



Experimental and Simulation Study on Removing Congo Red Dye from Neutral Wastewater Using Green Activated Carbon

Hind H. Thwaini ¹, Ammar S. Abbas ^{2*}, Rasha H. Salman ³, and Sarmad Al-Anssari ⁴

^{1,2,3} Department of Chemical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq.

⁴ Department of Petroleum Engineering, College of Engineering, Al-Naji University, Baghdad, Iraq.

● These authors contributed equally to this work

DOI: <https://www.doi.org/10.29194/NJES.29030482>

Received: Dec. 13, 2025 Revised: Jan. 3, 2026 Accepted: Jan. 30, 2026 Published: Sep. 20, 2026

Abstract

The removal of Congo red dye from industrial wastewater before its discharge to the environment is a critical problem, as it is non-biodegradable, toxic, and carcinogenic. Activated carbon was synthesized from a suggested sustainable source (sugarcane waste) and used as an adsorbent for the dye. Isotherm adsorption models and adsorption kinetics were investigated, and a simulated adsorption column model was proposed and developed based on the modified general rate model. The batch results showed that the highest removal rate achieved was 87.1% of the initial dye concentration (30 mg/L). The Freundlich isotherm model best described the equilibrium data, as evidenced by the high correlation coefficient (0.9535). Meanwhile, the maximum adsorption capacity was found to be 149.25 mg/g using the Langmuir isotherm. Furthermore, the kinetic results indicate that the pseudo-second-order model accurately describes the concentration-time relationship. A simulated maximum dynamic adsorption capacity of 0.096 mg/g was achieved at an optimal volumetric flow rate of 0.1 mL/min, with a dye concentration of 30 mg/L and a bed length of 39.69 cm. The continuous column efficiency increased with column length, reaching a maximum of 75% at 66.15 cm. Also, as the dye concentration increased, the column efficiency and dynamic adsorption capacity decreased. The study demonstrated an innovative approach to removing Congo red dye from its aqueous solution in a neutral medium using sustainably produced activated carbon derived from a sustainable source. A continuous removal process was simulated by developing a mathematical model based on adsorption curves and adsorption kinetics, which successfully described the adsorption process. This type of modeling, rather than relying on pre-existing equations, enables more efficient, scalable design.

Keywords: Sustainable Process, Kinetics, General Rate Model, Dynamic Column Adsorption.

* Corresponding author: Provide the corresponding author information and publisher here. E-mail address: ammarabbas@coeng.uobaghdad.edu.iq

1. Introduction

The rapid global population growth, coupled with the rapid development of services and industries, poses a dramatic threat to the environment and ecosystems, particularly water sources [1]. Organic dyes, such as Congo red (CR), are a key example of water contaminants that may limit the sustainable development of communities due to their harmful, toxic, non-biodegradable, accumulative, and carcinogenic nature [2]. These dyes have a direct impact on human health and an indirect effect via their influence on the ecosystem, particularly freshwater and food supplies [3]. Therefore, it is necessary to remove these pollutants from wastewater generated by the textile, leather, rubber, paper, and plastic industries before it is discharged into surface water. However, treating wastewater containing dyes, particularly CR, is challenging due to their complex chemical structures and high solubility in water [4]. Furthermore, the recent surge in industrial activities discharging dyes has made it increasingly difficult to predict the annual extent of growing pollution [5]. Subsequently, various health issues have

dramatically emerged in areas where dyes are released into the environment in an uncontrolled manner with industrial wastewater [6]. In this context, dye discharge can lead to dermatitis, ulcers, fever, and other health issues. Additionally, regarding aquatic life, an overdose of toxic synthetic compounds in wastewater can reduce biological oxygen demand and block sunlight, which impedes photosynthesis and oxygen replenishment [7].

CR, as an ionic dye commonly used in the textile industry, is very poisonous, carcinogenic, and may result in vomiting, blindness, and an allergic reaction [8][9]. Consequently, various techniques were developed for removing CR from wastewater prior to discharge into water streams, including sorption, oxidation, filtration, biodegradation, and membrane approaches, and biological treatment [10], electrocoagulation [11], electro-oxidation [12], photo-oxidation, and ozonation [13]. Despite the advantages of these methods, they also contain dramatic limitations, including high operational costs and insufficient removal rates. In line with this, the strong resistance to biological oxidation treatment, due to the interior closure of

aromatic rings in their molecular composition, adds another major limitation for dye removal activities [14].

Adsorption is a significant process in most natural, physical, biological, and chemical systems [15]. Adsorption methods have several advantages, including affordability, minimal maintenance requirements, sludge-free operation, ease of use, and removal of contaminants from the adsorbent surface [16]. Typically, adsorption is the most cost-efficient method for removing pollutants and toxic materials from the environment [17]. In this context, adsorption processes using solids, including activated carbon (AC) and synthetic resins, are widely employed across various industries and for the filtration of water and wastewater [18]. Characteristically, AC is a highly porous, poorly organized form of graphite, which is also known as activated charcoal. AC contains a broad range of pores, from visible fissures and fractures to molecular-sized pores [19]. After simple modifications and chemical treatments, the inexpensive, sustainably available biomass waste can be transformed into an AC adsorbent [20]. AC is a porous, readily available, and reasonably priced material that provides a large surface area for contaminant removal. Compared to other adsorbent materials, AC has the highest ratio of active surface sites per gram for adsorption [21]. Adsorption removal is a desirable treatment option due to its simplicity, lack of adverse effects, and effectiveness in eliminating a variety of contaminants from water. Dyes can also be removed from industrial wastewater using filtration, sedimentation, adsorption, and the advanced oxidation process [22]. Among these techniques, adsorption is one of the best methods for resolving problems in purification and separation technology, as it is easy and efficient. [23]. A sustainable wastewater treatment strategy can be achieved through the development of innovative, cost-effective, sustainable, and eco-friendly products. [24]. Adsorption technology offers an intriguing approach to eliminating toxic organic dyes from wastewater and agricultural wastes.

