



# Adsorptive removal of malachite green dye from aqueous solution using *Cordia africana* leaf as biosorbent

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## Abstract

An untreated biosorbent derived from the leaves of *Cordia africana* was utilized in this study for the first time to remove malachite green (MG) dye from aqueous solutions via batchwise adsorption. Comprehensive characterizations of the biosorbent were conducted, including Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and determination of the pH point of zero charge (pHpzc). The adsorption process was investigated under varying operational conditions: biosorbent dosage (0.25–0.65 g/100 mL), contact time (25–50 min), initial pollutant concentration (15–45 mg/L), and solution pH (4–9). Kinetic and isothermal models were employed to evaluate the adsorption mechanism. Characterization revealed an amorphous, heterogeneous surface. The biosorbent achieved an impressive MG removal efficiency of 98.9%, with a maximum Langmuir adsorption capacity ( $Q_{max}$ ) of 6.25 mg/g, indicating a monolayer chemisorption process in agreement with Langmuir and pseudo-second-order kinetics models. This study highlights the cost-effectiveness and potential of *Cordia africana* leaf-based biosorbent as a sustainable and efficient solution for the decolorization of MG-laden industrial effluents, providing a pathway for practical, large-scale applications.

**Keywords** Adsorption · Biosorbent · *Cordia Africana* · Malachite green · Wastewater treatment

## Introduction

Water scarcity and stress, driven by industrialization, are particularly severe in the textile industry, which contributes 9% of global industrial water pollution (Aravind and Sundaram 2021). Wastewater from textile processes, such as dyeing and finishing, contains high levels of pollutants, including biochemical oxygen demand (BOD) (432–1840 mg/L), chemical oxygen demand (COD) (635–4459 mg/L), dyes as heavy metals and volatile organic compounds (VOCs) leading to significant environmental harm (Dhameliya and

Ambasana 2023). In regions like Tirupur, the industry annually consumes 28.8 billion liters of groundwater, causing depletion and contamination (Aravind and Sundaram 2021). The Industrial Water Footprint (IWF) and grey water footprint methodologies highlight the sector's extensive freshwater use and its critical role in worsening water scarcity (Kumar et al. 2021).

Malachite green (MG) is a synthetic dye commonly employed in textile manufacturing. It is used as a dyeing agent in the textile manufacturing, as a food coloring agent in the food industry and used to effectively prevent fungus from growing on fish eggs in aquaculture industries (Yadav and Qanungo 2023; Nath et al. 2019; Idriss 2021). On the other hand, MG is persistent pollutant in wastewater and environment, posing hazards to human health and the aquatic organisms (Sharma et al. 2023). It has toxic properties that can induce cancer, irritation of the skin and eyes, and respiratory toxicity (Perendija et al. 2024; Raval et al. 2022). The concentration of MG in industrial wastewater varies based on the sector, but it is a common contaminant. The acceptable level of MG in water is 0.01 parts per million (ppm) (Khairil 2021). Therefore, the widespread use of MG necessitates stringent control measures to mitigate its

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adverse impacts on both human health and the ecosystem (Akram et al. 2023).

Conventional wastewater treatment methods have limitations due to factors like high costs, incomplete removal of contaminants, and the need for more reliable approaches (Younas et al. 2021; Eniola et al. 2022). These methods, such as physical, chemical, and biological treatments, may struggle with the removal of emerging contaminants and achieving complete purification (Somma et al. 2021). While techniques like coagulation, flocculation, and precipitation are commonly used, they have restricted scopes and may not effectively eliminate all pollutants (Rathi et al. 2021). Additionally, the removal of persistent dyes like MG by conventional methods can vary based on the type of treatment, operating conditions, and the properties of the compounds, leading to incomplete removal (Periyasamy 2024; Yildiz et al. 2024). To address these limitations, there is a growing need for more efficient and cost effective wastewater treatment technologies that can better handle the diverse composition of contaminants in wastewater.

Advanced wastewater treatment technologies encompass processes such as adsorption, ion exchange, reverse osmosis, electrodialysis, chemical oxidation, and microbial fuel cells (MFCs) (Chitthaluri et al. 2023; Malik et al. 2022). These techniques exhibit significantly enhanced pollutant removal efficiencies compared to conventional methods, including coagulation-flocculation and flotation (Gupta et al. 2021). Adsorption, for instance, is highlighted as a simple, sustainable and cost effective method for water treatment (Tony 2022; Chai et al. 2021). MFCs, on the other hand, utilize bacterial species to oxidize organic matter, reduce heavy metal content, and generate electricity while cleaning wastewater (Dhameliya and Ambasana 2023; Kumar et al. 2021; Yadav and Qanungo 2023; Nath et al. 2019; Idriss 2021; Sharma et al. 2023; Perendija et al. 2024; Raval et al. 2022; Khairil 2021; Akram et al. 2023; Younas et al. 2021; Eniola et al. 2022; Somma et al. 2021; Rathi et al. 2021; Periyasamy 2024; Yildiz et al. 2024; Chitthaluri et al. 2023; Malik et al. 2022; Malik et al. 2023; Gupta et al. 2021; Tony 2022; Chai et al. 2021; Roy et al. 2023; Yaqoob et al. 2021). These advanced methods address drawbacks of conventional techniques, such as high energy demand, production of by-products, and toxic effects, making them more efficient and environmentally friendly (Aravind and Sundaram 2021; Saravanan et al. 2021). Recent studies have demonstrated the efficiency of various adsorbents in removing emerging contaminants from wastewater. For example, nanocomposites like calcium-aluminum layered double hydroxide-loaded magnetic nanoparticles have shown high adsorption capacities for pollutants such as 4-nitrophenol (636 mg/g) (Messaoudi et al. 2024). Additionally, deep eutectic solvent-based composites have successfully removed dyes like malachite green with over 90% efficiency (Kurtulbaş et al. 2024). Metal-organic framework-derived magnetic nanocomposites

have also proved effective, combining adsorption and photocatalysis for organic pollutant removal (Miyah et al. 2024). Moreover, sustainable materials like mesoporous nanocellulose-hectorite beads have demonstrated excellent adsorption properties for methylene blue (Lastname et al. 2024).

Various biosorbents have been investigated for the adsorption of MG dye from wastewater, showcasing promising removal efficiencies and adsorption capabilities. Kiwi peel—based adsorbents, including nitric acid modified kiwi peel, demonstrated high selectivity towards cationic dye MG, with a maximum adsorption capacity of 580.61 mg/g for nitric acid modified kiwi peel (NA-KP) (Zhao et al. 2023). Ace-rola seed exhibited a remarkable performance with the highest elimination capacity of 103.50 mg/g for MG adsorption (Gadelha et al. 2023). Hydrochar derived from palm leaves showed enhanced adsorption capacity of 62.80 mg/g for MG, further improved by activation to 88% at 66 ppm (Hammud et al. 2023). Iron-zink nanocomposites synthesized with mint leaf extract achieved adsorption capacity of 92.59 mg/g for MG adsorption (Saad et al. 2023). Nano-bentonite (Çifçi 2023) and MgO-impregnated clay (Hür and Erken 2022) demonstrated high removal efficiencies of 98.6% and 97.04% for MG, respectively.

