



Hexavalent chromium adsorption from aqueous solution using *Cordia Africana* leaf based activated carbon

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Abstract

Chromium, a prevalent heavy metal pollutant originating from various industrial processes, poses significant risks if not properly treated. In this study, batch adsorption of hexavalent chromium (Cr^{6+}) from water was performed using activated carbon derived from *Cordia africana*. This application represents a novel approach, as the use of this material for Cr^{6+} removal has not been previously explored. The adsorbent was analyzed through Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and the Brunauer–Emmett–Teller (BET), and Fourier Transform Infrared (FTIR) methods, revealing its structural and surface properties. Adsorption kinetics followed the pseudo-first-order model ($R^2 = 0.99$), while the Koble Corrigan isotherm ($R^2 = 0.98$) most accurately expressed the adsorption behavior. The adsorption experiments achieved a maximum Cr^{6+} adsorption capacity of 52.2 mg/g. Thermodynamic studies indicated that the process is spontaneous and endothermic. Reusability tests demonstrated the stability of the adsorbent over five cycles, with removal efficiencies ranging from 99.7 to 75.1%. Overall, *Cordia africana* leaf-based activated carbon exhibited a promising adsorption capacity, making it a cost-effective and readily available adsorbent suitable for industrial wastewater treatment.

Keywords Activated carbon · Adsorption · *Cordia Africana* · Hexavalent chromium · Wastewater treatment

Introduction

Chromium, a naturally abundant element, primarily exists as trivalent (Cr (III)) and hexavalent (Cr (VI)), with Cr (III) being fairly non-hazardous and Cr (VI) posing severe environmental and health risks. Found in chromite ore, chromium is extensively utilized in electroplating, tanning, pigments, and chemical manufacturing, with Cr (VI) being particularly valued for its industrial applications (Görgüç et al. 2024; Khatua and Kumar Dey 2023). Specifically, in the metallurgical industry, it is essential for producing

stainless steel and various alloys, as well as for electroplating processes that enhance corrosion resistance (Martinuzzi et al. 2022; Okonkwo et al. 2022). The chemical industry employs chromium compounds in the manufacture of pigments, catalysts, dyes, paints, and wood preservatives (Panda et al. 2016; Puthran and Patil 2023). The leather tanning industry is also a major consumer, using chrome liquor or powder to produce durable leather products (Ding et al. 2022). Additionally, chromium acts as a mordant in textile dyeing processes, improving color retention (Islam et al. 2025). However, Cr (VI) is strongly soluble, mobile, and designated as a Group I carcinogen, linked to lung cancer and ecosystem contamination through industrial effluents (Park et al. 2023; Tulasi and Rao 2015). Its release into water bodies severely impacts aquatic life and soil health, necessitating stringent discharge regulations enforced by organizations such as the U.S. Environmental Protection Agency (USEPA) to mitigate its risks (Hossini et al. 2016; Khatua and Kumar Dey 2023). Given its widespread industrial use and hazardous nature, strict regulatory limits and effective remediation strategies are crucial to minimizing the environmental and health risks of Cr (VI), whose permissible

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limit in drinking water, as set by the World Health Organization (WHO), is 0.05 mg/L (Jacob and Soni 2024).

Conventional techniques such as chemical precipitation and coagulation-flocculation have been widely used for wastewater treatment; however, they often suffer from shortcomings including inadequate performance in treating a wastewater, elevated operational expenses, and additional waste generation (Madumo 2024). Advanced methods, including adsorption, electrochemical reduction, nanofiltration, and photocatalysis, offer improved performance by minimizing waste and enhancing Cr (VI) removal efficiency (Jiang 2024; Pandey et al. 2024). Despite their advantages, challenges related to scalability, energy consumption, and operational complexity hinder their widespread adoption. Among these advanced techniques, adsorption emerges as a particularly effective and viable option given its ease of use, budget friendly nature, as well as ability to achieve significant Cr (VI) adsorption efficiency using readily available adsorbents, presenting it as a potential solution for large-scale wastewater treatment applications (Khan et al. 2022).

Current Cr (VI) laden wastewater treatment techniques heavily rely on adsorption due to its efficiency and versatility, with various adsorbents showing promising results (Khan et al. 2022; Sumalatha* et al., 2019). Modified carbons, such as Zr/Fe-modified ordered mesoporous carbons, achieve over 90% Cr (VI) removal with a capacity of 50.1 mg g⁻¹ (Anastopoulos et al. 2018), while green adsorbents like radiation-functionalized cellulose-based materials (e.g., “ChromClear”) reduce Cr(VI) to below 20 µg.L⁻¹ with a capacity of 55 mg g⁻¹ (Rawat et al. 2024). Biochar effectively removes Cr (VI) through chemical bonding, reaching adsorption equilibrium within 100 min (Zhang et al. 2023), and *Saccharomyces cerevisiae* demonstrates 88.2% removal efficiency via bioaccumulation (Ashagrie et al. 2023). However, adsorption faces challenges, including efficiency variations (Zhang et al. 2023), and cost and scalability issues in large-scale applications (Rawat et al. 2024). Therefore, the search for an ideal adsorbent continues with the aim of replacing costly and non-sustainable commercial activated carbon with locally available alternatives.

Cordia africana, a widely available and multifunctional plant, holds significant potential for environmental remediation, particularly through the use of its leaves as effective adsorbents. Found abundantly across tropical and subtropical areas, especially in Africa, the plant is cultivated for timber, firewood, and medicinal applications, ensuring its accessibility (Matias et al. 2015; Nigussie et al. 2021). One of its most promising applications lies in wastewater treatment, where its leaves can be transformed into adsorbent possessing a large specific surface area (700 m²/g) and strong adsorption capacity, achieving up to 89% removal efficiency for Cr (III) (Kassahun et al. 2022b). Beyond environmental

benefits, *Cordia africana* leaves also contain bioactive compounds with antioxidant and antimicrobial properties, contributing to pharmaceutical advancements (Nigussie et al. 2021). As an adsorbent, it offers an efficient, cost-effective, and environmentally friendly alternative aligned with green chemistry principles (Anastopoulos et al. 2018). However, limited research has been conducted on the valorization of *Cordia africana* leaves as an adsorbent (Kassahun et al. 2022a; Teweldebrhan et al. 2025), highlighting the need for further exploration of this locally available biomass for wastewater treatment. Hence, this study aims to develop an activated carbon from *Cordia africana* leaves specifically to treat Cr (VI) in aqueous environments, an application that has not been previously investigated using this material.

Materials and methods

Preparation of *Cordia Africana* based activated carbon

The preparation of activated carbon from *Cordia africana* leaf began with the collection and washing of the leaves, followed by sun drying to remove moisture. The leaves, after drying, were then subjected to oven drying at 105 °C for 24 h using a Memmert UNB 400 drying oven, and was finely crushed using a grinding tool and pestle. The powdered material was treated with 85% phosphoric acid in a 1:1 proportion for activation, after which it was oven-dried at 100 °C for 4 h in the Memmert UNB 400 oven. The impregnated material was carbonized at 500 °C for 2 h in a Carbolite Gero CWF 1100 muffle furnace (Geng et al. 2020; Jagiełło et al. 2024). After cooling in a desiccator, the carbonized material was rinsed with distilled water to adjust the pH, and then dried in an oven at 105 °C for 24 h once again using the Memmert UNB 400 oven. Lastly, the developed adsorbent was stored in a sealed plastic container to maintain its quality (Hussien Hamad 2023).

Characterization of adsorbent

Scanning Electron Microscopy (SEM) was utilized to examine the surface structure of the developed adsorbent. Moreover, the Brunauer–Emmett–Teller (BET) method was applied to evaluate its specific surface area, whereas its crystalline structure was characterized using X-ray diffraction (XRD) providing insights into the structural arrangement and phase purity of the adsorbent (Fito et al. 2023a; Mengistu et al. 2023; Teweldebrhan 2025). On the other hand, Fourier Transform Infrared (FTIR) spectroscopy was utilized to analyze the functional groups of *Cordia africana* leaf-based activated carbon (Dimbo et al. 2024; Fito et al.

2023a, b, c, d). The proximate analysis of the activated carbon was determined to evaluate its key characteristics. Moisture content was measured according to ASTM D2867, while volatile matter was analyzed using ASTM D5832. Ash content was determined following ASTM D2866, and fixed carbon was then calculated by subtracting the sum of moisture, volatile matter, and ash contents from 100%. The pH point of zero charge (pHpzc) of the adsorbent was determined using the pH drift method (Boddu et al. 2025). A series of 50 mL NaCl solutions (0.01 M) were adjusted to initial pH values ranging from 2 to 12 using 0.1 M HCl or NaOH. 1 g of the adsorbent was added to each solution, and the suspensions were agitated for 48 h at room temperature. The final pH was recorded, and the pHpzc was identified as the point where the initial and final pH values were equal (Miyittah et al. 2016; Zyoud et al. 2019).

