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Optimization of Process Conditions for the Production of Biogas from Cow Dung

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Biogas recovery from animal waste could be the key to unlocking the financial and environmental benefits of managing manure produced by livestock operations as well as organic waste from food processing sectors. There is no doubt that in the near future, the world's energy supply market will be dominated by renewable and sustainable energy, since there is no alternative. While combustion is the most common method to gain energy from biomass such as wood and wood chips, the high content of water in animal slurry suits anaerobic digestion/fermentation for conversion to energy, in that direct combustion is not appropriate for most animal manures. However, biogas production is the technology that converts animal manure and other biomasses into viable fuel, recycling the carbon resource of animal slurry. This study critically evaluated the process conditions for biogas production yields from cow dung. The cow dung was pretreated and characterized, after which its proximate analysis were determined. Effects of process variables (cow dung/water ratio, catalyst dosage, and time) on the biogas yield were evaluated and optimized using the response surface methodology (RSM). The proximate analysis of the cow dung revealed that the moisture content falls within the acceptable limit of not more than 10% for long-term storage, an ash content of 5.52% was recorded; indicating a high mineral content of the cow dung sample and the volatile

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matter content value of 77.21% signifies the raw material suitability for biogas production. Furthermore, the results of the optimization of biogas production in this research work were found to have significance with the process parameters, thus, the optimum biogas yield of 51.97% was obtained at cow dung/water ratio of 0.46g/ml, catalyst dosage of 0.98g and time of 3days.

Keywords: Anaerobic digestion; bioenergy; cow dung; optimization.

1. INTRODUCTION

"Today, the spotlight in most developed countries is on the increasing world demand for energy and the high cost of oil and natural gas. This has heightened interest in alternative and renewable energy sources, such as biofuels, forest, wind, solar, and animal manure cow dung" [1,2]. "It is believed that after 2050's, 50% of the world energy share will come from renewable energy resources" [3]. "In the past, animal wastes were recovered and sold as a fertilizer or simply spread onto agricultural land, but the introduction of tighter environmental controls on odour and water pollution means that some form of waste management is now required, which provides further incentives for waste-to-renewable energy conversion" [4]. The most attractive and convenient method of converting these waste materials to useful forms is anaerobic digestion [5-20,21-24], which gives biogas that can be used as a fuel for internal combustion engines, to generate electricity from small gas turbines, burnt directly for cooking, or for space and water heating [25,26].

"Alternative reactor designs, such as anaerobic membrane bioreactors, have the potential to reduce capital costs dramatically and possibly to produce biogas with substantially more methane. Therefore, two-stage anaerobic digestion processes are often considered the optimal combination, namely, thermophilic hydrolysis/ acidogenesis and mesophilic methanogenesis" [18,27,28]. "Biogas production in a thermophilic regime is much higher than in the mesophilic and psychrophilic regimes. Modern thermophilic bioreactors can produce 2- 6 m^3 per m^3 of installation, which amounts to 5-15 kg of waste on a dry mass base (or 50-150 kg of wet mass). For mesophilic biogas installations, these values are 0.2-0.4 m^3 per m^3 of installation and 0.5-1 kg on a dry mass base (or 5-10 kg of wet mass). Biogas reactors, working in a thermophilic regime, can be introduced in agricultural farms where the number of livestock exceeds 5. Biogas produced on such farms can be used not only for cooking and heating water, but for dairy production as well. Every year, natural biodegradation of organic matter under anaerobic conditions is estimated to release 590–800 million tons of methane into the atmosphere" [29].

