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Research article

Optimization of Congo red dye adsorption with water hyacinth biomass adsorbent using response surface methodology

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Abstract

Importance of the work: Water hyacinth biomass has potential as a sustainable adsorbent for Congo red (CR) removal, addressing agricultural waste utilization and dye pollution.
Objectives: To optimize and model CR removal efficiency using water hyacinth biomass under varying adsorbent dose, dye concentration and pH.
Materials and Methods: Water hyacinth biomass was tested for CR removal using adsorption experiments. Response surface methodology (RSM) with Box-Behnken designs (17 experiments) was used to optimize the adsorbent dose, initial dye concentration and pH.
Results: Optimal adsorption achieved 94.76% removal efficiency, closely matching the predicted 98.74%. The mathematical model (developed using Design Expert v8.0.3) demonstrated a 4.03% deviation, confirming parameter optimization significantly ($p < 0.05$) impacted adsorption.
Main finding: Water hyacinth biomass was an efficient and eco-friendly adsorbent for CR. The results demonstrated that RSM was an appropriate and reliable tool for optimizing the efficiency of water hyacinth biomass as an adsorbent for CR, contributing to sustainable pollution control.

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Introduction

A major pollution problem is caused by progressive spread from the discharge of substantial amounts of wastewater contaminated with synthetic dyes from numerous industries, such as the textile industry (Roy and Mondal, 2017; Shabir et al., 2022). The impact extends beyond aquatic life, as the obstruction of sunlight by synthetic dyes leads to oxygen depletion for aquatic animals and inhibits photosynthesis in aquatic plants (Hoque, et al., 2024). Furthermore, these synthetic dyes are toxic and largely carcinogenic, posing serious health risks to humans (Bamroongwongdee et al., 2019; Ardila-Leal et al., 2021; Adeleke et al., 2024; Oyekanmi et al., 2022; Oyekanmi et al., 2024). Synthetic dyes released into the water bodies degrade into various harmful intermediate compounds, with these toxic chemicals generating much concern regarding health risks to humans and animals, as well as adverse impacts on ecosystems (Lellis et al., 2019; Khattab et al., 2020). Therefore, it is crucial to treat wastewater containing these toxic contaminants before it is discharged into the environment. Despite their low concentrations in water, these dyes pose major hazards as their high solubility in aquatic environments makes them difficult to eliminate from water sources (Al-Yousef et al., 2021; Al-Tohamy et al., 2022).

Congo red (CR), a chemically synthesized anionic dye, is known to greatly impact the environment when found in high concentrations in water sources (Sudarsan et al., 2025). CR is a benzidine-based anionic azo dye used in various industries, including textile, paper and fabric printing (Siddiqui et al., 2023). This dye is particularly concerning because it quickly elicits adverse reactions when ingested by living organisms (Sudarsan et al., 2025). Additionally, it has been identified as a carcinogen affecting blood coagulation and the respiratory system (Lade et al., 2015; Roy and Mondal, 2017; Rose et al., 2023; Siddiqui et al., 2023).

The adsorption efficiency of water hyacinth biomass for CR dye is strongly influenced by its surface properties, particularly the presence of negatively charged functional groups such as hydroxyl and carboxyl groups, as these functional groups facilitate electrostatic interactions with dye molecules, thereby enhancing adsorption capacity (Salahuddin et al., 2021). The cell wall of water hyacinth is primarily composed of lignin, hemicellulose and cellulose, which provide a diverse array of functional groups—including amines, carboxyls, hydroxyls, sulfhydryl and carbonyls—capable of interacting with and removing pollutants from water (Carneiro et al., 2022). The presence of micropores and a high surface area in water hyacinth biomass are fundamental characteristics that further contribute to its effectiveness as an adsorbent (Carneiro et al., 2022). Additionally, Fourier-transform infrared (FTIR) analyses have identified the presence of hydroxyl (-OH) and carboxyl (-COOH) groups in water hyacinth biomass, which play a major role in the adsorption process. (Uddin et al., 2014)