Stock solution Preparation and batch adsorption studies

A 1000 mg/L Cr (VI) stock solution was prepared by dissolving 2.83 g of $K_2Cr_2O_7$ in 1 L of distilled water. The stock solution was subsequently diluted with distilled water to achieve the desired initial Cr (VI) concentrations. Batchwise adsorption experiments for Cr (VI) removal were performed at room temperature, with a stirring speed set at 250 rpm. A specific amount of activated carbon was introduced to 100 mL of Cr (VI) solutions, adjusting the pH, exposure duration, initial chromium concentration, and adsorbent dose as needed. The batch adsorption was performed in 250 mL Erlenmeyer flasks. The samples were stirred, subsequently filtered using Whatman filter paper with a pore size of 0.45 μ m, and analyzed for Cr (VI) concentration using spectrophotometry. After reaction with 1, 5-diphenylcarbazide (1%), Cr (VI) absorbance was determined at 540 nm following the APHA method with a UV–VIS spectrophotometer (Fito et al. 2023d; Mengistu et al. 2023). The Cr (VI) adsorption capacity (Q_e) was determined employing Eq. 1.

$$Q_e = \frac{C_o - C_e}{m} \times V \quad (1)$$

where V is the volume (L), m is the weight of the adsorbent (g), C_o is the initial concentration of the synthetic wastewater before the adsorptive treatment procedures in mg/L and C_e is the concentration post treatment for a specific period. Moreover, Eq. 2 was used to calculate the percentage Cr (VI) removal (RE).

$$RE = \frac{C_o - C_e}{C_o} \times 100 \quad (2)$$

Adsorption kinetics

The adsorption mechanism and the rate in which the adsorbate was removed were analyzed using kinetic model (Babu et al. 2021). In the present work, adsorption kinetics were examined to evaluate the rate of Cr(VI) removal from an aqueous solution while keeping the initial pollutant concentration, pH and adsorbent dosage constant and varying the adsorption time. The adsorption kinetics was evaluated using the pseudo-first-order, pseudo-second-order, intraparticle diffusion and Elovich kinetic models, represented by Eqs. 3, 4, 5 and 6 respectively.

$$Q_t = Q_e(1 - e^{-K_1t}) \quad (3)$$

where Q_e (mg/g) is the equilibrium adsorption capacity, $k_f(\text{min})^{-1}$ is the pseudo first order equilibrium rate constant, and Q_t (mg/g) represents the quantity of Cr (VI) adsorbed per unit mass of the activated carbon at any given time t (minutes).

$$Q_t = \frac{Q_e^2 K_2 t}{1 + Q_e K_2 t} \quad (4)$$

where K_s ($\text{g} \cdot \text{mg}^{-1} \cdot \text{min}^{-1}$) denotes the pseudo-second-order equilibrium rate constant, Q_e (mg/g) represents the equilibrium adsorption capacity, and Q_t (mg/g) is the quantity of Cr(VI) adsorbed per unit mass of the adsorbent at any given time t (min). On the other hand, the intraparticle diffusion model is commonly applied to investigate the rate-limiting step in the adsorption process, particularly the diffusion of adsorbate molecules within the pores of the adsorbent. The model is mathematically expressed in Eq. 5.

$$Q_e = k_d \times t_{0.5} + C \quad (5)$$

where k_d is the intraparticle diffusion rate constant, and C is the intercept related to the boundary layer thickness (Moamen et al. 2023). The Elovich model is commonly used to describe chemisorption processes on heterogeneous surfaces, and the model is mathematically expressed in Eq. 6.

$$Qt = \frac{1}{\beta} \ln(\alpha \beta t + 1) \quad (6)$$

where α is the initial adsorption rate ($\text{mg/g} \cdot \text{min}$), β is the desorption constant (g/mg). This model assumes that the adsorption rate decreases exponentially with increasing surface coverage due to surface heterogeneity (Debord et al. 2022).

Adsorption isotherm

The analysis of adsorption isotherm data is essential for gaining insight into the interactions between adsorbate species and the adsorbent interface, as well as for assessing the adsorption efficiency of the system. Equilibrium data correlations help predict and interpret the adsorption process using theoretical or empirical models (Boddu et al. 2020, 2022). In this research, the Langmuir, Freundlich, Toth and Koble Corrigan isotherm models are evaluated, with their mathematical expressions presented in Eqs. 3, 8, 10 and 11 respectively.

$$\frac{Q_{max}KLC_e}{1 + K_L C_e} \quad (7)$$

$$Q_e = K_F C_e^{1/n} \quad (8)$$

Here, C_e (mg/L) represents the equilibrium concentration of chromium in solution, while Q_e (mg/g) denotes the quantity of metal adsorbed per gram of adsorbent at equilibrium. Q_{max} (mg/g) is the highest monolayer adsorption capacity, and K_L (L/mg) is the Langmuir isotherm constant. Additionally, the Freundlich isotherm model includes the parameter $1/n$, a non-dimensional parameter representing adsorption intensity, energy distribution, and adsorbent surface heterogeneity, while K_F (mg/g) denotes the adsorption capacity. The key features of the Langmuir isotherm can be further represented by the non-dimensional parameter R_L , as defined in Eq. 4.

$$R_L = \frac{1}{1 + K_L C_o} \quad (9)$$

where $R_L > 1$ suggests that the adsorption is unfavorable, linear when $R_L = 1$, and favorable for $R_L = 0$ (Ayawei et al. 2017). On the other hand, the Toth isotherm model is an adsorption isotherm used to describe equilibrium adsorption on heterogeneous surfaces. It is particularly effective when the adsorbent has sites with non-uniform energy distribution, and it can bridge the behavior between Langmuir and Freundlich isotherms. The model is mathematically presented in Eq. 10. Where K is the Toth equilibrium constant (L/mg), and nt is the heterogeneity parameter.

$$Q_e = \frac{Q_{max}K C_e}{[1 + (K C_e)^{nt}]^{1/nt}} \quad (10)$$

The Koble–Corrigan isotherm model is a three-parameter hybrid isotherm that combines features of both Langmuir and Freundlich isotherms. It is particularly useful for

describing adsorption equilibrium on heterogeneous surfaces and systems involving moderate adsorbate concentrations. The mathematical expression of the model is given in Eq. 11, where A and B are Koble–Corrigan constants, and nk is a dimensionless exponent that accounts for surface heterogeneity (Abiodun et al. 2023; Kanagalakshmi et al. 2024).

$$Q_e = \frac{A C_e^{nk}}{(1 + B C_e^{nk})} \quad (11)$$

Thermodynamics study

The thermodynamics of adsorption were evaluated to understand the feasibility and nature of the process. In this work, the thermodynamic parameters of the adsorption process were determined using equilibrium data obtained at varying temperatures (25–45 °C), while keeping other operational parameters constant. These included an initial Cr^{6+} concentration of 50 mg/L, pH 3, an adsorbent dosage of 0.8 g per 100 mL, and a contact time of 60 min. The Gibbs free energy change (ΔG°), which indicates the spontaneity of the adsorption process, was calculated using Eq. 12, where R is the universal gas constant and T is the absolute temperature.

$$\Delta G = -RT \ln KC \quad (12)$$

The enthalpy change (ΔH°), used to determine whether the process is endothermic or exothermic, and the entropy change (ΔS°), which reflects the degree of randomness at the solid–liquid interface, were obtained from the Van't Hoff plot of $\ln KC$ versus $1/T$, using the linear form of Eq. 13 (Miyittah et al. 2016; Zyoudd et al. 2019).

$$\ln KC = \frac{\Delta s}{R} - \frac{\Delta H}{RT} \quad (13)$$

Adsorbent Regeneration and Reusability

The regeneration and reusability of *Cordia africana* leaf-based activated carbon were evaluated to assess its potential for repeated use in the removal of hexavalent chromium (Cr^{6+}) from aqueous solutions (Katika et al. 2024). A chemical regeneration method using 0.1 M NaOH was employed. After each adsorption cycle, the exhausted adsorbent was treated with NaOH, thoroughly washed with distilled water until neutral pH, dried, and reused under the same operating conditions. This process was repeated for five consecutive adsorption–desorption cycles to evaluate the adsorbent's stability and performance over multiple uses (Abewaa et al. 2023a, b).

Results and discussion

Adsorbent characteristics

Proximate analysis

The proximate analysis of the activated carbon prepared from *Cordia africana* leaf reveals favorable physicochemical characteristics that support its potential as an effective adsorbent in environmental applications. A moisture content of 4.5% was recorded, indicating good thermal stability and minimal interference with adsorption processes due to the low presence of residual water. This value aligns closely with the 5.3% reported by (Kassahun et al. 2022b), suggesting consistent moisture behavior for this precursor. The volatile matter content was found to be 22.0%, which reflects effective removal of unstable components during carbonization while likely preserving oxygen-containing functional groups that enhance the material's reactivity toward various pollutants. This result is in good agreement with the 24% reported in related literature (Kassahun et al. 2022b). Additionally, an ash content of 8.8% was observed, slightly higher than the value reported by (Kassahun et al. 2022b), possibly due to differences in activation conditions and the inherent mineral content of the precursor. Although moderate, this ash content remains acceptable for water treatment purposes and may even contribute to catalytic or ion-exchange functionalities.

