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Optimization of Methylene Blue Dye Adsorption onto Coconut Husk Cellulose Using Response Surface Methodology: Adsorption Kinetics, Isotherms and Reusability Studies

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Abstract

In this study, coconut husk cellulose was employed as a cost-effective and environmentally friendly adsorbent to eliminate methylene blue (MB) dye from aqueous solutions. The successful development of response surface methodology paired with a central composite design (RSM-CCD) enabled the optimization and modelling of the adsorption process. The study investigated the individual and combined effects of three variables (pH, contact time, and initial MB dye concentration) on the adsorption of MB dye onto coconut husk cellulose. The developed RSM-CCD model exhibited a remarkable degree of precision in predicting the removal efficiency of MB dye within the specified experimental parameters. This was demonstrated by the strong regression parameters, with an R^2 value of 99.79% and an adjusted R^2 value of 99.6%. The study depicted that the optimal parameters for attaining a 98.8827% removal of MB dye using coconut husk cellulose were as follows: an initial MB dye concentration of 30 mg·L^{-1}, contact time of 120 minutes, and pH 7 at a fixed adsorbent dose of 0.5 g. The Freundlich isotherm model provided the most satisfactory description of the equilibrium adsorption isotherms, suggesting that MB dye adsorption onto coconut husk cellulose occurs on a heterogeneous surface. The experimental results demonstrated a strong agreement with the pseudo-second-order kinetics model, indicating that the number of active sites present on the cellulose adsorbent predominantly influences the adsorption process of MB dye. Additionally, the adsorbent made from coconut husk cellulose exhibited the potential to be reused, as it retained its efficiency for a maximum of three cycles of adsorption of MB dye. The results of this study show that coconut husk cellulose has the potential to be an effective and sustainable adsorbent for removing MB dye from aqueous solutions.

Keywords

Adsorption Kinetics, Isotherms, Optimization, Response Surface Methodology, Cellulose

1. Introduction

The proliferation of technological advancements globally across diverse sectors has resulted in an escalation of environmental pollution [1]. Water contamination is a prominent environmental concern on a global scale due to the limited availability of water supplies. An estimated 10% - 15% of the dyes utilized in sectors like textile, leather, pharmaceuticals, plastic, polymers, and pigment industries are discharged into industrial effluents while producing final goods [2]. Furthermore, with the expansion of the textile market, there has been a corresponding increase in the volume of wastewater generated by the textile sector, making the sector a significant contributor to global water pollution [3]. Dyes possess significant toxicity and pose a substantial risk to terrestrial and marine ecosystems even at very low concentrations [4]. The presence of dyes in wastewater, even in trace amounts, is remarkably objectionable and undesirable [5]. Availability of these compounds has a significant impact on the ecological conditions of water bodies, as they disrupt sunlight transmission, hence impeding the process of photosynthesis and the oxygenation of water reservoirs [6]. MB is a highly toxic thiazine dye used extensively in cotton dyeing. Numerous studies have demonstrated that MB dye causes nausea, ocular injury, vomiting, etc., in humans and animals [7].

Conventional water treatment technologies, including physiochemical processes, membrane processes, advanced oxidation processes, electrochemical technology, reverse osmosis, ion exchange, electrolysis, and electro-dialysis, are frequently employed in the removal of MB dye in water [8]. Nevertheless, the removal of pigmented contaminants from industrial wastewater using these techniques has significant limitations, including high costs, substantial energy demands, and the generation of hazardous byproducts. Hence, it is imperative to pursue advancing technologies and solutions that are more efficient, ecologically conscious, economically viable, and sustainable to address the issue of dye removal from industrial effluents.

Adsorption is widely recognized as a highly favorable and promising technique compared to the aforementioned alternatives. This recognition stems from its inherent simplicity, effectiveness, ease of operation, ability to regenerate adsorbents, and exceptional capacity to remove a wide range of dangerous compounds from contaminated effluents [9]. Adsorption efficiency is impacted by various parameters, such as adsorbent material properties, contaminant origin, and how the adsorbent and adsorbate interact [10]. A variety of adsorbents, such as bentonite, fly ash, wood shavings, silica, charcoal, china clay and activated carbon, have been researched for their effectiveness in the elimination of dyes from industrial wastewater [11]. Nevertheless, it is crucial to note that these adsorbents typically exhibit minimal adsorption capabilities, necessitating their utilization in significant quantities. Consequently, there exists an urgent requirement for the advancement of novel adsorbents that are both cost-effective and efficient, particularly those derived from natural resources and are biodegradable.

The coconut husk is an agricultural residue that is abundantly found in the coastal region of Kenya. The coconut husk refers to the external covering of the coconut fruit, constituting around 33% - 35% of the total mass of the fruit [12]. Coconut husk can be converted to suitable materials such as cellulose which can be used to adsorb contaminants from wastewater. Additionally, coconut husk cellulose presents a potential solution to waste management challenges while enhancing the demand for coconut by-products. The primary objective of the recent study was to optimize the adsorption efficiency of MB dye onto coconut husk cellulose using response surface methodology with the central composite design (RSM-CCD). Additionally, the study aimed to assess the adsorption isotherms, adsorption kinetics, and reusability of the adsorbent.