Adsorption is a physicochemical method known for its high dye removal efficiency, as well as offering simple design and operation, cost-effectiveness and minimal environmental impact (Oyekanmi et al., 2019; Sellaoui et al., 2021). The fundamental physical methods are ion exchange, membrane filtration, coagulation and adsorption (Wekoye et al., 2020; Manzoor et al., 2024). Among these methods, cost limitations arise due to the expensive materials and chemicals required. Consequently, there is a need to develop new techniques and adsorbent materials as alternatives for dye removal through adsorption (Roy et al., 2017; Yhon et al., 2023). Numerous studies have reported the effectiveness of activated carbon as an adsorbent for removing dyes from wastewater and water treatment systems (Latiff et al., 2016; Kumar et al., 2023). However, exploring other efficient and low-cost adsorbents that can replace activated carbon is essential. Research has focused on preparing inexpensive adsorbents from abundant agricultural waste materials that help reduce the energy required for waste disposal (Darwesh et al., 2023).

RSM is a robust experimental strategy for optimizing conditions using a multivariate approach (Khuri and Cornell, 2018). It uses a factorial design and regression analysis to assess and pinpoint important factors using mathematical models. This methodology involves analyzing experimental data and predicting the relationships between responses and variables, aiming to maximize outcomes, such as biomass or product yields (Kenari et al., 2021; Niyomvong et al., 2022).

The current study investigated the application of agricultural waste materials, specifically water hyacinth, to develop an adsorbent for removing CR dye by examining the optimal conditions for preparing an adsorbent to enhance the dye adsorption efficiency of water hyacinth.

Materials and Methods

Preparation of adsorbent material from water hyacinth biomass

The water hyacinth biomass was collected from a public canal in Uthai district, Phra Nakhon Si Ayutthaya province, Thailand. Stems approximately 30–40 cm long were selected and cleaned and their leaves and roots were removed. The cleaned stems were cut into approximately 1–2 cm long pieces and washed twice with deionized water. The biomass was weighed before drying (2,000 g) and then dried in a hot air oven at 70°C with the air flap open at 20% for 48 hr (resulting in a dry weight of 140 g). The dried biomass was ground into a fine powder using a multipurpose grinder and sieved through 40- and 60-mesh screens to obtain adsorbent particles of 250 µm. The adsorbent was stored in a desiccator until further use (Foroughi-Dahr et al., 2014). Before using the adsorbent material in the adsorption experiments, chlorophyll was removed from the water hyacinth biomass. To achieve this, 30 g of the 250 µm biomass particles were soaked in 800 mL of 95% ethyl alcohol for 15 min. Ethyl alcohol was removed and the biomass particles were washed twice with deionized water. The water hyacinth biomass was filtered through a grade C glass microfiber membrane (GF/C), using a vacuum filtration system. The biomass was dried at 110°C for 18 hr and ground to a fine powder using a multipurpose grinder. It was sieved through 40 and 60 mesh screens to obtain adsorbent particles of 250 µm. The prepared adsorbent material was stored in a zipper bag and desiccated until further use (Roh et al., 2012).

Preparation of Congo red dye

A stock solution of CR dye (100 mL) was prepared with a concentration of 100 mg/L by dissolving 1 mL of 10,000 mg/L CR dye solution (HiMedia; India) in 99 mL of deionized water. The stock solution was stored in a brown glass bottle to prevent degradation (Ponnusamy and Subramaniam, 2013). Solutions with concentrations of 0 mg/L, 20 mg/L, 40 mg/L, 60 mg/L, 80 mg/L and 100 mg/L were used to prepare a standard curve for the CR dye. The absorbance of the solution was measured at 497 nm using a spectrophotometer (Metertech Inc. ; Taiwan). Microsoft Excel (Version 2019; Microsoft Corp.; USA) was used to plot a standard curve for the CR dye at the specified concentrations.