Despite progress, there remains an unmet need for exploring underutilized, locally available biomass for biosorbent production. *Cordia africana*, a versatile and widely available plant, presents significant potential in this regard. Traditionally valued for applications ranging from medicinal uses to agroforestry, its leaves exhibit adsorption-relevant functional groups (e.g., hydroxyl, carbonyl, and carboxyl groups) (Nnamani et al. 2024; Gota et al. 2023; Salaudeen et al. 2022). Previous studies on *Cordia africana*-derived adsorbents focused on removing heavy metals like chromium from synthetic wastewater, demonstrating promising adsorption capabilities (Gebrehawaria 2016; Kassahun et al. 2022). However, research utilizing untreated *Cordia africana* leaves for dye removal remains absent. This study bridges these gaps by evaluating untreated *Cordia africana* leaf biosorbents for MG adsorption, aiming to provide a low-cost and effective solution for wastewater treatment. We hypothesize that untreated *Cordia africana* leaves possess sufficient adsorption capacity and functional groups to effectively remove MG from aqueous solutions. The novelty of this work lies in valorizing a widely available yet underexplored biomass for the targeted removal of MG, with potential scalability and practical implications.

## Materials and methods

### *Cordia africana* based biosorbent preparation

*Cordia africana* leaves were collected, washed with distilled water to remove any foreign materials, and then

sun-dried for 7 days in a controlled environment to minimize variable humidity. The dried leaves were oven-dried at 105 °C for 24 h to ensure complete moisture removal and prevent microbial growth. The dried material was then finely pulverized using a mortar and pestle, achieving a particle size of 250  $\mu\text{m}$ . To ensure consistent storage conditions, the prepared biosorbent was sealed in an airtight plastic container, preventing contamination and maintaining sample integrity until used for biosorbent characterization, batch adsorption, and kinetics and isotherm studies (Zhang et al. 2016). The steps involved are illustrated in Fig. 1.

## Biosorbent characterization

### pH point of zero charge (pHpzc)

Techniques such as acid titration and salt addition are widely utilized for determining the pH point of zero charge (pHpzc). In this study, the mass addition method of pHpzc determination was employed. Specifically, six 250 mL Erlenmeyer flasks were used to prepare 50 mL of 0.1 M NaCl, and pH variations between 2 and 12 were adjusted using either 0.1 M HCl or 0.1 M NaOH. Following pH adjustment, each flask received an addition of 1 g of the sample, and the samples were shaken at 125 rpm for 48 h. Finally, the pHpzc determination was made by plotting curves correlating the initial pH with the  $\Delta\text{pH}$  (pH initial—pH final) (Kifetew et al. 2024). Understanding pHpzc is crucial for predicting the biosorbent's behavior in various aqueous environments, influencing adsorption efficiency based on charge matching between the biosorbent and target pollutants.

## Surface morphology analysis

Scanning Electron Microscopy (SEM) analysis of biosorbents derived from *Cordia africana* leaf involves several steps. Initially, the prepared biosorbent samples are carefully mounted onto SEM stubs using conductive adhesive or double-sided carbon tape. Subsequently, the stubs are placed in the SEM chamber, and the instrument is evacuated to create a vacuum environment. The surface of the biosorbent is then scanned using a focused electron beam, causing interactions such as secondary electron emission, backscattered electron emission, and characteristic X-ray emission. These interactions are detected by specialized detectors to generate high-resolution images of the biosorbent surface, revealing its topography, morphology, and elemental composition. The SEM analysis provides valuable insights into the structural characteristics and surface features of the *Cordia africana* leaf-derived biosorbent, essential for understanding its efficacy in adsorption applications (Saad et al. 2023; Abewaa et al. 2023).

## X-ray diffraction (XRD) analysis

X-ray diffraction (XRD) is crucial equipment for analyzing the crystallinity or amorphous nature of biosorbents. In the context of biosorbents, XRD can be utilized to assess changes in crystalline structure post-treatment. It is essential for determining the amorphous fraction transformed to crystalline states, especially in the presence of impurities like oxygen, which can impact the results. XRD commonly employed in biosorption studies to identify the presence of amorphous phases or crystalline structures, providing valuable insights into the structural characteristics of biosorbents. By analyzing XRD patterns, researchers can distinguish between amorphous and crystalline regions within



**Fig. 1** Stages of biosorbent development from *Cordia africana* leaves: *Cordia africana* tree (A), dried *Cordia africana* leaves (B), and ground ready-made biosorbent (C)

biosorbents, aiding in understanding their structural properties and potential applications (Teweldebrihan and Gnaro 2024).

### Fourier transform infrared (FTIR) analysis

FTIR analysis of *Cordia africana* leaf biosorbent was performed using a PerkinElmer Spectrum 100 FTIR spectrometer (USA). The sample was prepared as a fine powder and placed in the sample compartment for analysis. The spectrum was recorded in the wavenumber range of 4000–400  $\text{cm}^{-1}$  with a resolution of 4  $\text{cm}^{-1}$ , and data was collected by averaging 32 scans to improve the signal-to-noise ratio. The resulting FTIR spectrum was analyzed to identify functional groups such as hydroxyl, alkyl, carbonyl, and alcohol/ether groups, which are crucial for understanding the biosorbent's chemical composition and its potential for applications like pollutant removal in water treatment.

### Batch adsorption experiments

The adsorption of malachite green (MG) dye onto untreated *Cordia africana* leaves was investigated under controlled experimental conditions. The biosorbent dosage was varied within the range of 0.25–0.65 g/100 mL, with values specifically set at 0.25, 0.35, 0.45, 0.55, and 0.65 g/100 mL. The contact time was adjusted between 25 and 50 min, using intervals of 25, 30, 35, 40, 45, and 50 min. The initial MG concentration was tested across the range of 15–45 mg/L, at specific values of 15, 20, 25, 30, 35, 40, and 45 mg/L. The solution pH was studied across the range of 4–9, focusing on integer values of 4, 5, 6, 7, 8, and 9 to evaluate the pH-dependent adsorption performance. A stock solution of MG (100 mg/L) was prepared by dissolving a 100 mg of MG dye in 1 L distilled water. The stock solution was then diluted to prepare concentrations ranging from 15 to 45 mg/L for the experiment. The adsorbent, *Cordia africana* leaves, was collected from Hossana, Ethiopia and was not pretreated before use. For the adsorption process, a measured volume of the MG solution (100 mL) was added to Erlenmeyer flasks. The pH of each solution was adjusted to the desired values using 0.1 M NaOH or HCl. A specific amount of the *Cordia africana* leaf adsorbent was then added to each flask, which was subsequently shaken on an orbital shaker to ensure uniform contact. The mixture was left to equilibrate for the designated contact time under controlled conditions. Afterward, the adsorbent was separated by filtration using Whatman filter paper, and the remaining MG concentration was measured with a Shimadzu UV-1800 Ultraviolet–visible spectroscopy (UV–VIS) (Japan) at a wavelength of 620 nm. The structure of malachite green is depicted in Fig. 2.