The development of inexpensive, sustainable adsorbents with high adsorption capacity is currently one of the most critical topics in wastewater treatment. The present study aims to produce AC from sugarcane residues as a sustainable source and to characterize its adsorption activity for the removal of CR dye from water. Experimentally, a study of dye removal via adsorption on AC was conducted to determine the isotherm models and kinetics governing the process. Further, a simulation of the adsorption column was performed using a general rate model and liquid-phase mass transfer. Subsequently, breakthrough curves were obtained under various operating conditions, including flow rate, bed length, and initial dye concentration (IC). This work provides insight into the sustainable utilization of organic waste, such as sugarcane, for AC production and the application of this eco-friendly powder as an adsorbent for CR dye removal, thereby protecting the ecosystem from these harmful chemicals.

2. Method and Experiments

2.1 Materials

Sugarcane is obtained from the city of Amara in southern Iraq, where millions of tons of the plant grow naturally. Homemade deionized water ($0.32 \times 105 \Omega$ cm resistivity) was used for the washing steps and to formulate the predesigned (simulated) wastewater. Sigma-

Aldrich provided sodium hydroxide (NaOH, $\geq 97\%$), hydrochloric acid (HCl, reagent grade, 37%), and CR dye, which were used exactly as supplied without further purification.

2.2 AC preparation

Initially, sugarcane was continuously rinsed with water to remove dust and impurities, then dried at 90°C for 24 hours. The dry cane was then ground and sieved to separate fractions with an average size of 1.0 mm. The subsequent powder was mixed with 1.5 M NaOH in a 1:5 ratio for 24 hours. After that, the mixture was washed with deionized water multiple times until it reached neutral pH (7). The neutral mixture was then dried overnight at 100°C . The mixture was then carbonized using a muffle furnace at 600°C for 2 hours. After activation, the produced AC was washed with 1 M hydrochloric acid (HCl) and subsequently with deionized water to remove reversibly adsorbed NaOH until no change in pH was observed. Eventually, the AC obtained was allowed to dry overnight at 110°C and kept stored in a clean, dry place for later use. The same preparation steps were followed, with the necessary changes made to the previously published procedure [20].

2.3 AC characterization techniques

The basic characterization tests for the prepared ACs were performed, namely apparent density (measured by the authors in the laboratory), surface area, and pore volume using the Brunauer-Emmett-Teller (BET) method via nitrogen adsorption and desorption at 77K using SA-9600 (Horibe, USA) instrument. A scanning electron microscope (SEM) was used to examine the surface of the prepared AC (FEI Inspect S50 at 25 kV and $500 \mu\text{A}$ (Company, Netherlands)). Also, energy-dispersive X-ray spectroscopy (EDX) was performed to analyze the element composition of the prepared AC using the Bruker XFlash-6110 (Germany).

2.4 Batch adsorption process

Tests for batch adsorption were conducted using simulated wastewater containing 30 mg/L of CR dye and varying amounts of AC (0.2 to 2 g/L). The samples have been shaken at 200 rpm and 25°C for 24 hours. Subsequently, each mixture was centrifuged (Low-speed centrifuge, Max 6000 rpm, Infitek) at 2000 rpm for 10 minutes, then filtered to remove the AC fines. A UV-Vis spectrometer (UV-9200, Envi Sense, England) was used to identify the CR concentrations in the initial and treated solutions at 497 nm. The amount of dye adsorbent per unit mass of AC adsorbent is represented by Eq. (1)[25].

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

Where q_e represents the adsorption capacity of the adsorbent (mg/g), C_0 (mg/L) is the IC of dye, and C_e (mg/L) is the final contraction of dye in the aqueous phase at time (t), the mass of AC is represented by m in g. In contrast, the volume of the sampled solution is represented by V in L.

3. Results and Discussion

3.1 AC characterizations

The measured solid particle density of the prepared AC (ρ_s) was 1.84 g/cm^3 . The measured density of the AC was greater than the density value of water; therefore, no quantities of the adsorbent were

observed floating on the surface of the water, especially after the beginning of the mixing.

The adsorption-desorption results indicated that the BET surface area and pore volume of the prepared AC were 1073.20 m²/g and 1.04 cm³/g, respectively. These results suggest that the prepared AC possesses a large surface area and pore volume, supporting its potential as an effective adsorbent for dyes and other organic pollutants.

SEM was employed to examine the surface morphology of the prepared AC. The microscopic image (Fig. 1) reveals a porous, irregular structure with a rough surface and a network of pores distributed throughout the imaged AC. This image confirms the successful formation of pores during the preparation and activation of the AC. Furthermore, the presence of well-defined pores with varying sizes and surface roughness can enhance mass transfer and facilitate the diffusion of CR dye molecules to active sites, thereby improving adsorption efficiency. Furthermore, the absence of sharp cracks may indicate the material's mechanical stability.

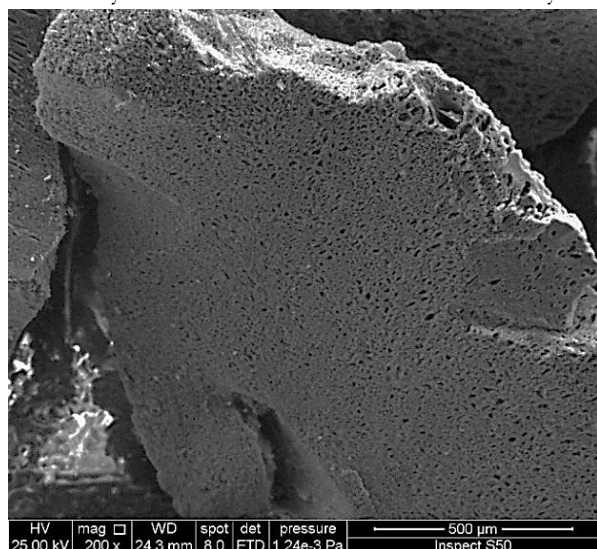


Figure 1. SEM images of the prepared AC.

Elemental composition analysis of the prepared AC by EDX (Fig. 2) revealed carbon as the only detectable element. The presence of carbon as the sole element of the AC indicates the material's high purity and the absence of inorganic or metallic impurities within the detection limits of this technique.