Analysis of Congo red dye adsorption efficiency

The CR dye adsorption efficiency was studied using a colorimetric method, measuring the dye concentration before and after adsorption by determining absorbance values. These values were compared to a standard curve to calculate the concentration. The adsorption efficiency of CR dye was calculated using Equation 1 (Litefti et al., 2019; Extross et al., 2022):

$$\% \text{ CR removal} = 100 \times (C_i - C_f) / 100 \quad (1)$$

where C_i is the initial concentration of CR dye and C_f is the final concentration of the Congo red dye, both measured in milligrams per liter.

Study of optimal conditions for adsorption of Congo red dye using response surface methodology

Based on a preliminary study on the optimal conditions for the adsorption of CR dye by a water hyacinth biomass adsorbent, the factors affecting adsorption were adsorbent dose, CR dye concentration and pH. Thus, these factors were studied using RSM to examine their relationships. The preliminary adsorption study allowed for the determination of three levels of interest: low (-1), medium (0) and high (+1). The Design-Expert software Version 8.0.3 trial (Stat-Ease Inc.; USA) was used, as shown in Table 3.3. A Box-Behnken design (BBD) was applied to study the effects of the relationships between each factor on the adsorption of CR dye by water hyacinth biomass using 17 experimental sets (Table 1). The experiments were carried out in a 100 mL volume at 30°C, with shaking at 200 revolutions per minute for 30 min. After each experiment, the solution was passed through Whatman filter paper No. 5 to separate the water hyacinth adsorbent. The absorbance of the resulting solution was measured at 497 nm to analyze the adsorption efficiency, according to Equation 1:

Table 1 Experimental design used in response surface methodology of three independent variables: adsorbent dose (X1), pH (X2) and Congo red concentration (X3)

Run No.	Level			Actual level			Adsorption efficiency (%)	
	X_1	X_2	X_3	X_1 (Adsorbent dose, g/L)	X_2 (pH)	X_3 (Congo red concentration, mg/L)	Actual	Predicted
1	-1	-1	0	0.1	2	60	74.74	57.16
2	1	-1	0	6	2	60	90.33	91.92
3	-1	1	0	0.1	10	60	0.09	-1.50
4	1	1	0	6	10	60	60.89	78.47
5	-1	0	-1	0.1	6	20	3.34	5.90
6	1	0	-1	6	6	20	91.92	75.31
7	-1	0	1	0.1	6	100	8.01	24.62
8	1	0	1	6	6	100	72.52	69.96
9	0	-1	-1	3	2	20	91.92	106.94
10	0	1	-1	3	10	20	57.38	56.41
11	0	-1	1	3	2	100	98.17	99.14
12	0	1	1	3	10	100	92.59	77.57
13	0	0	0	3	6	60	92.34	92.90
14	0	0	0	3	6	60	93.25	92.90
15	0	0	0	3	6	60	93.61	92.90
16	0	0	0	3	6	60	92.25	92.90
17	0	0	0	3	6	60	93.07	92.90

Results

Preparation of adsorbent from water hyacinth biomass

The adsorbent material derived from water hyacinth biomass was a relatively fine powder with a slightly greenish color. In contrast, the adsorbent material from the water hyacinth biomass that had undergone chlorophyll removal had a much lighter green color. Both types were used in subsequent experiments for the adsorption of CR dye.

Construction of standard curve for Congo red dye

The standard curve for the CR dye was constructed by studying the dye at concentrations of 0 mg/L, 20 mg/L, 40 mg/L, 60 mg/L, 80 mg/L and 100 mg/L in deionized water. The absorbance values at a wavelength of 497 nm showed an increase in absorbance corresponding to an increase in the CR dye concentration. A standard curve was prepared each time an adsorption study of the CR dye was conducted to ensure accurate and reliable results.

