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Assessment of the Influence of Process Parameters on The Optimization of Biogas Production from The Co-Digestion of Cow Dung, Chicken Waste, And Kitchen Waste as An Alternative Fossil Fuel

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ABSTRACT
The optimization of biogas production from organic wastes is essential for sustainable energy generation and effective waste management. This study investigates the influence of pH (6.5–7.5), retention time (15–35 days), and total solids (6–12%) on biogas yield from the co-digestion of cow dung, chicken waste, and kitchen waste under mesophilic conditions. Proximate and ultimate analyses confirmed suitable substrate characteristics, including favorable moisture content (68–80%) and C/N ratios within or near the optimal range for anaerobic digestion. A Box–Behnken Design within Response Surface Methodology was employed to develop a quadratic regression model. The model was statistically significant ($F = 63.06$, $p < 0.0001$) with strong predictive performance ($R^2 = 0.9895$) and a non-significant lack of fit. Retention time was the most influential parameter, followed by total solids. Optimal conditions (pH 7.063, 6% total solids, 35 days) produced 3105.40 mL of biogas. The results demonstrate an efficient predictive framework for optimizing renewable energy recovery from mixed organic wastes.

Keywords: Biogas, Anaerobic co-digestion, Response Surface Methodology, Box–Behnken Design; Process optimization, Renewable energy.

I. INTRODUCTION

Environmental awareness and concerns over global warming have become major policy priorities worldwide. The continued reliance on fossil fuels has contributed significantly to environmental problems such as climate change and rising global temperatures [1]. As energy demand increases and fossil fuel reserves decline, their negative environmental impacts are prompting governments and industries to transition toward renewable energy sources [2]. Bioenergy, in particular, is gaining attention due to its availability and lower carbon emissions, making it a promising clean-energy alternative.

Energy remains essential for human comfort and daily living, yet many developing countries face persistent energy shortages because of heavy dependence on fossil fuels [3]. With coal, oil, and natural gas expected to be depleted within the next century, there is an urgent need to identify and adopt sustainable energy options [1].

Biogas offers a practical solution, especially for rural communities. In many low-income regions, smallholder farmers burn biomass for waste disposal, overlooking its potential value as an organic fertilizer that could replace expensive chemical alternatives [4]. Through biogas technology, these farmers can convert waste into both renewable energy and nutrient-rich fertilizer, improving agricultural productivity and reducing reliance on costly chemical inputs. This research aims to optimize biogas production through the co-digestion of cow dung, chicken waste, and kitchen waste as an alternative to fossil fuels.

II. MATERIALS AND METHODOLOGY

2.1. Materials and equipment

The following materials and equipment were used in this study; cow dung, kitchen wastes, chicken wastes, distilled water, hydrochloric acid (HCL), sodium hydroxide (NaOH), digital pH meter, measuring cylinder, 2L bio-digesters, weighing balance, hot air oven, glass stirring rod, furnace, CHNS analyzer, gas outlet tubing, desiccator, laboratory mill, gas tubing outlet and thermal conductivity detector.

2.2 Methodology

These consist of the various steps that were followed to achieved the research objectives. This includes the collection and pre-treatment of biodegradable wastes, characterization of biodegradable wastes, fabrication of anaerobic bio-digesters, preparation of slurry, anaerobic digestion of biodegradable wastes, data collection, data analysis and optimization.

2.2.1 Collection and pre-treatment of wastes

Cow dung (CD), Kitchen waste (KW) and Chicken waste (CW) were obtained from Zango cattle market, food restaurant and poultry farm, respectively in Kaduna. The samples were oven-dried at 105 ± 2 °C for 24 hours and subsequently dried until constant weight to eliminate moisture and then ground using a laboratory mill to obtain a fine, homogeneous powder. The characteristics of the feedstocks used were evaluated using proximate and ultimate analysis.

2.2.2 Proximate analysis of wastes

The analysis of samples was carried out in order to determine the moisture content, pH, total solids, volatile solids and fixed solids for its suitability during biogas and digestate production using American Society of Testing and Materials (ASTM) E871, E1756, E872, and E1755.