2. Materials and Methods

2.1. Reagents and Methodology

The cellulose used in the present study as an adsorbent was extracted from coconut husks. In this process, coconut husks were subjected to milling and alkali pretreatment using 10% sodium hydroxide (NaOH) at 70˚C for 4 hours, followed by filtration and washing. The alkali pretreatment product underwent bleaching through the use of 12% sodium hypochlorite for 36 hours, followed by subsequent processes of filtration and washing. The products underwent a second round of alkali pretreatment and bleaching, after which they were again subjected to filtering and washing. The resultant product was subjected to a drying process before use. The methylene blue dye and other chemicals used in this study were of analytical grade and were maintained in a desiccator to prevent any alterations caused by moisture. The reagents and standards were prepared using deionized water. The pH of the MB dye solutions was adjusted by using 0.1M hydrochloric acid (HCl) and 0.1M sodium hydroxide (NaOH).

2.2. Central Composite Design

The traditional method of optimizing adsorption processes for achieving optimum dye removal efficiency, known as one factor at a time optimization, is an extensive process that necessitates conducting many experimental tests [13]. The efficacy of CCD in reducing the time and cost of experimental tests has been demonstrated in recent studies [14]. The present work employs this methodology to effectively improve process parameters for the adsorption of MB dye onto coconut husk cellulose. The 2^n factorial design with the origin at the center allows for the execution of multiple tests (N). The quadratic term is generated by the axial arrangement of the $2n$ points at a certain distance from the center, where n is the number of independent variables. The experimental design employed in the current study involves three independent variables. Given the above conditions, equation 1 can approximate the number of tests (N) needed for three independent variables.

$$N = 2^n + 2n + n_c = 2^3 + (3 \times 2) + 6 = 20 \tag{1}$$

Table 1 shows the low, center and high levels of the independent variables to be optimized in the adsorption of MB dye onto coconut husk cellulose.

2.3. Batch Adsorption Studies

The adsorption experiment tests were conducted following the CCD experimental model. The experimental procedure involved conducting every experiment within a 250 mL Erlenmeyer flask, which had a maximum capacity of 50 mL for the reaction mixture. The pH of the aqueous MB dye solutions was adjusted by adding an appropriate amount of either 0.1 M HCl or 0.1 M NaOH. The conical flask was filled with the prescribed initial MB dye concentration and combined with 0.5 g of coconut husk cellulose. The mixture was then subjected to swirling for a designated period using a level shaker, followed by centrifugation at 5000 rpm for 10 minutes. The UV-Vis spectrophotometer (UV-1800 SHIMADZU) was used to measure the absorption intensity of the supernatant solution at a wavelength of 664 nm. The concentration of dyes in the supernatant solution was calculated by using the calibration curve of methylene blue. The experimental tests were performed twice, with each run being randomly chosen, and the mean of the measurements was shown. Equation (2) was used to calculate the response of interest in this experimental design, which was the removal efficiency (%) of the MB dye;

$$\text{Removal efficiency}(\%) = (Co - Ce)/C \times 100 \tag{2}$$

where C_e (mg/L) is the concentration of the dye at equilibrium and C_0 is the initial concentration of MB dye. The adsorption capacity equilibrium q_e (mg·g^{-1}) was calculated using Equation (3);

$$\text{Adsorption capacity}(Qe) = ((Co - Ce)/W)V \tag{3}$$

Table 1. Actual experimental values and levels in CCD.

		Levels		
Factors	**Symbol**	**Low (−1)**	**Center (0)**	**High (+1)**
Contact time (minutes)	A	40	80	120
Dye concentration (mg·L^{-1})	B	30	65	100
pH	C	3	5	7

where C_e (mg/L) is the concentration at equilibrium, C_0 is the initial concentration of MB dye, W is the adsorbent mass (g), V is the volume of the dye solution (L).

2.4. Adsorption Kinetics

In this study, a fixed mass of coconut husk cellulose 0.5 g, initial MB concentration of 30 mg·L^{-1}, at pH 7, and varied contact time of 30, 60, 90, 120, 150 and 180 minutes were used in batch adsorption experiments at room temperature. The pseudo first and pseudo second order kinetic models were evaluated separately to analyze experimental data. Linear Equation (4) is the pseudo-first-order kinetic model.

$$\ln\left(q_e - q_t\right) = \ln q_e - k_1 t \tag{4}$$

Equation (5) is the linear form of the pseudo second-order kinetic model;

$$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} \tag{5}$$

where q_t and q_e refers to the adsorption capacity (mg·g^{-1}) at time t and equilibrium, respectively, k_1 is the equilibrium rate constant of pseudo-1st-order model (min^{-1}) and K_2 is the equilibrium rate constant of pseudo-second order model (g·mg^{-1}·min^{-1}).