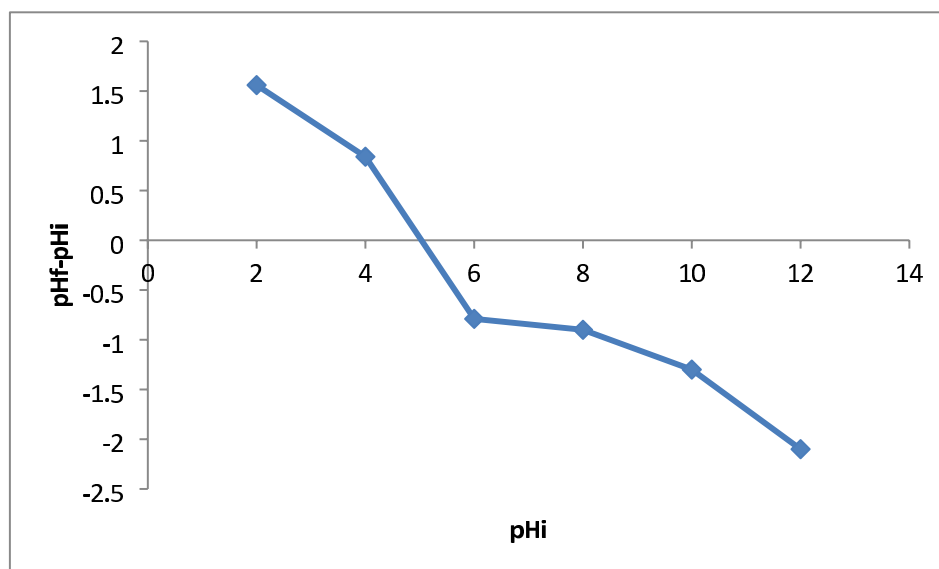
A fixed carbon content of 64.7% was determined, closely matching the 64% reported by (Kassahun et al. 2022b) and underscoring the well-developed carbonaceous structure of the material. This high fixed carbon percentage confirms the thermal stability and structural robustness of the activated carbon, which are essential traits for efficient adsorption.

Overall, the activated carbon derived from *Cordia africana* leaf demonstrates a well-balanced profile, low moisture content, moderate volatile matter, tolerable ash content, and high fixed carbon which make it a strong candidate for use in environmental remediation. These properties, combined with the likely presence of surface functional groups, contribute to its enhanced adsorption capacity for removing various contaminants such as hexavalent chromium, dyes, and other industrial pollutants from aqueous solutions.

pH point of zero charge

The point of zero charge (pH_{pzc}) of the activated carbon prepared from *Cordia africana* leaf was determined by plotting the difference between the final and initial pH (ΔpH) against the initial pH as shown in Fig. 1. The pH_{pzc} corresponds to the point where ΔpH equals zero, indicating no net proton exchange between the adsorbent surface and the solution. Based on the experimental data and linear interpolation, the pH_{pzc} was found to be approximately 5.03. This value suggests that the surface of the activated carbon is positively charged at pH values below 5.03, favoring the adsorption of anionic species, and negatively charged at pH values above 5.03, promoting the uptake of cationic pollutants (Mozhiarasi and Natarajan 2024; Patra et al. 2020). The relatively low pH_{pzc} indicates the acidic nature of the surface, likely attributed to the presence of oxygen-containing functional groups introduced during the activation process (Hoa et al. 2025). The pH at the point of zero charge (pH_{pzc}) of 5.03 determined for the chemically treated and thermally activated *Cordia africana*-based activated carbon is significantly lower than that of the untreated precursor material, which has a pH_{pzc} of around 6.5 (Teweldebrihan et al. 2025). This decrease indicates that the activation

Fig. 1 Point of zero charge ($\text{pH}_{\text{pzc}} \approx 5.03$) of activated carbon prepared from *Cordia africana* leaf



process introduces more acidic surface functional groups, enhancing the material's ability to adsorb positively charged species at pH values above 5.03.

BET surface area analysis

The specific surface area of *Cordia africana*-based activated carbon, determined to be 522 m²/g, is a crucial parameter influencing its adsorption performance. A high surface area indicates a well-developed porous structure, providing more active sites for contaminant uptake. This value suggests the presence of an extensive porous structure, which enhances adsorption capacity by facilitating the diffusion and entrapment of pollutants like Cr (VI), as further supported by SEM image showing a rough and porous surface morphology (Cao et al. 2019; Qu et al. 2021). The large surface area allows for increased bonding of Cr (VI) ions to functional groups, promoting strong electrostatic attraction and redox

interactions. As a result, this activated carbon can effectively capture and remove Cr (VI) from aqueous solutions, making it a highly efficient adsorbent for water treatment applications.

FTIR analysis

The FTIR band of *Cordia africana* leaf-based activated carbon indicates several distinct peaks, showing the existence of key functional groups responsible for adsorption interactions as shown in Fig. 2. The broad band at 3407 cm⁻¹ corresponds to O–H stretching vibrations from hydroxyl groups (Turki et al. 2018), which enhance hydrogen bonding and surface complexation with Cr (VI). The peak at 2956 cm⁻¹ is ascribed to C–H stretching from aliphatic hydrocarbons (Asemani and Rabbani 2020). A strong peak at 1735 cm⁻¹ represents C=O stretching from carboxyl or carbonyl groups (Fumoto et al. 2020), which play a significant part in