Optimal conditions for adsorbing chromogens using response surface methodology

Based on the initial experimental results of the optimal conditions for the adsorption of CR dye, three factors affecting adsorption were selected: amount of adsorbent material, dye concentration and pH. The interactions of these factors were studied using RSM. Three levels were identified in the initial adsorption study: low (-1), medium (0) and high (+1). The experiments were designed using the Design-Expert software, utilizing the BBD to investigate each factor's effects on the dye's adsorption by the water hyacinth adsorbent, resulting in 17 experimental runs. Validation of the mathematical model involved two steps for checking the data quality: 1) examining the residuals to determine whether they followed a normal distribution as verified in Fig. 1(a) that shows the data were distributed along a straight line; and 2) the stability of the variance was assessed using a residual plot across each factor level, as verified in Fig. 1(b) that indicates the residuals from the CR dye adsorption results were evenly distributed both positively and negatively, demonstrating stable variance(Lee et al., 2011). Thus, the validation confirmed that the residuals met both assumptions, indicating that the data from all 17 experimental runs were accurate and suitable for further analysis, which was based on analysis of variance (ANOVA), the coefficient of determination (R^2) and adjusted R^2 results.

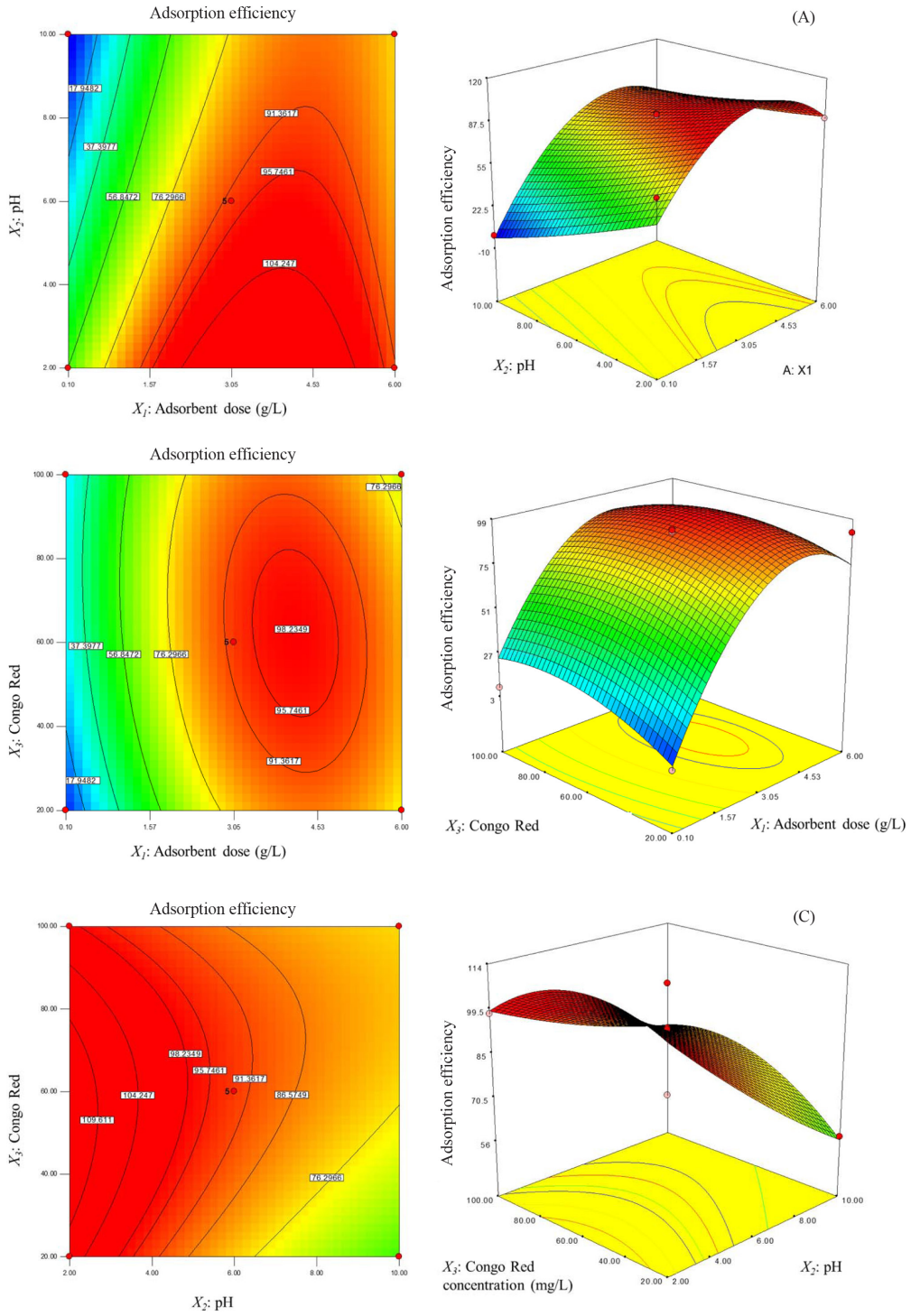


Fig. 1 Contour plot and response surfaces of combined effects of three variable factors on adsorption: (A) adsorbent dose and pH, (B) adsorbent dose and Congo red, (C) pH and Congo red.

Constructing prediction equation for Congo red dye adsorption