"Optimization of various process factors affecting biogas production is a complex process with a number of interactive controlling parameters. At the industrial level, even a small improvement in the process gives a better yield which may be beneficial commercially, making process optimization a major area of research" [30]. Several research studies to optimize some process variables for an increase in biogas production (Table 1) and methane yield have shown that co-digestion of organic wastes, such as animal manure combined with industrial, agricultural, and municipal wastes, may be a viable option [31]. A number of optimization methods have been used in biogas studies, including techniques such as Design of Experiment (DOE), Response Surface Methodology (RSM) with central composite design (CCD), and Box-Behnken design (BBD), in the optimization of agricultural and industrial biogas plants with respect to external and internal system variations and their effect on the rate and quality of methane produced from the fermentation and digestion of organic matter. Other techniques including artificial neural networks (ANN) and Taguchi have also been applied. Park and Lek [32] conceptualized that "artificial neural networks (ANN) are biologically inspired computational networks based on the study of the brain and the nervous system, and are used to solve many real complex problems. These computations are based on multilayer perception's that involve a supervised procedure that consists of three layers, namely, the input, hidden, and output layers". Artificial Neural Network (ANN) coupling Genetic Algorithm (GA) was used by Kana et al. [33] to model the non-linear behavior of the anaerobic process and optimize biogas production from mixed substrates that included cow dung. An evaluation of the optimal profile showed an increase of 8.64% in biogas production over that predicted by the optimized substrate profile. Production of the non-optimized profile started on the 8th day, compared to that of the 3rd day of the optimized one.

Table 1. Review of past works

S/N	Raw materials used	Operation mode	Operation conditions	Biogas yield	References
1	Cow dung	Retention time	22days	23.0cm³	[34]
2	Cow dung	Temperature	43.4 °C	75.4L/day	[35]
3	Cow dung	pH	7	124.3L/total mass of slurry (TMS)	[27]
4	Cow dung	Retention time	28days	53.85%	[26]
5	Cow dung	Sonication time Slurry ratio Retention time	25minutes 1.85 18days	17.772mL	[37]
6	Tofu, water hyacinth and cow manure	Retention time Tofu to water hyacinth to cow manure ratios	21days 4:2:2	60ppm	[31]
7	Coffee pulp and cow dung	Time Temperature Coffee pulp to cow dung ratio	90hrs 40℃ 1:3	144mL/kg	[14]

Thuiller [38] found the limitations of ANN that include the lack of fixed guidelines for an optimal ANN architecture, its “black-box model” behavior, and insufficient concepts of ecology and relations. However, RSM is important in process design and optimization, as well as for improving the performance of the system. The technique is very popular in physical and chemical experimental design and optimization for experimental cost reduction.

The optimization and control of systems such as the biochemical digestion of organic matter involving the use of microbial population with differing successions, poses challenges due to the underlying highly non-linear and complex processes. However, the flexibility and power of computational intelligence (CI) methods such as Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) have been employed beyond the simpler empirical models based on accurate measurements and observations for modeling and simulation techniques. Therefore, the aim of this study was to investigate the effects of slurry ratio, catalyst dosage, and time as well as their interactive effects on biogas production from cow dung using RSM.

2. MATERIALS AND METHODS

2.1 Raw Materials Collection

The raw material was obtained from the waste of native cows at Akpugo in Nkanu West Local Government of Enugu State, Nigeria. The raw material was bagged in clean polythene and transported immediately to the Chemical Engineering laboratory, Enugu State University of Science and Technology, Enugu State, for analysis.

2.2 Characterization of the Cow Dung

2.2.1 Determination of moisture content

The AOAC method (1990) was used. Porcelain crucibles were washed, dried in an oven at 100℃ for 30minutes, and allowed to cool in a desiccator. 1g of the sample was placed into the weighed crucible (A) and set in an oven at 105℃ for 4hours. The sample was removed from the oven and then cooled and weighed (B). The drying continued and the sample in the crucible was weighed until a constant weight was obtained.

$$\% \text{ moisture content} = \frac{A-B}{A} \times 100 \quad (1)$$

Where

A= Original weight of sample
B= weight of dried sample.

2.2.2 Determination of volatile matter content of the sample

5g of the sample (w_i) was measured and placed in a muffle furnace at 550℃ for 10minutes. It was then removed and allowed to cool in a desiccator. The procedure was repeated in triplicate and the final weights of the sample (w_f) were recorded using an electronic weighing balance; the average values were computed and used for analyses. The volatile matter (VM) was calculated using the equation:

$$\%VM = \frac{w_i - w_f}{w_i} * 100 \quad (2)$$

Where

w_i = initial weight of the sample
w_f = final weight of the sample

2.2.3 Determination of ash content

AOAC (1990) method was applied, 5g of the fine ground samples were weighed into porcelain crucibles and placed in an oven at 100 ℃, afterwhich were allowed to cool in a desiccator and its weight recorded. The samples were then placed inside a muffle furnace and heated at 600℃ for 4 hours. It was removed, cooled in a desiccator and the weights were recorded. The ash content was calculated thus:

$$\% \text{ Ash Content} = \frac{A-B}{C} * 100 \quad (3)$$

Where

A=weight of crucible + ash
B=weight of crucible
C=weight of original sample

2.2.4 Determination of the fixed carbon content of the sample

The fixed carbon (FC) of the sample was determined using the equation:

$$\%FC = 100\% - \%Ash - \%VM \quad (4)$$

Where

% Ash = determined ash contents
%VM = determined volatile matter

2.3 Determination of Energy Value

The samples plus 10cm ignition wires were measured. The two ends of the ignition wire were fixed on two electrode poles and allowed to keep in good touch with the sample. The oxygen bomb calorimeter model XRT-1A was filled with 10ml distilled water and the cover screwed down. The bomb was then filled with oxygen at a pressure of 2.8-3.0MPa and placed into the clamp in the inner canister. The required wires were connected and the temperature sensor was inserted inside the inner canister. The water was stirred for 2minutes and the initial temperature, T_o was recorded. The fire button was switched on and the instrument automatically measured and saved the data as the testing time reached 31 minutes. The final temperature T_f of the water was then recorded. Stirring was stopped and the temperature sensor was pulled out after which the lid was opened. The bomb calorimeter was removed and the oxygen inside was set free before it was opened. The length of the unburnt wire was then measured. The inner lining of the oxygen bomb was washed with some amount of distilled water. Two drops of methyl red indicator were added and titrated with 0.0709N sodium carbonate. The consumed volume of alkali used was then recorded. The heat of combustion was calculated:

$$\text{Calorific value} = \frac{E\Delta T - \Phi - V}{M} \quad (5)$$

Where

E = Energy equivalent of the calorimeter
Φ = Correction for heat of combustion of firing wire
ΔT = Change in temperature
V = Millimeters of standard alkali solution
M = Mass of the sample to be evaluated

2.4 Biogas Production

Onwuliri et al. [26] method of anaerobic digestion was employed in this experiment for biogas production. Fine powdered cow dung was weighed and mixed with distilled water (ratio of 1:10) in a 250ml conical flask. 0.9g of Al_2O_3 was added as catalyst and the slurry mixture thoroughly stirred. The flask containing the slurry was then connected to a rubber delivery tube conveying the gas to a burette filled with water and placed in an inverted position in a glass trough containing water such that the gas released from the digestion process was collected in the burette by water displacement method. The flask ends of each delivery tube were inserted into the mouth of the conical flask and held in place by cotton wool stuffed in the flask mouth. The connecting point of the tube and flask was sealed with adhesive tape to prevent leakage of gas from the flask. The contents of the flasks were allowed to undergo digestion for a retention period of 5 days with daily measurements of gas yields. Effects of process variables (cow dung/water ratio, catalyst dosage, and time) on the biogas yield were determined using an experimental design matrix. Response surface methodology (RSM) was then used to optimize the biogas yield.

3. RESULTS AND DISCUSSION

3.1 Proximate Analysis of the Sample

Proximate analyses of the cow dung sample are presented in Table 2. The moisture content was within the acceptable limit of not more than 10% for long-term storage. The low moisture content would enhance its storage stability by preventing mould growth and reducing moisture-dependent biochemical reactions. Ash content of 5.52% was recorded, which is an indication of the high mineral content of the cow dung sample. Volatile matter content value of 77.21% signifies cow dung's suitability for biogas production.

3.2 Effects of Process Variables on the Biogas Yield

Effects of cow dung/water ratio (g/ml), catalyst dosage (g), and time (days) are presented in Figs. 1a, 1b, and 1c respectively. It was observed from Fig. 1a that the biogas yield increased almost linearly with an increase in cow dung/water ratio to the peak at cow dung/water ratio of 0.4 and after which a significant decrease was observed. In Fig. 1b, the biogas yields increased with catalyst dosage until it attained the maximum at the catalyst dosage of 0.9g before it started retarding. The catalyst reduces the activation energy, resulting in a higher rate of reaction without being involved in the reaction. This trend was also noticed in Fig. 1c, just as the biogas yield increased with time and decreased after 3 days.