2.2.3 Ultimate analysis of wastes

The ultimate analysis, which determines the elemental organic composition of the substrates and their mixtures, namely carbon (C), hydrogen (H), nitrogen (N), and Sulphur (S), was carried out following the American Society of Testing and Materials (ASTM) standards D5373, E775, and D3176 [4]. The oxygen (O) content was calculated indirectly by deducting measured proportions of carbon, hydrogen, nitrogen, and Sulphur from 100% [5]. The carbon-to-nitrogen (C/N) ratio of each waste sample was then derived by dividing its carbon percentage by its nitrogen percentage.

2.2.4 Experimental design

This section explains the factors, levels, range of values and number of runs needed for the optimization using RSM. The number of experimental runs (N) for the Box-Behnken design (BBD) which is in three levels was calculated using Equation (1).

$$N=2k(k-1) + cp \quad \ldots (1)$$

Where; k is the number of factors and cp is the number of centre points [6].

The factors that affect biogas production process such as pH, Retention time and Total solids and the range of their values were obtained from literature [7], [8], [9], [10], [11].

2.2.5 Sizing of bio-digesters

Sixteen (16) laboratory-scale batch anaerobic digester system was designed and constructed using 2 L high-density polyethylene (HDPE) jerrycans, each with a working volume of 1.5 L and 0.5 L headspace to allow gas accumulation for anaerobic digestion of cow dung, kitchen waste and chicken wastes using the appropriate hand tools. Furthermore, the bio-digesters were tested in the Chemical Engineering Research Laboratory of ABU Zaria, Kaduna.

Each bio-digesters was fitted with a gas outlet tube connected to a 1 L graduated measuring cylinder placed in a water trough for gas collection by water displacement. The digesters were airtight, manually agitated twice daily, and operated under mesophilic conditions (30–37 °C). This setup ensured effective microbial activity and gas measurement accuracy. The design followed standard configurations adopted in similar laboratory studies by Deepanraj et al. [12], Twizerimana et al.[13], and Lukitawesa [14].

2.2.7 Biogas production

The biogas production from anaerobic digestion of CD, CW and KW wastes were carried out under ambient temperature in batch bio-digesters. Feedstock mixtures were prepared and loaded into the digesters, which were tightly sealed to maintain anaerobic conditions. Each digester was connected via flexible tubing to a 1 L graduated measuring cylinder submerged in water for biogas measurement by water displacement. The volume of displaced water represented the amount of biogas produced, and readings were taken daily throughout the digestion period. Digesters were manually agitated twice daily to enhance substrate microbe contact and minimize scum formation. Cumulative biogas volumes were recorded and used for subsequent statistical and model analyses. Retention time for the anaerobic digestion was varied between 15 to 35 days [15], [16].

2.2.8 Regression and model analysis

A second order polynomial model was fitted to the experimental results. The regression model was calculated by analyzing the analysis of variance (ANOVA), p-value and F-value. The adequacy of the model was expressed by the coefficient of determination (R^2). The model describes the interaction among the parameters influencing the biogas yield by varying them concurrently. The biogas yield (Y) was modelled using Equation (2)

$$Y=\beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \beta_{23} BC + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2 \quad \ldots (2)$$

Where; A, B and C are independent variables upon which Y is dependent, β_0 is the constant term, β_1, β_2 and β_3 are the linear coefficients, β_{12}, β_{13} and β_{23} are interaction coefficients and β_{11}, β_{22} and β_{33} are the quadratic coefficients.

2.2.9 Model optimization and validation experiment

Optimization of biogas yield was carried out using response surface methodology (RSM). The optimum values of the process variables and the biogas yield were predicted by the statistical software Design Expert 13.0 software. The optimum conditions were used for the validation experiment to confirms the model developed.

III. RESULTS AND DISCUSSION

3.1. Characterization of feedstocks

Table 1 presents the proximate characteristics of cow dung, chicken waste, and kitchen waste. Moisture content ranged from 68–80%, with cow dung recording the highest value (80%), followed by chicken waste (75%) and kitchen waste (68%). These values fall within the optimal 60–85% range for effective anaerobic digestion [17]. Adequate moisture enhances hydrolysis and microbial activity [18], though excessive moisture (>90%) may dilute substrates and reduce yield [19]. Total solids varied between 20–32%, with kitchen waste showing the highest TS (32%) due to fibrous components [20]. For wet digestion systems, moderate TS levels (5–12% in slurry form) are recommended to ensure effective mixing and mass transfer [21]. The pH values (6.5–7.3) were within the optimal range for methanogenic activity [5]. Volatile matter was highest in kitchen waste (84%), indicating high biodegradability and gas potential [22], while cow dung provides microbial stability during co-digestion [23].

