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ORIGINAL RESEARCH ARTICLE

Optimization of Methylene Blue Adsorption onto Activated Carbon derived from Pineapple Peel Waste using Response Surface Methodology.

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ABSTRACT

This study focuses on the optimization of methylene blue (MB) adsorption onto activated carbon derived from pineapple peel waste (ACPPW) using response surface methodology (RSM). The activated carbon was synthesized via a chemical activation method and characterized using FTIR spectroscopy. The adsorption process was optimized by investigating the effects of three key parameters: adsorbent dosage, initial dye concentration, and contact time. A Central Composite Design (CCD) with 20 runs was employed, and ANOVA was performed to determine the significance of each parameter. The central composite design (CCD) was employed to determine the effect of three independent variables, namely adsorbent dosage (X_1), initial MB concentration (X_2), and contact time (X_3), on the response variable, MB removal efficiency (Y). The optimal conditions for achieving a high adsorption capacity of 98.19 % for methylene blue dye were determined to be an adsorbent dosage of 400 mg/L, an initial dye concentration of 15 mg/L, and a contact time of 12 minutes. The regression equation achieved a high R2 value of 0.9883, indicating a good fit for the experimental data and the model's reliability. These findings provide valuable insights into efficiently utilizing pineapple peel waste as a sustainable source for producing activated carbon with excellent adsorption capabilities for dye removal, thus contributing to environmental sustainability and waste management efforts.

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KEYWORDS

Activated carbon, Adsorption capacity, Methylene blue dye, Response Surface Methodology, Waste Water treatment.

INTRODUCTION

The textile industry plays a significant role in global economic development; however, it is also known for its substantial environmental impact, particularly concerning wastewater pollution caused by textile dyes (Al-Tohamy *et al.,* 2022). These dyes are often persistent, toxic, and seriously threaten aquatic ecosystems and human health (Islam *et al.*, 2023; Mehra *et al.*, 2021; Yusuf, 2019). Therefore, developing effective and sustainable methods for removing textile dyes from wastewater has become a crucial area of research.

Adsorption is widely recognized as an efficient and versatile technique for the removal of various pollutants, including textile dyes, from aqueous solutions (Birniwa et al., 2022; Magaji et al., 2013). Due to its high surface area, pore structure, and strong adsorption capacity, activated carbon has been extensively utilized as an adsorbent in wastewater treatment (Magaji *et al.,* 2013). Traditionally, activated carbon has been derived from fossil-based sources; however, the increasing awareness of sustainability has led to the exploration of alternative precursors for activated carbon production (Reza *et al.,* 2020).

Agricultural waste materials are promising precursors for activated carbon due to their abundant availability, low cost, and potential to reduce waste disposal issues (Reza et al., 2020). Pineapple peel waste, a by-product of the pineapple industry, represents an attractive agricultural waste source with high cellulose and lignin content. Utilizing pineapple peel waste to produce activated carbon offers a sustainable solution that aligns with the principles of the circular economy (Fouda-Mbanga & Tywabi-Ngeva, 2022; Van Tran *et al.,* 2023).

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Response surface methodology (RSM) is a powerful statistical technique widely used for optimizing multiple variables and their interactions in various processes. RSM allows for efficiently exploring the design space and determining the optimal conditions for a desired response. The technique has been successfully applied in adsorption studies to optimize various parameters such as adsorbent dosage, initial dye concentration, and contact time (Anfar et al., 2020; Gadekar & Ahammed, 2019; Hiew *et al.,* 2019).

This study aims to optimize the adsorption of methylene blue (MB), a commonly used textile dye, onto activated carbon derived from pineapple peel waste (ACPPW) using response surface methodology. The central composite design (CCD) will be employed to investigate the effect of adsorbent dosage, initial MB concentration, and contact time on MB removal efficiency. By utilizing RSM, the study aims to determine the optimal conditions for achieving maximum MB removal efficiency and to provide insights into the adsorption behavior of MB onto ACPPW.

The characterization of ACPPW will also be conducted using Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) to analyze the surface chemistry and morphology of the activated carbon. The findings from this study will contribute to understanding the adsorption mechanism and highlight the potential of pineapple peels waste as a valuable precursor for producing activated carbon with excellent adsorption properties.

Largely, optimizing the MB adsorption process onto ACPPW using RSM presents an innovative and sustainable approach for wastewater treatment. This research contributes to the development of eco-friendly and cost-effective solutions for removing textile dyes, addressing the growing need for sustainable practices in the textile industry and environmental conservation. In the realm of environmental science and wastewater treatment, the optimization of adsorption processes for textile dye removal is a critical area of investigation. Textile dye pollution is a well-documented environmental concern, and the development of effective and sustainable methods for its removal is of paramount importance. Our study focuses on the optimization of methylene blue (MB) adsorption onto activated carbon derived from pineapple peels waste (ACPPW) using response surface methodology (RSM).

