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Optimization of Crystal Violet Adsorption onto Black Soldier Fly Pupae-Modified Avocado Seed Adsorbent Using Response Surface Methodology

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ABSTRACT

Crystal violet (CV) is a cationic dye widely used in various industrial applications, and its presence in the environment poses a potential risk to water quality. This study aimed to optimize the CV adsorption capability of a Black Soldier Fly pupae-modified avocado seed adsorbent (AS-BSF) using a Response Surface Methodology (RSM) with a Box-Behnken design (BBD). The quadratic model was statistically significant ($p < 0.0001$), with an R^2 of 0.9070 and an adjusted R^2 of 0.8139. Initial CV concentration and solution pH were significant linear factors, and all quadratic terms also significantly affected adsorption capacity. The model predicted optimum conditions of pH 7.75, an initial concentration of 1522.38 mg L⁻¹, a contact time of 46.83 min, and an adsorbent heating temperature of 47.93°C, yielding a predicted adsorption capacity of 166.916 mg g⁻¹ and a desirability value of 0.874. Experimental validation under the optimized conditions yielded an adsorption capacity of 169.114 mg g⁻¹. These results show that RSM-BBD effectively models and optimizes the CV adsorption capacity of the AS-BSF adsorbent.

Contribution to Sustainable Development Goals (SDGs):

SDG 6: Clean Water and Sanitation

SDG 12: Responsible Consumption and Production

SDG 9: Industry, Innovation and Infrastructure

1. INTRODUCTION

1.1. Research Background

The textile industry, inks, printing, and microbiological processes are just a few of the many uses for crystal violet (CV), a cationic dye. Because of its very stable chemical structure, CV can degrade water quality and, at certain concentrations, interfere with aquatic species' need for light penetration, which makes its presence in wastewater concerning [1]. Due to its ease of use and the ability to employ a wide range of inexpensive materials as adsorbents, adsorption is one of the most popular techniques for removing color from aqueous solutions [2]. Because biomass is readily available, renewable, and can be derived from biological sources or agricultural waste, using it as an adsorbent is a desirable method for treating wastewater. One kind of agro-

industrial waste that may be used as an adsorbent is avocado seed [3].

An earlier study demonstrated the potential of avocado seeds (AS) as a biomass-based material for removing cationic dyes, finding that avocado seed powder can remove CV from aqueous solutions [4]. Black Soldier Fly (BSF) pupae have the potential to serve as a modifying biomass because their chemical composition differs from that of avocado seed biomass and may contribute different surface functionalities to the resulting material. This reasoning is supported by a prior study showing that modifying avocado peel with maggot biomass changed the adsorbent surface properties and made more adsorption sites available, as demonstrated by FTIR, SEM-EDX, and XRF analyses, increasing the adsorbent capacity to remove CV [5]. Therefore, incorporating BSF pupae into avocado seed biomass was explored as a strategy to potentially modify the physicochemical properties and adsorption behavior of the resulting adsorbent.



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Adsorption capacity can be affected by adsorption parameters such as pH, initial concentration, contact time, and adsorbent heating. Because the effect of one parameter may depend on the conditions of others, the problem becomes more complicated. As a result, ideal circumstances may not accurately reflect the interactions among variables if a single factor is changed in isolation. A statistical technique called Response Surface Methodology (RSM) can develop mathematical models, assess the impact of process factors, and identify optimal system conditions. RSM makes it possible to assess interaction, quadratic, and linear effects among variables in a single model [6]. The Box-Behnken Design (BBD) is one experimental design that can be applied to RSM. This design enables the creation of a quadratic model with a comparatively efficient number of experiments by using three levels for each variable. RSM-BBD is hence appropriate for adsorption processes with multiple interacting factors.