Table 2. Proximate analyses of the cow dung

Composition	Values
Volatile matter content (%)	77.21
Ash content (%)	5.52
Moisture content (%)	7.13
Fixed carbon (%)	10.14
Energy Value (kJ/100g)	2588.15

3.3 RSM Results

The RSM results are presented in Table 3. Highest values of biogas yield were recorded at the midpoint of the process variables. This is an indication that the interactive effect of the variables on each of the responses is in parabolic form [39].

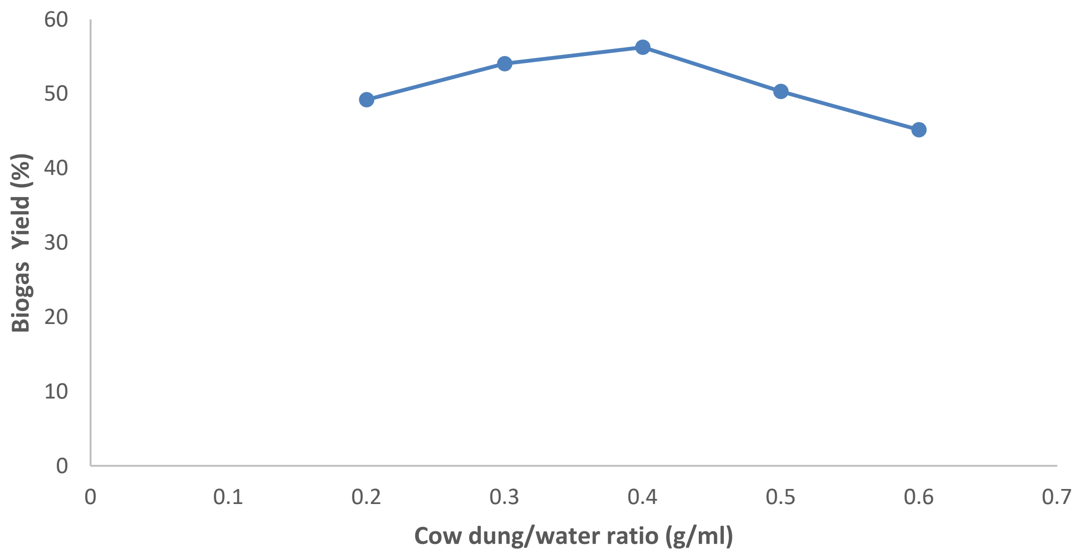

Fig. 1a. Effect of cow dung/ water ratio on the biogas yield

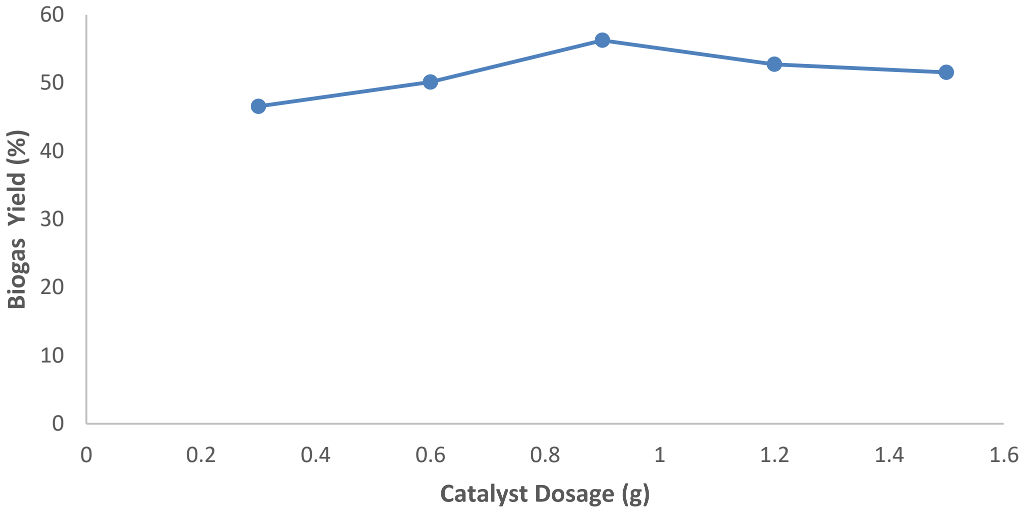

Fig. 1b. Effect of catalyst dosage on the biogas yield

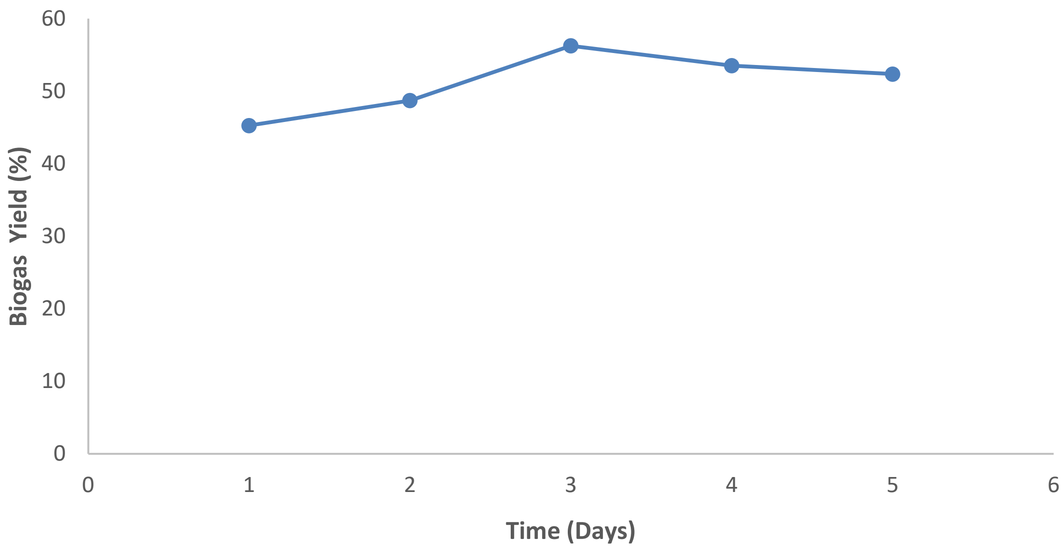

Fig. 1c. Effect of time on the biogas yield

3.4 ANOVA for Quadratic Model

Analysis of Variance (ANOVA) (Table 4) for the response surface model fit was carried out to validate the predictive and modeling capability of RSM. The ability was judged based on the values of important model parameters like the 'Adequate precision', 'Lack of fit' and the coefficient of determination (R^2). The