Effective Removal of Malachite Green from Aqueous Solutions Using Magnetic Nanocomposite: Synthesis, Characterization, and Equilibrium Study

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In this work, magnetized activated Juniperus procera leaves (Fe₃O₄@AJPL) were successfully prepared via chemical activation of JPL and in situ coprecipitation with Fe₃O₄. A Fe₃O₄@AJPL nanocomposite was successfully applied for the elimination of malachite green (MG) dye from aqueous media. The prepared Fe₃O₄@AJPL adsorbent was characterized by SEM, EDX, TEM, XRD, FTIR, TGA, and BET surface area analyses. The BET surface area and pore size of the Fe₃O₄@AJPL nanocomposite were found to be 38.44 m²/g and 10.6 nm, respectively. The XRD and FTIR results indicated the formation of a Fe₃O₄@AJPL nanocomposite. Different parameters, such as pH of the solution (3–8), adsorbent dosage (10–100 mg), temperature (25–45°C), contact time (5–240 min), and initial MG concentrations (20–350 mg/L), for the elimination of the MG dye using Fe₃O₄@AJPL were optimized and found to be 7, 50 mg, 45°C, 120 min, and 150 mg/L, respectively. The nonlinear isotherm and kinetic studies exhibited a better fitting to second-order kinetic and Langmuir isotherm models, with a maximum monolayer adsorption capacity of 318.3 mg/g at 45°C, which was highly superior to the previously reported magnetic nanocomposite adsorbents. EDX analyses confirmed the presence of nitrogen on the Fe₃O₄@AJPL surface after MG adsorption. The calculated thermodynamic factors indicated endothermic and spontaneous processes. The desorption of MG dye from Fe₃O₄@AJPL was performed using a solution of 90% ethanol. Finally, it could be concluded that the designed Fe₃O₄@AJPL magnetic nanocomposite will be a cost-effective and promising adsorbent for the elimination of MG from aqueous media.

1. Introduction

Water pollution by organic wastes produced by human activities is considered as one of the most dangerous environmental problems which have threatened human health and other living organisms. Dyes are widely utilized in different industries such as pharmaceuticals, paper, plastics, leather, and textiles. Malachite green (MG) has been extensively used in various fields such as in food processing, textile, cosmetic, pharmaceutical, plastic, and paper industries [1]. MG is used in aquaculture industries due to its great fungicide and bactericidal efficacy. Thus, it is extremely toxic to humans, plants, and aquatic fauna [2, 3], and it can cause carcinogenesis damage to the kidney and liver [4, 5]. Due to the toxicity and carcinogenic effect of MG dye ions, their removal from the aqueous environment is highly demanded. Therefore, the removal of dyes such as MG from wastewaters or surface waters is mandatory for the protection of human health. