. Masinde[1*], Daudi M. Nyaanga[2], Musa R. Njue[2] and Joseph W. Matofari[3]

[1] Mechanical and Industrial Engineering Department, Masinde Muliro University of Science and Technology, P.O. Box 190 – 50100, Kakamega, KENYA.
[2] Agricultural Engineering Department, Egerton University, P.O. Box 536 – 20115, Egerton, KENYA.
[3] Dairy, Food Science and Technology, Egerton University, P.O. Box 536 – 20115, Egerton, KENYA.
Email: `he.masb62@gmail.com`

Abstract. Optimization was done by investigating the interaction effects of total solids, mesophilic temperature, and substrate retention time on biogas production in a batch biodigester. The volume of the biodigester was 0.15m^3. Central composite design of Response Surface Methodology was used to design the experiment. Total solid levels were varied from 6.31% to 9.68%, temperature was from 26.59°C to 43.41°C, and substrate retention time was from 9.95 to 20.04 days. Analysis of results was done using Design Expert software statistical package (version 10.0.0.3). It gave a coefficient of determination of 0.9665 which indicated a high correlation between the variables. All the variables had a significant effect. The highest biogas production rate of 75.41litres/day (or 0.50 m^3 of biogas per m^3 of digester volume per day, m^3/m^{3}d) was achieved at a level of 8% total solids, a temperature of 43.41°C, and a substrate retention time of 15 days.

Keywords: optimization, biogas production, total solids, mesophilic temperature, substrate retention time.

1 Introduction

Optimization is the act of achieving the best possible result under given circumstances. In design, construction and maintenance, engineers have to make decisions. The aim of such decisions is either to minimize the effort or to maximize benefit. The effort or benefit can be expressed as a function of certain design variables. Hence optimization is the process of finding conditions that give the minimum or the maximum value of a function [1]. Efforts to maximize biogas production are currently being done by using various feedstocks. Reungsang *et al* [2] used Response surface methodology (RSM) with a central composite design (CCD) to optimize the key factors affecting methane production from the acidic effluent coming from the sugarcane juice hydrogen fermentation process. The parameters studied were substrate concentration, ratio of $NaHCO_3$ to substrate concentration, and initial pH. The maximum methane yield of 367 mL CH_4/g-volatile solid (VS) added was obtained at the optimum conditions of 13,823 mg-COD/L, an $NaHCO_3$ to substrate concentration ratio of 3.09, and an initial pH of 7.07. Methane yield was enhanced 4.4-fold in comparison to raw effluent. Sathish and Vivekanadan [3] studied the optimal conditions for biogas generation from anaerobic digestion of rice straw in a 1m^3 floating drum anaerobic digester using RSM. The parameters were temperature, pH, substrate concentration, and agitation time. The highest level of biogas of 0.72m^3 was produced at an optimum temperature of 50°C, pH 7.5, substrate concentration of 110.70 kg, and an agitation time of 5 seconds, respectively. Saleh *et al* [4] investigated the effects of temperature, palm oil mill effluent (POME) volume, inoculum volume, and co-substrate addition such as oil palm empty fruit bunch (EFB) and palm kernel on the anaerobic digestion process for biogas and methane production. RSM by Box-Behnken design verified that the specific biogas production rate and methane yield were mainly affected by the operating temperature and co-substrate addition. The optimal conditions for the maximum specific biogas production rate (0.0574 m^3/ kg chemical oxygen demand per day) and methane yield (25.6%) were predicted by multiple response optimization and verified experimentally at 47.8°C operating temperature, 50.4 mL POME volume, and 5.7 g EFB addition. Other similar works have been reported by Pannucharoenwong[5] among others.