A calibration curve was prepared by varying the initial MG concentrations (5, 10, 15, 20, 25, and 30 mg/L)

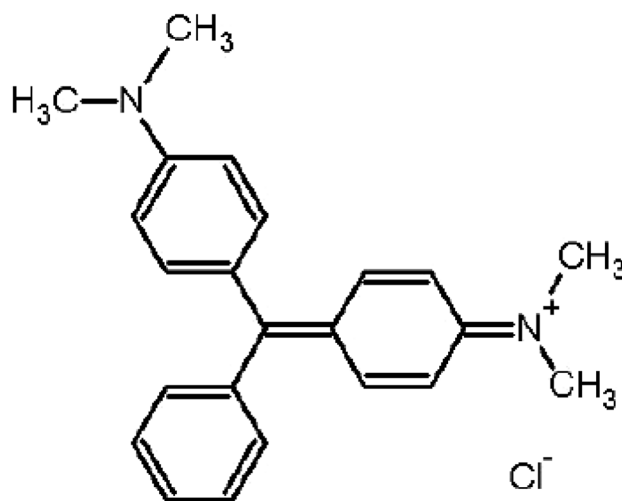


Fig. 2 Structure of malachite green

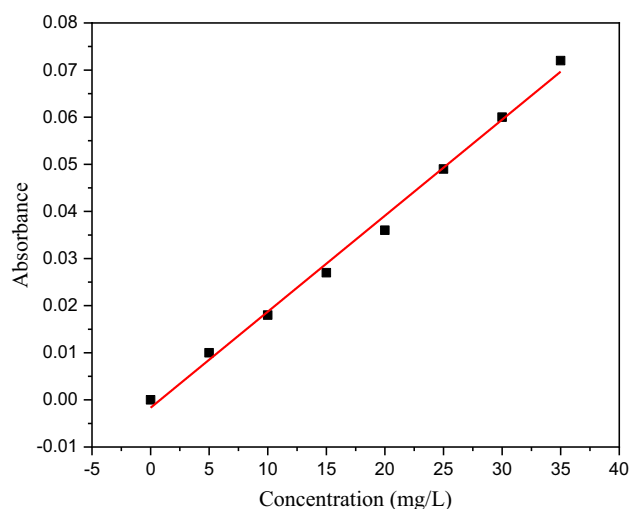


Fig. 3 Calibration curve development for malachite green adsorption from aqueous solution

as shown in Fig. 3. The absorbance of each solution was measured using a UV–VIS spectrophotometer at the dye's maximum wavelength. The Beer-Lambert equation was applied to establish a linear relationship between absorbance and concentration. Unknown MG concentrations were then determined using the derived linear equation.

The amount of MG adsorbed was calculated in terms of removal efficiency (Eq. 1) and adsorption capacity (Eq. 2) (Sonawane and Shrivastava 2009).

$$\text{Removal Efficiency (RE)} = \frac{(C_o - C_t)}{C_o} \times 100 \quad (1)$$

$$\text{Adsorption capacity}(Q_e) = (C_o - C_e) \times \frac{V}{M} \quad (2)$$

where  $C_o$  is the initial concentration of the pollutant in the solution (mg/L) and  $C_e$  is the concentration of the pollutant in the solution at equilibrium (mg/L),  $V$  is the volume of the solution (L) and  $m$  is the mass of the adsorbent used (g).

### Adsorption isotherm

In adsorption studies, the Langmuir and Freundlich isotherm models are frequently employed. The Langmuir model posits monolayer adsorption on a uniform surface without interactions between adsorbate molecules, whereas the Freundlich model proposes a heterogeneous surface with multilayer adsorption and interactions between adsorbate molecules. The linear equation for the Langmuir isotherm is expressed using Eq. 3.

$$\frac{1}{Q_e} = \frac{1}{Q_{\max}} + \frac{1}{KLQ_{\max}} \times \frac{1}{C_e} \quad (3)$$

where  $Q_e$  is the amount of adsorbate adsorbed,  $Q_{\max}$  is the maximum adsorption capacity,  $K_L$  is the Langmuir constant, and  $C_e$  is the equilibrium concentration of the adsorbate (Langmuir 1918). The linear form of the Freundlich isotherm is shown in Eq. 4.

$$\log Q_e = \log K_F + \frac{1}{n} \times \log C_e \quad (4)$$

where  $K_F$  is the Freundlich constant and  $1/n$  is the Freundlich exponent (Freundlich 1906). The linear forms of the Langmuir and Freundlich equations are preferred because they simplify data analysis by allowing for direct calculation of key adsorption parameters through straightforward linear regression, without the need for complex curve fitting or optimization procedures (González-López et al. 2022; Serafin and Dziejarski 2023).

### Adsorption kinetics

The investigation of adsorption kinetics involves analyzing the rate at which solutes are adsorbed onto surfaces and the time they spend there. Pseudo-first-order (PFO) and pseudo-second-order (PSO) models are frequently employed to describe this process. The PFO and PSO models are based on reaction rates similar to first and second-order kinetic reactions, respectively. These models help determine the adsorption rate constants ( $k_1$  for PFO and  $k_2$  for PSO) by considering two important regions in the adsorption process: the kinetic and equilibrium phases. These models help in understanding the adsorption process by analyzing the amount of adsorbate adsorbed over time and determining the rate constants for the adsorption process (Ebelegi

et al. 2020). Equations 5 and 6 represent the PFO and PSO respectively.

$$\log(Q_e - Q_t) = \log Q_e - \frac{K_1 \times t}{2.303} \quad (5)$$

$$\frac{t}{Q_t} = \frac{1}{K_2 \times Q_e^2} + \frac{t}{Q_e} \quad (6)$$

where,  $Q_e$  is the amount of adsorbate adsorbed at equilibrium (mg/g),  $Q_t$  is the amount of adsorbate adsorbed at time  $t$  (mg/g),  $k_1$  is the pseudo-first-order rate constant (1/min),  $t$  is the contact time (min),  $k_2$  is the pseudo-second-order rate constant (g/(mg.min)) (Lagergren 1898; Ho and McKay 1999).