2.5. Adsorption Isotherms

Adsorption studies were carried out by changing the initial concentration of MB dye between 20 and 100 mg/L. pH, adsorbent dose, and contact time were held constant at pH 7, 0.5 g, and 120 minutes, respectively. The Langmuir and Freundlich isotherm models were used to align with the experimental results in order to appropriately depict the interaction between the MB dye and the cellulose adsorbent at equilibrium. The linear form of the model equation is presented as follows:

$$\ln\left(q_e\right) = \ln\left(K_F\right) + \frac{1}{n}\left(\ln C_e\right) \tag{6}$$

The Langmuir isotherm model equation is expressed in linear form as follows:

$$\frac{C_e}{q_e} = \frac{1}{q_m K_L} + \frac{C_e}{q_m} \tag{7}$$

where C_e is the MB concentration at equilibrium (mg·L^{-1}), q_e is the adsorption capacity at equilibrium (mg·g^{-1}), K_L is the Langmuir adsorption constant (L·mg^{-1}), K_F is Freundlich adsorption constant, and n is the heterogeneity factor and q_m is the maximum adsorption capacity (mg·g^{-1}).

2.6. Desorption and Reusability Studies

A batch adsorption experiment was performed at room temperature for 120 minutes with an initial MB dye concentration of 30 mg/L and an adsorbent dosage of 0.5 g to explore the reusability of the cellulose used as an adsorbent.

Adsorbent desorption was accomplished after attaining equilibrium by dissolving 0.5 g of saturated cellulose adsorbent in 50 mL of 0.5 M HCl as the desorbing agent. A level shaker was used to agitate the mixture for one hour followed by filtration, washing with deionized water and oven dried before use.

3. Results and Discussion

3.1. Response Surface Methodology Modelling Using Central Composite Design

The application of RSM-CCD was employed to optimize the experimental parameters for the effective adsorption of methylene blue dye molecules onto coconut husk cellulose. Three independent factors were chosen for investigation: contact time, MB dye solution pH, and initial MB dye concentration (mg/L). The aim was to examine their linear effects, two-factor interactions and quadratic effects. The selection of these parameters was informed by existing literature on the adsorption of MB dye [15], as well as by the findings of preliminary investigations conducted in the laboratory. The amount of adsorbent (g) was held constant at 0.5 g. Table 2 demonstrates the experimental design matrix for

Table 2. Experimental design matrix.

Runs		Actual values for variables			Removal efficiency %	
Standard Order	Run order	A: Time (min)	B: Dye concentration (mg/L)	C: pH	Y	Ŷ
20	1	80	65	5	**90.5**	**90.9**
12	2	80	124	5	**92.3**	**92.4**
14	3	80	65	8.36	**94.6**	**94.7**
15	4	80	65	5	**90.5**	**90.9**
2	5	120	30	3	**84.2**	**84.2**
18	6	80	65	5	**90.6**	**90.9**
7	7	40	100	7	**90.5**	**90.2**
3	8	40	100	3	**75.9**	**75.7**
9	9	13	65	5	**79.4**	**80.0**
4	10	120	100	3	**84.4**	**84.4**
8	11	120	100	7	**96.5**	**96.7**
13	12	80	65	1.64	**71.7**	**71.9**
6	13	120	30	7	**96.8**	**96.8**
10	14	147	65	5	**91.6**	**91.3**
16	15	80	65	5	**91.4**	**90.9**
19	16	80	65	5	**90.9**	**90.9**
17	17	80	65	5	**91.3**	**90.9**
5	18	40	30	7	**92.3**	**92.0**
1	19	40	30	3	**77.8**	**77.3**
11	20	80	6	5	**93.5**	**93.8**

the examined factors and the responses (Y for the experimental removal efficiency and Ŷ for the predicted removal efficiency).

A quadratic CCD model was obtained for the optimization MB dye molecules adsorption onto coconut husk cellulose. The Design Expert 13 software suggested quadratic polynomial model, which links the response (removal efficiency) to the selected factors involved in the adsorption of MB dye onto coconut husk cellulose, as shown in Equation (8):

$$\begin{aligned}\hat{Y} = {} & 45.5344 + 0.2801A - 0.1182B + 10.6174C + 0.00032 - 0.0069AC \\ & -0.000714BC - 0.00114A^2 + 0.000645B^2 - 0.6641C^2\end{aligned} \tag{8}$$

The sign preceding the chosen independent, quadratic, and interaction model terms was utilized to determine if each model term has a positive or negative impact on the MB adsorption process. In the equation, the positive coefficient values indicate that the independent and interaction terms favor the MB dye adsorption process whereas a negative coefficient values negatively affect the adsorption process within the design space [16]. **Table 3** demonstrates the evaluation of the predictive capability of the designed model in terms of MB dye removal (%). The model's suitability was assessed through the use of statistical parameters, including analysis of variance (ANOVA) and coefficient of determination (R^2). An estimated adjusted determination coefficient of 0.9960 was observed, indicating a high level of predictive accuracy in the model. Therefore, the proposed model has the ability to explain 99.6% of the total variability seen in the data regarding MB dye adsorption.