Response surface methodology (RSM) is one of the most effective approaches for designing experiments, for building models, and for determining optimal conditions on responses which are influenced by several independent variables [6-9]. Apart from defining the influences of independent variables on the responses, RSM also determines the effect of interaction between parameters to obtain the best performance on a system [10, 11]. Experiments designed by using RSM have fewer runs, and also give similar results which are comparable to a full-factorial design, and enables an effective evaluation of interaction between individual factors to provide the best combination for optimal performance [12, 13]. RSM is a collection of statistical and mathematical techniques used for developing, improving, and optimizing processes [14]. The most extensive applications of RSM are in situations where several input variables potentially influence some performance measure or quality characteristic of a process; most applications of RSM are sequential in nature, and are performed within some region of the independent variable space called the operability region [15]. RSM is robust; it makes the process consistent on target, and is relatively insensitive to factors that are difficult to control [16, 17].

Two types of RSM are used in design of experiments: Box–Wilson, and Box–Behnken [18]. The Box–Wilson, which is also called central composite design (CCD), has three different design points: edge points are in two-level designs (±1), star points at $\pm\alpha$ that take care of quadratic effects, and centre points (0) [13]. CCD does testing at five levels. The edge points are at the design limits, star points are at some distance from the centre depending on the number of factors in the design; the star points extend the range outside the low and high settings for all factors, while the centre points complete the design [19]. CCD provides high quality predictions over the entire design space, is suitable for fitting a quadratic surface, and usually works well for process optimization [20]. Box-Behnken design is an independent quadratic design because it does not contain an embedded factorial or fractional factorial design [21]. In this design, the treatment combinations at the midpoints of edges of the process space and at the centre, require three levels of each factor: −1, 0, and +1, and has fewer treatment combinations than CCD [19].

A biodigester is any manufactured device or system in which a biologically active environment or a chemical process is carried out which involves microorganisms or biochemically active substances derived from such organisms is supported [22]. There are many designs of biogas plants but the most common ones in Kenya include the lagoon, floating drum, fixed dome and flexible structure bio-digester models [23, 24]. A fixed dome is a biodigester which consists of a reactor with a fixed, non-movable gas holder, which sits on the reactor. Regarding the flow pattern of anaerobic digesters, two basic types can be distinguished: batch and continuous. In continuous flow reactors the processes involved in anaerobic digestion proceed spatially as well as temporarily in parallel steps whereas batch reactors exhibit temporarily staggered sequences [25]. The operation of batch-type digesters consists of loading the digester with organic materials and allowing it to digest; once the digestion is complete, the effluent is removed and the process is repeated [25].

A parameter is any of the factors that limit the way in which something can be done. In this study, the parameters that have been considered are total solids, temperature, and substrate retention time; and their effect on biogas production rate in a fixed dome biodigester under laboratory conditions. Biodigesters operate at different environmental and management conditions. Other parameters that affect the efficient production of biogas include lack of feedstock, appropriate design of digesters, development of inoculums, pH, loading rate, hydraulic retention time (HRT), Carbon: Nitrogen (C:N) ratio, and volatile fatty acids [26]. Defects in digester construction and microbiological failure are, also, major areas of concern and are crucial for the optimization of biogas production technologies and their economic viability [27].

Total solids are defined as a measure of dry matter left after the moisture has been removed from a moist sample. Substrate concentration can be determined in terms of volatile solids or total solids. Volatile solids content is determined by igniting the feedstock at 550°C in an incinerator and then weighing the remaining contents [28]. Total solids is the measurement of dry matter as a percentage, and is determined by drying the sample at 103 − 105°C in succession until no further change in weight is observed [28].

Anaerobic fermentation is, in principle, possible between a temperature of 3°C and approximately 70°C [25]. There are three main temperature regimes for anaerobic digestion (AD): psychrophilic (<

25°C), mesophilic (30-40°C) and thermophilic (50-70°C) [29]. The best temperatures are 10°C, 37°C and 52°C for psychrophilic, mesophilic, and thermophilic bacteria, respectively [30]. In AD, the formation and consumption of products at different temperatures can occur at different rates, causing transient accumulation of potentially inhibitory substances [31]. Consequently, temperature is a critical factor affecting anaerobic digestion because it influences both system heating requirements and methane production [32].

Substrate retention time refers to the mean length of time that the material fed into the batch digester takes before it is emptied [33]. Shorter retention times are known to be associated with acidification especially fatty acids, and can cause inhibitory effects [34]. Nonetheless, shorter substrate retention times allow for increased process efficiency and decreased capital costs, although longer substrate retention times are necessary for the digestion of lignocellulosic wastes [35]. Generally, mesophilic digestion can be accomplished within 15 – 30 days [36].

2 Materials and Methods

2.1 Design of Experiment

Central composite design was used to get the matrix of experiments with three factors, each being tested at five different levels. The response was biogas production (Y). The factors were: substrate retention time (x_1), total solids (x_2), and temperature (x_3). Design Expert software (version 10.0.0.3, Stat-Ease, Inc., Minneapolis, United States) statistical package was used to generate Table 1 and Table 2 for the experiment. The levels of every factor were as indicated in Table 1. In the design space, the highest level was coded as +1, the centre point was 0, and the lowest level was coded as –1. The outer design space points corresponding to α were ± 1.68179. $\alpha = 2^{k/4}$, where k is the number of factors [8, 37]. In this case, $k = 3$. There was a total of 20 runs of experiments; comprising of 6 centre points and 14 axial points. If a full factorial experiment were done, there would have been 5^3 (or 125) runs of experiments.

Table 1. Factors and their coded and actual values

Factor	Symbol	Unit	Coded and Actual Values				
			–1.68	–1.00	0.00	+1.00	+1.68
SRT	x_1	days	9.95	12.00	15.00	18.00	20.04
TS	x_2	%	6.31	7.00	8.00	9.00	9.68
Temp	x_3	°C	26.59	30.00	35.00	40.00	43.41

Actual values (x_i) were found from equation (1) [2, 36, 38] as:

$$x = \frac{x_i - x_0}{\Delta x} \tag{1}$$

where:

$i = 1, 2,$ and 3
x_i = the input variable
x_0 = the value of x_i at the centre point
Δx = the step change between input variables
x = the coded value.

2.2 Statistical Analysis and Modeling

A second order mathematical model was used to fit the quadratic equation [39-42] as given below.

$$Y = \beta_0 + \sum_i \beta_i x_i + \sum_{ij} \beta_{ij} x_i x_j + \sum_{ii} \beta_{ii} x_i^2 \tag{2}$$

The interpretation of equation (2) is as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{33} x_3^2 \quad (3)$$

where:

Y is the measured response
x_1, x_2, and x_3 are coded input variables
β_0 is the intercept term
β_1, β_2, and β_3 are coefficients showing the linear effects
β_{12}, β_{13}, and β_{23} are cross-product coefficients showing the interaction effects
β_{11}, β_{22}, and β_{33} are the quadratic coefficients

2.3 Verification of Optimized Results

In this study, optimization was done with the predictive model for the response as a function of substrate retention time, total solids, and temperature. The model was based on results from CCD on biogas production. Setting numerical optimization criteria was by Design Expert software (version 10.0.0.3). This software uses an optimization method developed by Derringer and Suich [43], and is described by Montgomery*, et al.* [14]. This criteria was also used by Avicenna*, et al.* [44]. The objective function was to maximize biogas production (Y); subject to the variables (A: substrate retention time, B: total solids, and C: temperature) and their respective constraints as shown below:

Maximize

$$\begin{aligned} Y = &-901.41 + 15.21A + 183.25B + 7.74C - 0.56AB + 0.04AC + 0.06BC \\ &- 0.41A^2 - 11.47B^2 - 0.11C^2 \end{aligned} \quad (4)$$

Subject to: $12 \le A \le 18$; $7 \le B \le 9$; $30 \le C \le 40$

Table 2. Criteria.

Name	Goal	Lower limit	Upper limit
A: SRT (days)	In range	12.00	18.00
B: TS (%)	In range	7.00	9.00
C: Temp (°C)	In range	30.00	40.00
Y: Biogas production (litres/day)	Maximize	33.01	75.41

This procedure generated Table 3.