## Results and discussions

### Biosorbent characteristics

#### SEM

The surface morphology analysis of the untreated biosorbent prepared from *Cordia africana* leaf using SEM revealed a heterogeneous and porous surface structure as shown in Fig. 4. This characteristic surface morphology is crucial for enhancing adsorption efficiency by providing more active sites for pollutant binding (Wang et al. 2020). Additionally, the SEM analysis showed that the biosorbent surface was full of cracks, which further supports its potential for effective dye molecules removal. The porous nature of the surface observed in the SEM image suggests that the biosorbent has a high capacity for adsorption due to increased accessibility of binding sites for MG molecules. The surface morphology

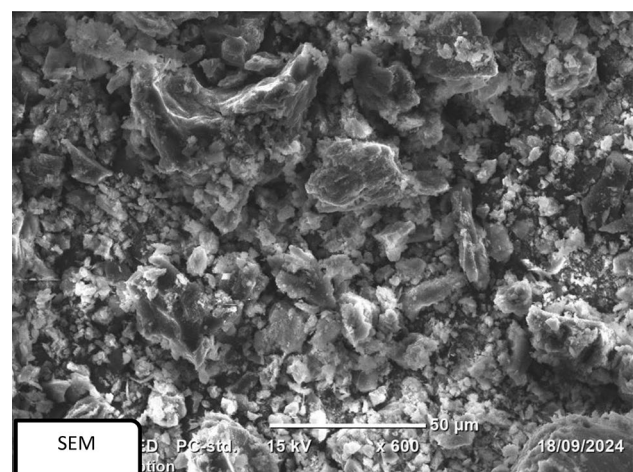


Fig. 4 SEM morphology of *Cordia africana* leaf based biosorbent

of *Cordia africana* leaf-based biosorbents, with its rough and irregular structure, provides more active sites for dye adsorption. High porosity enhances the material's ability to trap and retain malachite green molecules, increasing its adsorption capacity (Faheem et al. 2024; Zu-Yi et al. 2024). This unique surface morphology highlights the promising potential of the *Cordia africana* leaf-derived biosorbent for effectively removing contaminants from water and wastewater.

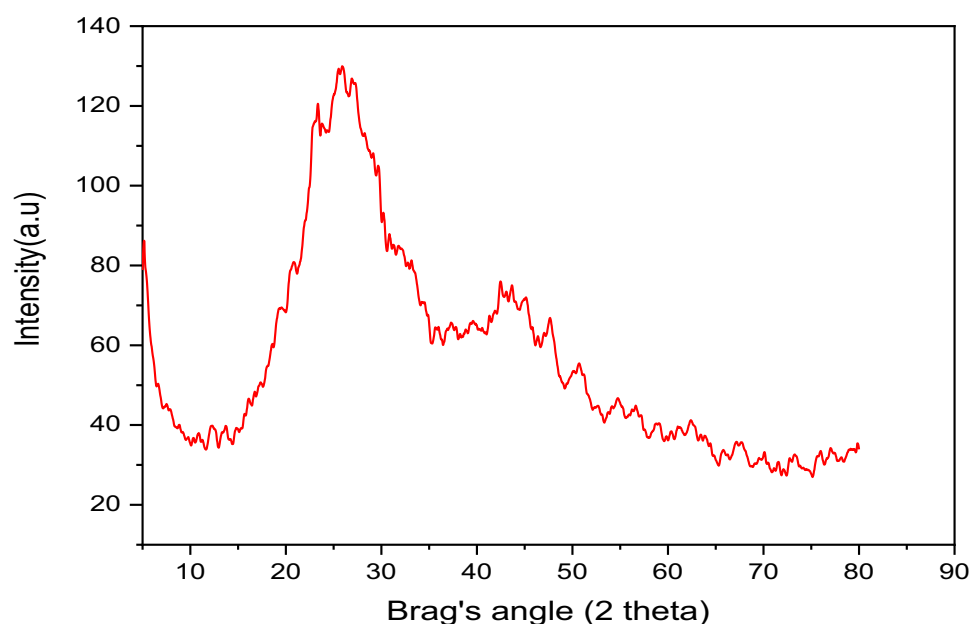
## XRD

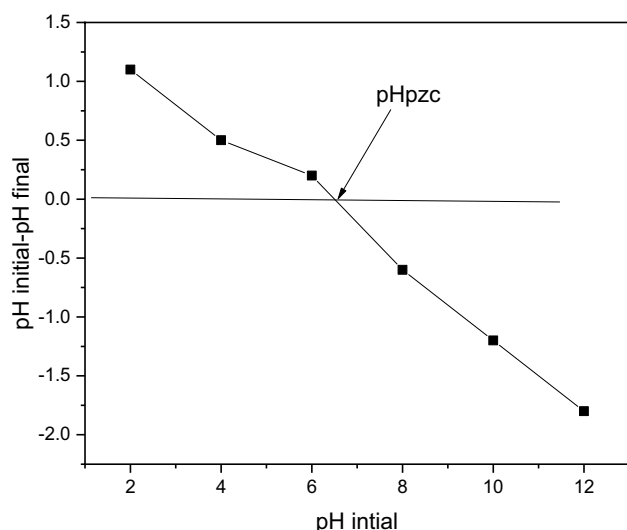
The XRD analysis of the biosorbent derived from *Cordia africana* leaves indicates predominantly amorphous characteristics, with a notable peak observed at a  $2\theta$  angle of  $22^\circ$ , as shown in Fig. 5. This peak corresponds to the characteristic diffraction of cellulose I, which is a well-known feature of cellulose structures (Singh et al. 2020). The standard card (PDF #123456) used for spectrum identification is referenced to confirm the presence of cellulose (Monograph 1956). The peak at  $22^\circ$  is typical of the cellulose I structure, reflecting the crystalline nature of the cellulose component within the biosorbent (Montoya-Escobar et al. 2022). This crystalline cellulose structure plays a significant role in enhancing the adsorption capacity and effectiveness of the biosorbent for removing contaminants such as MG from aqueous solutions. Further studies on the exact role of this crystalline cellulose in adsorption will provide deeper insights into its potential for environmental remediation applications (Kaur et al. 2022; Aslam, et al. 2023; Garba et al. 2020).

## pHpzc

Understanding the pHpzc is vital for optimizing adsorption processes, as it helps predict the biosorbent's behavior under different pH conditions. When the pH of the solution is below the pHpzc, the biosorbent surface tends to be positively charged due to the dominance of  $H^+$  ions, favoring the adsorption of negatively charged contaminants. Conversely, when the pH surpasses the pHpzc, the biosorbent surface acquires a negative charge due to the prevalence of  $OH^-$  ions, facilitating the adsorption of positively charged contaminants (Gamboa et al. 2024; Patel et al. 2023). In the case of *Cordia africana* leaf-based biosorbent, with a measured pHpzc of 6.5 as shown in Fig. 6, several implications arise. MG is a cationic dye, meaning it carries a positive charge in solution. At a pH above the pHpzc (6.5), the biosorbent's surface is likely to be negatively charged, enhancing its affinity for MG through electrostatic attraction. Since the pHpzc is 6.5, it suggests that the biosorbent's surface will carry a net positive charge at lower pH values. The net charge of the *Cordia africana* leaf-based biosorbent is primarily determined by the functional groups present on its surface, such as hydroxyl ( $-OH$ ), carboxyl ( $-COOH$ ), and amino ( $-NH_2$ ) groups. These functional groups can ionize depending on the pH of the solution, influencing the overall charge of the biosorbent. At lower pH values, the carboxyl and amino groups tend to protonate, contributing to a positive surface charge, while at higher pH values, these groups deprotonate, resulting in a negative charge. These surface functional groups play a critical role in determining the biosorbent's affinity for different contaminants, with

**Fig. 5** XRD pattern for *Cordia africana* based biosorbent





**Fig. 6** pH<sub>pzc</sub> of *Cordia africana* based biosorbent

electrostatic interactions between the charged groups and the contaminants significantly influencing the adsorption process. Therefore, for maximum adsorption of MG, operating at a pH above 6.5 might be favorable, as the negatively charged biosorbent surface can efficiently attract and adsorb the positively charged dye molecules. Generally, knowing the pH<sub>pzc</sub> of *Cordia africana* leaf-based biosorbent provides valuable insights into its surface charge properties and aids in designing efficient adsorption processes, particularly for removing MG and other cationic contaminants from wastewater (Adewuyi 2020; Maksoud et al. 2020; Aigbe et al. 2022).