The prediction equation for CR dye adsorption was developed by analyzing the data presented in Table 1 to identify the appropriate equation model. Using the statistical summary results from the Design-Expert Version 8.0.3 trial software, the most suitable model for predicting CR dye adsorption was determined. Based on the evaluation of the R^2 values (Tables 2 and 3), quadratic models were acceptable as prediction models for CR dye adsorption on the adsorbent material. A quadratic model had the highest R^2 value of 0.9123, indicating it was the most suitable equation model to best explain the relationship between the various variables and the adsorption capacity of the water hyacinth adsorbent for CR dye, as shown in Equation 2:

$$R1 = 92.90 + 28.69A - 18.03B + 3.34C + 11.30AB - 6.02AC + 7.24BC - 38.73A^2 + 2.34B^2 - 10.23C^2 \quad (2)$$

where A is the adsorbent dose (measured in grams per liter), B is the pH and C is the CR dye concentration (in milligrams per liter).

Analysis of variance for model adequacy and quality

ANOVA was conducted to evaluate the adequacy and quality of the model (Equation 2). Model adequacy was assessed using the model and lack-of-fit values, whereas model quality was determined using the R^2 and adjusted R^2 values (Table 4).

Table 2 Statistics by source (squares, degrees of freedom, value and prob > F)

Source	Sum of Squares	Degrees of freedom	Mean Square	F	*p* value	
Mean vs. Total	85,614.660	1	85,614.660			
Linear vs. Mean	9,271.510	3	3,090.500	4.250	0.027	Suggested
2FI vs. Linear	865.500	3	288.500	0.340	0.800	
Quadratic vs. 2FI	6,951.490	3	2,317.160	9.870	0.007	Suggested
Cubic vs. Quadratic	1,641.550	3	547.180	1,572.900	< 0.001	Aliased
Residual	1.390	4	0.350			
Total	1.04E+05	17	6138.01			

Table 3 Statistics by source (dev., R-squared, PRESS)

Source	Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	26.98	0.495	0.378	0.067	17,480.08	Suggested
2FI	29.32	0.541	0.266	-0.842	34,503.71	
Quadratic	15.32	0.912	0.799	-0.402	26266.91	Suggested
Cubic	0.59	0.999	0.999	+	Aliased	

Dev. = Deviation
R^2 = Coefficient of Determination
Adjusted R^2 = Adjusted Coefficient of Determination
Predicted R^2 = Predicted Residual Sum of Squares
PRESS = Predicted Residual Sum of Squares

Table 4 Analysis of variance for model regression representing adsorption efficiency