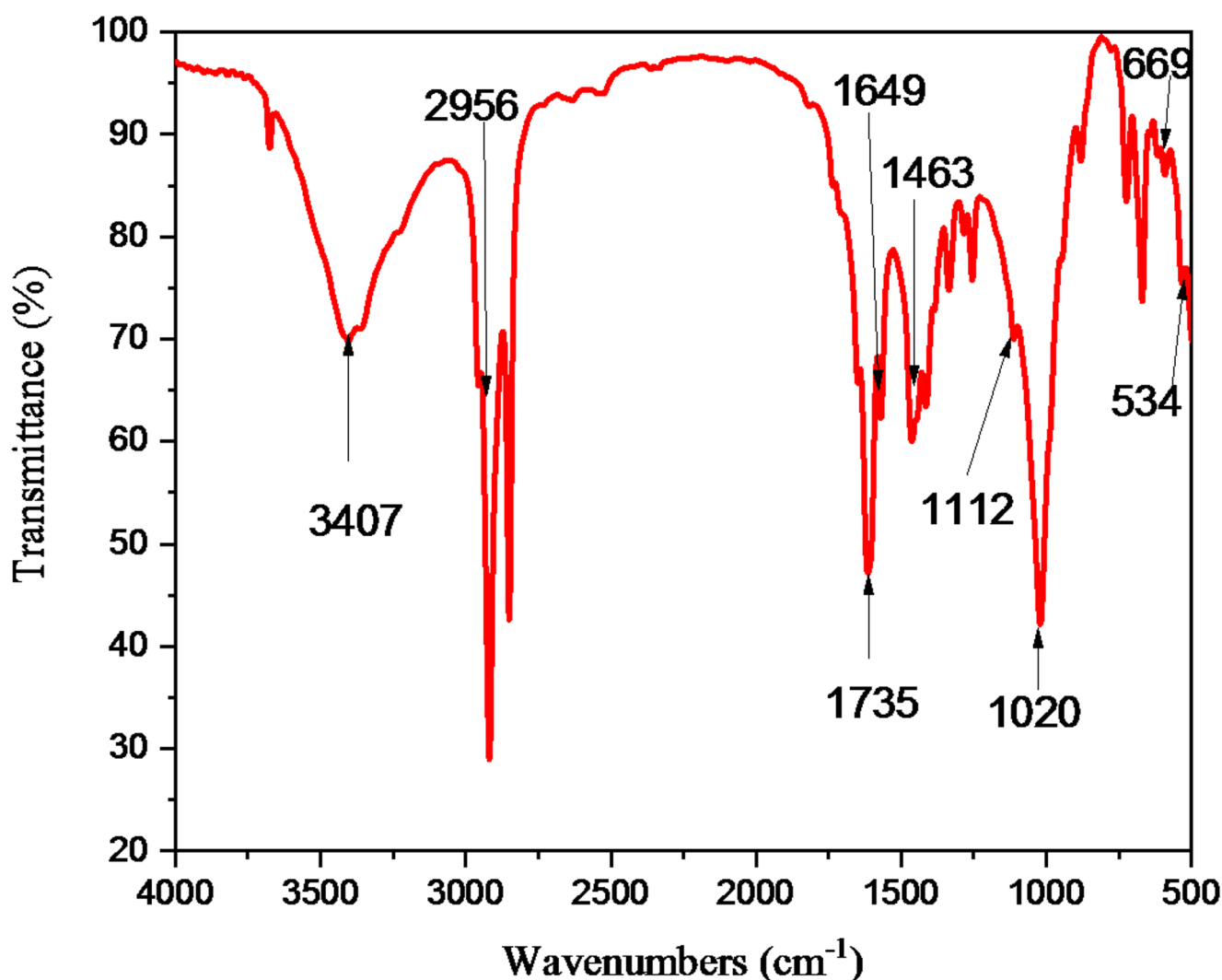


Fig. 2 FTIR spectra of *Cordia africana* leaves based activated carbon

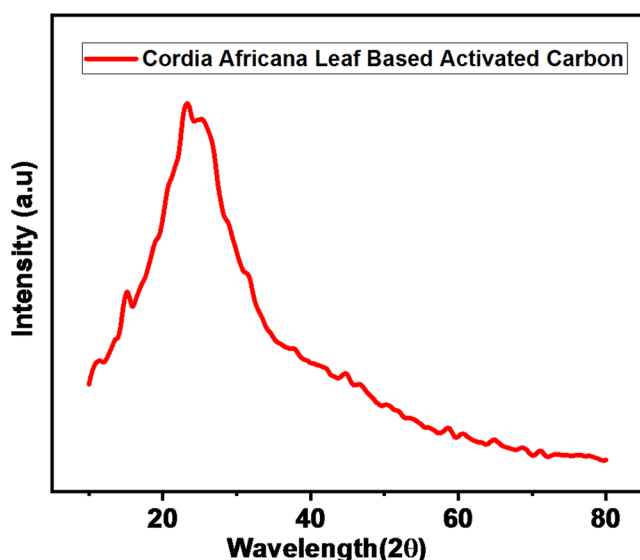


Fig. 3 XRD pattern of *Cordia africana* leaves based activated carbon

electrostatic interactions and redox reactions with Cr (VI). The peaks at 1649 cm^{-1} and 1463 cm^{-1} aligns with C=C stretching of aromatic rings and C–O stretching of carboxylates, respectively (Acik et al. 2011), influencing surface charge and adsorption behavior. The peaks at 1112 cm^{-1} and 1020 cm^{-1} are linked to C–O–C stretching from ether and phenolic groups, which contribute to adsorption via complexation (Abbas et al. 2017). Finally, the absorption bands at 669 cm^{-1} and 534 cm^{-1} suggest metal–oxygen (M–O) vibrations (Palmer et al. 2007), indicating possible mineral components that further aid Cr (VI) removal. These functional groups collectively facilitate Cr(VI) adsorption through electrostatic attraction, reduction, and surface complexation mechanisms, making this material highly effective for aqueous Cr(VI) remediation (Lingamdinne et al. 2024; Mozhiarasi and Natarajan 2024).

XRD analysis

The XRD pattern of *Cordia africana* leaf-based activated carbon reveals a broad peak around $2\theta \approx 20\text{--}30^\circ$, indicating a predominantly amorphous structure with disordered carbon domains (Yarik et al. 2025) as shown in Fig. 3. This amorphous nature enhances surface functionality, allowing the incorporation of oxygen-containing functional groups such as hydroxyl and carboxyl that facilitate Cr (VI) adsorption through electrostatic attraction and redox interactions. The disordered carbon structure also suggests a high surface area and porosity, these being crucial for effective ion diffusion and adsorption (Teweldebrihan et al. 2025). Thus, the highly porous and chemically active nature of the activated carbon makes it an excellent candidate for Cr (VI) decontamination from water systems.

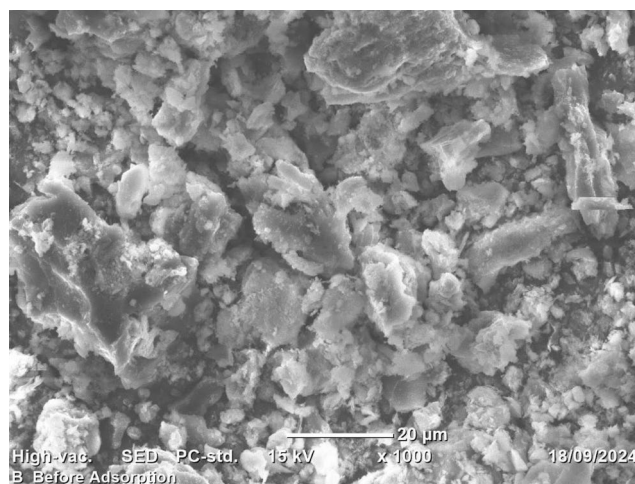


Fig. 4 SEM of the *Cordia africana* leaves based activated carbon

SEM analysis

The SEM image of *Cordia africana*-based activated carbon before adsorption reveals a highly porous, irregular, and fragmented structure with a rough surface, indicating that a well-developed porous network was formed during the activation process, as shown in Fig. 4. These pores significantly enhance the material's surface area, creating abundant active sites for adsorption (Liu et al. 2023; Xia et al. 2020). The rough texture and porous nature facilitate the diffusion and entrapment of contaminants, making it highly effective for the decontamination of Cr (VI) from water systems. Cr (VI) removal primarily occurs through adsorption onto the porous surface, electrostatic interactions between Cr (VI) ions exhibiting a negative charge and functional groups with a positive charge. The well-developed pore structure enhances mass transfer, enabling Cr (VI) ions to interact with deeper adsorption locations, leading to high removal efficiency and making this activated carbon a potential material for treating contaminated water and wastewater (Deng et al. 2022; Yuan et al. 2023).

Effect of the adsorption controlling parameters

Effect of pH

The pH-dependent removal of Cr (VI) using activated carbon prepared from *Cordia africana* was investigated, and the results are shown in Fig. 5. Cr (VI) removal performance enhanced with a decrease in pH, a trend consistent with previous studies on *Rumex abyssinicus* and *Parthenium hysterophorus*-derived activated carbons (Abewaa et al. 2024; Fito et al. 2023a). For a fixed adsorbent dosage (0.8 g), exposure duration (60 min), and initial Cr (VI) concentration (50 mg/L), the maximum decontamination

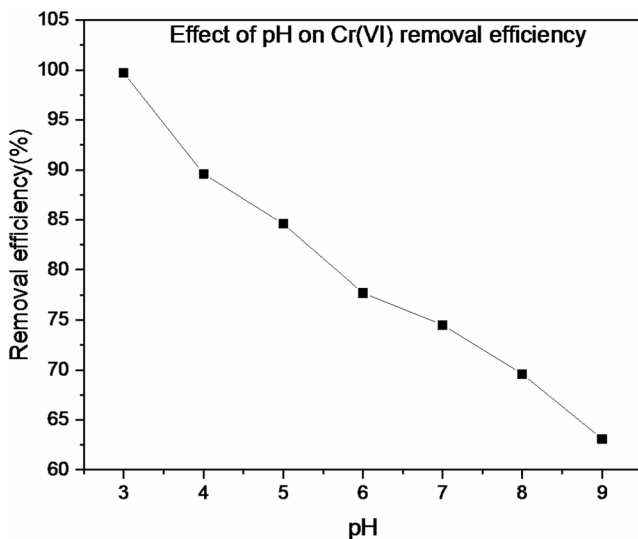


Fig. 5 Impact of pH variation on the efficiency of Cr (VI) removal by *Cordia africana*-based activated carbon

capability of 99.7% was achieved at acidic pH values at room temperature. The highest Cr (VI) removal occurred at pH 3, beyond which the removal efficiency declined considerably. Similar findings were reported by (Rakhunde et al. 2012) using a speciation diagram. Cr (VI) exists primarily as hydrogen chromate (HCrO_4^-) at pH values below 6.8 and as chromate (CrO_4^{2-}) at higher pH. Under low pH conditions, the adsorbent surface become increasingly acquires a positive charge through protonation, enhancing electrostatic force between the adsorbent and Cr (VI) species with a negative charge such as HCrO_4^- , $\text{Cr}_2\text{O}_7^{2-}$, and CrO_4^{2-} . This explains the enhanced adsorption at acidic pH values. Contrary to this, with an increase in pH, the adsorbent surface acquires a more negative charge, causing electrostatic repulsion and a reduction in adsorption performance (Sebabi et al. 2024; Sewwandi et al. 2024). Generally, although electrostatic attraction is crucial for Cr (VI) adsorption at low pH, once the active sites are saturated, other mechanisms may dominate Cr (VI) removal.

Effect of adsorbent dosage

Figure 6 illustrates how varying the adsorbent dose influences Cr (VI) removal efficiency. The quantity of adsorbent used ranged from 0.2 g to 1.0 g while keeping other parameters constant to assess its impact on removal efficiency. Higher adsorbent doses led to enhanced removal efficiency, as more active sites were accessible on the adsorbent surface, facilitating the adsorption of Cr (VI) ions. The average removal efficiency increased from 56.2 to 99.6% as the adsorbent amount was raised from 0.2 g to 0.8 g. However, beyond 0.8 g, the removal efficiency plateaued, indicating that the available Cr (VI) ions in solution were nearly

exhausted, and further increases in adsorbent dosage did not significantly enhance removal. Comparable findings have been documented by Hu et al., who attributed the effect to an enhanced in the effective surface area accessible for adsorption. Thus, the results confirm that Cr (VI) removal raises with increasing *Cordia africana* activated carbon dosage until equilibrium is reached at 0.8 g, beyond which additional adsorbent does not significantly enhance removal efficiency (El-Desouky et al. 2024).

Effect of initial chromium concentration

The percentage removal of Cr (VI) by *Cordia africana* leaf-based activated carbon declined with an increase in the starting Cr (VI) concentration. The adsorption efficiency ranged from 99.7% at 50 mg/L to 66.5% at 100 mg/L. As depicted in Fig. 7, the adsorption process was rapid at the beginning but gradually declined as the starting concentration increased. This tendency can result from the accessibility of unsaturated binding sites at reduced concentrations, allowing efficient metal ion attachment. Nevertheless, with a rise in the starting concentration of Cr (VI), the binding sites became progressively saturated, resulting in decreased removal efficiency. The optimal initial Cr (VI) concentration for maximum removal (99.7%) was found to be 50 mg/L. Due to the fact that the quantity of free adsorption sites remained constant while the number of Cr (VI) ions increased, the removal efficiency exhibited an inverse relationship with the initial Cr (VI) concentration. This observation aligns with previous studies (Acharya et al. 2024; Al-Sareji et al. 2024), confirming that at higher contaminant concentrations, the adsorption capacity is limited by active site saturation.