1.2. Literature Review

1.2.1. Avocado seed

Tropical and subtropical climates are ideal for the avocado plant (*Persea americana*). In 2022, Indonesia produced 669.260 metric tons of avocados. However, seeds, skins, and fruit pulp, which make up 30% of the fruit's weight, are waste products of industrial and human use [7]. This offers an opportunity to use avocado seeds as an adsorbent. Numerous published studies have employed avocado seeds as adsorbents. Mahmoud et al. (2022) removed Cr(VI) using avocado pits, with optimum adsorption capacity of 21.8 mg g⁻¹ [8]. M. Essoufy et al. (2024) removed tartrazine and basic yellow 28 dyes using avocado seeds, with optimum adsorption capacities of 38.43 mg g⁻¹ and 49.30 mg g⁻¹, respectively [9]. Bazzo et al. (2016) removed crystal violet using avocado seeds, with optimum adsorption capacity of 95.9 mg g⁻¹ [4].

Avocado seeds contain cellulose, hemicellulose, and lignin. Avocado seeds also contain secondary metabolites such as flavonoids, phenolics, alkaloids, and tannins. Phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K) are among the minerals found in avocado seeds [10]. Hydroxyl (O-H), aromatic (C=C), carbonyl (C=O), and carboxyl (-COOH) groups are commonly reported in lignocellulosic biomass. Based on previous studies, these functional groups may contribute to the adsorption of cationic dyes such as crystal violet, supporting the potential of avocado seeds as an eco-friendly adsorbent [11]. Although avocado seeds have been reported to possess adsorbent properties for crystal violet, modifications were carried out as a means of enhancing their adsorption performance [12].

1.2.2. Black Soldier Fly

The family *Stratiomyidae* includes the Black Soldier Fly (*Hermetia illucens*), which is typically found in tropical areas. One well-known insect that has the potential to be used as a bioconversion agent for many kinds of organic waste and livestock manure is the BSF [13]. The egg, larval, prepupal, pupal, and adult fly stages make up the BSF life cycle [14]. According to Liu et al. 2017, the pupal stage contains up to 46% protein, followed by 8.2% fat, 9.6% ash, and 13% chitin. The composition of BSF pupae is of interest for adsorption applications because protein-containing materials may possess chemical functional groups capable of interacting with CV molecules. For example,

functional groups such as carbonyl (C=O) and carboxyl (COO⁻) may improve the adsorption interaction [15]. BSF has been used as an adsorbent in several studies, including the adsorption of Methylene Blue [16], Bromophenol Blue [17], and the adsorption of Cr (VI) in a composite with durian fruit [18]. While BSF-derived biomass has been studied as an adsorbent, this work uses it as a modifying biomass. This approach is predicated on the qualities of the two biomass types, which may enhance one another. Combining these biomass components may yield a material with adsorption properties distinct from those of the individual biomasses.

1.2.3. Response Surface Methodology

Response Surface Methodology is a statistical and mathematical approach that describes a dataset behavior for statistical prediction by fitting polynomial models to experimental data. To attain optimal performance, the goal is to optimize the levels of these factors simultaneously [19]. DOE (Design of Experiments) identifies design variables with a major impact for further research. Central Composite Designs (CCD), 3k-factorial designs, and Box-Behnken Designs (BBD) are examples of second-order designs, whereas 2-factorial, simplex, and Plackett-Burman designs are the most popular first-order designs [20]. The BBD and CCD are the two primary designs utilized in RSM. To efficiently estimate the first- and second-order coefficients of the mathematical model, BBD recommends choosing points from a three-level factorial arrangement. Reports have used RSM-BBD to optimize dye adsorption across a variety of adsorbent materials. Using locally sourced clay, Loqman et al. (2017) optimized the removal of CV using BBD while accounting for the starting dye concentration, adsorbent dosage, and contact time [21]. Another study achieved ideal circumstances with a removal efficiency of 97.86% by using calcium silicate waste as a CV adsorbent and applying BBD, taking into account the starting CV content, contact time, adsorbent dose, and pH as process factors [22]. Although avocado seed and BSF-derived biomass have individually been investigated as low-cost biosorbents, limited information is available regarding the use of BSF pupae as a modifying biomass for avocado seed-based adsorbents. Furthermore, the simultaneous optimization of CV adsorption using a BSF pupae-modified avocado seed adsorbent through RSM-BBD remains limited.

1.3. Research Objective

This study aims to optimize CV adsorption conditions using an avocado seed adsorbent modified with BSF pupae (AS-BSF) via Response Surface Methodology combined with the Box-Behnken Design (RSM-BBD). We evaluated the effects of process variables and their interactions on adsorption capacity using analysis of variance (ANOVA), and used a quadratic model to describe the relationship between process variables and the adsorption response. The optimum conditions were determined through a numerical optimization approach and subsequently validated experimentally. This approach is expected to provide a robust statistical basis for determining optimum operating conditions for CV adsorption using AS-BSF, whilst also offering a more effective strategy for using biomass to treat dyes in aqueous solutions.

2. MATERIALS AND METHODS

2.1. Materials

Avocado seeds were collected from Tebo Regency, Jambi, whilst Black Soldier Fly pupae were collected from a maggot farmer in the city of Padang, West Sumatra. The chemicals used were Crystal Violet dye, HNO₃ p.a., NaOH, CHCl₃ p.a., CH₃OH p.a., C₂H₅OH p.a. (all chemicals used were sourced from Merck). Distilled water and buffer solution were also used.

2.2. Instruments

The instruments used in this study included an analytical balance (Shimadzu ATX224R), a pH meter (Metrohm), a UV-Vis spectrophotometer (Thermo Scientific Genesys 20), and standard laboratory glassware (Pyrex). The statistical analysis and experimental design were performed using Design-Expert version 13 (Stat-Ease, Inc., USA).

2.3. Sample Preparation

Avocado seed powder was prepared to a particle size of $\leq 36 \mu\text{m}$ by sieving through a 400 mesh sieve. It was then activated with a 0.01 M HNO₃ solution at a solid-to-liquid ratio of 1:3 (w/v) for 120 min, following a previously reported method [23]. The activated powder was washed repeatedly with distilled water until the filtrate reached approximately neutral pH, then dried at 60°C for 60 min. Defatting of the BSF pupae powder was carried out using a previously reported method involving chloroform and methanol [24]. A total of 10 g of BSF pupae powder was macerated with 30 mL of chloroform and 70 mL of methanol. The mixture was stirred at 200 rpm for 24 hours, then filtered and air-dried. The adsorbent was modified by mixing 9 g avocado seed powder and 9 g BSF pupa powder in 75 mL ethanol, followed by sonication for 15 min and air-dried at room temperature [25]. The BSF pupae-modified avocado seed adsorbent (AS-BSF) was subsequently used in the CV adsorption experiment.

2.4. Determination of Adsorption Capacity for Crystal Violet Dye

The adsorption experiments were carried out in batches by mixing 0.1 g of adsorbent with 25 mL of CV solution at 200 rpm, under conditions determined using the RSM-BBD model. The adsorbent was then separated from the solution, and the residual CV dye concentration was determined by UV-Vis spectrophotometer at 590 nm. The adsorption capacity for CV dye was calculated using Equation 1.

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (1)$$

Where C_0 and C_e are the initial and equilibrium concentrations (mg L^{-1}) of the CV dye, m (g) is the mass of the adsorbent, and V (L) is the volume of the solution.

2.5. Experimental Design and Response Surface Methodology

The Design-Expert 13 software was used to perform RSM optimization with the Box-Behnken Design (BBD). In this design, the predicted response (Y) is adsorption capacity, influenced by four parameters: pH (7–9), initial concentration

(1400–1600 mg L^{-1}), contact time (30–60 min), and heating adsorbent (25–75°C).

The experimental ranges were defined based on preliminary screening to establish a suitable domain for RSM-BBD optimization. The selected domain enabled identification of the optimal zone and evaluation of each factor at three levels. The relatively high initial CV concentration was included to assess adsorption capacity under high solute loading, rather than to represent typical wastewater concentrations, as adsorption capacity (q_e) was the optimization response.

Table 1 presents the variables and their level codes, with each factor studied at three levels (-1, 0, and +1). The RSM-BBD method generated 29 adsorption condition designs, as shown in Table 2. The response values were obtained experimentally. After obtaining the response values, statistical analysis and visualization were conducted to investigate the effects of these parameters and determine the optimum adsorption conditions.

Table 1. Experimental design levels for various parameters

Factor	Name	Units	Variable Level Code		
			-1	0	+1
A	pH		7	8	9
B	Initial concentration	mg L^{-1}	1400	1500	1600
C	Contact time	min	30	45	60
D	Heating adsorbent	°C	25	50	75

Table 2. Experimental design matrix using the RSM-BBD method

Run	pH	Initial concentration (mg L^{-1})	Contact time (min)	Heating adsorbent (°C)
1	8	1600	30	50
2	7	1500	45	75
3	9	1500	45	75
4	8	1500	45	50
5	7	1500	60	50
6	8	1400	45	25
7	8	1400	30	50
8	8	1600	45	75
9	8	1500	30	25
10	8	1400	45	75
11	8	1400	60	50
12	9	1500	30	50
13	7	1500	45	25
14	9	1500	45	25
15	8	1600	60	50
16	8	1500	60	25
17	8	1500	45	50
18	7	1600	45	50
19	7	1400	45	50
20	9	1500	60	50
21	9	1600	45	50
22	8	1600	45	25
23	8	1500	45	50
24	8	1500	45	50
25	9	1400	45	50
26	8	1500	45	50
27	8	1500	60	75
28	8	1500	30	75
29	7	1500	30	50

The relationship between the independent parameters and the predicted response is given by the following quadratic equation (2):

$$Y = b_0 + \sum_{i=1}^n b_i x_i + \sum_{i=1}^n b_{ii} x_i^2 + \sum_{i \neq j}^n b_{ij} x_i x_j \quad (2)$$

where x_i and x_j denote the independent variables at their coded levels, Y stands for the predicted response, and the terms b_{ij} , b_{ii} , b_i , and b_0 represent the interaction, quadratic, linear, and intercept coefficients, respectively, while n indicates the number of independent variables [26]. The goodness of fit and statistical significance of the developed model were assessed using the coefficient of determination (R^2), analysis of variance, and the p -value.

3. RESULT AND DISCUSSION

3.1. Effects of Process Variables on Crystal Violet Adsorption Capacity

The determination of the CV adsorption capacity by the AS-BSF adsorbent using the RSM-BBD method involved four adsorption parameters. The parameters varied as independent variables included pH (7-9), initial concentration (1400-1600 mg L⁻¹), contact time (30-60 min), and adsorbent heating (25-75°C). Variations in these four parameters resulted in differences in the CV adsorption capacity produced for each treatment.

Table 3 presents the results of 29 experimental runs designed using the RSM-BBD method. The measured CV adsorption capacities of the AS-BSF ranged from 150.41 to 169.29 mg g⁻¹. The highest value was obtained in run 23 under conditions of pH 8, an initial concentration of 1500 mg L⁻¹, a contact time of 45 min, and a heating temperature of 50°C. Conversely, run 25 showed the lowest CV adsorption capacity at pH 9, an initial concentration of 1400 mg L⁻¹, a contact time of 45 min, and a heating temperature of 50°C.

The mathematical model used to predict the adsorption capacity of the CV dye followed a second-order polynomial equation. The regression equations in terms of coded factor and actual factors are presented in Equations (3) and (4), respectively. Coded-factor equation:

$$q_e = +166.23 - 2.97A + 2.28B + 0.6371C - 0.5097D + 1.15AB - 0.7645AC - 0.6371AD - 0.2548BC + 0.1274CD - 5.59A^2 - 4.37B^2 - 3.10C^2 - 2.02D^2 \quad (3)$$

Actual-factor equation:

$$q_e = -1124.41605 + 72.75727A + 1.25111B + 1.92828C + 0.491009D + 0.011468AB - 0.050968AC - 0.025484AD - 0.000170BC - 1.00000 \times 10^{-8}BD + 0.000340CD - 5.58529A^2 - 0.000437B^2 - 0.013780C^2 - 0.003228D^2 \quad (4)$$

In the coded-factor equation, A, B, C, and D represent pH, initial concentration, contact time, and heating adsorbent, respectively. These variables indicate their respective experimental values within the studied ranges in the actual-factor equation. While the

actual-factor equation estimates adsorption capacity using the experimental values of the independent variables, the coded regression equation makes it easier to evaluate the relative effects of the process variables.