Source	Sum of Squares	Degrees of freedom	Mean Square	F	*p* value
Model	17,088.500	9	1,898.722	8.090	0.006
X_1	6,582.634	1	6,582.634	28.046	0.001
X_2	2,599.566	1	2,599.566	11.076	0.013
X_3	89.311	1	89.312	0.380	0.557
AB	510.986	1	510.986	2.177	0.184
AC	144.841	1	144.841	0.617	0.458
BC	209.670	1	209.670	0.893	0.376
A^2	6,315.681	1	6,315.681	26.909	0.001
B^2	23.016	1	23.016	0.098	0.763
C^2	440.385	1	440.385	1.876	0.213
Residual	1,642.937	7	234.705		
Lack of Fit	1,641.546	3	547.182	1,572.904	< 0.001
Pure Error	1.39152	4	0.348		
Cor Total	18,731.430	16			

Coefficient of determination (R^2) = 0.912; Adjusted-R^2 = 0.799.

The model values for the adsorption of CR dye using the water hyacinth adsorbent were evaluated to determine the factors' adequacy. Factors A, B and A^2 were not significant ($p > 0.05$), with values of 0.0011, 0.0126 and 0.0013, respectively. The quality of the model was determined using the R^2 value of 0.9123, indicating that 91.23% of the experimental data matched the predicted data using the model. The prediction accuracy was assessed using the adjusted R^2 value that is in the range 0–1, where Metertech Inc., Taiwan values closer to 1 indicate higher accuracy (Jiang et al., 2017). The adjusted R^2 value for the adsorption of the CR dye using water hyacinth adsorbent was 0.7995, indicating a prediction accuracy of 79.95%.

Fig. 1 illustrates the relationship between the predicted and actual values, showing that the data points were closely aligned with the expected trend, indicating that the model provided highly accurate predictions (Yatish et al., 2016). Based on these results, the adequacy and reliability of the model were high, with minimal differences between the predicted and actual experimental values (Lee et al., 2011).

The interaction relationships and ideal values of the variables were determined by analyzing the response surface plots. Figs. 1A–1C display the response graphs of the independent parameters on adsorption efficiency. The high *p*-values (0.1836 > 0.05, 0.4576 > 0.05 and 0.3760 > 0.05) in Table 3 demonstrated that there were no significant interactions between these parameters and adsorption efficiency (Fig. 1).

The effects of the pH and adsorbent dose on the adsorption efficiency are displayed in Fig. 1A. The adsorption effectiveness increased with doses in the range 0.1–3.8 g/L; however, it fell outside of that range. The adsorption efficiency increased as the pH decreased from 10 to 2. Based on the effect of adsorbent dose and CR concentration on adsorption efficiency, the adsorption efficiency improved in the range 0.1–4.3 g/L but decreased at greater levels. Similarly, the adsorption efficiency increased when the CR concentration was in the range 20–60 mg/L but dropped beyond that point.

The relationship between the pH and CR concentration is shown in Fig. 1C. The adsorption efficiency increased with increasing Conge red concentration in the range 20–60 mg/L but fell outside this range. The adsorption efficiency increased as the pH decreased from 10 to 2.

Validation of experimental results using predicted equations

The experimental results predicted by the equations were validated to ensure the practical applicability of the design generated using the Design-Expert Version 8.0.3 software. The model predicted that an adsorption efficiency of 98.74% occurred at 3.9 g/L of adsorbent dose, pH 3.9 and 92.90 mg/L CR concentration. Validation of the experimental model, repeated thrice under optimum conditions, produced an observed value of 94.76 g/L, close to the predicted value of 98.74 g/L. When the two datasets were combined to calculate the bias, the result was 4.03%, which was less than the predetermined bias threshold of 5%, showing that the optimal conditions for adsorption efficiency utilizing the water hyacinth adsorbent, as predicted by the mathematical model, were reliable. In conclusion, the developed mathematical model was appropriate for forecasting the adsorption efficiency of the water hyacinth adsorbent.