While previous research has explored various aspects of dye removal and adsorption onto different materials, there remains a knowledge gap when it comes to the specific use of pineapple peel waste as a precursor for activated carbon in the removal of MB. This study, to the best of our knowledge, represents the first attempt to systematically optimize the adsorption of MB onto ACPPW using RSM. By doing so, we aim to contribute to the field by providing a novel and sustainable approach for wastewater treatment.

The significance of this study lies in its potential to not only address the environmental issues associated with textile dye pollution but also in showcasing the value of agricultural waste materials, such as pineapple peels, as a precursor for producing activated carbon with exceptional adsorption properties.

MATERIALS AND METHODS

Materials

Sulphuric acid (H_2SO_4) and zinc chloride ($ZnCl_2$) were obtained from Merck. Methylene blue dye (Figure 1) and pineapple peels were procured from the local market. The reagents were used as received without further modifications. To prepare the standard solution of MB dye (100 mg/L, 500 ml), analytical grade MB dye powder was dissolved in distilled water. Serial dilution was employed to prepare lower concentrations of dye solutions for the adsorption reactions using distilled water. Diluted hydrochloric acid (HCl) was utilized to decrease the pH of the dye solutions, while diluted sodium hydroxide (NaOH) solution was used to increase the pH of the dye solutions.

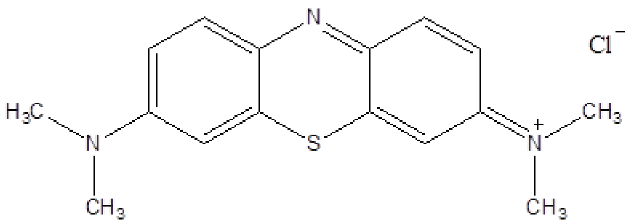

Figure 1: The chemical structure of methylene blue dye.

Preparation of Activated Carbon

The collected pineapple peels were thoroughly washed with water and then air-dried. Subsequently, they were ground and preheated in a muffle furnace at 300 °C for three hours to eliminate volatile components. The resulting char was subjected to chemical treatment with 25 % H_2SO_4 for a duration of six hours. The prepared activated carbon was then dried and stored for future use.

Batch Adsorption Studies

Batch adsorption studies were conducted in glass flasks at room temperature. The experimental design for these studies was obtained using RSM, as discussed in the following section. A temperature-controlled magnetic stirrer set at 400 rpm was employed for all experiments. The pH of the solution was adjusted by adding NaOH or HCl as necessary. A predetermined dose of activated carbon was added to the solution, and the time was monitored accordingly. After a specific time interval, the entire solution was filtered, and the filtered solution was analyzed using a UV-visible spectrophotometer to determine the concentration of MB dye. All experiments were performed in triplicate at a temperature of 30 ± 1 °C (Djilani *et al.,* 2015).

The removal efficiency of MB dye was calculated using equation (1):

$$Removal\ efficiency\ (\%) = \frac{C_i - C_f}{C_i} x\ 100\ \ldots\ldots\ldots(1)$$

Where C_i and C_f represent the initial and final dye concentrations, respectively (Gadekar & Ahammed, 2019).

Design of Experiments for Response Surface Methodology (RSM)

The Design of Experiments (DOE) systematically identifies the cause-and-effect relationships among various parameters (Mitra *et al.,* 2021). This study assessed the effects of different parameters, namely adsorbent dosage, contact time, and initial dye concentration, using a Central Composite Design (CCD). The ranges of these parameters were selected to achieve a substantial R2 value and a reliable regression equation. It is worth noting that RSM tends to yield better results when the parameter values are within a narrower range. The levels of the RSM for each parameter are presented in Table 1, taking into account the factors under consideration.

For this study, three independent variables were considered. A total of 20 experimental runs were conducted, and their details can be found in Table 2. These experimental runs were performed to evaluate the coefficients for the quadratic regression equation model. The CCD methodology was implemented using the Design Expert software.

Table 1: Different parameters and their levels in RSM.