Effect of contact time

As shown in Fig. 8, the adsorption efficiency of *Cordia africana* leaf-based activated carbon increased with longer contact time. However, optimal exposure duration of 60 min was identified as the most cost-effective for the adsorption process. The rapid initial adsorption rate can be explained by the ample availability of binding sites on the adsorbent surface, as noted by (Din et al. 2014). In the later stages, adsorption becomes an attachment-controlled process resulting from the reduced amounts of available binding sites. The smooth and continuous uptake curve of Cr (VI) over time suggests monolayer adsorption on the adsorbent surface, a trend in line with the observations of (Jain et al. 2021). The removal efficiency of Cr (VI) increased from 52.3% at 10 min to 99.6% at 60 min, beyond this point, no significant additional adsorption occurred, indicating saturation of the bonding sites available with Cr (VI) ions.

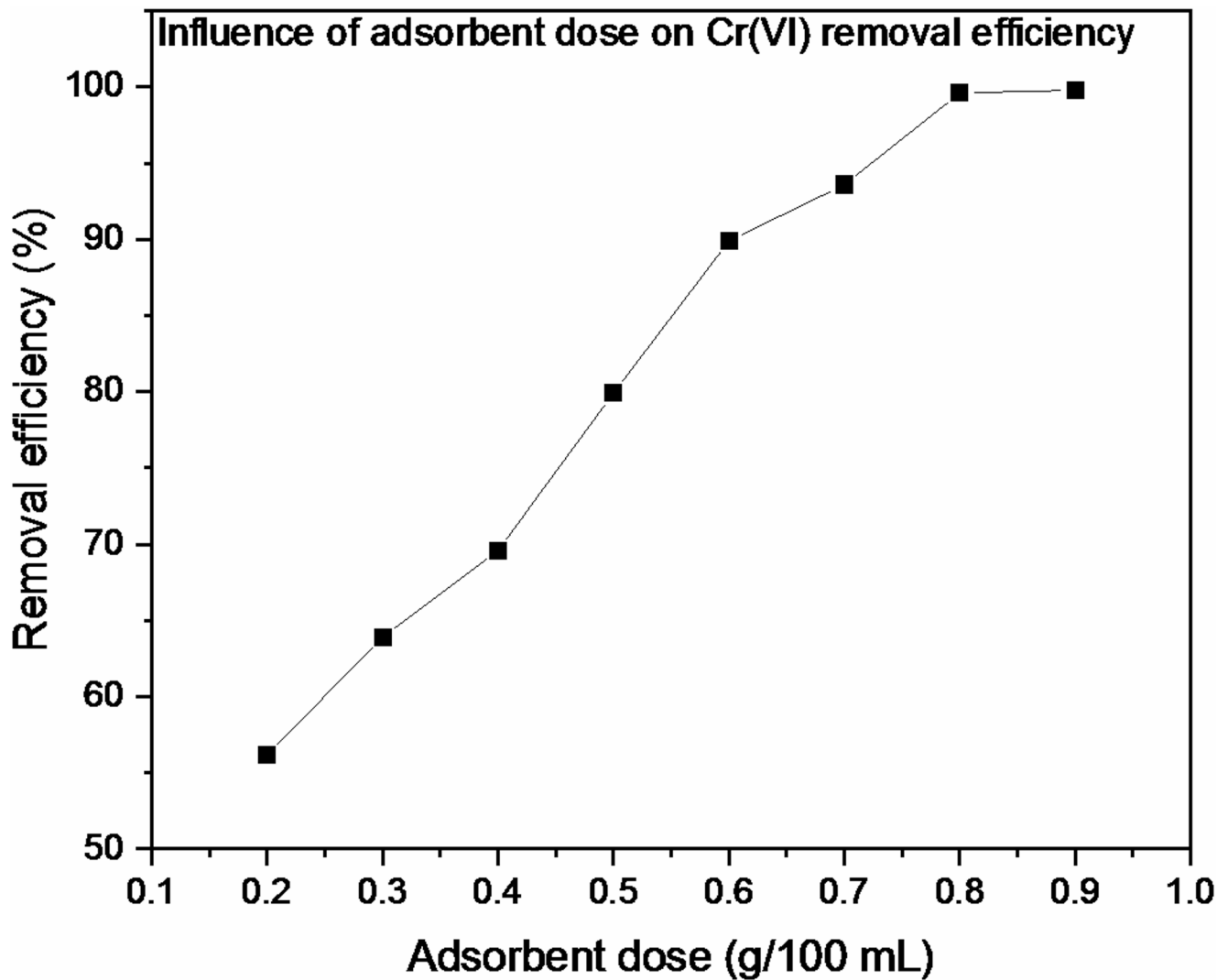


Fig. 6 Adsorbent dosage-dependent Cr (VI) removal performance of *Cordia africana*-based activated carbon

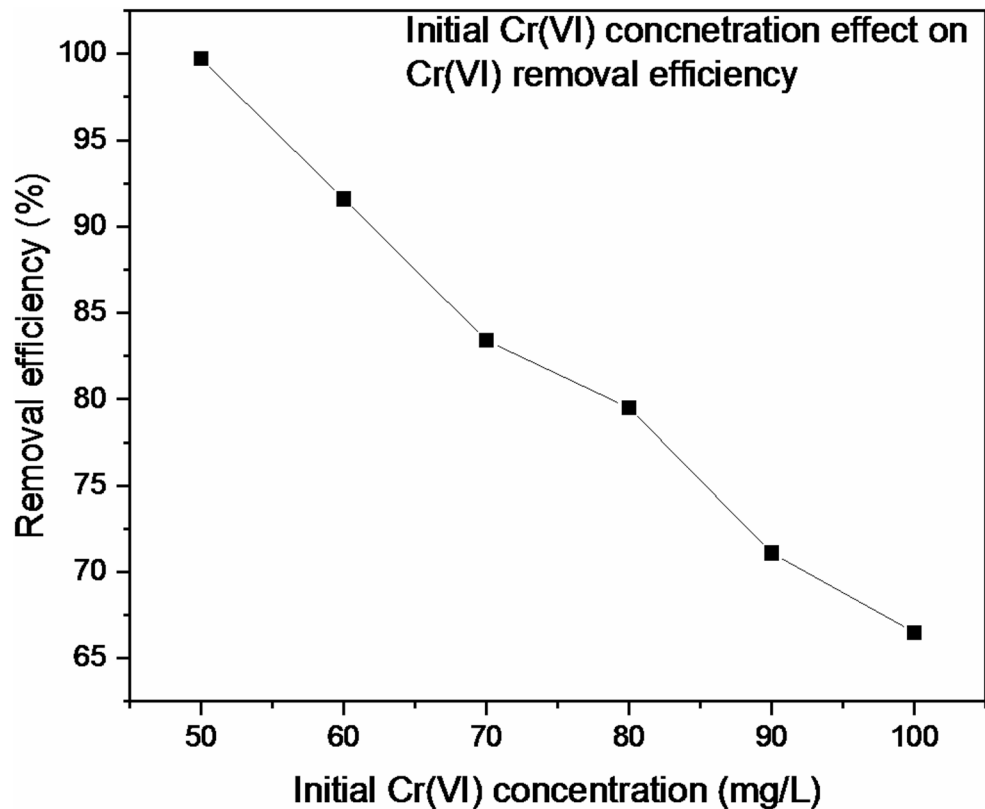
Adsorption isotherm

Adsorption isotherm models were employed to evaluate the adsorption capacity and understand the interaction mechanisms between Cr(VI) and *Cordia africana*-based activated carbon. These models also helped determine whether the adsorption process followed a monolayer or multilayer mechanism, and whether the adsorbent surface was homogeneous or heterogeneous. The Langmuir isotherm model assumes monolayer adsorption onto a surface with a finite number of identical sites (Zelmanov and Semiat 2011). The non-linear Langmuir plot produced a $Q_{\max}$ value of 53.95 mg/g and a Langmuir constant (K_L) of 0.60 L/mg, with a correlation coefficient (R^2) of 0.9712, indicating a strong fit to the experimental data as shown in Fig. 9. The experimental $Q_{\max}$ of 51.5 mg/g closely aligns with the model-predicted value, confirming the reliability of this model in describing the adsorption capacity. Moreover, the

Langmuir separation factor (R_L) was calculated as 0.77, which lies between 0 and 1, signifying a favorable adsorption process. The relatively low root mean square error (RMSE) of 2.35 further supports the model's accuracy in predicting experimental outcomes.