Discussion

The water hyacinth biomass used for preparing the adsorbent material primarily consisted of lignocellulosic components, particularly from the roots and stems. The cell wall structure of the specific type of water hyacinth used in this research contains approximately 33% hemicellulose, 25% cellulose and 10% lignin (Salahuddin et al., 2021). The current study utilized water hyacinth biomass for adsorption due to its promising chemical properties, as these components play a crucial role in dye adsorption due to their functional groups, such as hydroxyl (-OH) and carboxylic (-COOH) groups, which facilitate interactions with dye molecules (Kezerle et al., 2018).

The current results regarding the suitable amount of water hyacinth biomass adsorbent (adsorbent dose) aligned with Litefti et al. (2019), who investigated the adsorption of CR dye using pine bark and found that increasing the amount of adsorbent in the experiment resulted in a decrease in adsorption efficiency; this may have been due to the initial decrease in the concentration of the CR dye due to early-stage adsorption, which affects the adsorbent-adsorbate interaction. When the dye concentration decreases, it leads to an equilibrium or saturation of the active sites on the adsorbent surface, thus decreasing the adsorption capacity with increasing adsorbent amounts (Fegousse et al., 2019; Litefti et al., 2019; Chan et al., 2024). Additionally, a high concentration of adsorbent particles compared with the solution volume can lead to particle aggregation, reducing the surface area for dye adsorption. Furthermore, the observed 2.75% adsorption efficiency in the experiment without adsorbent could be attributed to the 60 min of the experiment

during which the CR dye degraded due to light exposure, which in turn lowered the measured absorbance and impacted adsorption efficiency (Parvin et al., 2019). Abbas and Trari (2023) studied the suitable concentration of CR dye, where an increase in the solution concentration could have enhanced the adsorption process owing to an increased mass-transfer rate, caused by the concentration gradient between the dye on the adsorbent particles and the solution. They suggested that during the initial adsorption stage, the dye diffuses rapidly onto the surface of the adsorbent (film diffusion), resulting in a high adsorption efficiency in the early stages. The current experiment was conducted during 60 min, which might explain why the experiment with the highest dye concentration achieved the highest adsorption efficiency. However, if the adsorption duration was extended beyond 60 min, the adsorption efficiencies may become similar across all dye concentrations because the dye molecules diffuse into the pores (particle diffusion) and subsequently adsorb onto the internal pore surfaces (adsorption), leading to an adsorption equilibrium (Abdoul et al., 2023; Alardhi et al., 2023). This process would cause the adsorption efficiency to slow and eventually stabilize (Banerjee and Chattopadhyaya, 2017).

Several studies reported that the temperature did not significantly affect the adsorption efficiency of CR dye on various types of adsorbent materials, such as with aloe vera peel (Khaniabadi et al., 2017) and mango seed shells (Ponnusamy and Subramaniam, 2013). In the present study, the optimal pH for Congo red (CR) dye adsorption was determined using water hyacinth as the adsorbent. The results showed that maximum adsorption occurred at low pH levels, which aligns with the findings of Ponnusamy and Subramaniam (2013), who reported effective CR dye removal using mango seedshell adsorbents under similar acidic conditions. This phenomenon could be attributed to the high concentration of H^+ ions in the acidic solutions, which saturated the surface of the adsorbent material. At low pH, the adsorbent surface becomes positively charged, facilitating electrostatic attraction between the positively charged surface and the negatively charged CR dye molecules (Ponnusamy and Subramaniam, 2013; Lafi et al., 2019; Al-Harby; Albahly and Mohamed, 2021). This stabilization may have contributed to the similar adsorption efficiencies observed across the current experimental neutral-to-alkaline pH range. The model coefficients generated via the regression analysis for each variable are listed in Table 3.