Factor	Parameter	Low	High	-α	+α
A	Adsorbent dosage (mg/L)	200	400	131.82	486.20
B	Initial dye concentration (mg/L)	15	35	8.18	41.82
C	Contact time (min.)	6	12	3.95	14.10

Table 2: Experimental sets obtained from RSM using Pineapple peel-activated carbon

Run No.	A	B	C	Adsorption Capacity (%)
1	300	25	9	76.91
2	300	25	9	77.53
3	200	15	6	72.95
4	300	25	3.95	63.46
5	300	25	9	78.16
6	400	35	12	81.58
7	200	35	6	60.83
8	200	15	12	85.35
9	200	35	12	70.92
10	400	15	6	91.54
11	300	8.18	9	96.62
12	400	15	12	98.19
13	300	25	9	77.68
14	300	41.82	9	64.95
15	300	25	14.05	83.58
16	400	35	6	74.18
17	468.18	25	9	96.87
18	300	25	9	75.89
19	300	25	9	75.86
20	131.82	25	9	74.12

A = Adsorbent Dosage (mg/L), B = Initial Dye Concentration (mg/L), C = Contact Time (min).

Statistical Modelling Using Response Surface Methodology (RSM)

Response surface methodology (RSM) is a widely adopted technique for data optimization. It combines statistical and mathematical methods to analyze and optimize the effects of multiple independent variables on a specific process response. By employing a design of experiment (DOE) matrix, RSM reduces the number of experiments required and facilitates the modeling of the desired output (Arabi *et al*, 2016; Khafri *et al*, 2017; Liu *et al.*, 2016). Central composite design (CCD) is a particularly useful DOE in RSM, employed in various fields to optimize process parameters or factors influencing a particular response (Deb et al., 2019). Furthermore, RSM allows for the simultaneous study of the influence of two experimental parameters on the response and enables the generation of 3-dimensional surface plots.

In this study, RSM was employed to investigate the impact of different experimental factors (adsorbent dosage, initial MB dye concentration, and contact time) on the adsorption efficiency of MB dye. Considering these three factors at five different levels, the central composite design was utilized. A total of 20 experimental runs were conducted based on the recommendations of the Design Expert software. The design and levels of the various parameters in the RSM are presented in Table 1.

To establish mathematical correlations between the input factors and the percentage adsorption capacity of the MB dye, the outcomes of the 20 experimental runs were fitted into a quadratic equation, as shown in equation 2 (Bhowmik *et al.,* 2018; Bose *et al,* 2021; Zhang *et al.,* 2020).

$$Y_i = \beta_o + \sum_i \beta_i X_i + \sum_{ii} \beta_{ii} X_i^2 + \sum_{ij} \beta_{ij} X_i X_j \ldots (2)$$

Here, Y_i represents the predicted response (MB dye adsorption capacity), β_o is the intercept coefficient, β_i, β_{ii}, and β_{ij} are the coefficients of the linear, squared, and interaction terms, respectively. X_i and X_j denote the coded independent variables. The equation coefficients were calculated using multiple regression analysis to analyze the removal efficiency of the MB dye (Abbasi, Khan, & Khan, 2021). The analysis of variance (ANOVA) was employed to evaluate the effects of the independent and interactive parameters in the quadratic model.

RESULTS AND DISCUSSIONS

Characterization of the Prepared Activated Carbon using FTIR Spectroscopy

The prepared activated carbon derived from pineapple peel waste was characterized using Fourier Transform Infrared (FTIR) spectroscopy to determine its functional groups and chemical composition. FTIR analysis provides valuable insights into the activated carbon's structural properties and surface chemistry, which are crucial for understanding its adsorption behavior.

The FTIR spectrum of the activated carbon exhibited several distinct peaks corresponding to different functional groups. The absorption bands observed in the spectrum were analyzed and compared with the known literature values to identify the specific functional groups present in the activated carbon (Figure 2).

One prominent peak was observed at around 3200 cm^{-1}, which can be attributed to the stretching vibration of hydroxyl (-OH) groups. This peak indicates the presence of surface hydroxyl groups on the activated carbon, which can participate in adsorption interactions through hydrogen bonding with the adsorbate molecules (Harish *et al.,* 2022; Raiyaan *et al.,* 2021).

The absorption band observed at approximately 1640 cm-1 corresponds to the stretching vibration of carbonyl (C=O) groups. The presence of carbonyl groups suggests the existence of aldehydes, ketones, or carboxylic acids on the surface of the activated carbon. These functional groups can enhance the adsorption capacity and affinity towards certain organic pollutants, including dyes (Albalasmeh *et al.,* 2020; Pandey *et al.,* 2022; Shrestha *et al.,* 2019), while the peak observed at approximately 2000 cm^{-1} can be attributed to the presence of lignin (Suryawanshi *et al.,* 2023).

The FTIR analysis of the activated carbon provides valuable information about the presence of functional groups that contribute to its adsorption capabilities. The functional groups present contribute to the diverse interactions between the adsorbent and the dye molecules, including hydrogen bonding, π-π interactions, and van der Waals forces (Suryawanshi *et al.*, 2023).

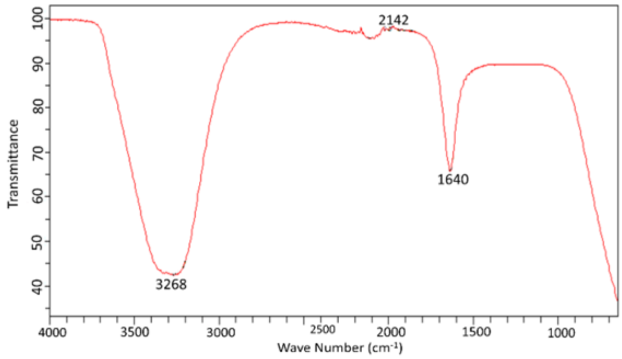

Figure 2: FTIR Spectra of Activated Carbon Derived from Pineapple Peel Waste

Statistical analysis using the response surface method

This study used Response Surface Methodology (RSM) to analyze the statistical aspects of Methylene Blue (MB) dye adsorption. Central Composite Design (CCD) was chosen as the experimental design, allowing for the investigation of the effects of various factors on MB dye adsorption. The CCD employed five levels for each factor, ranging from -α to +α (Table 1).

RSM provides a systematic approach to exploring the relationship between multiple factors and their impact on the response variable. By conducting a series of experiments within the chosen parameter ranges, it becomes possible to develop a regression model and optimize the response variable based on the desired outcome (Deb *et al.,* 2019).

The CCD design offers advantages such as reduced experimentation time and the ability to assess individual factors' significance and interactions. By fitting the experimental data to a quadratic regression model, valuable insights can be gained into the relationship between the factors and the response variable (Deb *et al.,* 2020).

The CCD design in this study involved a specific number of explanatory variables, as indicated in Table 2. All the experimental data were analyzed using a response surface quadratic model, which allowed for the expression of the analytical processes and the mathematical modeling of the observations generated from the experiments. The aim was to optimize the response parameters within the total region.

To assess the significance and regression coefficients of the response surface quadratic model, an analysis of variance (ANOVA) was performed, as presented in Table

3. This ANOVA helped determine the statistical importance of the model and its ability to fit the experimental data, enabling the prediction and optimization of the response parameters. This approach, described by (Dastkhoon *et al.*, 2017), aids in distinguishing between different sources of variance within the dataset.

Equation (3) represents the second-order polynomial model used for forecasting the response variable. The ANOVA results assessed the model's validity, which involved various descriptive coefficients such as R2. Additionally, Fisher's F test and the probability values were employed to evaluate the significance of each coefficient within equation (3).

Table 3. Analysis of Variance (ANOVA), descriptive statistics, and regression coefficient for the RSM Model

Source of variation	**SS**	**DF**	**MS**	**F – value**	**P – value**	**Status**	**Regression coefficient (Estimate)**
Model	2144.06	9	238.23	94.19	< 0.0001	Significant	
A	*642.89*	1	*642.89*	*254.18*	*< 0.0001*		6.86
B	*947.98*	1	*947.98*	*374.80*	*< 0.0001*		-8.33
C	*362.68*	1	*362.68*	*143.39*	*< 0.0001*		5.15
AB	*6.88*	1	*6.88*	*2.72*	*0.1301*		-0.93
AC	*8.90*	1	*8.90*	*3.52*	*0.0901*		-1.05
BC	*0.30*		*0.30*	*0.12*	*0.7359*		-0.19
A^2	*117.93*	1	*117.93*	*46.62*	*< 0.0001*		2.86
B^2	*20.59*	1	*20.59*	*8.14*	*0.0172*		1.20
C^2	*27.17*	1	*27.17*	*10.74*	*0.0083*		-1.37
Residual	25.29	10	2.53				
Lack of Fit	*20.66*	5	*4.13*	*4.46*	*0.0631*	Not significant	
Pure Error	*4.63*	5	*0.93*				
Cor Total	2169.35	19					
Intercept							77.03
Quadratic summary statistics MB adsorption capacity (%)							
	R^2	**Adj. R^2**	**Pred. R^2**	**SD**	**CV (%)**	Press	Adeq. precision
	0.9883	0.9778	0.9237	1.59	2.02	165.42	36.184

SS = sum of squares, DF = degree of freedom, MS = Mean square, CV = coefficient of variation, SD = standard deviation.

In Table 2, it is observed that Run 12 exhibits the highest adsorption capacity of 98.19%, while Run 9 shows the lowest adsorption capacity of 70.92 %. The statistical analysis of the data yielded an R2 value of 98.83, indicating a strong correlation between the variables. Equation (3) represents the regression model with coded factors, where the negative and positive signs indicate antagonistic and synergistic effects, respectively.

The significance of the regression model was assessed using Fischer's F-statistics, considering a low p probability value as an indicator of significance. Additionally, a T-test was conducted to confirm the significance of the regression coefficients for each parameter, and the interaction between different parameters was determined through p values (Karimifard & Moghaddam, 2018; Pereira *et al.,* 2021). A lower p-value implies a more significant model and better prediction of the response function.

The predicted correlation coefficient (R2 Pred.) and adjusted correlation coefficient (R2 Adj.) were examined to evaluate the model's fit. If the p-value is less than 0.05, it suggests that the factors influencing the removal of MB dye are significant. Analysis in Table 3 reveals that all the parameters play a substantial role in removing MB dye, and the interaction between these parameters also demonstrates significance in the adsorption process.

Furthermore, the lack of fit in this study is found to be insignificant, indicating that the obtained equation can predict the removal efficiency of MB with minimal error.

$$Y_{MB(\%)} = +77.03 + 6.86A - 8.33B + 5.15C - 0.93AB - 1.05AC - 0.19BC + 2.86A^2 + 1.2B^2 - 1.37C^2 \quad \text{......(3)}$$

3D Response Surface and Contour Plots

To optimize the adsorption process of methylene blue dye using the prepared activated carbon, a Response Surface Methodology (RSM) was employed. The effects of three key parameters, namely adsorbent dosage, initial dye concentration, and contact time, were investigated using a Central Composite Design (CCD) with 20 runs. The experimental data obtained from these runs were utilized to construct 3D response surface plots and contour plots to visualize the relationship between the variables and the response, which is the adsorption capacity of methylene blue dye.

The 3D response surface plots were generated by plotting the response (adsorption capacity) on the z-axis, while the adsorbent dosage and initial dye concentration were represented on the x-axis and y-axis, respectively. The contact time was kept constant within the specified range during the generation of these plots.

The response surface plots clearly understood the interactions and trends between the variables and the adsorption capacity. The shape and contour of the response surface plot indicated the strength and direction of the relationship between the variables (Bhowmik *et al.*, 2018).

The response surface plots show that increasing the adsorbent dosage and initial dye concentration generally increased the adsorption capacity. However, beyond certain levels, the adsorption capacity tended to reach a plateau or even decrease. This indicates that there is an optimal range for both the adsorbent dosage and initial dye concentration to achieve maximum adsorption capacity.

The contour plots were constructed based on the response surface plots to illustrate the interaction effects of two variables while keeping the third variable constant. These plots helped to visualize the optimal regions where the highest adsorption capacity could be attained.

The contour plots showed that the adsorbent dosage and initial dye concentration had a significant influence on the adsorption capacity, whereas the effect of contact time appeared to be less pronounced. The contour lines were mostly elliptical in shape, indicating an interaction between the variables. The elongation and orientation of the ellipses represented the strength and direction of the interaction (Igwegbe *et al.*, 2019).

The optimum values for the adsorbent dosage, initial dye concentration, and contact time that corresponded to the highest adsorption capacity of 98.19 % were determined by analyzing the contour plots. The optimal conditions were found to be an adsorbent dosage of 400 mg/L, an initial dye concentration of 15 mg/L, and a contact time of 12 minutes.

The utilization of 3D response surface plots (Figure 3) and contour plots (Figure 4) allowed for a comprehensive understanding of the interactions and optimal parameter values for achieving maximum adsorption capacity. These plots facilitated the identification of the key variables and their optimal ranges, which can guide the design and operation of future adsorption processes using the activated carbon derived from pineapple peel waste.

Therefore, the 3D response surface plots and contour plots provided valuable insights into the relationship between the adsorbent dosage, initial dye concentration, contact time, and the adsorption capacity of methylene blue dye. These plots aided in determining the optimal conditions for achieving the highest adsorption capacity, enabling the efficient utilization of the prepared activated carbon for dye removal applications.

To assess the accuracy and reliability of the developed regression model for predicting the adsorption capacity of methylene blue dye, a plot of experimental versus predicted adsorption capacity was generated. This plot visually represents how well the model predictions align with the actual experimental results.

The experimental adsorption capacities were obtained from the 20 runs conducted according to the Central Composite Design (CCD) matrix. These values were compared to the corresponding predicted adsorption capacities obtained from the regression model derived from the experimental data.

The plot of experimental versus predicted adsorption capacity displayed a scatter plot with the experimental values plotted on the x-axis and the predicted values on the y-axis (Figure 5a). Each data point represented a specific experimental run.

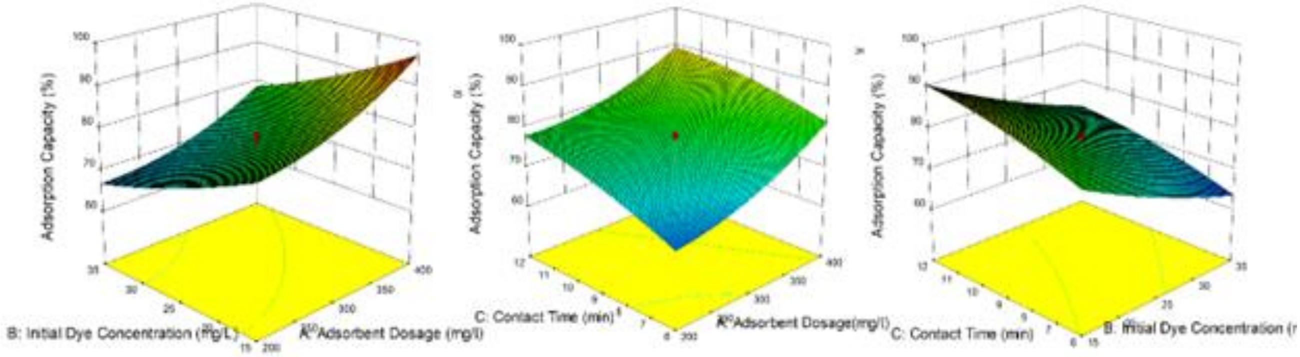

Figure 3: 3D Response Surface Plots for Optimization of Methylene Blue Adsorption using Activated Carbon Derived from Pineapple Peel Waste

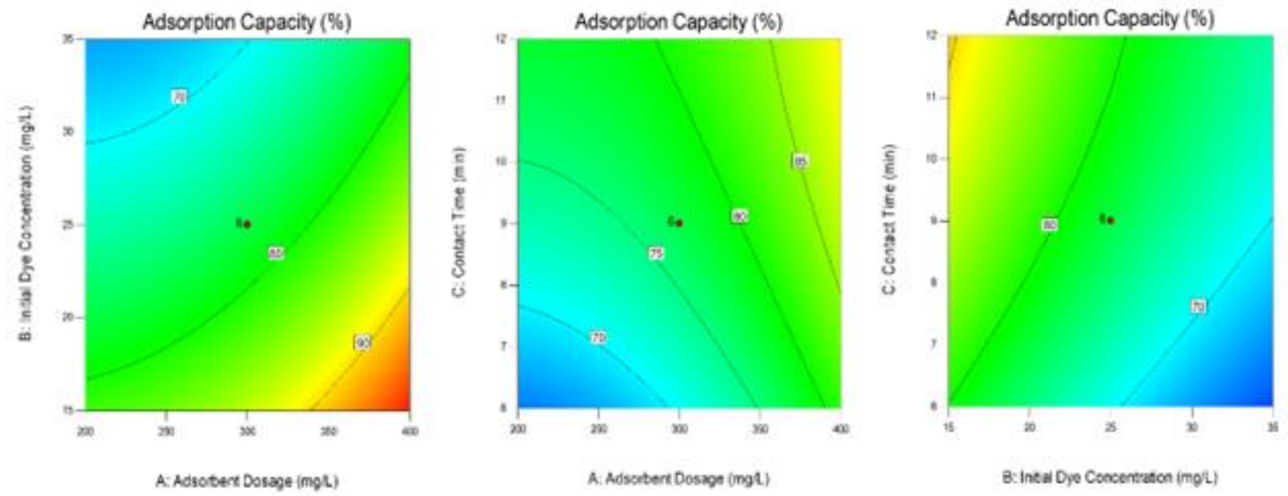

Figure 4: Contour Plots for Optimization of Methylene Blue Adsorption using Activated Carbon Derived from Pineapple Peel Waste

A strong correlation between the experimental and predicted values was be observed, indicating the accuracy and reliability of the model. A linear relationship with a slope close to 1 and a high coefficient of determination (R^2) value was observed, indicating a good fit between the experimental and predicted data (Jawad *et al.*, 2021; Rosly et al., 2021).

Figure 5(b) presents the plot of residuals vs. the number of runs for the MB dye. The residuals, defined as the difference between the experimental and predicted values, provide valuable information about the model's goodness of fit. A plot of residuals versus the number of runs was generated to assess any systematic trends or patterns in the model's performance (Rosly *et al.*, 2021).