Table 3. Influent preparation

TS (%)	Cow dung: water dilution	Cow dung (kg)	Water (kg)
7.642	1:1.441	49.160	70.840
7.697	1:1.424	49.505	70.495
7.724	1:1.416	49.669	70.331

Gas collection was by water displacement method. Biogas analysis was done using a Gas Chromatograph. Experiments were done on the first three optimized solutions. The results were compared.

3 Results

Table 4. Experiment matrix, actual and predicted results

Run	Factors			Biogas production			
	A:SRT (days)	B:TS (%)	C:Temp (°C)	Actual (l/d)	Predicted (l/d)	Actual (m^3/m^3d)	Predicted (m^3/m^3d)
1	15.00	8.00	35.00	72.11	73.16	0.48	0.48
2	15.00	8.00	35.00	72.90	73.16	0.48	0.48
3	15.00	6.32	35.00	45.73	51.82	0.30	0.34
4	15.00	8.00	35.00	71.56	73.16	0.47	0.48
5	18.00	7.00	40.00	66.91	68.89	0.44	0.45
6	12.00	7.00	40.00	67.48	65.35	0.44	0.43
7	15.00	8.00	26.59	52.71	55.96	0.35	0.37
8	18.00	9.00	30.00	36.40	39.99	0.24	0.26
9	15.00	8.00	35.00	71.80	73.16	0.47	0.48
10	15.00	8.00	35.00	71.96	73.16	0.47	0.48
11	15.00	9.68	35.00	33.01	29.74	0.22	0.19
12	15.00	8.00	35.00	72.30	73.16	0.48	0.48
13	12.00	9.00	30.00	45.88	45.57	0.30	0.30
14	20.04	8.00	35.00	61.52	61.88	0.41	0.41
15	12.00	7.00	30.00	58.00	55.95	0.38	0.37
16	12.00	9.00	40.00	52.65	56.17	0.35	0.37
17	9.95	8.00	35.00	61.25	63.56	0.40	0.42
18	18.00	7.00	30.00	59.14	57.09	0.39	0.38
19	18.00	9.00	40.00	49.17	52.99	0.32	0.35
20	15.00	8.00	43.41	75.41	74.79	0.50	0.49

Table 5. Analysis of variance

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	3037.53	9	337.50	32.09	< 0.0001
A-SRT	10.43	1	10.43	0.99	0.3428
B-TS	577.69	1	577.69	54.93	< 0.0001
C-Temp	411.52	1	411.52	39.13	< 0.0001
AB	22.88	1	22.88	2.18	0.1710
AC	2.30	1	2.30	0.22	0.6500
BC	0.66	1	0.66	0.062	0.8079
A^2	194.38	1	194.38	18.48	0.0016
B^2	1891.36	1	1891.36	179.83	< 0.0001
C^2	107.16	1	107.16	10.19	0.0096
Residual	105.17	10	10.52		
Cor Total	3142.71	19			

Other Statistics

$R^2 = 0.9665$; Adjusted $R^2 = 0.9364$; Predicted $R^2 = 0.7442$; C.V.% = 5.41; Adequate precision = 19.562; PRESS = 803.97; Standard deviation = 3.24; Mean = 59.89