Table 4 illustrates the ANOVA results for the optimization of MB dye adsorption onto coconut husk cellulose. A statistical model is considered significant when it has a high F value (530.77) and a low p value (less than 0.05) [17]. The F-value of a model is estimated as the ratio of the individual terms' mean squares to the residuals' mean squares. The p-value is the probability associated with the observed F-statistic value and is used to evaluate the null hypothesis's validity. Parameters that exhibit statistical significance are characterized by a p-value that is lower than 0.05. The variables A, B, C, AB, AC, A^2, B^2, and C^2 exhibited statistical significance in the designed model. The insignificance of the lack of fit can be inferred from the "Lack of fit value" of 1.43 when compared to the pure error. The adsorption of methylene blue dye is significantly influenced by contact time (A), starting dye concentration (B), and pH (C). This implies

Table 3. Adequacy of the model tested.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	<0.0001	<0.0001	0.7937	0.7135	
2FI	0.9528	<0.0001	0.7523	0.6645	
Quadratic	**<0.0001**	**0.3529**	**0.9960**	**0.9894**	**Suggested**
Cubic	0.4736	0.1922	0.9960	0.9126	Aliased

Table 4. Analysis of variance (ANOVA), test of significance for MB adsorption on cellulose from coconut husks.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	943.09	9	104.79	530.77	<0.0001	significant
A-Contact time	154.39	1	154.39	782.00	<0.0001	
B-Initial Dye Concentration	2.48	1	2.48	12.55	0.0053	
C-pH	623.99	1	623.99	3160.61	<0.0001	
AB	1.62	1	1.62	8.21	0.0168	
AC	2.42	1	2.42	12.26	0.0057	
BC	0.0200	1	0.0200	0.1013	0.7568	
A^2	48.03	1	48.03	243.29	<0.0001	
B^2	9.01	1	9.01	45.63	<0.0001	
C^2	101.70	1	101.70	515.13	<0.0001	
Residual	1.97	10	0.1974			
Lack of Fit	1.16	5	0.2322	1.43	0.3529	not significant
Pure Error	0.8133	5	0.1627			
Cor Total	945.07	19				

that the developed model demonstrates a strong connection between the input variables.

Table 5 displays an estimated adjusted determination coefficient of 0.9960, indicating a substantial level of significance as the selected model is able to account for 99.6% of the entire variation in MB adsorption data. The determined value of the signal to noise ratio, also known as the appropriate precision ratio, was 78.8958, which suggests that the model exhibits a satisfactory level of signal. Given that the predicted and adjusted coefficient of determination exhibit a satisfactory level of concurrence, with a difference of less than 0.2, and the adequate precision ratio exceeds 4, it is justifiable to employ the quadratic model for the purpose of investigating the design space and identifying the optimal conditions for the adsorption process.

The assumption of a normal distribution of experimental data holds significant importance in the realm of statistical analysis [18]. Figure 1 illustrates the normal probability distribution of externally studentized residuals. The experimental data exhibits a linear relationship, hence, it can be inferred that the residual distribution conforms to a normal distribution [17]. The observed data points have a clear normal distribution, devoid of any outliers, and are evenly distributed across the range of −4 to +4 studentized residuals.

Figure 2 shows a perturbation plot that was employed to assess and evaluate the impact of various factors on MB adsorption onto coconut husk cellulose. The pronounced curvature seen suggests that the independent factors (A-contact time, B-initial dye concentration and C-pH) have a substantial influence on the adsorption of methylene blue. The curve depicted in Figure 3 exhibits a

Table 5. Quadratic model fit statistics.

Std. Dev.	0.4443	R^2	0.9979
Mean	88.34	**Adjusted** R^2	0.9960
C.V. %	0.5030	**Predicted** R^2	0.9894
		Adeq Precision	78.8958

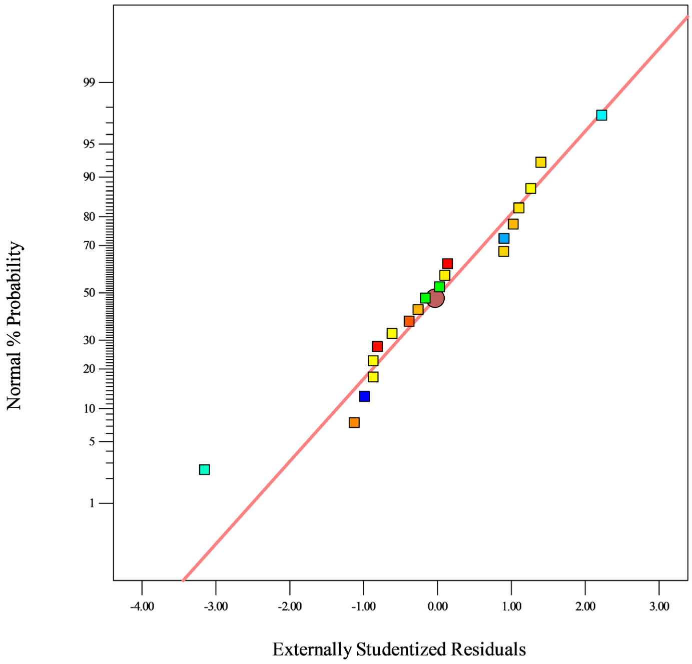


Figure 1. Normal probability plot of the externally studentized residuals.