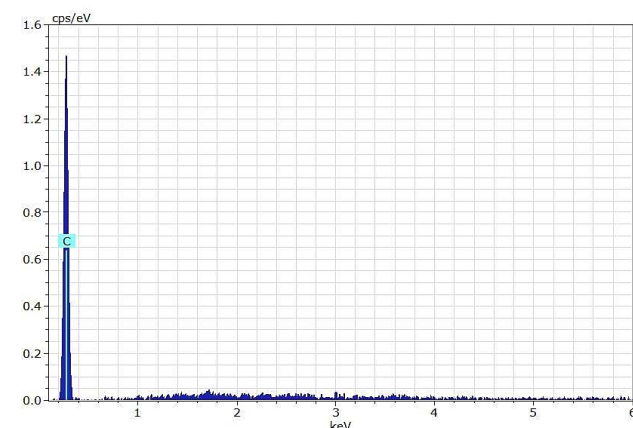


Figure 2. EDX results for the prepared AC.

The simple elemental composition (carbon only) ensures that the adsorption behavior is unaffected by any extraneous phases.

Furthermore, the presence of highly porous, heterogeneous pores and a coarse surface texture, as seen in the SEM image (Fig. 1), provides qualitative evidence of extensive pore development, which is consistent with the results of the surface area and pore volume analyses.

3.2 Equilibrium results and isotherms

The dye equilibrium concentration is used as a model to examine adsorption equilibrium capacity behavior, as shown in Fig. 3, where q_e is plotted against C_e for the laboratory results (black points). The equilibrium concentration increased from 1.50 to 14.6 mg/L, and the equilibrium adsorption capacity increased from 12 to 77 mg/g.

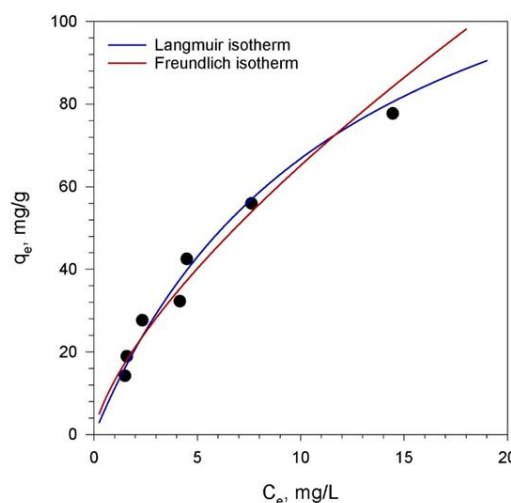


Figure 3. Experimental adsorption equilibrium capacity versus equilibrium concentration (black point), the Langmuir isotherm (blue line), and the Freundlich isotherm (red line) for CR dye adsorption on AC.

The relationship between the quantity of dye adsorbed by AC (q_e) and the concentration of dye remaining in the aqueous phase (C_e) at equilibrium was described using an adsorption isotherm. Moreover, the achieved equilibrium isotherms are key to understanding the type of adsorption and the adsorbent's performance [26].

The adsorption behaviors of dyes on solid adsorbents have been understood using various adsorption isotherm models [27]. The Langmuir isotherm model (LIM) and the Freundlich isotherm model (FIM) have been fitted to the data in this examination. In this present study, synthetic wastewater containing 30 mg/L of CR dye was used to investigate the adsorption isotherm.

The LIM is effectively utilized to describe all monolayer adsorption processes with a homogeneous surface [28]. Adsorption is thought to occur at uniform sites inside the adsorbent. Additionally, it describes a homogeneous process in which each molecule retains its sorption activation energy and enthalpy constant, without the adsorbate traveling across the surface. Eq. (2) represents the LIM.

$$q_e = \frac{q_m b C_e}{1 + b C_e} \quad (2)$$

Where q_m is the adsorbent's maximum adsorption capacity in mg/g and b is the Langmuir adsorption equilibrium constant. The Langmuir model's results are displayed in Fig. 3 (blue line), with a maximum adsorption capacity (q_m) of 149.25 mg/g at 25 °C and a correlation coefficient (R^2) of 0.9347.

The FIM is an empirical equation that represents multilayer adsorption on a heterogeneous surface with sites having various energies [29], and represents a non-ideal and reversible adsorption process [30]. The FIM is represented in Eq. (3).

$$q_e = K_f C_e^{1/n} \quad (3)$$

Where K_f , and n are the Freundlich constants revealing the relative adsorption capacity of the adsorbent (mg/g) and the intensity or the heterogenous factor, respectively. The relative adsorption capacity was 13.12 mg/g, the intensity (n) was 1.44, and the model R^2 was 0.9535. This suggests that the n value reflects the degree of nonlinearity in the relationship between solution concentration and adsorption. When $n=1$, adsorption is linear; if $n<1$, it indicates chemical adsorption; and if $n>1$, it points to physical adsorption. The value of n is greater than one in the present work, indicating that the adsorption was normal. This can be attributed to a surface site dispersion or other features that reduce the amount of adsorbent adsorbed to a surface density between 1 and 10, resulting in excellent adsorption [31].

Table 1 summarizes the parameters obtained from the isotherm models and the corresponding correlation coefficients (R^2). The data show that the R^2 values for the FIM and LIM were 0.9535 and 0.9347, respectively, accurately representing the dye's equilibrium adsorption on AC. The results indicate that FIM best describes the adsorption, consistent with published work [32].

Table 1. R^2 and constants for each equilibrium isotherm model.

Model	Model parameters	Parameter value	R^2
LIM	q_m , mg/g	149.25	0.9347
	b , L/mg	0.0811	
FIM	K_F , mg^{1-n}/g	13.126	0.9535
	n , -	1.437	

In this work, the prepared AC demonstrated a high adsorption capacity for the CR dye, achieving 149.25 mg of CR per gram of the prepared AC and a removal rate of approximately 87.1%. Comparing these results with those of previous studies [33], [34], [35], it is evident that the current AC manufactured from sugarcane residue achieved a q_m significantly greater than the reported values for conventional AC derived from another biomass, which ranged from 19.6 to 53.2 mg/g. Although those studies reported removal rates under limited IC and optimal pH. The discrepancy between the current and previously reported results indicates that the removal rate alone does not necessarily reflect the overall efficiency of the adsorbent, whereas the q_m value is a more accurate indicator of the adsorbent's quality, surface area, porosity development, and the density of its active sites. Therefore, the AC currently prepared can be considered a sustainable and promising absorbent, with a high removal rate, superior q_m , and applicability for removing various pollutants, especially dyes (such as CR dyes) and other organic pollutants found in wastewater.