## FTIR analysis

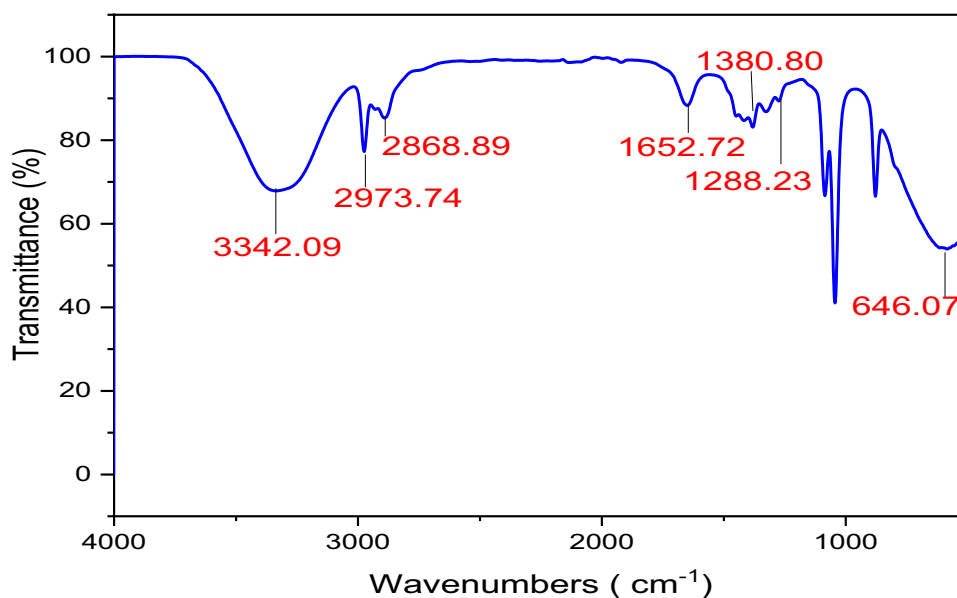
The FTIR spectrum of *Cordia africana* leaf biosorbent reveals a range of functional groups that contribute to its potential for pollutant adsorption as shown in Fig. 7. The broad peak at  $3342.09\text{ cm}^{-1}$  is attributed to O–H stretching vibrations, indicating the presence of hydroxyl groups, which are likely involved in hydrogen bonding. The peaks at  $2973.74\text{ cm}^{-1}$  and  $2868.89\text{ cm}^{-1}$  correspond to C–H stretching and bending vibrations, pointing to alkyl groups and potentially aldehyde or other functional groups. The peak at  $1652.72\text{ cm}^{-1}$  is associated with C=O stretching, suggesting carbonyl groups from compounds like carboxylic acids or esters. The presence of C–H bending vibrations at  $1380.80\text{ cm}^{-1}$  and C–O stretching at  $1288.23\text{ cm}^{-1}$  indicates the presence of aliphatic groups and alcohols or ethers, respectively. Finally, the peak at  $646.07\text{ cm}^{-1}$  signifies C–H out-of-plane bending, which may be indicative of aromatic or unsaturated systems (Gebrehawaria 2016; Kassahun et al. 2022). Collectively, these functional groups such as hydroxyl, alkyl, carbonyl, alcohols, and possibly aromatic structures enhance the biosorbent's effectiveness for adsorption, likely contributing to its utility in environmental applications such as water treatment and pollutant removal.

## Effects various operating parameters

### Effect of pH

The pH ranging from 4 to 9 was evaluated for its impact on the removal efficiency of MG onto *Cordia africana* based biosorbent. Accordingly, increasing pH from 4 to 9 increased the removal efficiency of the pollutant from

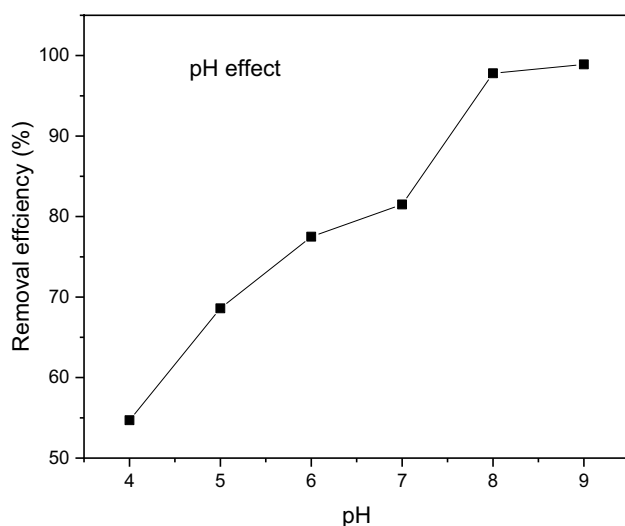
**Fig. 7** FTIR analysis of *Cordia africana* leaf based biosorbent



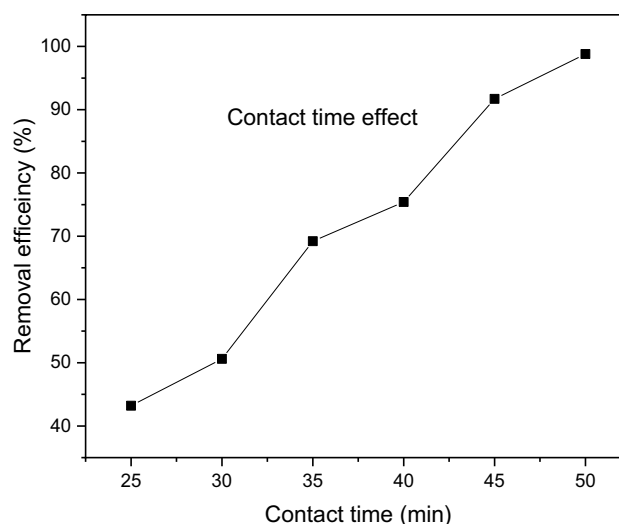
synthetic wastewater from 54.7 to 98.9% as shown in Fig. 8. This provides insights into the pH effect on removal efficiency. The trend observed shows a gradual increase in removal efficiency with increasing pH. This pattern can be attributed to the surface charge of the biosorbent and the dye molecules. At higher pH levels, the biosorbents may carry a more negative charge, enhancing the electrostatic attraction with the positively charged MG molecules, leading to increased adsorption efficiency. This trend aligns with the general behaviour observed in adsorption processes involving MG removal from aqueous solutions (Bai et al. 2025; Moustafa 2023).