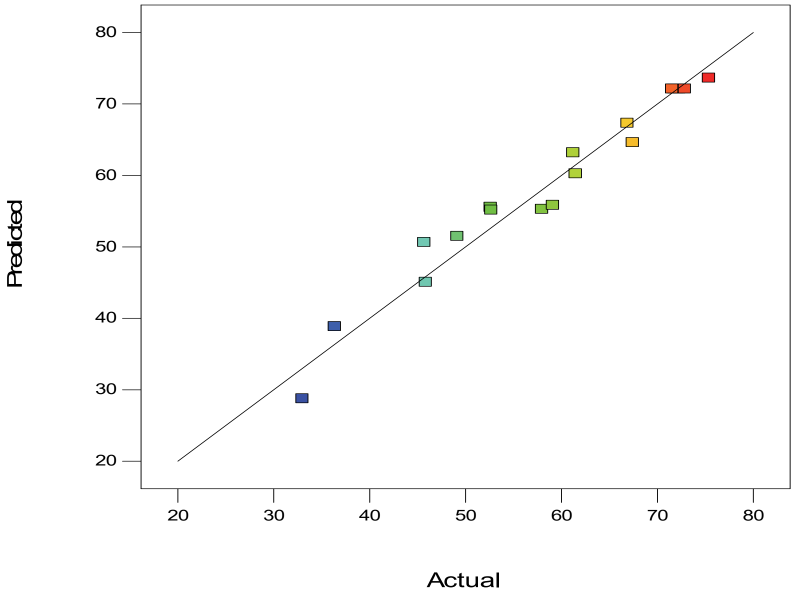

Figure 1. Predicted vs Actual results

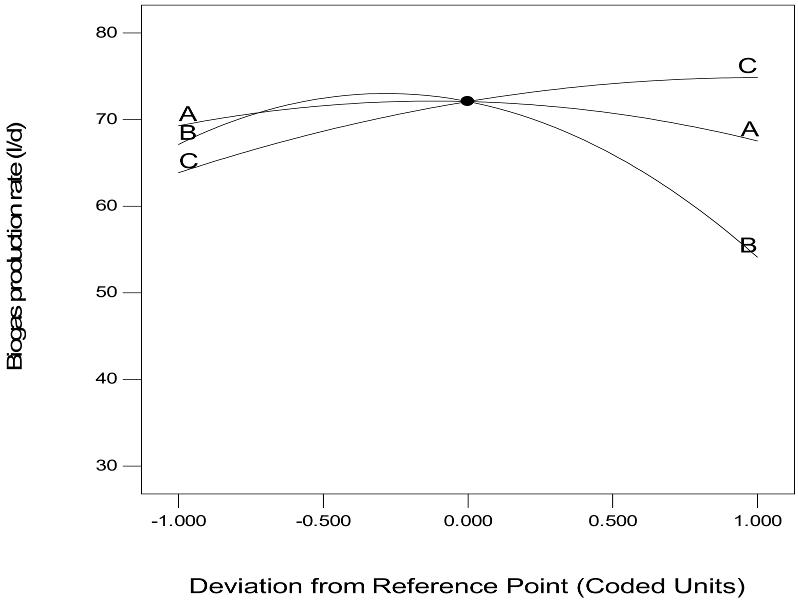

Figure 2. Perturbation

Table 6. Optimized results and experimental results

Solution	Factors			Biogas production (l/d)	
	SRT (days)	TS (%)	Temp (°C)	Optimized	Experiment
1	15.339	7.642	39.643	75.578	69.855
2	15.179	7.697	39.202	75.612	70.929
3	15.385	7.724	38.979	75.530	68.247

4 Discussions

4.1 Prediction Model

Experimental results as well as the predicted values for biogas production rate are given in Table 4. A combination of factors which yielded the highest biogas production of 75.41 litres per day (or 0.502 m^3 of biogas per m^3 of digester volume per day, m^3/m^3d) was a substrate retention time of 15 days, total solids of 8%, and a temperature of 43.4°C.

A regression analysis was done based on the experimental results using the Design Expert 10.0.0.3 statistical package, and it yielded a relationship given by equation (4) with its respective boundary limits. Equation (4) was used to predict the values corresponding to the actual ones, and most of them are very close. These values are in agreement with $0.4m^3/m^3d$ reported by Nyaanga [45], and Moog*, et al.* [46].

4.2 Analysis of Variance (ANOVA)

The analysis of variance is necessary in order to determine the significance and adequacy of the model [42]. The statistical significance of the second-order polynomial equation was checked by an F-test (ANOVA). Table 5 shows the statistics. The ANOVA was used to evaluate the significance of the quadratic polynomial model [47]. For each term in the model, a large F-value and a small P-value would imply a more significant effect on the respective response variable [48].