3.3 Adsorption kinetics

The kinetics of the adsorption process and the time-dependent measurement of dye concentration were studied over 240 minutes (4 hours), as shown in Fig. 4. During this time, the IC (30 mg/L) decreased with increasing adsorption time. The decrease was sharp during the first 60 minutes, followed by a less pronounced reduction between 60 and 120 minutes. Afterward, throughout the process, the

concentration did not change significantly, reaching a final concentration of 4 mg/L.

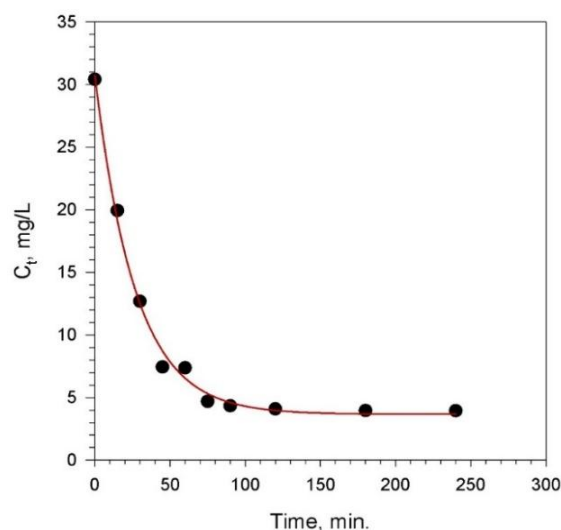


Figure 4. The effect of time on equilibrium concentration.

The pseudo-first-order (PFO, Eq. 4), pseudo-second-order (PSO, Eq. 5), and intraparticle-diffusion (IPD, Eq. 6) kinetic models were used. The adsorption rate constants for each model were determined by solving their linear form using linear regression and the least squares criterion [36], [37], [38].

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (4)$$

Where q_e , q_t , k_1 , and t are the adsorption capacity of dye at equilibrium (mg/g), the adsorption capacity of dye at any time (mg/g), the adsorption rate constant for PFO (1/min), and time (min).

$$\frac{t}{q_t} = \frac{1}{k_2 q_e} + \frac{t}{q_e} \quad (5)$$

Where k_2 is the adsorption rate constant for PSO (g/mg min)

$$q_t = k_3 t^{1/2} + C \quad (6)$$

Where k_3 is a constant of the IPD rate ($\text{mg}/\text{min}^{1/2}$, g), while C represents the thickness of the boundary layer (mg/g). The step is controlled by several diffusion rates, including film and pore diffusion.

Table 2 summarizes the obtained kinetic model parameters for dye adsorption on AC, which are consistent with a PSO model, as indicated by the highest R^2 (0.9588), but are not appropriate for the PSO or IPD models.

Table 2. The rate constants for the adsorption of dye on AC at 25 °C.

Adsorption kinetic model	Model parameters	Parameter value at 25°C	R^2
PFO	q_e , mg/g	556.129	0.6887
	k_1 , 1/min	6.321	
PSO	q_e , mg/g	555.556	0.9588
	k_2 , g/mg. min	8.6868×10^{-5}	
IPD	C	133.38	0.7558
	K_3	33.861	

3.4 General rate model and aqueous phase mass transfer

The CR dye species may be transported both axially and radially through the fixed-bed column after adsorption onto the AC

adsorbent particles. Nevertheless, the level of pollutants in the radial direction is insignificant. Thus, based on the hypotheses, the partial difference can be used to characterize the material balance of the AC in the adsorber, Eq. (7) [39].

$$\varepsilon \frac{\partial C(z,t)}{\partial t} + (1 - \varepsilon) \rho_b \frac{\partial q(z,t)}{\partial t} = -v \frac{\partial C(z,t)}{\partial z} \quad (7)$$

where t refers to the time, ρ_b is the particle of adsorbent density (g/cm^3), q is the concentration of the adsorbed adsorbate (mg/g), and C is the solute concentration in the bulk solution (mg/L). The initial and the boundary conditions were described by Eqs. (8) and (9).

$$\text{At } t = 0: C(z, 0) = 0 \text{ and } q(z, 0) = 0 \quad (8)$$

$$\text{At } z = 0: C(0, t) = C_0$$

$$\text{At } z = L: \frac{\partial C(L, t)}{\partial z} = 0 \quad (9)$$

The study assessed breakthrough curves by plotting the effluent concentration ratio (C/C_0) against the adsorption period at 25°C . A mathematical model was developed and solved using the data obtained from adsorption isotherms and kinetic calculations.

Furthermore, the following values were used to solve the model: the solid particle density (ρ_s), the column cross-sectional area (A_s) of 0.7854 cm^2 , and the bed voidage (ε_b) of 0.4764 .

By varying stream velocity, AC amount, and initial AC concentration, breakthrough curves were obtained. The following characteristics can be used to characterize the breakthrough behavior of dye adsorption [40].

The period (t_b) is equal to the amount of time needed for bed to reach its adsorption capacity, as in Eq. (10) [41].

$$t_b = \int_0^\infty \left(1 - \frac{C}{C_0}\right) dt \quad (10)$$

- According to Eq. (11), the bed's usable capacity until the breakpoint time was reached (t_b) when $C/C_0 = 0.05$.

$$t_u = \int_0^{t_b} \left(1 - \frac{C}{C_0}\right) dt \quad (11)$$

- According to Eq. (12), the bed's length is utilized up to breakpoints (H_B).

$$H_B = \frac{t_u}{t_t} H_T \quad (12)$$

Where (t_u/t_t) is the overall adsorption capacity fraction and (H_T) is the adsorbent amount length in m.

- Eq. (13) is the unused bed length (H_{UNB}) in m.

$$H_{UNB} = H_T - H_B \quad (13)$$

The mass transfer zone (L_{MTZ}) is the region of the bed where significant adsorption occurs and travels up the bed column, which was used in Eq. (14).

$$\text{Eq. } L_{MTZ} = L \times \frac{t_s - t_b}{t_s} \quad (14)$$

Where t_s is the exhaustion time in minutes.

- Eq. (15) utilized the total adsorbent mass (m_{adsorbed}) in mg.

$$m_{\text{adsorbate}} = \frac{\dot{V} C_0}{1000} \int_0^\infty \left(1 - \frac{C}{C_0}\right) dt = \frac{\dot{V} C_0}{1000} \times t_t \quad (15)$$

Here, $\dot{V}$ is the mean aqueous phase flow rate in milliliters per minute.