ANOVA showed that the model was highly significant with low P-value of 0.0001 and high F-value of 142.43. In this case A, B, C, AB, AC, BC, A^2, B^2, C^2 are significant model terms. The predicted R^2 of 0.8838 is in reasonable agreement with the adjusted R^2 of 0.9853; i.e., the difference is less than 0.2. Adequate precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. The ratio of 43.159 indicates an adequate signal for this study. This model can be used to navigate the design space.

Table 3. Biogas yield under different setup conditions

Std	Run	Factor 1 A: Cow dung/ water ratio g/ml	Factor 2 B: Catalyst dosage G	Factor 3 C: Time day	Response biogas yield %
6	1	0.6	0.3	5	35.91
4	2	0.6	1.5	1	39.03
18	3	0.4	0.9	3	52.26
13	4	0.4	0.9	1	45.25
7	5	0.2	1.5	5	44.35
9	6	0.2	0.9	3	49.21
11	7	0.4	0.3	3	46.56
14	8	0.4	0.9	5	52.35
3	9	0.2	1.5	1	40.56
17	10	0.4	0.9	3	52.26
10	11	0.6	0.9	3	45.17
5	12	0.2	0.3	5	43.45
8	13	0.6	1.5	5	44.29
15	14	0.4	0.9	3	52.26
19	15	0.4	0.9	3	52.26
2	16	0.6	0.3	1	23.84
12	17	0.4	1.5	3	51.55
1	18	0.2	0.3	1	38.58
20	19	0.4	0.9	3	52.26
16	20	0.4	0.9	3	52.26