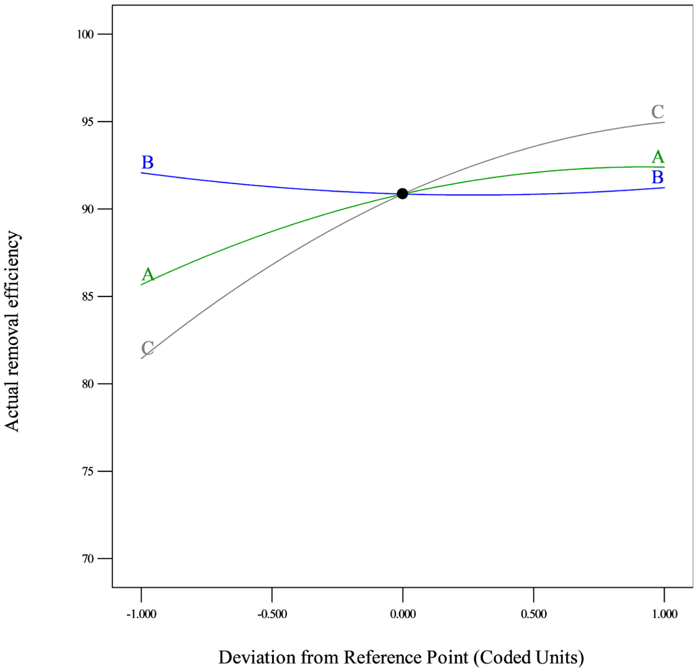


Figure 2. Perturbation plot of MB adsorption.

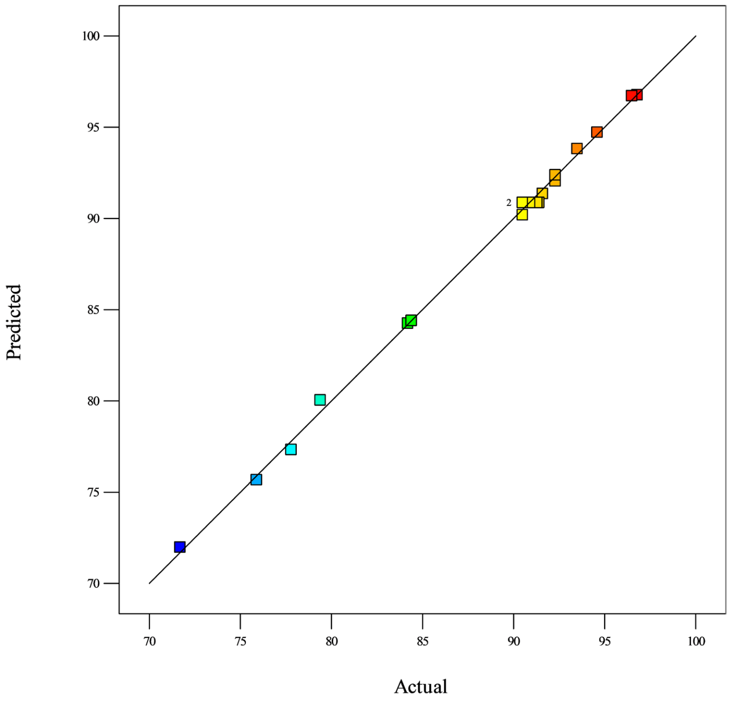


Figure 3. Plot of actual versus predicted values.

robust linearity between the predicted and experimental values of adsorption of MB dye onto coconut husk cellulose, hence indicating the high level of accuracy of the presented data.

3.2. Interactive Effects of Factors Involved in the Adsorption of MB Dye by Coconut Husk Cellulose

MB dye removal efficiency from wastewater or an aqueous solution is dependent on the interaction effects of two or more variables in addition to their independent effects. Contour plots were produced to investigate the variables' interactions on MB dye removal. Optimum removal (96.8%) occurred at pH 7, 30 $mg \cdot L^{-1}$ initial MB dye concentration, and 120 minutes at 0.5 g cellulose adsorbent mass. **Figure 4** illustrates how the initial dye concentration and contact time interaction have a positive impact on MB dye removal. Individually as the contact time increases the removal efficiency increases whereas as initial dye concentration increases the removal efficiency decreases. Hence, there is a clear indication that the effect of contact time is dominant compared to that of the initial MB dye concentration.

Figure 5 shows that increasing both contact time pH favors MB dye adsorption. MB dye adsorption on cellulose is caused by electrostatic interactions between dye molecules and cellulose as hydroxyl groups on cellulose fibers are negatively charged while the MB dye is positively charged in water. The high concentration of H^+ ions at lower pH levels leads to repulsion of the MB molecules from the adsorbent surface, reducing adsorption efficiency. Additionally, as contact time increases, MB dye molecules are sufficiently adsorbed to the coconut