Table 2 indicates that cow dung (28.7:1) and kitchen waste (26.8:1) fall within the optimal C/N ratio range of 20–30:1 for methane production [24], [25], whereas chicken waste (14.8:1) presents ammonia inhibition risk due to excess nitrogen [3]. Elemental analysis showed kitchen waste had the highest carbon content (51%) [26], chicken waste the highest nitrogen (3.1%) [20], and cow dung moderate values supportive of process stability [25]. Low sulfur content (0.10–0.15%) minimizes hydrogen sulfide formation risks [3].

Table 1: Proximate analysis of feedstock

Parameter	Cow Dung	Chicken Waste	Kitchen Waste
Moisture Content (%)	80.00	75.00	68.00
Total Solids (TS, %)	20.00	25.00	32.00
Ph	7.10	7.3	6.50
Volatile Matter (Vm, % TS)	65.00	70.00	84.00
Fixed Solids (Fs, %TS)	13.00	17.00	5.00

Table 2: Ultimate analysis of feedstock

Parameter	Cow Dung	Chicken Waste	Kitchen Waste
Carbon (%)	43.00	46.00	51.00
Hydrogen (%)	5.90	6.50	6.00
Nitrogen (%)	1.50	3.10	1.90
Sulfur (%)	0.12	0.15	0.10
C/N Ratio	28.7:1	14.8:1	26.8:1

3.2 Analysis of Variance (ANOVA) and Model Fitness

The ANOVA results (Table 3) indicate that the quadratic model was statistically significant ($F = 63.06$, $p < 0.0001$). The high coefficient of determination ($R^2 = 0.9895$) shows that approximately 99% of the variation in biogas yield was explained by the model, demonstrating strong predictive capability. This aligns with findings by Tetteh et al. [27], who reported R^2 values above 0.95 in similar RSM-based biogas optimization studies.

Among the linear terms, retention time (B) and total solids (C) were significant ($p < 0.05$), confirming their direct influence on substrate degradation and microbial contact time. However, pH (A) was not significant as a linear term ($p > 0.05$), indicating that yield optimization occurs within a narrow pH window rather than through continuous increase, which agrees with established methanogenic sensitivity outside optimal limits [28]. While the interaction term AB was insignificant, AC and BC were significant ($p < 0.05$), and all quadratic terms (A^2, B^2, C^2) were significant, confirming curvature effects in the response surface.

Model validation statistics (Table 4) further confirmed robustness, with high adjusted R^2 (0.9738) and predicted R^2 (0.8773) values showing good agreement (difference < 0.2), indicating minimal overfitting. The Adeq Precision value (27.6432) demonstrated a strong signal-to-noise ratio, while the low coefficient of variation (5.41%) reflected high experimental reliability [29].

Table 3: Regression Model and Analysis of Variance

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	6.401E+06	9	7.112E+05	63.06	< 0.0001	Significant
A-pH	9940.50	1	9940.50	0.8815	0.3840	Not significant
B-Retention time	4.050E+06	1	4.050E+06	359.12	< 0.0001	Significant
C-Total Solids	1.458E+05	1	1.458E+05	12.93	0.0114	Significant
AB	57360.25	1	57360.25	5.09	0.0650	Not Significant
AC	1.533E+05	1	1.533E+05	13.59	0.0102	Significant
BC	3.938E+05	1	3.938E+05	34.92	0.0010	Significant
A^2	7.617E+05	1	7.617E+05	67.54	0.0002	Significant
B^2	7.478E+05	1	7.478E+05	66.31	0.0002	Significant
C^2	81082.56	1	81082.56	7.19	0.0365	Significant
Residual	67663.00	6	11277.17			
Lack of Fit	47357.00	3	15785.67	2.33	0.2524	not significant
Pure Error	20306.00	3	6768.67			
Cor Total	6.468E+06	15				