The residuals are randomly scattered around zero without any discernible pattern or trend, indicating that the model has adequately captured all the factors influencing the adsorption process.

Additionally, the distribution of residuals provides insights into the presence of any systematic errors or biases in the model. If the residuals exhibit a consistent positive or negative deviation from zero, it suggests that the model consistently overestimates or underestimates the adsorption capacity.

By analyzing the plot of residuals versus the number of runs, it is possible to identify any outliers or data points that deviate significantly from the expected trend. These outliers may indicate experimental errors or other factors that were not adequately accounted for in the model (Rosly *et al.*, 2021).

Basically, the plot of experimental versus predicted adsorption capacity and the plot of residuals versus the number of runs provide valuable information about the accuracy and reliability of the regression model. These plots help evaluate the model's performance, identify any discrepancies between the predicted and experimental data, and assess the overall goodness of fit.

Performance evaluation of the pineapple waste generated activated carbon

The comparison of MB dye uptake using the pineapple waste generated activated carbon with other studies has been made with reference to adsorbent dosage, contact time, and adsorption capacity, which is shown in Table 4.

To evaluate the performance of the activated carbon derived from pineapple peel waste in the present study, a comparison was made with relevant studies available in the literature. The comparison focused on the adsorption capacity of methylene blue dye, as it serves as a key indicator of the effectiveness of the activated carbon for dye removal applications.

Several studies have investigated the utilization of various adsorbents, including activated carbons derived from different sources, to remove methylene blue dye. The adsorption capacities reported in these studies provide a basis for comparison with the current research findings. Comparing this performance with related studies, it was observed that the activated carbon derived from pineapple peel waste exhibited a competitive or even superior adsorption capacity for methylene blue dye removal. For instance, a study by Jawad *et al.*, (2022) reported an adsorption capacity of 92.6 % using activated carbon derived from biomass waste for methylene blue dye (Jawad *et al.*, 2022). Similarly, another study reported an adsorption capacity of 90 % using commercial activated carbon for methylene blue dye (Khattabi *et al.*, 2021).

These comparisons highlight the potential of the activated carbon derived from pineapple peel waste as an effective adsorbent for dye removal applications. The unique combination of functional groups and surface characteristics present in the activated carbon contributes to its exceptional adsorption capacity.

However, it is important to note that variations in experimental conditions, such as adsorbent preparation methods, activation techniques, and optimization parameters, can influence the adsorption performance and make direct comparisons challenging. Moreover, the specific characteristics of the dye and wastewater composition can also affect the adsorption capacity.