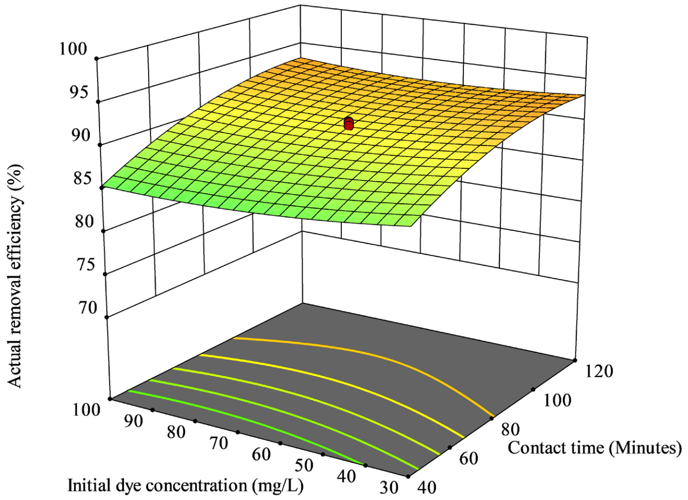


Figure 4. 3D-surface plot of the effect of initial dye concentration and contact time on MB removal efficiency (%) by coconut husk cellulose.

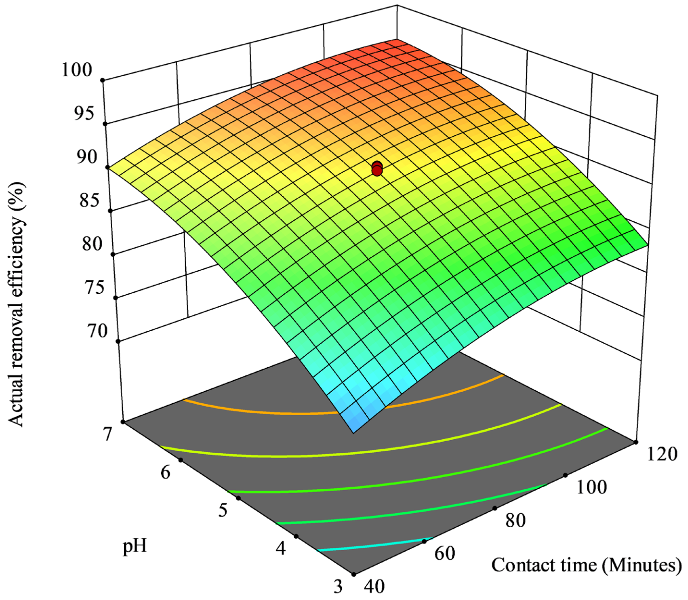


Figure 5. 3D-surface plot of the effect of contact time and pH on MB removal efficiency (%) by coconut husk cellulose.

husk cellulose thereby increasing the removal efficiency. The interaction of pH and contact time favored adsorption of MB onto coconut husk cellulose indicating a positive interaction effect.

Figure 6 demonstrates how the interaction of pH and initial MB dye concentration has a negative impact on the adsorption efficiency as indicated by the surface plot. Individually increasing pH increases the adsorption efficiency whereas an increase in dye concentration decreases adsorption efficiency.

3.3. Optimization Using the Desirability Function

In numerical optimization, it is common to define specific objectives for each

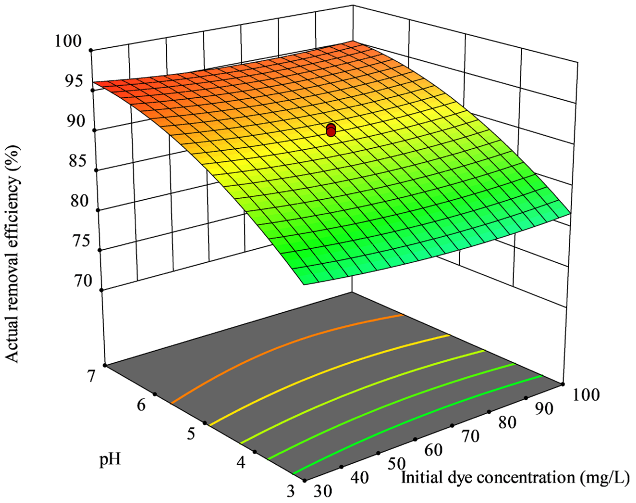


Figure 6. 3D-surface plot of the effect of initial dye concentration and pH on MB removal efficiency (%) by coconut husk cellulose.

element and response. These objectives can include maximizing or minimizing certain variables, targeting specific values, ensuring variables fall within a certain range, or setting factors to exact values [19]. In this study, the independent variables were assigned specific ranges of values (pH 3 - 7, dye concentration 30 - 100 mg/L, and contact length 40 - 120 minutes), whereas the dependent variable was optimized to attain optimal removal efficiency. At an initial pH of 7, an initial dye concentration of 30 mg/L, and a contact time of 120 minutes, the optimal predicted removal efficiency of MB dye was found to be 98.8827% as shown in **Figure 7**. The results of the confirmatory experiment demonstrated a methylene blue dye removal efficiency of 96.762% under optimal conditions, in contrast to the methylene blue dye removal efficiency of 98.8827% predicted by the model. This observation highlights the appropriateness and accuracy of the model, as the difference between the predicted and experimental values falls within an acceptable range.