Table 4: Model Fitness Summary

Parameter	Value
Std. Dev.	106.19
Mean	1963.44
C.V. %	5.41
R^2	0.9895
Adjusted R^2	0.9738
Predicted R^2	0.8773
Adeq Precision	27.6432

3.3 Response surface and contour plots analysis

The relationships between the independent variables and biogas yield were illustrated using 3D response surface plots and 2D contour plots. In the 3D plots, two variables were varied while the third was kept constant. The contour plots showed the interaction strength: circular contours indicated weak or insignificant interactions, while elliptical contours signaled strong interactions [30]. Design Expert 13.0 was used to generate the response surfaces and contour plots.

Figures 1 and24 show the interaction between retention time and pH, revealing that biogas yield increases with longer retention time and pH values in the neutral to slightly alkaline range. Figures 3 and 4 illustrate the combined effects of total solids and retention time, with both factors positively influencing biogas output. Figures 5 and 6 depict the interaction between total solids and pH, indicating that biogas production is highest at moderate levels of both variables. Overall, pH, retention time, and total solids significantly influenced biogas yield.

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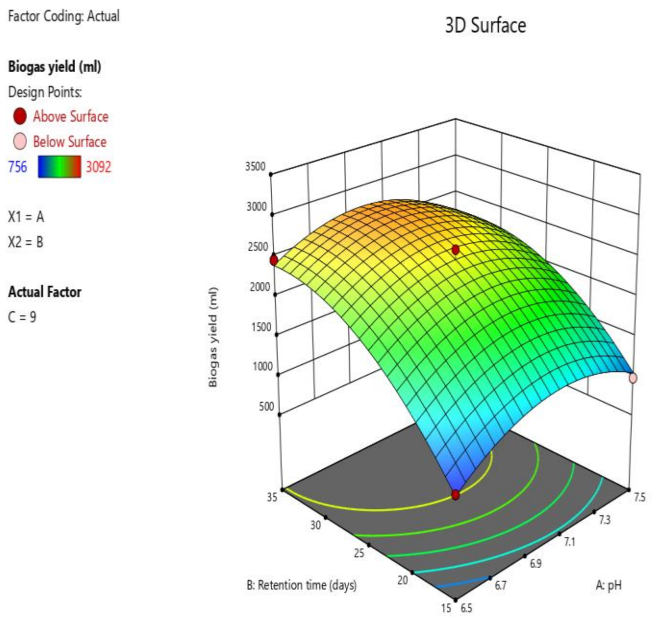