### Effect of contact time

The effect of varying contact time on the removal efficiency of MG is presented in Fig. 9. The findings suggest a significant correlation between exposure duration and the efficiency of malachite green removal using *Cordia africana* based biosorbent. As the exposure duration increases from 25 to 50 min, there's a noticeable trend of increased removal efficiency. At the initial stages (25–30 min), there's a relatively gradual rise in removal efficiency. However, between 35 and 45 min, there's a more pronounced increase, indicating that the biosorbent requires sufficient time to adsorb MG effectively. Notably, the removal efficiency reaches its peak at 50 min, with a significant removal rate of 98.8%. This pattern suggests that longer contact times allow for more thorough adsorption of MG onto the biosorbent, likely due to increased surface area interaction and binding sites becoming saturated over time (Rangabhashiyam et al. 2018; Swan and Zaini 2019). It



**Fig. 8** Effect of pH on the removal efficiency of malachite green from an aqueous solution at an adsorbent dosage of 0.65 g/100 mL, an initial dye concentration of 15 mg/L, and a contact time of 50 min

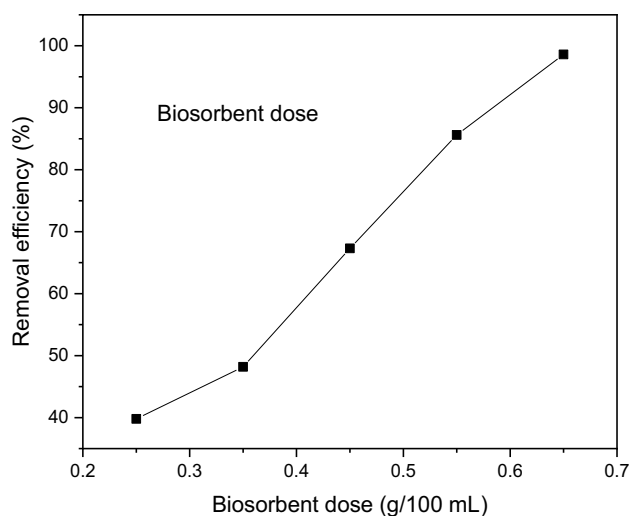


**Fig. 9** Effect of contact time on the removal efficiency of malachite green dye from aqueous solution at pH 6, dye concentration of 15 mg/L and adsorbent dosage of 0.65 g/100 mL

also implies the potential for optimizing the process for practical applications by determining the most efficient contact time to achieve desired removal efficiency while minimizing resource usage.

### Effect of biosorbent dose

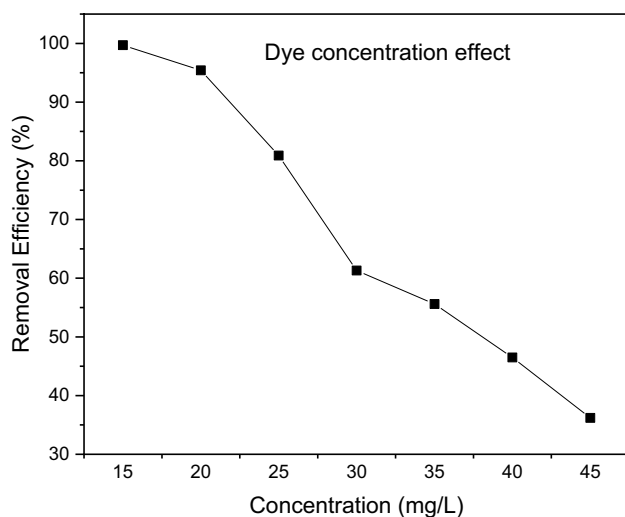
The influence of varying biosorbent dose (0.25–0.65 g/100 mL) on the removal efficiency of MG is shown in Fig. 10. This investigation into the influence of varying biosorbent dose on the removal efficiency of MG using *Cordia africana* based biosorbent reveals an interesting trend. As the dosage of the biosorbent increases from 0.25 to 0.65 g/100 mL, there's a clear and consistent improvement in removal efficiency. At lower dosages (0.25–0.35 g/100 mL), the removal efficiency starts relatively low but shows a noticeable increase. However, it's between 0.45 and 0.65 g/100 mL that the removal efficiency experiences a more substantial enhancement, reaching a notable 98.6% at the highest dosage. This trend indicates that higher doses of the biosorbent lead to greater removal efficiency of MG. This might be explained by the increased availability of active sites biosorbent surface, allowing for increased adsorption of the dye molecules (Karić et al. 2022; Elgarahy et al. 2021; Hamad and Idrus 2022). The results suggest that optimizing the dosage of *Cordia africana* based biosorbent can significantly enhance its effectiveness in removing MG from solution, which could have implications for industrial or environmental remediation.



**Fig. 10** Effect of biosorbent dose on the removal efficiency of malachite green from aqueous solution at constant pH of 9, contact time of 50 min and dye concentration of 15 mg/100 mL

### Effect of initial pollutant concentration

The exploration into the impact of varying initial MG concentrations on the removal efficiency using *Cordia africana* based biosorbent uncovers an intriguing relationship as shown in Fig. 11. At lower initial dye concentrations (15–20 mg/L), the removal efficiency is remarkably high, with values exceeding 95%. However, as the initial MG dye concentration increases beyond this range, there's a noticeable decline in removal efficiency. The decrease becomes more pronounced as the concentration rises above 25 mg/L.

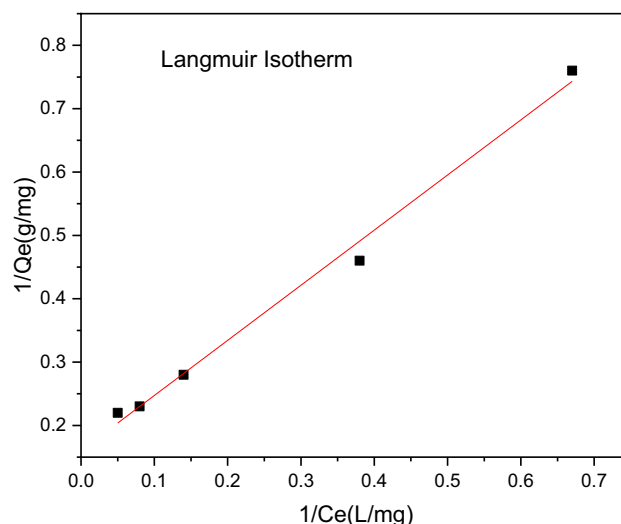


**Fig. 11** Effect of initial dye concentration on the removal efficiency of malachite green from aqueous solution at constant adsorbent dose of 0.65 g/100 mL, contact time of 50 min and pH of 9