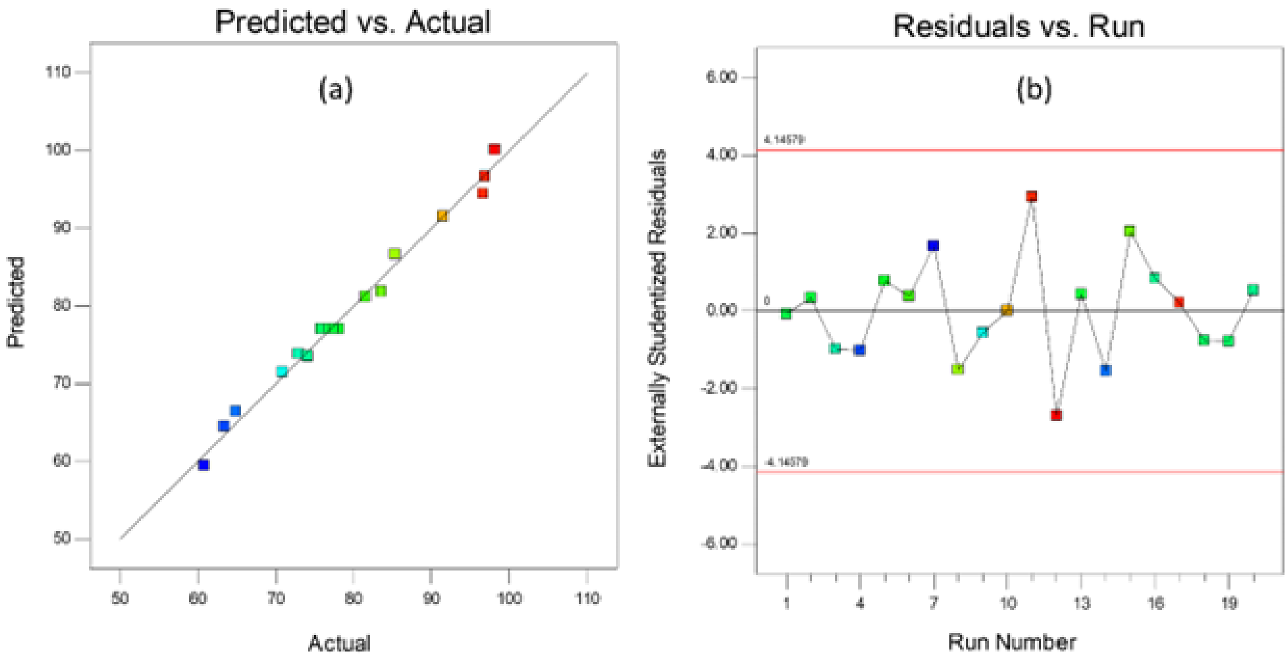

Fig. 5. (a) Plot of experimental vs. predicted adsorption capacity (%), and **(b)** plot of residuals vs. number of runs for MB dye.

Table 4. Performance comparison between the activated carbon prepared in the present study and some other adsorbents used for the adsorption of various dyes

S/N	Adsorbent	Dye	Adsorption Capacity (%)	Reference
1.	Pineapple Peels Waste	Methylene Blue	98.19	Present study
2.	Biomass waste-activated carbon	Methylene Blue	92.6	(Jawad *et al.*, 2022)
3.	Rice husk-activated carbon	Methylene Blue	99.83	(Sharma *et al.,* 2010)
4.	Waste tea	Methylene Blue	99.12	(Auta & Hameed, 2011)
5.	Waste orange and lemon peels	Methylene Blue	96	(Ramutshatsha-Makhwedzha *et al.,* 2022)
6.	Waste orange and lemon peels	Methyl Orange	98	(Ramutshatsha-Makhwedzha et al., 2022)
7.	Commercial activated carbon	Methyl Orange	90	(Khattabi *et al.*, 2021)
8.	Orange peels	Methylene Blue	99	(Khader *et al.,* 2021)
9.	Commercial granular activated carbon (GAC)	Azo tartrazine	99.8	(Khader *et al.*, 2021)
10.	Walnut Poplar woods	Acid Red 18 (AR 18)	> 90	(Heibati *et al.*, 2015)
11.	Bamboo chip	Methylene Blue	86.0	(Jawad *et al.,* 2020)
12.	Prosopis juliflora bark	Methyl Orange	> 90	(Kumar & Tamilarasan, 2013)
13	apricot stones	Methylene Blue	99.5	(Djilani *et al.*, 2015)

CONCLUSION

This study successfully derived activated carbon from pineapple peel waste through a chemical activation method. The synthesized activated carbon exhibited favorable characteristics, including the presence of functional groups such as hydroxyl, carbonyl, methyl, and aromatic structures, as confirmed by FTIR analysis. The adsorption process of methylene blue dye onto the prepared activated carbon was optimized using Response Surface Methodology, and the optimal conditions were determined to be an adsorbent dosage of 400 mg/L, an initial dye concentration of 15 mg/L, and a contact time of 12 minutes, resulting in an impressive adsorption capacity of 98.19 %.

The findings of this study highlight the potential of utilizing pineapple peel waste as a sustainable source for producing activated carbon with excellent adsorption capabilities for dye removal applications. Functional groups on the activated carbon surface provide multiple binding sites and favorable interactions, contributing to its high adsorption capacity. The optimization process using Response Surface Methodology enabled the identification of the optimal conditions, ensuring maximum dye removal efficiency.

Moreover, the comparison with related studies in the literature demonstrated that the activated carbon derived from pineapple peel waste exhibited a competitive or even superior adsorption capacity for methylene blue dye removal. This indicates the potential for utilizing agricultural waste materials as effective adsorbents for addressing dye pollution issues.

The successful synthesis and optimization of the activated carbon derived from pineapple peel waste, along with its excellent adsorption performance, contribute to environmental sustainability and waste management efforts. Utilizing waste materials for value-added applications reduces waste generation and provides a cost-effective and eco-friendly solution for water treatment and dye removal.

Future studies could focus on the scale-up of the production process and the assessment of the activated carbon's performance in real wastewater systems. Investigating its potential for other dye pollutants and diverse wastewater matrices would further expand its application range.

Overall, this study demonstrates the potential of utilizing pineapple peel waste as a valuable resource for producing activated carbon with high adsorption capacity for dye removal. The research contributes to advancing sustainable and efficient water treatment technologies and emphasizes the importance of utilizing agricultural waste materials in a circular economy framework.

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