Table 4. ANOVA for quadratic model

Source	Sum of squares	DF	Mean square	F-value	P-value
Model	1046.20	9	116.24	142.43	< 0.0001
A-Cow dung/water ratio	77.90	1	77.90	95.45	< 0.0001
B-Catalyst dosage	98.85	1	98.85	121.12	< 0.0001
C-Time	109.49	1	109.49	134.16	< 0.0001
AB	53.51	1	53.51	65.56	< 0.0001
AC	9.40	1	9.40	11.51	0.0069
BC	7.78	1	7.78	9.53	0.0115
A^2	89.82	1	89.82	110.05	< 0.0001
B^2	40.76	1	40.76	49.95	< 0.0001
C^2	46.34	1	46.34	56.78	< 0.0001
Residual	8.16	10	0.8161		
Lack of Fit	8.16	5	1.63		
Pure Error	0.0000	5	0.0000		
Cor Total	1054.36	19			
Std. Dev.	0.9034		R^2		0.9923
Mean	45.68		Adjusted R^2		0.9853
C.V. %	1.98		Predicted R^2		0.8838
			Adequate Precision		43.1595

3.5 Mathematical Model of Cow Dung Biogas Yield

Mathematical model of the cow dung yield in terms of significant factors is presented in Equation 6. The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

$$\text{Biogas yield} = +52.52 - 2.79A + 3.14B + 3.31C + 2.59AB + 1.08AC - 0.9863BC - 5.71A^2 - 3.85B^2 - 4.10C^2 \quad (6)$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

3.6 Graphical Analysis of the Results

Graphical analyses of the process conditions for the biogas yield from cow dung are shown in Figs. 1d – 1g. In Fig. 1d, the predicted versus actual biogas yield revealed a linear graph. The points were clustered along the line of best fit, which indicates that the generated model adequately predicted the experimental data [40-42]. Figs. 1e – 1g are the 3-D (3-dimentional) plots that revealed the interactive effects of the process conditions of: cow dung/water ratio, catalyst dosage and time on the biogas yield. They all displayed parabolic curves, which agree with the established quadratic model. More so, an optimum biogas yield of 51.97% was obtained at a cow dung/water ratio of 0.46g/ml, catalyst dosage of 0.98g, and time of 3.14days.