3.4. Adsorption Kinetics

To accurately depict the adsorption kinetics of MB dye onto coconut husk cellulose, the study applied both the pseudo-first order and pseudo-second order kinetic models [20]. **Table 6** displays the linear representation of the adsorption kinetics model, together with their respective constants. According to the findings shown in **Table 6**, it was established that the adsorption process of MB dye onto coconut husk cellulose adhered to the pseudo second order kinetic model, shown in **Figure 8**. Under the optimal conditions, it was observed that the pseudo-second order kinetic model demonstrated a notably higher degree of linearity, with a significantly elevated correlation coefficient (R^2 = 99.992%), in contrast to the pseudo-first order kinetic model (R^2 = 54.448%). In addition, there was a significant difference between the q_e value ($q_{e,calc}$ = 2.9108 mg/g) calculated from the pseudo-second-order model and the experimental value ($q_{e,\,exp}$ = 2.9034 mg/g) to that of the pseudo-first-order model. Consequently, the pseudo-second-order model better fits the adsorption of MB dye onto coconut

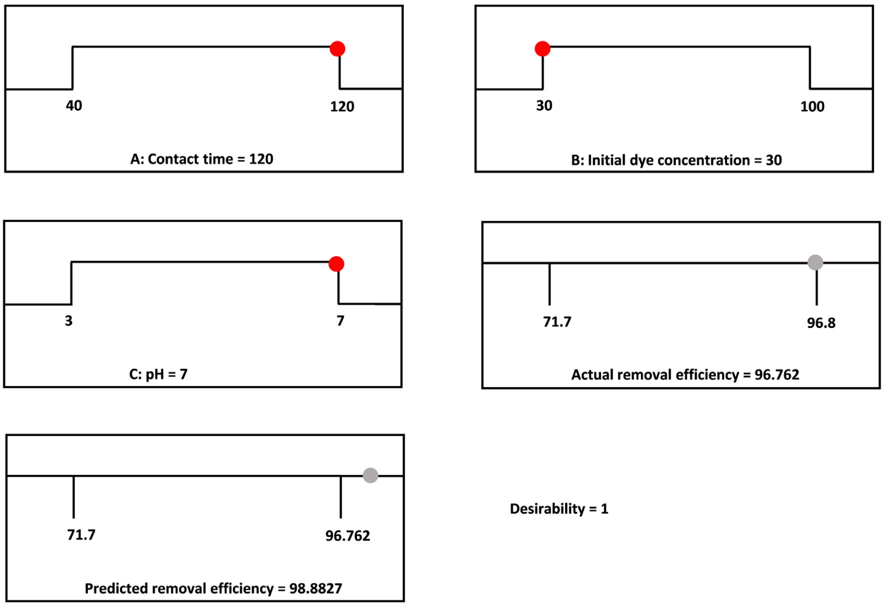
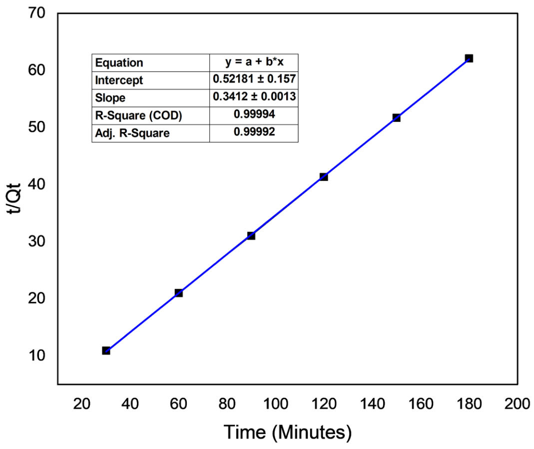


Figure 7. Desirability ramp for optimization of factors and MB dye removal efficiency.

Table 6. Adsorption Kinetics model parameters.

Kinetic model	Equation	Constants
Pseudo-first-order	$\ln\left(q_e - q_t\right) = \ln\left(q_e\right) - k_1 t$	$q_{e,\,exp} = 2.9034\ \text{mg}\cdot\text{g}^{-1}$ $K_1 = 0.02484\ \text{min}^{-1}$ $R^2 = 0.54448$ $q_{e,calc} = 0.1305\ \text{mg}\cdot\text{g}^{-1}$
Pseudo-second-order	$\frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e}$	$q_{e,\,exp} = 2.9034\ \text{mg}\cdot\text{g}^{-1}$ $K_1 = 0.2066\ \text{g}\cdot\text{mg}^{-1}\cdot\text{min}^{-1}$ $R^2 = 0.99992$ $q_{e,calc} = 2.9108\ \text{mg}\cdot\text{g}^{-1}$



Equation	y = a + b*x
Intercept	0.52181 ± 0.157
Slope	0.3412 ± 0.0013
R-Square (COD)	0.99994
Adj. R-Square	0.99992

Figure 8. Linear plot of pseudo-second order kinetic model.

husk cellulose. This model highlights the notable influence of the quantity of available active sites on the cellulose adsorbent concerning the efficiency of MB adsorption. These findings are consistent with those presented by [21] in their study on the adsorption kinetics of MB dye using magnetic iron oxide nanosorbent.