- Eq. (16) represents the dynamic adsorption capacity (q_d) in mg/g .

$$q_d = \frac{\dot{V} C_0}{m} t_t = \frac{m_{\text{adsorbate}}}{m} \quad (16)$$

Here, q_d is the dye load mg/g , and m is the weight of the AC.

- Eq. (17) represents the treated effluent volume (V_{eff}) in ml.

$$V_{\text{eff}} = \dot{V} \times t_s \quad (17)$$

3.5 Designing and simulating a continuous adsorber

Numerous operating parameters affected the expected outcomes of dye treatment via adsorption in a fixed-bed continuous column. Fluid volumetric flow, bed length, and IC were examined as operational factors and their consequences. The mathematical model was used to simulate the breakthrough curve of a two-phase fixed-bed continuous adsorption column.

3.5.1 Fluid volumetric flow rate effect on bed column performance

The influence of the inlet volumetric flow rate on the fixed-bed column loaded with AC was examined. At a constant particle diameter, the bed column efficiency was measured at various volumetric flow rates (0.1, 0.25, and 0.4 mL/min). Additionally, the length of the fixed-bed and the dye starting load were examined at 25°C . The breakthrough curves for various volumetric flow rates are shown in Fig. 5.

Table 3 summarizes how the liquid's volumetric flow rate affects the characteristic features of the breakthrough curves. The curves become steeper and reach saturation more rapidly as the flow rate increases, due to a shorter adsorbent residence time in the column. Thus, a shorter saturation period was observed with increased flow rate [42]. As a result, the dye aqueous solution left the fixed-bed column before reaching equilibrium. Saturation time (t_s) dropped from 159 to 41 minutes when fluid flow rate increased from 0.1 to 0.4 mL/min .

Table 3 shows that the dynamic adsorption capacity (q_d) decreased from 0.096 to 0.009 mg/g as the fluid flow rate increased from 0.1 mL/min to 0.4 mL/min . This indicates that while the fluid flow rate increased from 0.1 mL/min to 0.4 mL/min . Therefore, for adsorption of the CR on AC and in subsequent experiments, an optimal aqueous phase flow rate of 0.25 mL/min was required, yielding an adsorption capacity of 0.024 mg/g .

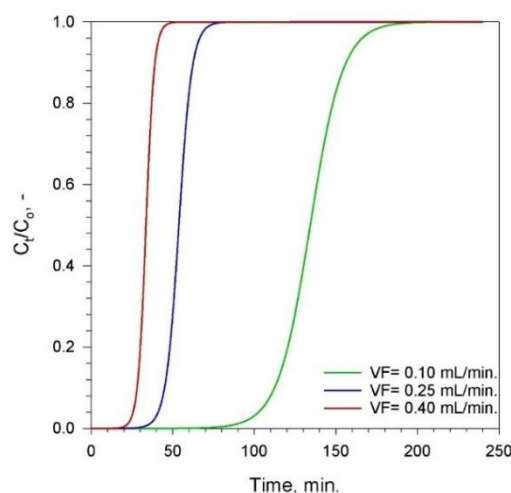


Figure 5. Modeled breakthrough behavior for CR removal at various aqueous phase volumetric flow rates for a bed length of 39.69 cm and an IC of 30 mg/L .

3.5.2 Bed length effect on adsorber efficiency

The influence of varying column bed lengths (L) of 13.23 , 39.69 , and 69.15 cm on breakthrough curves was investigated. The breakthrough isotherms for CR adsorption onto the AC are shown in Fig. 6, considering different bed lengths, a volumetric flow rate of

0.25 mL/min, and an inlet dye concentration of 30 mg/L. Table 4 summarizes that as bed length increases, both t_u and t_t increase.

Table 3. Effects of volumetric flow rate on breakthrough curve parameters at an IC of 30 mg/L, and bed length of 39.69 cm.

V , mL/min	t_u , min	t_t , min	η , %	H_B , m	H_{UNB} , m	L_{MTZ} , m	$m_{adsorbed}$, mg	q_d , mg/g	V_{eff} , mL
0.1	100	159	64	25.00	14.69	13.47	1.908	0.096	64
0.25	41	64	63	25.40	14.29	13.03	0.480	0.024	16
0.4	25	41	61	24.21	15.48	14.52	0.192	0.0009	4

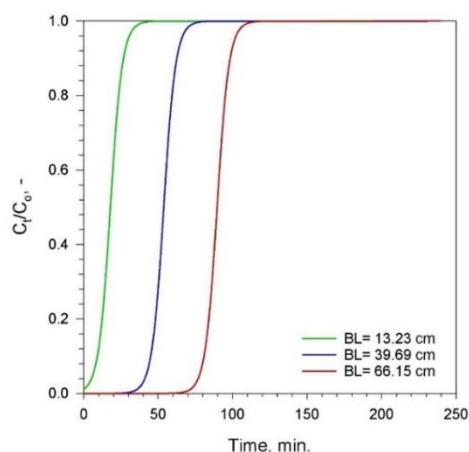


Figure 6. Modeled breakthrough behavior for dye adsorption onto AC at various bed lengths for a volumetric flow rate of 0.25 mL/min, and an IC of 30 mg/L.

Table 4. Effects of bed length on breakthrough curve parameters at an IC of 30 mg/L, and volumetric flow rate of 0.25 mL/min.

L , cm	t_u , min	t_t , min	η , %	H_B , m	H_{UNB} , m	L_{MTZ} , m	$m_{adsorbed}$, mg	q_d , mg/g	V_{eff} , mL
13.23	6	31	18	2.43	10.80	10.66	0.225	0.011	8
39.69	41	64	64	25.34	14.35	13.02	0.480	0.024	16
66.15	74	99	75	49.51	16.64	14.03	0.743	0.037	25

Fig. 6 shows that the normalized effluent concentration (C/C_0) increased rapidly with the smallest bed length compared to the larger one. This is mainly related to the extended mass transfer in larger beds [43]. Additionally, the CR removal from the aqueous phase required a longer adsorption time in the AC bed, leading to a rise in the η of dye removal from 18 to 75% with increased bed length.