In contrast, the Freundlich isotherm model, which describes adsorption on heterogeneous surfaces and multilayer formation (Inyinbor et al. 2024; Mahgoub et al. 2024), yielded constants of $n=2.97$ and $K_F = (\text{mg/g (L/mg)}^{1/n})$. The $1/n$ value of 0.337 shown in Table 1, falling between 0 and 1, suggests a favorable adsorption process with surface heterogeneity. Although the Freundlich model also provided a good fit with $R^2 = 0.9445$, its higher RMSE of 3.27 indicates a slightly less accurate prediction compared to the Langmuir model. To further explore surface heterogeneity and energetic variation, the Toth isotherm model was applied. It generated a strong correlation ($R^2 = 0.9747$) with parameters $K=0.77$ and $nt=0.70$, alongside a low RMSE

Fig. 7 Influence of initial chromium concentration on Cr (VI) removal efficiency by activated carbon prepared from *Cordia africana*



of 2.21, suggesting that the Toth model effectively accounts for deviations from ideal monolayer adsorption behavior. Among all the models tested, the Koble–Corrigan isotherm exhibited the best fit with the experimental data, presenting the highest R^2 value of 0.9772 and the lowest RMSE of 2.09. The constants derived were $A=41.6$, $B=1.00$, and $nk=0.90$, indicating strong interaction between Cr(VI) and the heterogeneous surface of the activated carbon. Generally, while all models confirmed the effectiveness of *Cordia africana*-based activated carbon for Cr (VI) adsorption, the Koble–Corrigan model provided the most accurate representation of the experimental data, followed closely by the Toth and Langmuir models. These results suggest that the adsorption process likely involves a combination of monolayer and heterogeneous multilayer mechanisms, with varying site energies across the adsorbent surface (Ghorbali et al. 2024).

Kinetics study

Adsorption kinetics models are vital for understanding the dynamics of the adsorption process, as they describe both the adsorption rate and the mechanisms that control adsorbate transport at the solid–liquid interface (Balsamo and Montagnaro 2019). In this study, the pseudo-first-order, pseudo-second-order, intraparticle diffusion, and Elovich kinetic models were applied to evaluate the adsorption of

the target contaminant onto *Cordia africana* activated carbon. As shown in Fig. 10; Table 2, the pseudo-first-order model exhibited the best statistical performance, with the highest determination coefficient ($R^2 = 0.989$) and the lowest root mean square error (RMSE=0.234), indicating that this model effectively describes the adsorption behavior under the conditions studied.

In contrast, the pseudo-second-order model provided a slightly lower R^2 (0.979) and higher RMSE (0.325), suggesting a less accurate representation. Although the model is often associated with chemisorption, in this case, its predictions did not align as well with the experimental data. The intraparticle diffusion model yielded an R^2 of 0.943 and RMSE of 0.531, with a non-zero intercept, implying that intraparticle diffusion may contribute to the overall mechanism but is not the sole rate-limiting step (Mohamed Nasser et al. 2024). Meanwhile, the Elovich model, often used to describe heterogeneous surface adsorption, also demonstrated a good fit ($R^2 = 0.967$, RMSE=0.405), supporting the presence of chemically active and heterogeneous adsorption sites.

Despite the relevance of other models, the superior fit of the pseudo-first-order model suggests that physical adsorption dominates the process, governed primarily by diffusion-controlled mechanisms rather than chemisorption. Therefore, the pseudo-first-order model is considered the

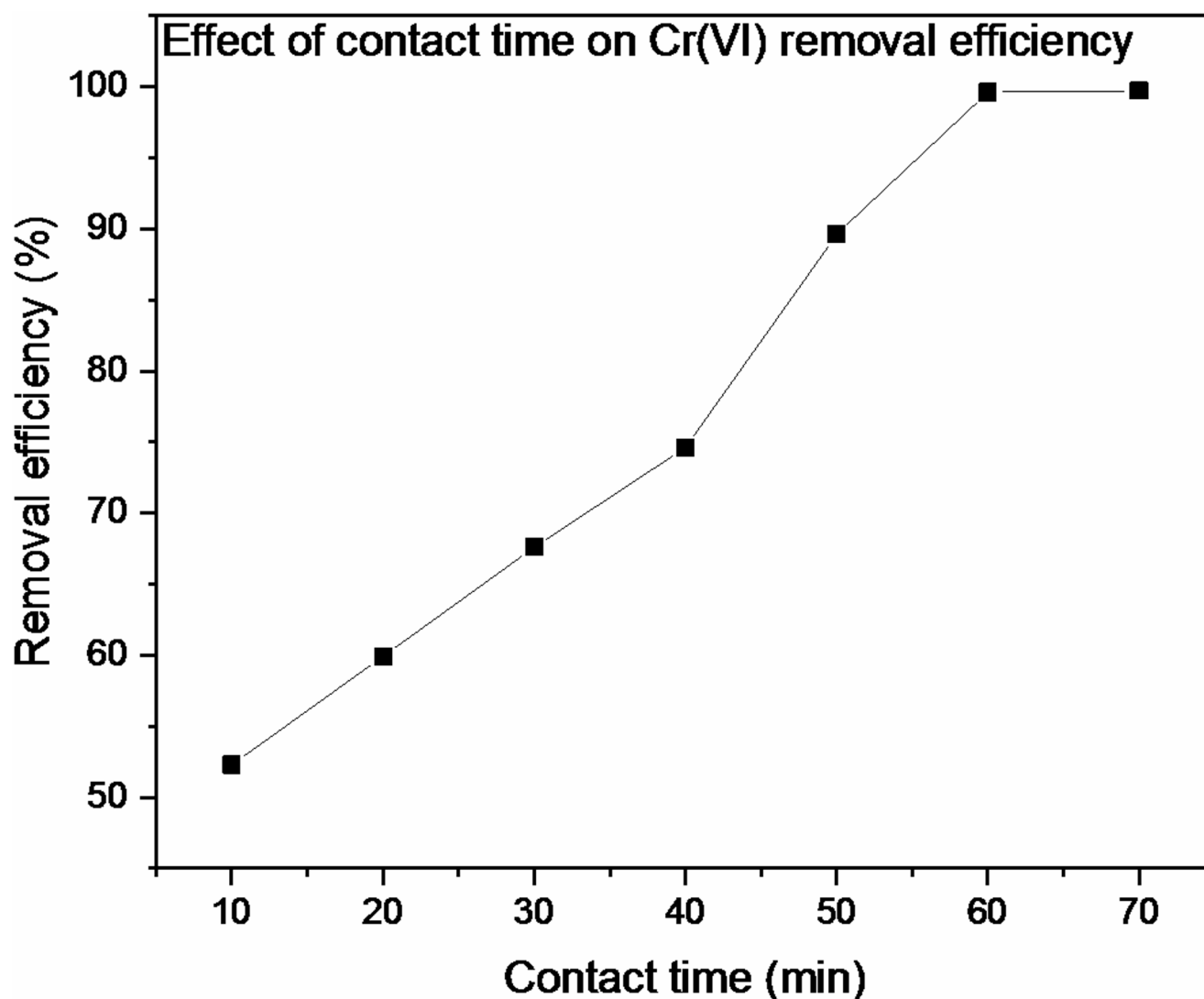


Fig. 8 Variation in Cr (VI) removal efficiency with respect to contact time using activated carbon from *Cordia africana*

most appropriate for describing the adsorption kinetics of the system investigated.

Thermodynamics study

The adsorption thermodynamics was conducted to evaluate the nature, feasibility, and potential mechanism of Cr (VI) removal using *Cordia africana* leaf-based activated carbon. The results revealed that the process is both spontaneous and endothermic as shown in Fig. 11. The positive enthalpy change ($\Delta H^\circ = +68.81$ kJ/mol) indicates that adsorption is favored at elevated temperatures, while the positive entropy change ($\Delta S^\circ = +241.48$ J/mol·K) reflects an increase in disorder at the solid–liquid interface, likely due to desolvation of Cr (VI) ions and structural rearrangements on the adsorbent surface (Abewaa et al. 2023; Romal and Ong 2024). Furthermore, the negative Gibbs free energy values (ΔG°

ranging from -3.6 to -8.5 kJ/mol) across the studied temperature range confirm the spontaneity of the process and its enhanced favorability at higher temperatures (Chiban et al. 2016).