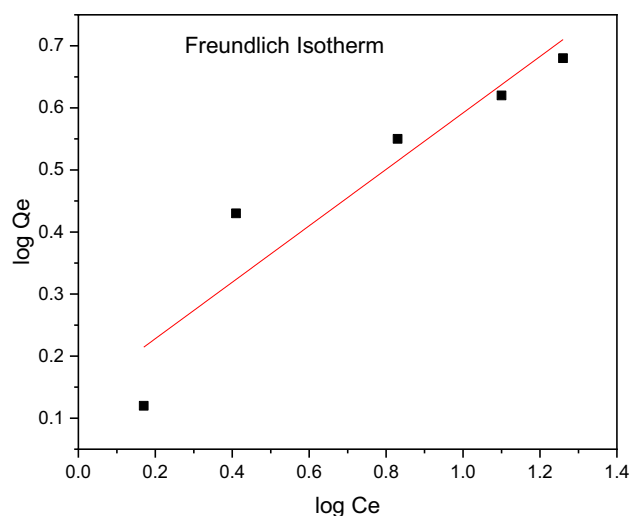
This trend suggests that the efficiency of the biosorbent in removing MG is inversely related to the initial concentration of the dye. At lower concentrations, there may be more available binding sites on the biosorbent relative to the amount of dye present, leading to higher removal efficiency. Conversely, with increasing concentration, the available binding sites reach saturation more rapidly, leading to a decrease capacity for dye removal (Moustafa 2023; Mashkoo et al. 2022). These findings indicate that while *Cordia africana* based biosorbent is highly effective at low initial dye concentrations, its efficiency diminishes as the concentration of malachite green in the solution rises. This insight could inform the optimization of biosorbent usage in scenarios where varying dye concentrations are encountered, such as in wastewater treatment processes.

### Adsorption isotherm

The adsorption performance of MG onto the *Cordia africana* leaf-based biosorbent was analyzed using the Langmuir and Freundlich isotherm models, with the corresponding fits shown in Figs. 12 and 13. A comparative analysis reveals that the Langmuir model yielded a superior correlation coefficient ( $R^2=0.99$ ) compared to the Freundlich model ( $R^2=0.88$ ) as shown in Table 1. This strong agreement between the experimental and predicted data indicates that the Langmuir model more accurately describes the adsorption mechanism. The Langmuir model assumes monolayer adsorption on a homogeneous surface where all binding sites are identical and energetically equivalent. This is consistent with the experimental results, as the calculated  $Q_{max}$  of 6.25 mg/g represents the maximum adsorption



**Fig. 12** Langmuir isotherm plot for the adsorption of malachite green dye onto *Cordia africana* biosorbent at pH 9, contact time of 50 min and adsorbent dosage of 0.65 g/100 mL



**Fig. 13** Freundlich isotherm plot for malachite green adsorption onto *Cordia africana* based biosorbent at pH 9, contact time of 50 min and adsorbent dosage of 0.65 g/100 mL

**Table 1** The calculated parameters for the Langmuir and Freundlich isotherm models

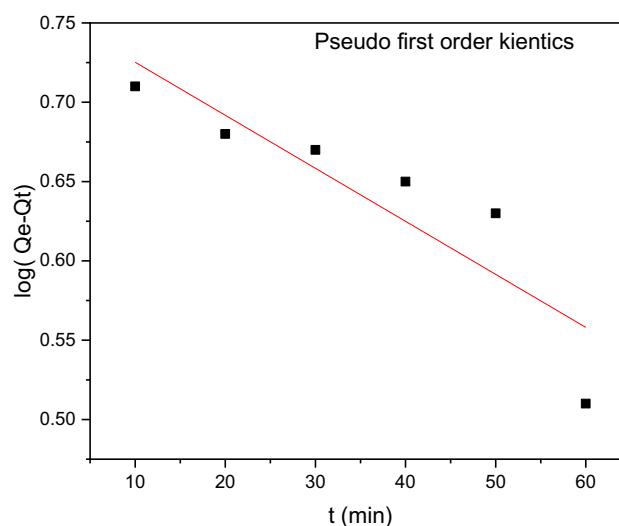
| Parameter       | Langmuir model     | Freundlich model                                                     |
|-----------------|--------------------|----------------------------------------------------------------------|
| $Q_{max}$       | 6.25 mg/g          | –                                                                    |
| $K_L$           | 0.18 L/g           | –                                                                    |
| $R^2$           | 0.99               | 0.88                                                                 |
| $R_L$           | 0.79               |                                                                      |
| $K_F$           | –                  | $1.38 \text{ (mg/g)} \left(\frac{\text{L}}{\text{mg}}\right)^{0.45}$ |
| $1/n$           | –                  | 0.45                                                                 |
| Linear equation | $Y = 0.87X + 0.16$ | $Y = 0.45 X + 0.14$                                                  |

capacity achievable when all high-affinity sites are occupied. The dimensionless separation factor ( $R_L = 0.79$ ) further reinforces the favorable nature of the adsorption process. These findings imply that the biosorbent provides a finite number of well-defined adsorption sites, which aligns with the Langmuir model's assumptions. On the other hand, the Freundlich model, with its empirical foundation, assumes heterogeneous adsorption onto sites with varying affinities. While the Freundlich constants ( $K_F = 1.38 \text{ (mg/g)} \left(\frac{\text{L}}{\text{mg}}\right)^{0.45}$  and the  $1/n$  of 0.45) suggest a favorable adsorption process, the lower  $R^2$  value indicates that this model captures the experimental data less effectively. The deviation might be attributed to the uniform nature of the binding sites on the *Cordia africana* leaf-based biosorbent, which the Freundlich model does not consider. Furthermore, the Langmuir model's prediction of a uniform adsorption process, likely dominated by chemisorption, aligns with the biosorbent's interaction

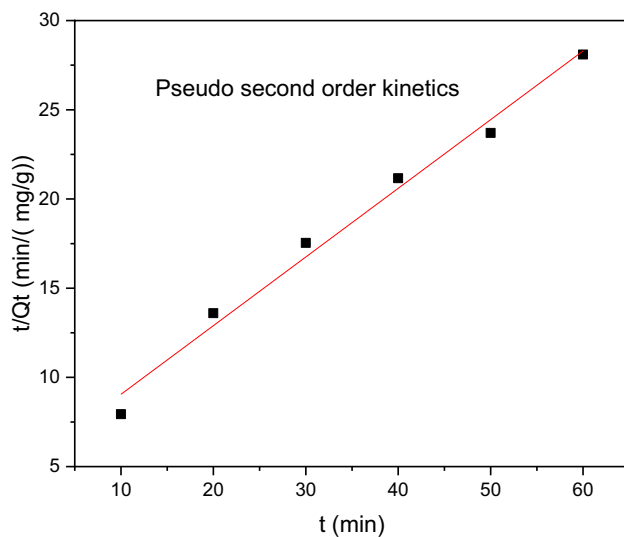
mechanisms. This uniformity suggests stronger, specific interactions between MG molecules and the adsorbent surface, as opposed to multilayer or physisorption mechanisms implied by the Freundlich model (Ghoohestani et al. 2024; Vieira et al. 2022). In conclusion, the higher  $R^2$  value, along with the correspondence of key parameters such as  $Q_{max}$  and  $R_L$ , underscores the appropriateness of the Langmuir model in describing the observed adsorption behavior. The better alignment of this model with the adsorption process confirms the monolayer and homogeneous nature of the binding sites, making it more suitable for this study compared to the Freundlich model (Akram et al. 2023).