The adsorbent weight required for treatment increases with larger column bed length, thereby increasing the volume of aqueous solution removed.

When the bed length was expanded, the amounts of dye extracted from the inflow stream and q_d increased. Thus, a large volume of adsorbent creates a significant support area, providing the adsorbate with more active adsorbent sites and an extended bed length [44].

3.5.3 Inlet concentration effect on adsorption capacity

Modeled breakthrough behaviors for CR adsorption at various IC (20-60 mg/L) and a bed length of 39.69 cm are shown in Fig. 7, and Table 5 summarizes their results. When the inlet CR concentration increased from 20 to 60 mg/L, the breakthrough curves became sharper. Because slower transit of CR molecules is anticipated at lower input adsorbate concentrations, the extended contact time supports the complete saturation of the adsorbent surface's active sites at lower adsorbate dosages. When the initial CR dye concentration was lowered to 20 mg/L, the t_u decreased from 88 to

40 minutes, and the t_t decreased from 66 to 15 minutes under a high inlet concentration.

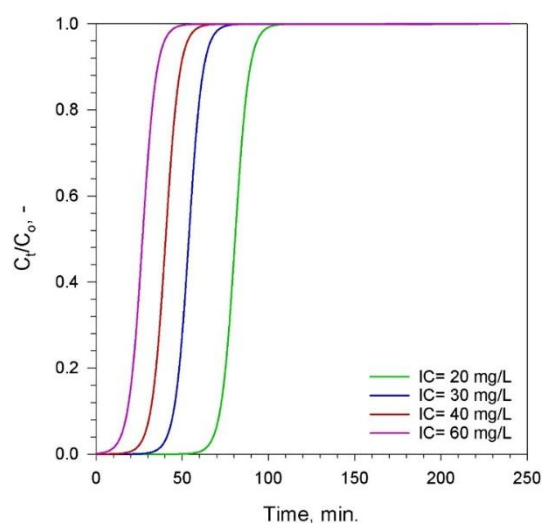


Figure 7. Modeled breakthrough behavior for dye adsorption onto AC at various IC for a volumetric flow rate of 0.25 mL/min, and 39.69 cm bed length.

Table (5): Effects of IC on breakthrough curve parameters for a volumetric flow rate of 0.25 mL/min, and 39.69 cm bed length.

C_0 , mg/L	t_u , min	t_t , min	η , %	H_B , m	H_{UNB} , m	L_{MTZ} , m	$m_{adsorbed}$, mg	q_d , mg/g	V_{eff} , mL
20	66	88	75	29.76	9.93	8.569	1.320	0.066	22
30	41	64	64	25.40	14.29	13.020	0.640	0.032	16
40	28	52	53	21.03	18.66	17.550	0.390	0.019	13
60	15	40	35	13.89	25.80	24.900	0.200	0.010	10

As the inlet CR concentration increases, the AC bed might saturate more quickly with adsorbed CR dye, thereby shortening t_s and reducing the volume of treated effluent. The breakthrough curves, on the other hand, were less steep as the mass transfer driving force decreased, resulting in a higher LMTZ of 24.9 cm and a lower inlet CR concentration.

4. Conclusion

This work effectively establishes that sugarcane-based AC is an efficient, cost-effective, and environmentally friendly adsorbent for removing CR dye from wastewater. The adsorption process study showed that the FIM better described the equilibrium data; the measured maximum adsorption capacity was 149.25 mg/g, and the process kinetics were described by the PSO model, with a maximum removal efficiency of 87.1% for an IC solution of 30 mg/L. The column efficiency increased with column length and reached its maximum (75%) in the longest column. However, changing the volumetric flow rate to 0.4 mL/min and the IC to 60 mg/L significantly reduces the adsorption capacity and removal efficiency. In contrast, increasing bed length significantly increases removal efficiency by increasing adsorption capacity. In summary, AC made from sugarcane is an environmentally friendly, sustainable adsorbent that effectively adsorbs CR dye from neutral solutions, unlike commercial AC. In addition, the improved model has supported an efficient design and scale-up process, and the simulation results have provided important information for the design of a successful adsorption column for CR dye adsorption from neutral wastewater.