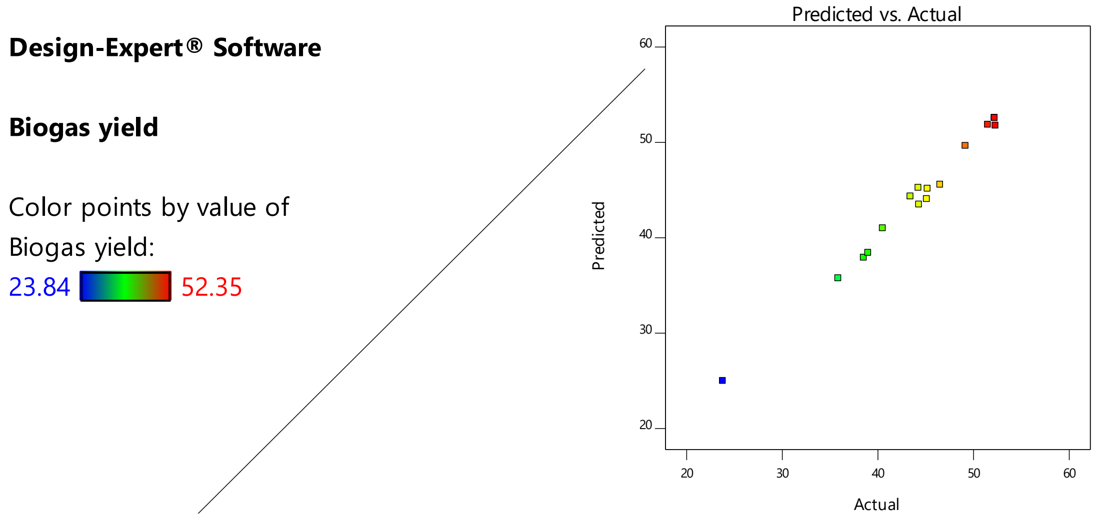

Fig. 1d. Graph of predicted versus actual biogas yield

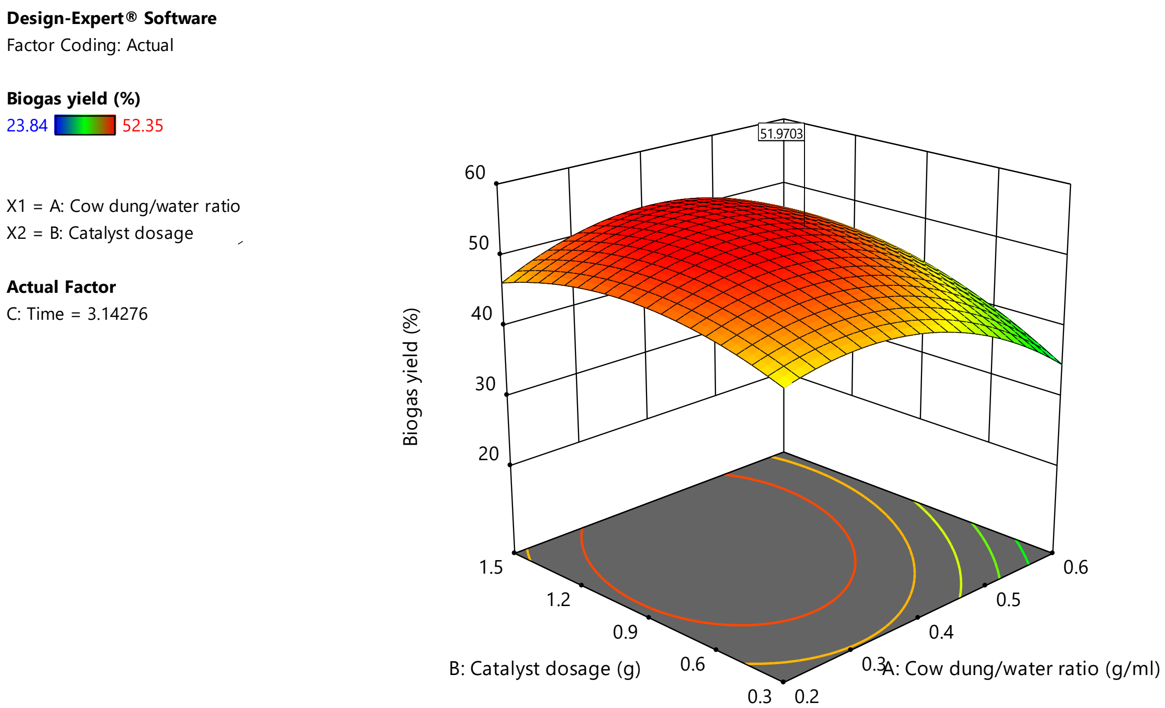

Fig. 1e. Graph of biogas yield versus catalyst dosage and cow dung/water ratio

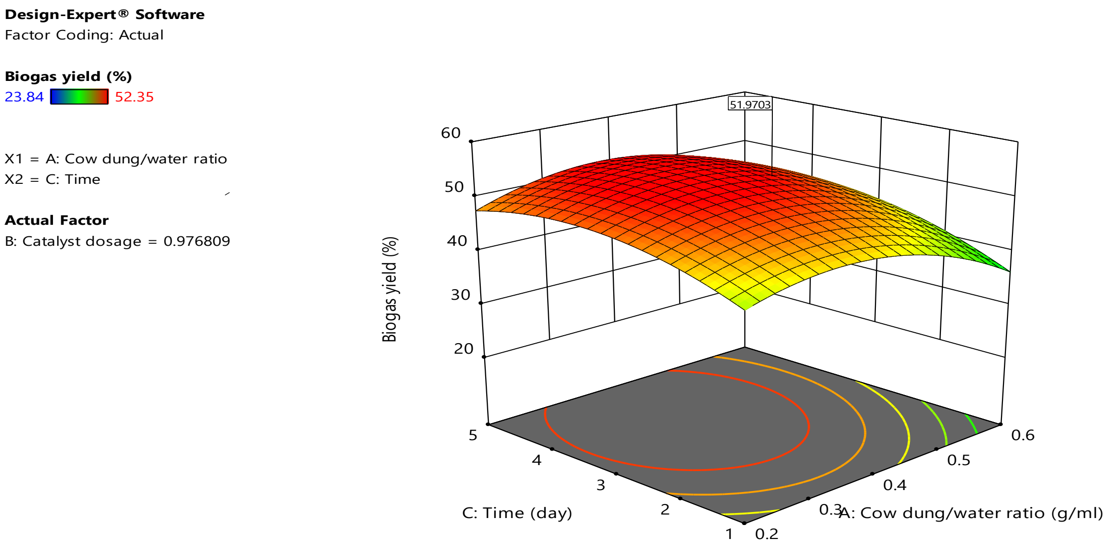

Fig. 1f. Graph of biogas yield versus time and cow dung/water ratio

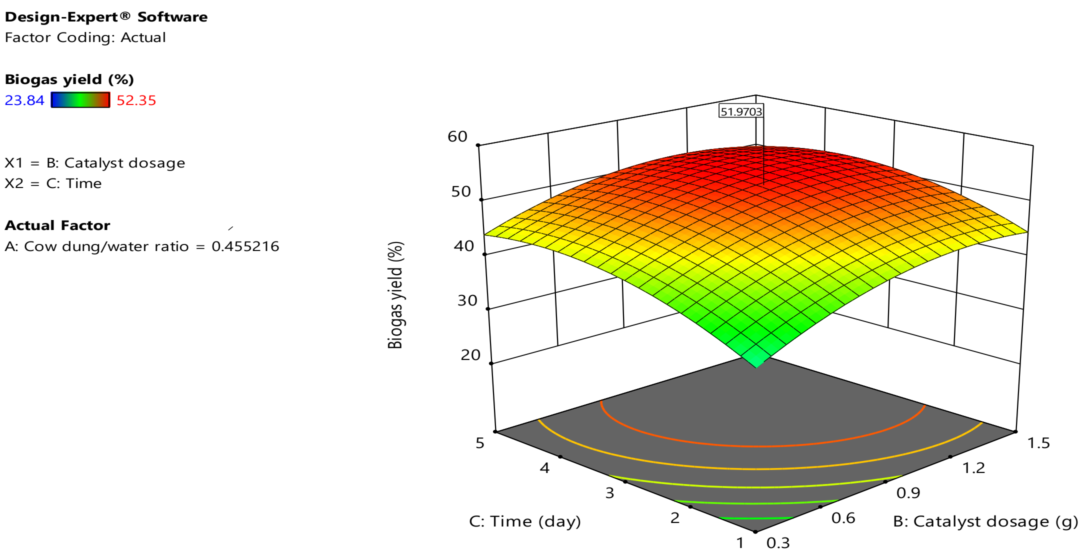

Fig. 1g. Graph of biogas yield versus time and catalyst dosage

4. CONCLUSION

Energy security, economic development, and protection of the earth are the priorities of the national energy policy of every country in the modern world. Biogas could be a solution to the growing demand for renewable energy sources. This clean and accessible source of energy can help reduce carbon emissions, manage organic waste, and generate electricity, heat, and even transportation. It is estimated that using upgraded biogas for transportation reduces greenhouse gas emissions significantly. Furthermore, the digestate produced during biogas production is a benefit that can be used as fertilizer and returned to the soil. Turning waste into energy through biogas production is not only a viable option with considerable potential to reduce or even eliminates dependence on fossil fuels, but also a sustainable and efficient way to produce decentralized energy with a smaller carbon footprint. From the results of this research, it was evidently seen that the cow dung/water ratio, catalyst dosage, and time of 0.46g/ml, 0.98g and 3.14days respectively, gave the optimum biogas yield of 51.97%, which signifies that the control parameters can greatly affect the biogas yield and thus process performance.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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