## Adsorption kinetics

The experiment conducted for kinetics studies of MG dye adsorption onto *Cordia africana* leaf based biosorbent yielded insightful results as shown in Figs. 14 and 15. The PFO kinetics model exhibited a  $R^2$  of 0.98, a  $k_1$  of 0.0076/min, and calculated  $Q_e$  value of 5.75 mg/g. On the other hand, the PSO kinetics model showed a  $R^2$  of 0.99, a  $K_2$  of 0.005 g/(mg.min), and calculated  $Q_e$  of 6.25 mg/g as shown in Table 2. These results suggest that the adsorption of MG onto *Cordia africana* leaf based biosorbent follows PSO kinetics indicating more likely chemisorption. Moreover the better fit of the PSO model to the experimental data suggests that chemisorption is the dominant mechanism for the adsorption of MG onto the *Cordia africana* leaf-based biosorbent, indicating strong chemical interactions between the dye molecules and the functional groups on the biosorbent surface (Rehman et al. 2019a, b; Rashid et al. 2024).



**Fig. 14** Pseudo first order kinetics model for adsorption of malachite green from aqueous solution at pH 9, initial dye concentration of 15 mg/L and adsorbent dosage of 0.65 g/100 mL



**Fig. 15** Pseudo second order kinetics model for malachite green adsorption from aqueous solution at pH 9, initial dye concentration of 15 mg/L and adsorbent dosage of 0.65 g/100 mL

**Table 2** Kinetic model parameters

| Parameter       | PFO                   | PSO                |
|-----------------|-----------------------|--------------------|
| $Q_e$           | 5.75 mg/g             | 6.25 mg/g          |
| $K_1$           | 0.0076/min            | –                  |
| $R^2$           | 0.98                  | 0.99               |
| $K_2$           | –                     | 0.005 g/(mg.min)   |
| Linear equation | $Y = -0.0033X + 0.76$ | $Y = 0.16X + 5.20$ |

The *Cordia africana* leaf-based biosorbent applied in this work to remove malachite green dye from aqueous solution is compared with other adsorbates, and the result is depicted in Table 3. The biosorbent exhibited greater removal efficiency compared to other untreated adsorbents, showcasing its applicability.

The mechanism of MG adsorption onto the *Cordia africana* leaf-based biosorbent is predominantly governed by chemisorption, as evidenced by FTIR analysis, isotherm modeling, and kinetic studies. The FTIR spectrum reveals key functional groups, including hydroxyl (O–H), carbonyl (C=O), and aliphatic C–H and C–O groups, indicating their involvement in binding MG molecules through strong chemical interactions such as hydrogen bonding and electron exchange. The Langmuir isotherm model, with a high  $R^2 = 0.99$ , demonstrates monolayer adsorption on homogeneous, high-affinity sites, consistent with specific, localized chemisorption. Furthermore, the pseudo-second-order kinetic model, which better fits the adsorption data ( $R^2 = 0.99$ ), confirms the process is driven by valence forces, reflecting strong interactions between MG molecules and the biosorbent surface. Together, these findings highlight that the adsorption mechanism is predominantly chemisorption, involving the active functional groups of the biosorbent, with uniform adsorption behavior dominated by strong chemical binding rather than physisorption or multilayer processes (Hussain et al. 2021; Rehman et al. 2015; Kanwal et al. 2024). However, a thorough study is needed to fully understand the adsorption mechanism involved in removal of MG onto *Cordia africana* leaf based biosorbent.

**Table 3** Comparison of removal efficiency of various adsorbents for malachite green removal

| S. no | Adsorbent                      | Removal efficiency (%) | Adsorption capacity(mg/g) | Optimal conditions                                                            | References                |
|-------|--------------------------------|------------------------|---------------------------|-------------------------------------------------------------------------------|---------------------------|
| 1     | Lemon leaf powder              | 82.21                  | 8                         | T=303 K, adsorbent dose = 20 g/L, MG concentration = 50 mg/L                  | Babu and Priyanka (2023)  |
| 2     | Nano-bentonite                 | 96.5                   | 17.2                      | t=60 min, pH=9, adsorbent dose = 1 g/L, MG concentration = 50 min             | Moustafa (2023)           |
| 3     | <i>Humulus Lupulus</i> stems   | 98.4                   | 398.9                     | T=120 min, adsorbent dose = 2 g/L, MG concentration = 100 mg/L, pH=8, T=298 K | Perendija et al. (2024)   |
| 4     | <i>Bambusa vulgaris</i> leaves | 95                     | 151.7                     | pH=6, T=298 K                                                                 | Ghosh et al. (2022)       |
| 5     | <i>Catha edulis</i> stem       | 83.65                  | 5.62                      | pH=10, MG concentration = 10 mg/g, adsorbent dose = 0.5 g/100 mL and t=60 min | Abate et al. (2020)       |
| 6     | modified chitosan composite    | –                      | 4.8                       | T=323 K, adsorbent dose = 0.1 g/20 mL, pH=8, t=60 min                         | Arumugam et al. (2019)    |
| 7     | chitosan ionic liquid beads    | –                      | 0.24                      | pH=4, adsorbent dose = 0.008 g/100 mL, t=20 min, MG concentration = 5 mg/L    | Naseeruteen et al. (2018) |
| 8     | <i>Cordia africana</i> leaf    | 98.9                   | 6.25                      | T=50 min, pH=9, adsorbent dose = 0.65 g/100 mL, MG concentration = 15 mg/L    | This work                 |

## Conclusion

This study demonstrated the effectiveness of a biosorbent derived from *Cordia africana* leaves for the removal of malachite green (MG) dye from aqueous solutions. The adsorption efficiency was influenced by key operational parameters, including biosorbent dosage, contact time, initial pollutant concentration, and solution pH. The MG removal increased with higher pH, longer exposure duration, and greater biosorbent dose, achieving a removal efficiency of 98.9%. In contrast, a higher initial pollutant concentration reduced the removal performance. Adsorption isotherms and kinetics revealed a maximum Langmuir adsorption capacity  $Q_{\max}$  of 6.25 mg/g and adherence to the Langmuir model and PSO kinetics, indicating a chemisorption-driven monolayer adsorption process. These findings underscore the potential of *Cordia africana* leaf-derived biosorbent as a cost-effective and sustainable material for treating industrial wastewater contaminated with MG dye. Compared to other biosorbents, its efficiency and accessibility suggest feasibility for scale-up. Future investigations should aim at thorough characterization of the material, testing with real wastewater samples, performing an economic analysis, and exploring thermodynamic properties to validate its broader application in industrial wastewater management.

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**Data availability** All data generated is included in the main body of the manuscript. No datasets were generated or analysed during the current study.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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