Table 3. Results of CV dye adsorption capacity using the RSM-BBD method

Run	pH	C ₀ (mg L ⁻¹)	t (min)	T (°C)	q _e (mg g ⁻¹)	
					Actual	Predicted
1	8	1600	30	50	162.18	160.65
2	7	1500	45	75	161.65	161.73
3	9	1500	45	75	156.04	154.51
4	8	1500	45	50	164.20	166.23
5	7	1500	60	50	162.16	161.92
6	8	1400	45	25	160.10	158.07
7	8	1400	30	50	153.47	155.59
8	8	1600	45	75	159.12	161.61
9	8	1500	30	25	161.14	161.12
10	8	1400	45	75	157.54	157.05
11	8	1400	60	50	156.01	157.37
12	9	1500	30	50	154.00	154.70
13	7	1500	45	25	160.12	161.48
14	9	1500	45	25	157.06	156.80
15	8	1600	60	50	163.71	161.42
16	8	1500	60	25	162.16	162.13
17	8	1500	45	50	166.74	166.23
18	7	1600	45	50	160.14	160.38
19	7	1400	45	50	158.56	158.12
20	9	1500	60	50	152.98	154.45
21	9	1600	45	50	156.58	156.72
22	8	1600	45	25	161.67	162.63
23	8	1500	45	50	169.29	166.23
24	8	1500	45	50	165.72	166.23
25	9	1400	45	50	150.41	149.88
26	8	1500	45	50	165.21	166.23
27	8	1500	60	75	161.65	161.37
28	8	1500	30	75	160.12	159.84
29	7	1500	30	50	160.12	159.12

The coded regression equation indicates that the response was influenced by both linear and quadratic effects of the investigated variables. Although the linear coefficients of initial CV concentration (B) and contact time (C) were positive, whereas those of pH (A) and heating adsorbent (D) were negative, the negative quadratic coefficients for all variables indicate downward curvature of the response surfaces. As a result, rather than being purely monotonic, the impacts of the various components should be evaluated within the examined experimental ranges. The presence of curvature and a nonlinear response are further indicated by the negative quadratic components, indicating that ideal conditions might exist within the factor ranges under investigation [27].

The ANOVA results (Table 4) indicated that the developed model was significant ($F = 9.75$; $p < 0.0001$). The R^2 value of 0.9070 indicates that the model explains 90.70% of the variation

in CV adsorption capacity, while the Adjusted R^2 was 0.8139 after accounting for the number of model terms. The difference between these values indicates that the quadratic model's complexity should be considered when interpreting its goodness of fit. The Predicted R^2 of 0.5840 was lower than the Adjusted R^2 , suggesting that the model's predictive performance for new observations was more moderate than its goodness of fit to the experimental data. Nevertheless, the non-significant Lack of Fit result ($p = 0.5948$) indicated no statistically significant evidence of model inadequacy relative to the pure error. The low coefficient of variation ($CV = 1.17\%$) further indicated good experimental precision. In addition, the Adeq Precision value of 12.1473, which was greater than 4, indicated an adequate signal-to-noise ratio for navigating the investigated design space. Therefore, the model was considered suitable for describing the experimental response and identifying the optimum conditions within the investigated factor ranges, although its predictive performance for observations beyond the fitted experimental data should be interpreted with caution.

Table 4. ANOVA results of the quadratic model for removal of CV dyes using AS-BSF