5. References

- [1] I. Ali, M. Asim, and T. A. Khan, "Low-cost adsorbents for the removal of organic pollutants from wastewater," *J. Environ. Manage.*, vol. 113, pp. 170–183, 2012, <https://doi.org/10.1016/j.jenvman.2012.08.028>.
- [2] I. S. Al-Bayati, S. Abd Muslim Mohammed, and S. Al-Ansari, "Recovery of Methyl Orange from Aqueous Solutions by Bulk Liquid Membrane Process Facilitated with Anionic Carrier," *AIP Conf. Proc.*, vol. 2414, no. August, 2023, <https://doi.org/10.1063/5.0114631>.
- [3] Z. Kılıç, "The importance of water and conscious use of water," *International Journal of Hydrology*, vol. 4, no. 5, pp. 239–241, 2020, <https://doi.org/10.15406/ijh.2020.04.00250>.
- [4] A. Jasińska, A. Walaszczyk, and K. Paraszkiwicz, "Omics-Based Approaches in Research on Textile Dye Microbial Decolorization," *Molecules*, vol. 29, no. 12, pp. 1–24, 2024, <https://doi.org/10.3390/molecules29122771>.
- [5] S. Benkhaya, S. M'rabet, and A. El Harfi, "Classifications, properties, recent synthesis and applications of azo dyes," *Heliyon*, vol. 6, no. 1, 2020, <https://doi.org/10.1016/j.heliyon.2020.e03271>.
- [6] A. Soltani, M. Faramarzi, and S. A. M. Parsa, "A review on adsorbent parameters for removal of dye products from industrial wastewater," *Water Quality Research Journal*, vol. 56, no. 4, pp. 181–193, 2021, <https://doi.org/10.2166/wqrj.2021.023>.
- [7] B. M. Al-Sakkaf, S. Nasreen, N. Ejaz, and F. Feng, "Degradation Pattern of Textile Effluent by Using Bio and Sono Chemical Reactor," *J. Chem.*, vol. 2020, 2020, <https://doi.org/10.1155/2020/8965627>.
- [8] S. I. Siddiqui et al., "Investigation of Congo Red Toxicity towards Different Living Organisms: A Review," *Processes*, vol. 11, no. 3, pp. 1–12, 2023, <https://doi.org/10.3390/pr11030807>.
- [9] Z. Y. Velkova, G. K. Kirova, M. S. Stoytcheva, and V. K. Gochev, "Biosorption of Congo Red and methylene blue by pretreated waste streptomyces fradiae biomass - Equilibrium, kinetic and thermodynamic studies," *Journal of the Serbian Chemical Society*, vol. 83, no. 1, pp. 107–120, 2018, <https://doi.org/10.2298/JSC170519093V>.
- [10] S. Haran and S. K. Ali, "Methods for Removing Dyes from Polluted Water; A Review," *Journal of Engineering*, vol. 28, no. 9, pp. 70–85, 2022, <https://doi.org/10.31026/j.eng.2022.09.05>.
- [11] D. P. W. Sheng, M. R. Bilad, and N. Shamsuddin, "Assessment and Optimization of Coagulation Process in Water Treatment Plant: A Review," *ASEAN Journal of Science and Engineering*, vol. 3, no. 1, pp. 79–100, 2023, <https://doi.org/10.17509/ajse.v3i1.45035>.
- [12] H. H. Thwaini and R. H. Salman, "Phenol removal by electro-Fenton process using a 3D electrode with iron foam as particles and carbon fibre modified with graphene," *Journal of Electrochemical Science and Engineering*, vol. 13, no. 3, pp. 537–551, 2023, <https://doi.org/10.5599/jese.1806>.
- [13] S. Wijannarong, S. Aroonsrimorakot, P. Thavipoke, charaporn Kumsopa, and S. Sangjan, "Removal of Reactive Dyes from Textile Dyeing Industrial Effluent by Ozonation Process," *APCBEE Procedia*, vol. 5, pp. 279–282, 2013, <https://doi.org/10.1016/j.apcbec.2013.05.048>.
- [14] S. K. Kamal, Z. M. Mustafa, and A. S. Abbas, "Reaction Kinetics and Mass Transfer of Photocatalytic Fenton for Phenol Degradation in a Petroleum Refinery Wastewater," *Tikrit Journal of Engineering Sciences*, vol. 32, no. 1, Mar. 2025, <https://doi.org/10.25130/tjes.32.1.30>.
- [15] A. D. N'diaye, "Nonlinear Analysis of The Kinetics and Equilibrium for Adsorptive Removal of Paranitrophenol by Powdered Activated Carbon," *ASEAN Journal of Science and Engineering*, vol. 3, no. 3, pp. 271–280, 2023, <https://doi.org/10.17509/ajse.v3i3.49136>.
- [16] M. Akhtar, M. Sarfraz, and M. Ahmad, "Use of low-cost adsorbent for waste water treatment : Recent progress , new trend and future perspectives," *Desalination Water Treat.*, vol. 321, no. November 2024, p. 100914, 2025, <https://doi.org/10.1016/j.dwt.2024.100914>.
- [17] A. M. Badran, U. Utra, N. S. Yussof, and M. J. K. Bashir, "Advancements in Adsorption Techniques for Sustainable Water Purification: A Focus on Lead Removal," *Separations*, vol. 10, no. 11, pp. 1–26, 2023, <https://doi.org/10.3390/separations10110565>.
- [18] Y. El Maguana, N. Elhadiri, M. Benchanaa, and R. Chikri, "Activated Carbon for Dyes Removal: Modeling and Understanding the Adsorption Process," *J. Chem.*, vol. 2020, 2020, <https://doi.org/10.1155/2020/2096834>.
- [19] R. Ganjoo, S. Sharma, A. Kumar, and M. M. A. Daouda, "Activated Carbon: Fundamentals, Classification, and Properties," *Activated Carbon*, no. May, pp. 1–22, 2023, <https://doi.org/10.1039/bk9781839169861-00001>.
- [20] M. S. Abdulrahman, A. A. Alsarayreh, S. K. A. Barno, M. A. Abd Elkawi, and A. S. Abbas, "Activated carbon from sugarcane as an efficient adsorbent for phenol from petroleum refinery wastewater: Equilibrium, kinetic, and thermodynamic study," *Open Engineering*, vol. 13, no. 1, 2023, <https://doi.org/10.1515/eng-2022-0442>.
- [21] S. Ho, "Removal of Dyes from Wastewater by Adsorption onto Activated Carbon: Mini Review," *Journal of Geoscience and Environment Protection*, vol. 08, no. 05, pp. 120–131, 2020, <https://doi.org/10.4236/gep.2020.85008>.
- [22] E. Rapo and S. Tonk, "Factors Affecting Synthetic Dye Adsorption ; Desorption Studies : A Review of Results from the Last Five Years," *Molecules*, vol. 26, pp. 5419, 2021, <https://doi.org/10.3390/molecules26175419>.
- [23] F. K. Al-Jubory, A. S. Abbas, and I. M. Mujtaba, "Adsorptive removal of ciprofloxacin from simulated wastewater using crosslinked starch ester: Isotherms, kinetics, thermodynamics, modeling, and simulation for continuous operation," *Chemical Engineering Research and Design*, vol. 200, no. October, pp. 332–343, 2023, <https://doi.org/10.1016/j.cherd.2023.10.051>.
- [24] A. A. Hambisa, M. B. Regasa, H. G. Ejigu, and C. B. Senbeto, "Adsorption studies of methyl orange dye removal from aqueous solution using Anchote peel-based agricultural waste adsorbent," *Appl. Water Sci.*, vol. 13, no. 1, pp. 1–11, 2023, <https://doi.org/10.1007/s13201-022-01832-y>.