3.5. Adsorption Isotherms

The equilibrium interaction between the MB dye and the cellulose adsorbent was accurately described using the Langmuir and Freundlich isotherm models [22] [23]. The Freundlich isotherm model takes into account the presence of surface heterogeneity in the adsorbent material and the exponential distribution of active sites and adsorption energies [24]. The Langmuir isotherm theory suggests that the highest adsorption capacity is achieved when a monolayer of adsorbate molecules is established on the adsorbent's surface, and this process exclusively takes place at designated, uniform sites within the adsorbent material [25]. **Table 7** provides the linear representation of the isotherms together with their respective constants. The Freundlich isotherm model accurately described the isotherms experimental data, as evidenced by the results presented in **Figure 9** and the strong correlation coefficient reported in **Table 7**. The findings illustrate that the adsorption of MB onto cellulose extracted from coconut husks follows a multilayer adsorption mechanism on a surface that exhibits heterogeneity. The adsorption intensity, denoted as 'n' serves as a measure of the adsorption surface's heterogeneity. A favorable adsorption process is typi.

Table 7. Adsorption isotherm parameters.

Isotherm model	Equation	Constants
Langmuir isotherm	$\frac{C_e}{q_e} = \frac{1}{q_m K_L} + \frac{C_e}{q_m}$	$q_{max} = 42.7168$ mg·g^{-1} $K_L = 0.0858$ L·mg^{-1} $R_L = 0.35 - 0.1$ $R^2 = 0.8593$
Freundlich isotherm	$\ln(q_e) = \ln(K_F) + \frac{1}{n}(\ln C_e)$	$K_F = 3.3458$ $1/n = 0.8777$ $n = 1.1393$ $R^2 = 0.9995$

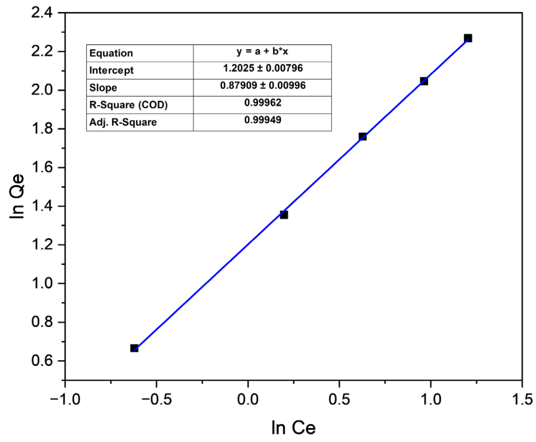


Figure 9. Linear plot of Freundlich isotherm model.

3.6. Desorption and Reusability Studies

Adsorbent regeneration and reusability are critical to consider for industrial application. The adsorbent should be reusable with no considerable degradation in its affinity for contaminants [26]. In this study, approximately 88% of the MB dye was desorbed, and the reusability of cellulose from coconut husks was studied in two successive cycles, as shown in **Figure 10**. The results indicated that the cellulose from coconut husks is easily recyclable/reusable, with a removal effectiveness of more than 86% even after the second sequential batch of adsorption/desorption cycles.

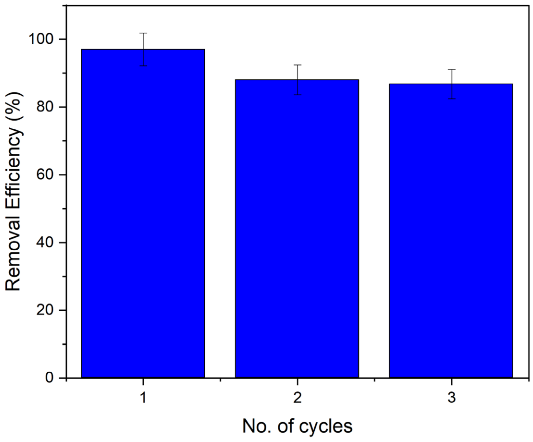


Figure 10. Removal efficiency of MB dye onto cellulose from coconut husks in three cycles.

4. Conclusion

In conclusion, this research employed coconut husk cellulose as an adsorbent to eliminate MB dye from aqueous solutions, due to its natural, cost-effective, and environmentally friendly attributes. Utilizing RSM-CCD, the study systematically assessed the impact of independent factors, individually and in combination, on MB dye adsorption. The developed model was reliable, with a high correlation between the model-predicted outcomes and experimental values (R^2 = 99.79%). Notably, the solution pH emerged as a pivotal process variable in MB dye adsorption onto coconut husk cellulose. Under room temperature conditions, the optimal removal efficiency was achieved with an initial MB dye concentration of 30 $mg \cdot L^{-1}$, 120 minutes' contact time, a pH level of 7, and a fixed adsorbent mass of 0.5 g. The Freundlich isotherm model excellently described the adsorption data (R^2 = 99.91%), while the kinetic data indicated the dominance of the pseudo-second-order adsorption mechanism (R^2 = 99.992%). Importantly, desorption and reusability studies confirmed that the coconut husk cellulose adsorbent could be recycled with only a minor reduction in its adsorption capacity. This study underscores the potential of coconut husk cellulose as an eco-friendly and sustainable solution for dye removal from wastewater, contributing to environmental preservation and the promotion of environmentally sound alternatives in the realm of water treatment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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