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	478.44	14	34.17	9.75	< 0.0001
A-pH	106.08	1	106.08	30.26	< 0.0001
B-Initial concentration	62.19	1	62.19	17.74	0.0009
C-Contact time	4.87	1	4.87	1.39	0.2581
D-Heating adsorbent	3.12	1	3.12	0.8893	0.3617
AB	5.26	1	5.26	1.50	0.2408
AC	2.34	1	2.34	0.6670	0.4278
AD	1.62	1	1.62	0.4632	0.5072
BC	0.2597	1	0.2597	0.0741	0.7894
BD	2.50E-09	1	2.50E-09	7.132E-10	1.0000
CD	0.0649	1	0.0649	0.0185	0.8937
A ²	202.35	1	202.35	57.73	< 0.0001
B ²	124.14	1	124.14	35.42	< 0.0001
C ²	62.36	1	62.36	17.79	0.0009
D ²	26.40	1	26.40	7.53	0.0158
Residual	49.08	14	3.51		
Lack of Fit	34.01	10	3.40	0.9029	0.5948
Pure Error	15.07	4	3.77		
Cor Total	527.52	28			
$R^2 = 0.9070$	Adjusted $R^2 = 0.8139$		C.V.% = 1.17		
SD = 1.87	Predicted $R^2 = 0.5840$		Adeq Precision = 12.1473		

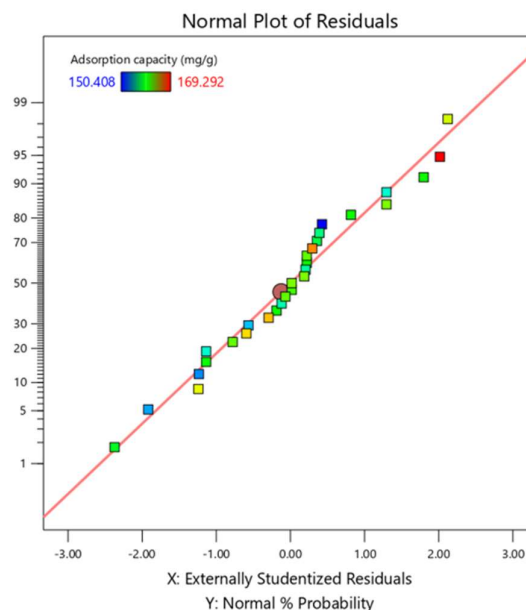


Figure 1. Plot of normal probability for CV removal using AS-BSF

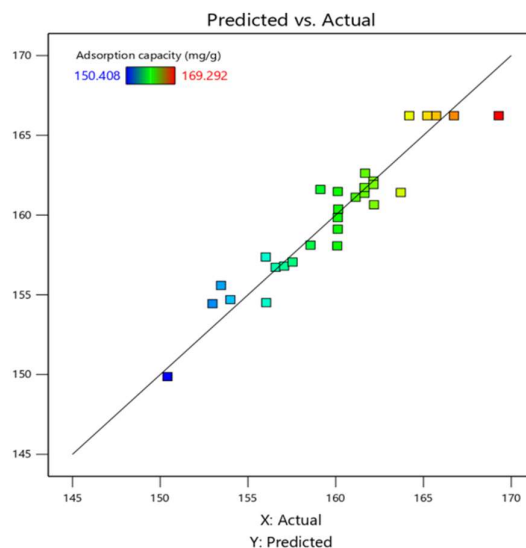


Figure 2. Observed values versus the predicted values for CV dye adsorption

The normal probability plot in Figure 1 indicated that the residuals approximately followed a normal distribution, as most data points lay close to the diagonal reference line without major deviations. This graphical pattern suggests that the normality assumption was reasonably satisfied within the experimental data. The predicted versus actual plot in Figure 2 showed a generally close correspondence between the experimentally observed adsorption capacities and the model predictions, with most data points located near the diagonal reference line. This pattern indicates that the model fits the response well over the experimental range under study. In RSM-based research, including adsorption processes, these two diagnostic plots are frequently used to assess model adequacy [28].