Reusability study

The activated carbon derived from *Cordia africana* leaves exhibited a high initial Cr(VI) removal efficiency of 99.7%. After regeneration, the removal efficiency slightly decreased to 98.6% in the first reuse cycle as shown in Fig. 12. Subsequent cycles showed a gradual decline with efficiencies of 92.6% (second cycle), 90.4% (third cycle), 82.4% (fourth cycle), and 75.1% (fifth cycle). These results demonstrate that *Cordia africana*-based activated carbon maintains substantial adsorption capacity over multiple regeneration cycles, highlighting its potential for sustainable and

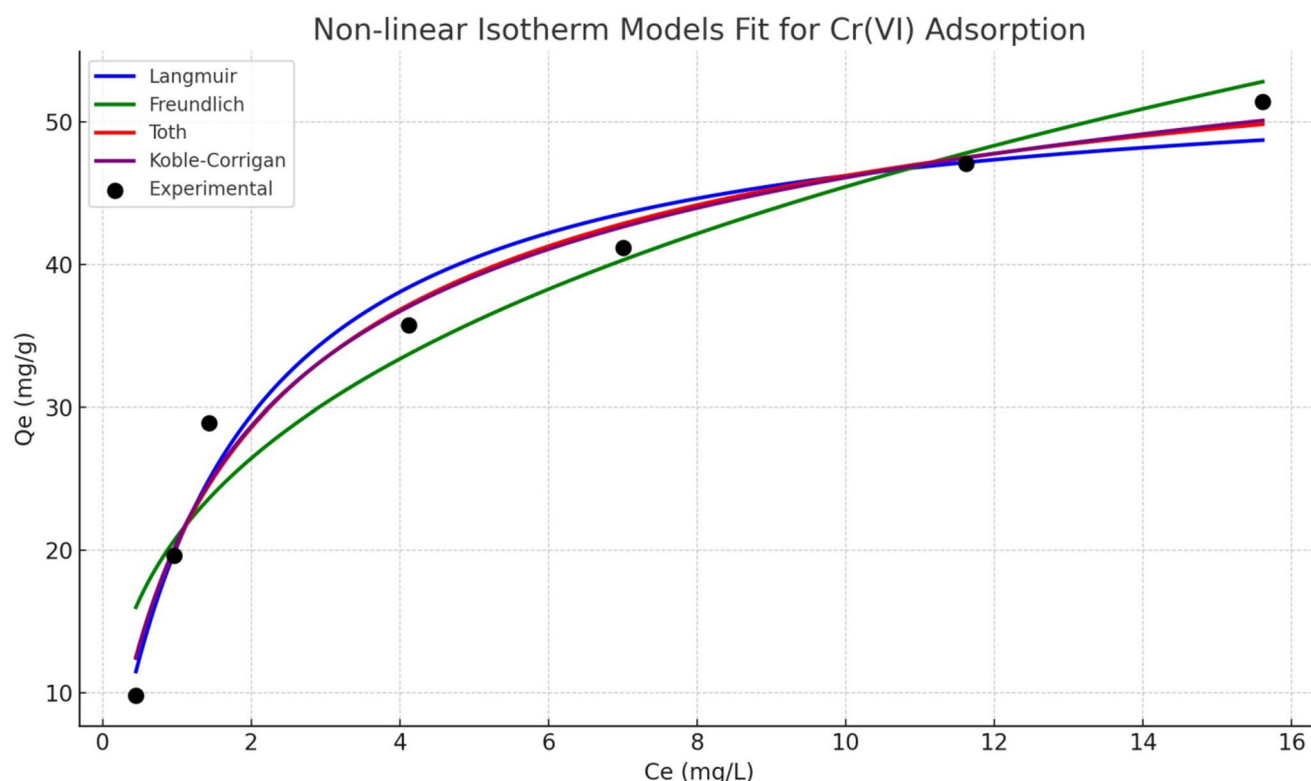


Fig. 9 Non-linear isotherm plots for the adsorption of Cr(VI) onto *Cordia africana* leaf-based activated carbon fitted with Langmuir, Freundlich, Toth, and Koble–Corrigan models

Table 1 Parameters of the Langmuir and Freundlich isotherm models

Isotherm	Parameters	Values
Langmuir	R^2	0.9712
	$Q_{\max}(\text{mg/g})$	53.95
	$K_L(\text{L/mg})$	0.60
	R_L	0.77
	RMSE	2.35
Freundlich	R^2	0.9445
	n	2.97
	$1/n$	0.337
	$K_F(\text{mg/g (L/mg)}^{1/n})$	20.92
	RMSE	3.27
Toth	R^2	0.9747
	K	0.77
	nt	0.70
	RMSE	2.21
Koble Corrigan	R^2	0.9772
	A	41.6
	B	1.00
	nk	0.90
	RMSE	2.09

cost-effective Cr (VI) remediation. The gradual decline in Cr(VI) removal efficiency over successive cycles is likely due to partial blockage or loss of active sites, structural degradation, and incomplete desorption during regeneration (Bayuo et al. 2020; Chen et al. 2022; Wang et al. 2017). These factors reduce the number of available binding sites,

though the adsorbent still retains significant capacity, indicating good reusability.

Comparative analysis

The *Cordia africana* leaf-based activated carbon, with a specific surface area of 522 m²/g and Cr (VI) adsorption capacity of 52.2 mg/g, demonstrates superior performance compared to several other biomass-derived adsorbents as shown in Table 3. For example, although wood sawdust (Janiszewska et al. 2021) has the same surface area, it shows a lower capacity (36.7 mg/g), and *Sesbania sesban* (Vu et al. 2024) with a slightly higher surface area (562 m²/g) adsorbs only 5.3 mg/g. Even adsorbents with significantly higher surface areas, such as olive waste (Ba et al. 2018) (1050.9 m²/g, 74.9 mg/g), do not proportionally outperform *Cordia africana*, indicating that surface area alone does not govern adsorption efficiency. The remarkable performance of *Cordia africana* can be attributed to the presence of favorable surface functional groups and pore structure, which enhance Cr (VI) binding. This highlights the importance of surface chemistry and adsorbent origin in designing effective and sustainable materials for heavy metal remediation.

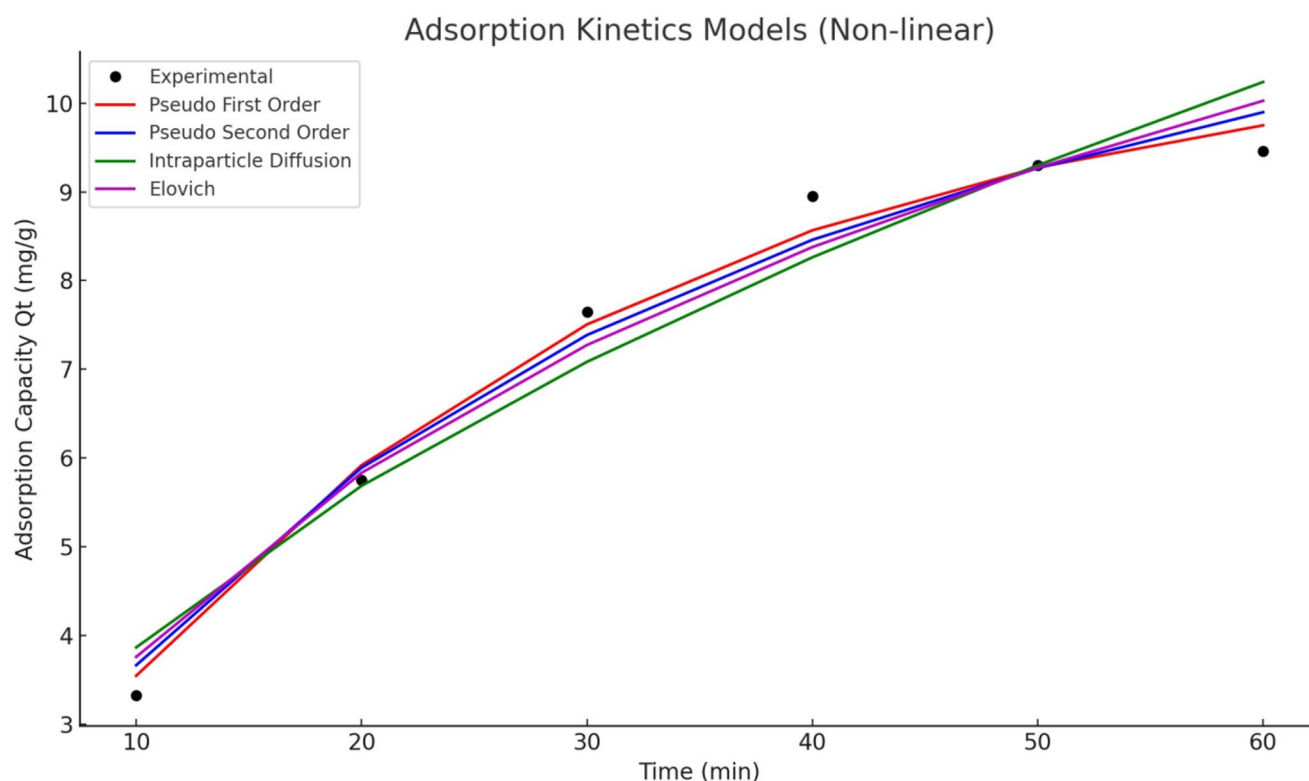


Fig. 10 Non-linear kinetic model fitting of experimental adsorption data onto *Cordia africana* activated carbon using pseudo-first-order, pseudo-second-order, intraparticle diffusion, and Elovich models

Table 2 Kinetic model parameters and determination coefficients computed for the adsorption of Cr (VI) onto *Cordia Africana* leaf-derived activated carbon

Kinetics model	Parameters	Values
Pseudo first order	R^2	0.989
	K_1	0.04 min^{-1}
	Q_e	10.71 mg/g
	RMSE	0.234
Pseudo second order	R^2	0.979
	K_2	$0.0024 \text{ g/mg} \cdot \text{min}$
	Q_e	13.53 mg/g
	RMSE	0.325
Intraparticle diffusion model	R^2	0.943
	K_d	$1.39 \text{ mg/g} \cdot \text{min}^{0.5}$
	C	0.527
	RMSE	0.531
Elovich	$R^2 \alpha \beta$	0.967
	RMSE	0.573
		0.210
		0.405