- [25] R. S. Ingole, D. H. Lataye, and P. T. Dhorabe, "Adsorption of phenol onto Banana Peels Activated Carbon," *KSCE Journal of Civil Engineering*, vol. 21, no. 1, pp. 100–110, 2017, <https://doi.org/10.1007/s12205-016-0101-9>.
- [26] S. Basu, G. Ghosh, and S. Saha, "Adsorption characteristics of phosphoric acid induced activation of bio-carbon: Equilibrium, kinetics, thermodynamics and batch adsorber design," *Process Safety and Environmental Protection*, vol. 117, pp. 125–142, 2018, <https://doi.org/10.1016/j.psep.2018.04.015>.
- [27] M. A. Zenasni, B. Meroufel, A. Merlin, and B. George, "Adsorption of Congo Red from Aqueous Solution Using CTAB-Kaolin from Bechar Algeria," *J. Surf. Eng. Mater. Adv. Technol.*, vol. 04, no. 06, pp. 332–341, 2014, <https://doi.org/10.4236/jsemet.2014.46037>.
- [28] M. T. Yagub, T. K. Sen, S. Afroze, and H. M. Ang, "Dye and its removal from aqueous solution by adsorption: A review," *Adv. Colloid Interface Sci.*, vol. 209, pp. 172–184, 2014, <https://doi.org/10.1016/j.cis.2014.04.002>.
- [29] O. Üner, Ü. Geçgel, and Y. Bayrak, "Adsorption of Methylene Blue by an Efficient Activated Carbon Prepared from Citrullus lanatus Rind: Kinetic, Isotherm, Thermodynamic, and Mechanism Analysis," *Water Air Soil Pollut.*, vol. 227, no. 7, 2016, <https://doi.org/10.1007/s11270-016-2949-1>.
- [30] P. Ehiomogbe, I. I. Ahuchaogu, and I. E. Ahaneku, "Review of adsorption isotherms models," *Acta Technica Corviniensis*, vol. 14, no. 4, pp. 87–96, 2022.
- [31] A. A. Haji and N. M. Sh. Mohammed, "Optimization of Arsenic Adsorption onto Cativated Carbon Dreived from Potato Peel Using Response Surface Methodology," *Science Journal of University of Zakho*, vol. 7, no. 2, Jun. 2019, <https://doi.org/10.25271/sjuoz.2019.7.2.594>.
- [32] I. Aminu, S. M. Gumel, W. A. Ahmad, and A. A. Idris, "Adsorption Isotherms and Kinetic Studies of Congo-Red Removal from Waste Water Using Activated Carbon Prepared from Jujube Seed," *Am. J. Analyt. Chem.*, vol. 11, no. 01, pp. 47–59, 2020, <https://doi.org/10.4236/ajac.2020.111004>.
- [33] H. S. Benammar, S. Guergazi, S. Youcef, and L. Youcef, "Removal of congo red and naphthol blue black dyes from aqueous solution by adsorption on activated carbon. Characterization, kinetic and equilibrium in nonlinear models studies," *Desalination Water Treat.*, vol. 221, pp. 396–405, May 2021, <https://doi.org/10.5004/dwt.2021.27031>.
- [34] J. A. Akande, Adeogun A I, and Uzosike A S, "Publication of the European Centre for Research Training and Development-UK Removal of Congo Red Dye from Simulated Wastewater Using Activated Carbon Derived from Corn Cobs; Kinetics and Equilibrium Studies Removal of Congo Red Dye from Simulated Wastewater Using Activated Carbon Derived from Corn Cobs; Kinetics and Equilibrium Studies Publication of the European Centre for Research Training and Development-UK," *Global Journal of Pure and Applied Chemistry Research*, vol. 11, no. 1, pp. 1–19, 2023, <https://doi.org/10.37745/gipacr.2023/vol11n1119>.
- [35] V. Nakro et al., "Efficient Removal of Congo Red Dye Using Activated Carbon Derived from Mixed Fish Scales Waste: Isotherm, Kinetics and Thermodynamics Studies," *Nature Environment and Pollution Technology*, vol. 24, pp. 339–353, Jan. 2025, <https://doi.org/10.46488/NEPT.2024.v24iS1.026>.
- [36] J. Wang and X. Guo, "Adsorption kinetic models: Physical meanings, applications, and solving methods," *J. Hazard. Mater.*, vol. 390, no. January, p. 122156, 2020, <https://doi.org/10.1016/j.jhazmat.2020.122156>.
- [37] U. A. Edet and A. O. Ifelebuegu, "Kinetics, isotherms, and thermodynamic modeling of the adsorption of phosphates from model wastewater using recycled brick waste," *Processes*, vol. 8, no. 6, 2020, <https://doi.org/10.3390/PR8060665>.
- [38] M. Musah, Y. Azeh, J. Mathew, M. Umar, Z. Abdulhamid, and A. Muhammad, "Adsorption Kinetics and Isotherm Models: A Review," *Caliphate Journal of Science and Technology*, vol. 4, no. 1, pp. 20–26, 2022, <https://doi.org/10.4314/cajost.v4i1.3>.
- [39] M. S. Shafeeyan, W. M. A. Wan Daud, and A. Shamiri, "A review of mathematical modeling of fixed-bed columns for carbon dioxide adsorption," *Chemical Engineering Research and Design*, vol. 92, no. 5, pp. 961–988, 2014, <https://doi.org/10.1016/j.cherd.2013.08.018>.
- [40] I. S. Aldabagh and K. K. Hummadi, "Comprehensive characterization for efficient adsorption of Tetracycline from wastewater from the synthesis of nanoparticles by batch and fluidized bed column," *Environmental Advances*, vol. 19, no. September 2024, p. 100606, 2025, <https://doi.org/10.1016/j.envadv.2024.100606>.
- [41] Y. N. Dhoble, "Column Studies for the Simultaneous Removal of Phenol, Ammonia and Thiocyanate by the Adsorption with Steel Slag," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 6, no. 1, pp. 2919–2929, 2018, <https://doi.org/10.22214/ijraset.2018.1402>.
- [42] J. T. Nwabanne and P. K. Igbokwe, "Adsorption Performance of Packed Bed Column for the removal of Lead (ii) using oil Palm Fibre," *Int. J. Appl. Sci. Technol.*, vol. 2, no. 5, pp. 106–115, 2012.
- [43] M. F. M. Yusop et al., "Effect Bed Height on Adsorption of Cu(II) by Using Corncob Based Activated Carbon," vol. 200, no. ICoST, pp. 164–168, 2021, <https://doi.org/10.2991/aer.k.201229.023>.
- [44] A. Ghribi and M. Bagane, "Adsorptive Removal of Congo Red Dye from Aqueous Solution Using Natural Clay in a Fixed Bed Column," *Iranian Journal of Chemistry and Chemical Engineering*, vol. 42, no. 12, pp. 4097–4107, 2023, <https://doi.org/10.30492/ijcce.2023.1989371.5861>.