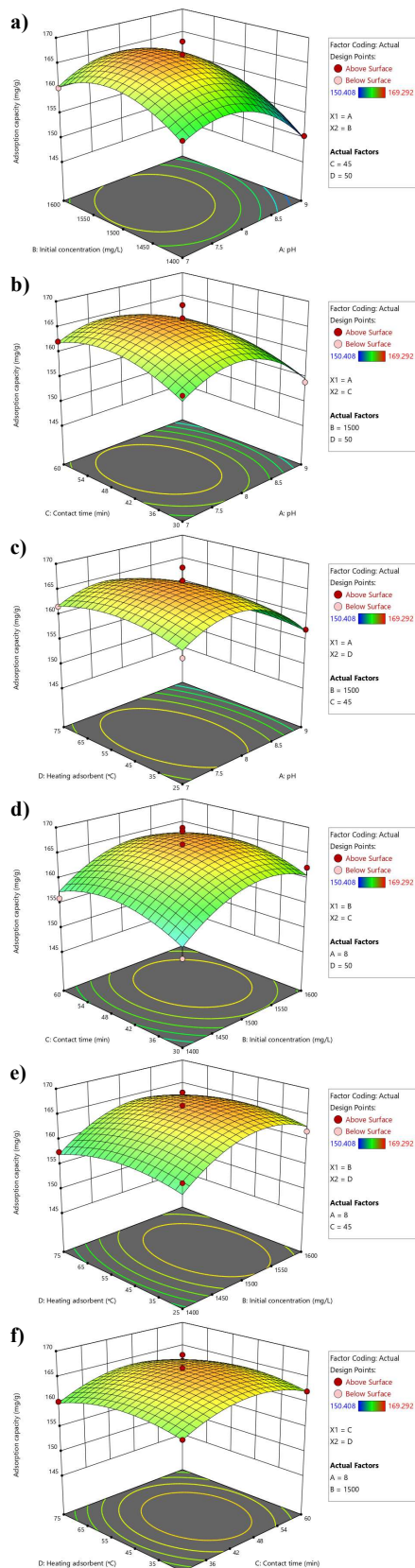


Figure 3. Three-dimensional response plots showing the combined effects of pairs of process variables on the predicted CV adsorption capacity: (a) pH vs. initial concentration, (b) pH vs. contact time, (c) pH vs. heating adsorbent, (d) initial concentration vs. contact time, (e) initial concentration vs. heating adsorbent, and (f) contact time vs. heating adsorbent.

The three-dimensional response surface plots in Figure 3 (a–f) illustrate the combined effects of pairs of process variables on the predicted CV adsorption capacity of AS-BSF, while the remaining variables were maintained at their center levels. All two-factor interaction terms in the quadratic model were statistically non-significant ($p > 0.05$). Therefore, the response surface plots should not be interpreted as evidence of statistically significant interactions between the corresponding variables. Instead, they graphically represent the simultaneous variation of two factors within the investigated experimental domain.

In general, the response surface is curved, indicating a non-linear relationship between the process variables and the adsorption capacity. This pattern is consistent with the ANOVA results, which show that all quadratic terms have significant effects and negative coefficients. For all factor combinations, adsorption capacity tends to reach higher values in the interior regions of the surface before decreasing under certain conditions across the factor range studied. This indicates that an increase in a factor does not always result in a linear increase in adsorption capacity and that there is an optimal region that can be predicted using the RSM model [29]. Loqman et al. (2017) also reported using response surface plots in RSM-BBD to visualize the effects of process variables and identify the optimal region for CV adsorption [21].