Based on the current results, the pH significantly affected the adsorbent activity, which was consistent with the work of Roy and Mondal (2017), who reported that biosorption was a promising alternative for dye removal from wastewater. Their study investigated CR adsorption using the burned roots of *Eichhornia crassipes* (BREC) biomass. The batch experiments showed that BREC could remove up to 94.35% of CR under optimized conditions. They analyzed key parameters (initial concentration, pH, adsorbent dose and contact time) using RSM, with their results presenting a good fit using a quadratic model. The optimal conditions were identified as an initial CR concentration of 5 mg/L, pH of 7, adsorbent dose of 0.125 g and contact time of 45 min. The high removal efficiency and regeneration potential of the BREC biomass underscored its applicability for industrial and household use, offering valuable insights for scaling up the process.

The current study incorporated parameters consistent with those used in other biomass studies, such as Laxmi et al. (2023). Their research utilized biochar made from breadfruit leaves to remove toxic CR dye. The biochar was characterized using X-ray diffraction, Fourier transform infrared spectroscopy, and field emission scanning electron microscopy with energy-dispersive X-ray spectroscopy techniques. RSM and the BBD were used to determine the optimal conditions for CR adsorption. Their study explored different ranges of dye concentration (5–50 mg/L), contact time (30–240 min), pH level (6–9) and dosage (0.5–2 g/100 mL). According to their RSM-BBD analysis, a maximum removal efficiency of 99.96% for CR was achieved at a pH of 6.37, dye concentration of 45 mg/L, contact time of 105 min and dosage of 1.92 g.

The adsorption of CR dye onto water hyacinth biomass was substantially influenced by the solution's physicochemical characteristics (pH, ionic strength and the charge properties of both the dye and the adsorbent). In acidic environments, the adsorbent surface tends to acquire a positive charge, enhancing the electrostatic attraction between the dye and the biomass. In addition, variations in ionic strength, which are associated with changes in electrical conductivity and ion concentrations, can modulate the adsorption capacity. Often, higher ionic strengths lead to increased adsorption due to strengthened electrostatic interactions (Cetina et al., 2024). Additionally, the degree of dissociation of the CR dye and the surface charge of the water hyacinth biomass play pivotal roles in determining the nature and strength of their interactions (Cetina et al., 2024). These insights highlight the importance of carefully controlling physicochemical parameters to optimize dye removal processes in wastewater treatment applications (Nguyen et al., 2020; Ige et al., 2024).

Rose et al. (2023) reported on the adsorption of CR dye onto a cationic amino-modified walnut shell (CMWS). Their study involved characterization and optimization using RSM with a central composite design to determine the optimal conditions for dye removal with minimal experimentation. Their results showed that CMWS achieved a maximum removal efficiency of 94.12%, substantially higher than that of raw walnut shells.

The cumulative evidence presented in this discussion suggests that optimizing the operational parameters is essential for maximizing adsorption efficiency, thereby contributing valuable insights for future applications in wastewater treatment. In summary, the BBD used in this study generated a highly significant quadratic polynomial to determine the appropriate concentrations of elements with a substantial impact on removing CR dye using water hyacinth adsorbent materials. In addition, this result confirmed that RSM could be used to determine the best adsorption parameters for the CR dye in this study.

Conclusions

This investigation revealed that the water hyacinth biomass adsorbent could effectively remove CR dye from deionized water and that RSM could be used to determine the best adsorption parameters for CR dye. Optimal adsorption was achieved at 94.76% under the conditions of 3.9 g/L adsorbent dose, pH 3.9 and 92.90 mg/L CR concentration. The adsorbent dose, CR dye concentration, pH, temperature and contact time were all factors that influenced the CR dye adsorption using the water hyacinth biomass adsorbent. Thus, the water hyacinth biomass adsorbent could successfully remove CR dye and the mathematical model developed in this study could be used in environmental analyses.

Ethics statements

This research was approved for sample collection within the area of Phranakhon Si Ayutthaya Rajabhat University by the Faculty of Science and Technology Executive Committee. This study did not involve research on humans or animals.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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