Adsorption mechanism

The adsorption of hexavalent chromium onto *Cordia africana* activated carbon is primarily governed by physisorption, as indicated by the best fit to the pseudo-first-order kinetic model ($R^2 = 0.989$) and the low activation energy inferred from thermodynamic parameters (Kassahun et al. 2022b; Tibebu et al. 2025). The process

is spontaneous (negative ΔG°) and endothermic (positive ΔH°), suggesting enhanced adsorption at elevated temperatures (Sahmoune 2019). BET analysis confirms a high surface area ($522 \text{ m}^2/\text{g}$) and a porous structure with pore sizes favorable for effective chromium ion diffusion and retention. SEM images reveal a highly porous and heterogeneous surface. The FTIR spectra revealed that functional groups such as O–H, C=O, and C–O, confirming the involvement of surface functionalities in the adsorption process. The pH_{pzc} of 5.03 implies that at solution pH above 5.03, the adsorbent surface is negatively charged, favoring electrostatic attraction of the positively charged chromium species. Conversely, below pH 5.03, the surface acquires a positive charge, enhancing adsorption of negatively charged chromium ions (Liu et al. 2023). XRD analysis reveals the predominantly amorphous nature of the adsorbent, which is typical of activated carbons and beneficial for adsorption due to the presence of disordered surface structures and defects (Wibawa et al. 2020). Generally, the adsorption mechanism involves multilayer physical adsorption enhanced by surface porosity, electrostatic interactions, and hydrogen bonding. Surface heterogeneity and pore structure enable both rapid external surface adsorption and intraparticle diffusion, while functional groups contribute to weak chemical interactions.

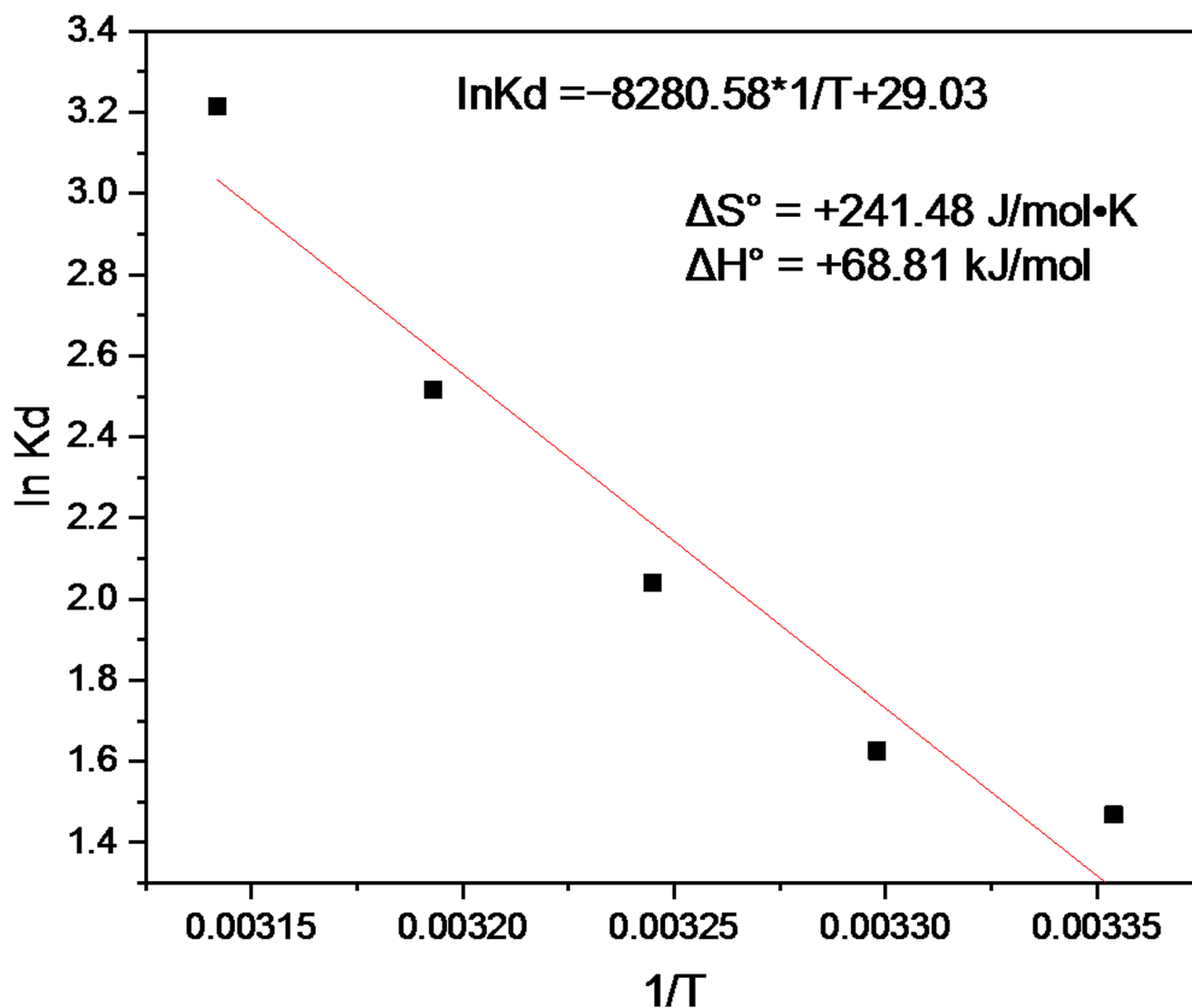


Fig. 11 Van't Hoff plot for the adsorption of Cr(VI) onto *Cordia africana* leaf-based activated carbon

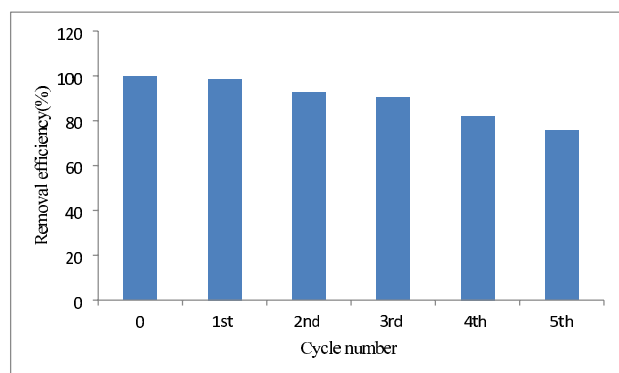


Fig. 12 Reusability of *Cordia africana* activated carbon for Cr (VI) adsorption over five cycles

Limitation of the study

Despite the valuable findings presented, this study has several limitations. First, certain characterizations such as ultimate analysis of the raw biomass, Boehm's titration for acidic and basic surface groups, and point of zero charge (pHpzc) for both precursor and activated carbon were not performed due to equipment and time constraints. The absence of FTIR analysis after adsorption restricts detailed understanding of the functional groups involved in the removal mechanism. Furthermore, N₂ adsorption-desorption isotherm data including pore size distribution and BJH analysis were limited, which could have provided deeper insight into the porosity characteristics. Finally, while a regeneration study was conducted, long-term adsorbent stability over multiple cycles requires further investigation. Future work will aim

Table 3 Comparison of specific surface area and cr (VI) adsorption capacity of *Cordia Africana* leaf-based activated carbon with other biomass-derived adsorbents

S.No	Activated carbon precursor	Specific surface area (m ² /g)	Adsorption capacity (mg/g)	Reference
1.	<i>Scots pine</i>	741	80.6	(Janiszewska et al. 2021)
2.	Wood Sawdust	522	36.7	(Janiszewska et al. 2021)
3.	<i>Sesbania sesban</i>	562	5.3	(Vu et al. 2024)
4.	Sugar beet residue	2002.9	163.7	(Zhao et al. 2021)
5.	Olive waste	1050.9	74.9	(Ba et al. 2018)
6.	Corn husk	-	30.3	(Ammar et al. 2021)
7.	Eucalyptus Sawdust	-	34.07	(Khushk et al. 2019)
8.	<i>Cordia africana</i> leaf	522	52.2	This work

to address these gaps for a more comprehensive evaluation of *Cordia africana*-based activated carbon.

Conclusion

The present study showcased the potential of *Cordia africana* leaf-derived activated carbon as an efficient adsorbent for removing Cr (VI) from water systems. Optimal adsorption conditions were achieved at pH 3, an initial Cr (VI) concentration of 50 mg/L, an adsorbent dose of 0.8 g/L, and exposure duration of 60 min, resulting in a highest removal percentage of 99.7. The adsorption kinetics followed the pseudo-first-order model ($R^2 = 0.99$), whereas equilibrium data were best represented by the Koble Corrigan model ($R^2 = 0.98$). Overall, *Cordia africana* leaf-based activated carbon appears to be promising, locally available, cost-efficient and eco-benign adsorbent for Cr (VI) removal from contaminated water. However, further post-adsorption characterization is needed to fully understand the adsorption mechanism at the molecular level. The study was limited to laboratory batch experiments, so scale-up feasibility remains untested. Additionally, the adsorption performance in multi-contaminant systems was not evaluated, which is important for real wastewater applications.

Author contributions M.D.T., M.A.G., and M.O.D. contributed to the experimental design, supervision, data analysis, and writing and editing of the manuscript. The data collection was carried out by M.D.T. and M.A.G.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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