A model F-value of 32.09 was found. There was a chance of less than 0.01% that a value this much could be caused by noise. Hence the model was chosen for the experiment. Model values whose 'prob>F' are less than 0.05 (i.e. $p < 0.05$) are significant. In this case, the linear effects of total solids (B) and temperature (C) were significant. The quadratic effects of substrate retention time (A^2), total solids (B^2), and temperature (C^2) were significant. The interaction effects of AB, AC and BC were insignificant. All the significant factors had an individual effect on biogas production rate.

A coefficient of determination (R^2) is used to measure the variability in the actual response values that can be described by the corresponding independent factors [40]. R^2 was 0.9665; it implied that a sample variation of 96.65% of the total variation could be explained by the model, and only 3.35% could not be explained by the model for this work. For a good statistical model, the R^2 should be in the range of 0.75–1.0 which indicates a good fit of the model [49].

The adjusted R^2 of 0.9364 was also very high. It indicated the higher significance of the model. The predicted R^2 value of 0.7442 showed reasonable agreement with the adjusted R^2 value of 0.9364. The threshold is that the difference between the adjusted R^2 and the predicted R^2 should be less than 0.2 [50]. The difference here is 0.1922. This indicated a good agreement between the observed and the predicted values as demonstrated in table 5.

The percentage of coefficient of variation (CV %) is a measure of residual variation of the data relative to the size of the mean; the higher the value of CV, the lower is the reliability of experiment [51]. A lower CV of 5.41% indicated a greater reliability of the experiment. As a general rule, a model can be considered reasonably reproducible if the CV is not greater than 10% [52]. This model is reproducible.

Adequate precision is a measure of signal to noise ratio; a ratio greater than 4 is desirable [53]. In this case, the ratio was 19.562; which indicated an adequate signal. This model can be used to navigate the design space. The Predicted Residual Sum of Squares (PRESS) is a measure of how well the model fits each point in the design; the smaller the PRESS statistics, the better would be the model fitting the data points [52]. Here the value of PRESS found was 803.97. This value is small; it shows that the model fits well on each point in the design.

4.3 Diagnostics

Figure 1 shows that the predicted results lie within the normal probability curve. The actual results also exhibit the same behavior. Outliers also exist, implying the errors inherent in the experiment due to the losses of biogas and the accuracy of the equipment used to monitor the anaerobic process. However, a high R^2 value that was found emphasizes a high degree of similarity that was observed between the predicted and the experimental values. It can be concluded that the model has satisfied the assumptions of the analysis of variance and also reflected the accuracy and applicability of RSM to optimize the process factors for the efficient generation of biogas [40].

4.4 Perturbation

Perturbation is a deviation of a system, moving object, or process from its regular or normal state or path, caused by outside influence. Perturbation plot provides silhouette views of the response surface. For response surface designs, the perturbation plot shows how the response changes as each factor moves from the chosen reference point, with all other factors held constant at the reference value [54]. Design Expert sets the reference point default at the middle of the design space (the coded zero level of each factor).

Figure 2 represents a comparison of the effect of process parameters at the midpoint (coded 0) in the design space. When B (TS) and C (Temperature) are held at their respective midpoints, it shows that A (SRT) gives a steadily higher biogas production rate from day 12 up to its midpoint value (day 15), and then the rate starts decreasing. Similarly for B, the rate increases from 6.31% TS, then starts dropping before the midpoint (8% TS) is reached. Thereafter the rate decreases steadily. For C, the rate increases uniformly from 25°C to the midpoint (35°C), then the trend continues up to 40°C.

4.5 Verification of Optimized Results

The results are given in table 6. It can be observed that the optimized biogas production for solutions 1, 2 and 3 are higher than experimental ones by 8.19%, 6.60% and 10.67%, respectively. For the results to be valid, the difference between the actual value and the predicted value should be less than 20% [50]. The differences are within the range hence the optimization is admissible.

5 Conclusions

During optimization, a biogas production rate of 75.41 l/d (or $0.50 m^3/m^3 d$) was achieved at a substrate retention time of 15 days, 8% total solids, and a temperature of 43.41°C. Optimized results are in agreement with the experimental results.

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