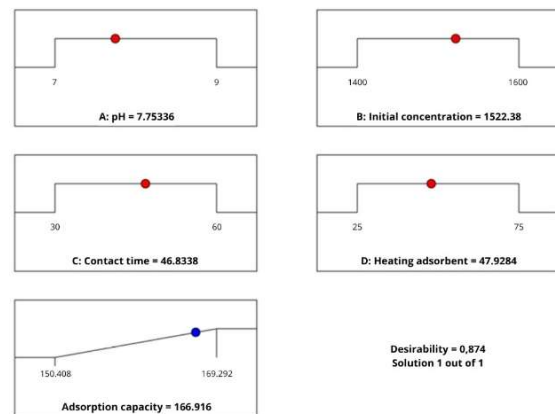


Figure 4. Optimum conditions for CV dye adsorption capacity

The outcomes of the optimization using RSM shown in Table 13. The optimization predicted the maximum adsorption capacity under the conditions of pH 7.75, initial concentration of 1522.38 mg L⁻¹, contact time of 46.83 min, and heating adsorbent of 47.93°C. Under these conditions, the model predicted an adsorption capacity of 166.916 mg g⁻¹ with a desirability of 0.874. This desirability value indicates a high degree of success for the optimization objective, as it is close to 1 [30]. The desirability feature method, which determines the ultimate conditions based entirely on the RSM model, has also been used to optimize CV adsorption using BBD. To validate the predictive capability of the developed quadratic model, the optimized conditions were tested experimentally in three independent replicates. The adsorption capacities obtained were 168.774, 170.303, and 168.264 mg g⁻¹, resulting in an experimental mean of 169.114 ± 1.061 mg g⁻¹. This experimental value was compared with the adsorption capacity predicted by the numerical optimization (166.916 mg g⁻¹), with a relative difference of 1.32%. The close agreement between the experimental and predicted values supports the predictive capability of the developed quadratic

model. These validation results support the finding that the advanced second-order polynomial model has good predictive capability and can be used to determine the best conditions for CV adsorption by the AS-BSF adsorbent. The validation technique, which involved assessing predicted and experimental responses, was also employed in the RSM-BBD study on CV adsorption.

Table 5. Comparison of the crystal violet adsorption capacity of AS-BSF with that of other adsorbents

Adsorbent	q _{max} (mg g ⁻¹)	Reference
Maggot-modified avocado peel	223.49	[5]
NaOH-modified avocado shells	179.80	[12]
BSF Pupae-modified avocado seed	169.114	This work
Wheat bran	116.94	[31]
Sugarcane bagasse	107.5	[32]
TiO ₂ nanotubes (TNTs)	84.7	[33]
Cedar cone	13.6	[34]
Bitter gourd	2,407	[35]

The experimental adsorption capacity of the AS-BSF adsorbent was compared with those reported for other adsorbents used for CV removal to provide context for the adsorption performance obtained under the optimized conditions (Table 5). The adsorption capacity obtained in this study (169.114 ± 1.061 mg g⁻¹) was higher than those reported for wheat bran, *sugarcane bagasse*, TiO₂ nanotubes, cedar cone, and bitter gourd waste, but lower than those reported for maggot-modified avocado peel (223.49 mg g⁻¹) and NaOH-modified avocado peel (179.80 mg g⁻¹). Overall, these results indicate that the AS-BSF adsorbent exhibited competitive adsorption performance compared with several previously reported adsorbents. However, direct comparisons should be interpreted cautiously because the reported values may be influenced by differences in adsorbent preparation, experimental conditions, and methods used to determine adsorption capacity.

The utilization of avocado seed and BSF pupae biomass offers a viable method for turning biomass-derived resources into a value-added adsorbent for dye removal from a sustainability standpoint, which is in line with the concepts of the circular economy. Compared with traditional synthetic adsorbents, these biomass-based compounds may offer advantages in raw material availability and adsorbent production costs. However, the energy needed for drying and heating, as well as the use of chemicals during adsorbent preparation, should be considered for the overall process sustainability. Additionally, this work did not examine CV-loaded adsorbent management, regeneration, and reuse, which should be assessed in subsequent research before practical implementation. By promoting water treatment, sustainable material development, and biomass valorization, respectively, this strategy may help achieve SDGs 6, 9, and 12.

4. CONCLUSION

The optimization of crystal violet (CV) adsorption capacity by an adsorbent derived from avocado seeds modified with Black Soldier Fly pupae (AS-BSF) was successfully achieved using Response Surface Methodology with a Box–Behnken design. The resulting second-order polynomial model was significant and described the relationship between process variables and adsorption capacity, yielding an R² value of 0.9070. pH and initial

CV concentration were linear factors that significantly influenced the response, whereas the quadratic effects of all factors indicated non-linear relationships. Optimum conditions were identified at a pH of 7.75, an initial CV concentration of 1522.38 mg L⁻¹, a contact time of 46.83 minutes, and an adsorbent heating temperature of 47.93°C, resulting in a predicted adsorption capacity of 166.916 mg g⁻¹. Experimental verification yielded an adsorption capacity of 169.114 mg g⁻¹, which differed by only 1.32% from the predicted value. Thus, the developed RSM-BBD model can be used to determine optimal conditions and predict CV adsorption capacity by AS-BSF within the investigated range.

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