Figure 1: Response Surface Plot for pH and Retention time

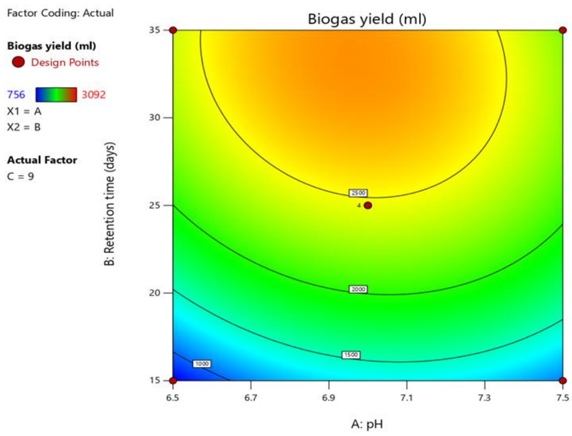

Figure 2: Contour Plot for pH and Retention time

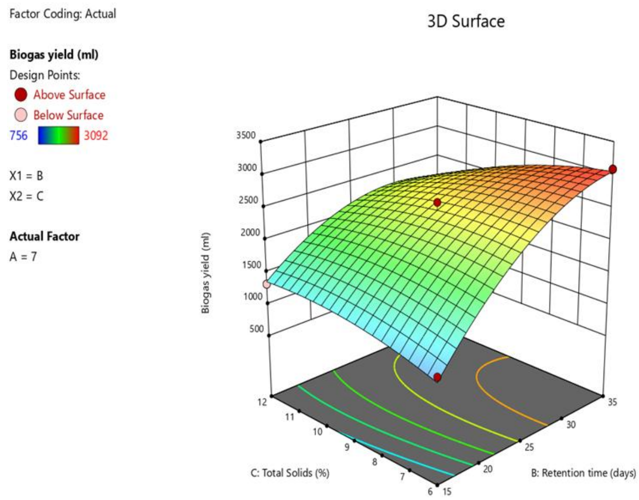

Figure 3: Response Surface Plot for Retention time and Total solids

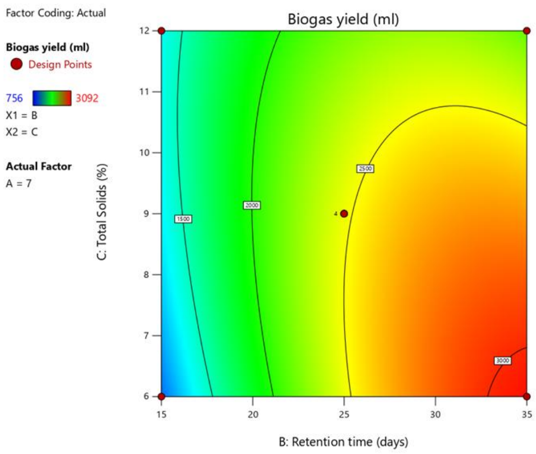

Figure 4: Contour Plot for Retention time and Total solids

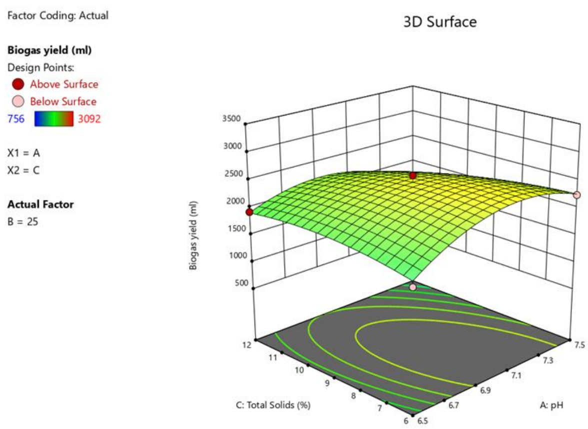

Figure 5: Response Surface Plot for Total solids and pH

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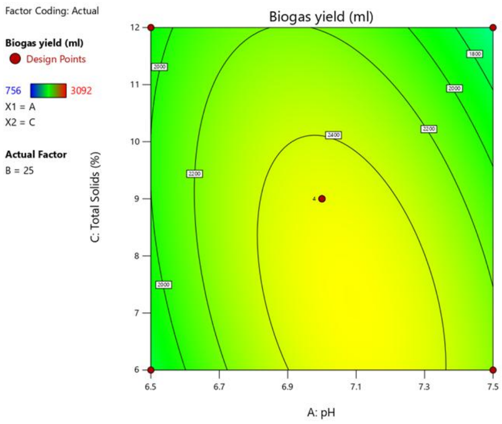

Figure 6: Contour Plot for Total solids and pH

3.2 Model optimization and validation experiment

Optimization was carried out to determine the best experimental conditions for maximizing biogas production. This process identifies the most desirable settings based on the goals assigned to each factor and response [31]. In this study, the pH, retention time, and total solids were set "in range," while biogas yield was set to "maximize," since it is the main output of the process. The objective of the model was therefore to achieve the highest possible biogas yield. The optimization constraints, including the experimental variables and biogas yield limits, are presented in Table 5.

Table 5: Constraints for Experimental conditions and Biogas yield

Name	Goal	Lower Limit	Upper Limit
A: pH	is in range	6.5	7.5
B: Retention time(days)	is in range	15	35
C: Total Solids (%)	is in range	6	12
Biogas yield (ml)	maximize	756	3092

The validation experiment indicates that the maximum biogas yield was obtained when the values of each parameter were set as the optimum values as shown in Table 6. It implies that the strategy to optimize the experimental conditions and to obtain the maximum biogas yield using RSM for the biogas production in this study was successful at the highest desirability of 0.987.

Table 6: Optimum Values for Experimental Condition and Biogas Yield

Number	pH	Retention time	Total Solids	Biogas yield	Desirability	
1	**7.063**	**35.000**	**6.000**	**3061.590**	**0.987**	**Selected**
2	7.067	35.000	6.000	3061.569	0.987	
3	7.066	34.879	6.000	3059.766	0.986	
4	7.056	34.876	6.000	3059.591	0.986	
5	7.071	34.845	6.000	3059.171	0.986	
6	7.073	35.000	6.114	3053.920	0.984	
7	7.063	35.000	6.142	3052.369	0.983	

The validation experiment yielded 3105.40 ml of biogas under optimal conditions of pH 7.063, total solids 6%, and a retention time of 35 days using cow dung, chicken waste, and kitchen waste under mesophilic conditions. These results confirm that pH, total solids, and retention time significantly enhance anaerobic digestion performance.

The optimum pH value (7.063) aligns with the pH 7.11 reported by Yusof et al. [32] for co-digestion of food waste and poultry manure. The optimal total solids content of 6% is consistent with the value reported for human excreta by Gohil et al. [33]. Similarly, the 35-day retention time agrees with findings from poultry waste digestion by Dornelas et al. [34]. The biogas yield obtained (3105.40 ml) also corresponds closely with the 3400 ml yield reported for palm oil mill residue with zeolite immobilization by Olalusi et al. [35].

3.3 Effects of Total Solids on Biogas Production

In this study, the Box–Behnken Design model identified 6% TS as the optimum level, producing the highest biogas yield. Although some studies report optimal TS ranges of 7–10% [12], [36], the lower value observed here reflects the characteristics of the mixed substrates (cow dung, poultry waste, and kitchen waste) and the digestion conditions used. At 6% TS, the substrate was well-diluted, improving microbial contact, reducing inhibitory compound buildup, and enhancing organic matter breakdown. Higher TS levels may have increased viscosity, restricted microbial movement, and reduced digestion efficiency.

Overall, the results indicate that for this particular substrate combination, a lower TS concentration (6%) created the most favorable conditions for microbial activity and biogas production, demonstrating that optimal TS levels depend on feedstock composition and operational parameters.

3.4 Effect of pH on Biogas Production

In this study, the pH significantly affected biogas yield, with the optimal pH value determined at 7.062. This lies within the commonly reported mesophilic optimum range of 6.8–7.5 [12]. Within this range, acidogenic and methanogenic activities are well balanced ensuring adequate conversion of volatile fatty acids (VFAs) into methane. At lower pH levels, excessive acid accumulation can inhibit methanogenic activity, leading to process instability and reduced gas output. Conversely, higher pH values beyond 8.0 tend to suppress microbial metabolism by creating an unfavorable alkaline environment. The optimal pH obtained in this study therefore indicates a stable balance between acid formation and methane generation, ensuring efficient digestion and enhanced gas yield.

3.6 Effect of Retention Time on Biogas Production

The results of this study revealed that biogas yield increased with longer retention times up to 35 days, after which no significant improvement was observed. This trend is consistent with the findings of [37], who reported that retention periods within 30–40 days are generally suitable for mesophilic digestion. At shorter retention times, the digestion process may be incomplete, resulting in lower methane yield due to insufficient microbial degradation.

However, excessively long retention times can lead to digester inefficiency, as additional time does not proportionally increase gas output but reduces system throughput [38]. Therefore, the observed optimum retention time of 35 days in this study indicates the period required for the microbial community to achieve complete stabilization of the substrate mixture (cow dung, poultry waste, and kitchen waste) under the prevailing mesophilic conditions. This balance between degradation efficiency and operational economy supports maximum biogas yield without process instability.

IV. CONCLUSION

The study successfully optimized biogas production from the co-digestion of cow dung, chicken waste, and kitchen waste using Response Surface Methodology. The optimum conditions were identified as pH 7.063, total solids 6%, and retention time 35 days under mesophilic conditions, yielding a maximum biogas output of 3105.40ml. These findings demonstrate that slightly alkaline conditions, low solids concentration, and extended retention time enhance microbial activity and substrate degradation.

Retention time was identified as the most influential parameter, followed by total solids, while pH showed minimal linear influence within the studied range (6.5–7.5). The statistical robustness of the model was confirmed by the non-significant lack of fit ($p = 0.2524$) and low coefficient of variation (5.41%), indicating high precision, reliability, and predictive capability.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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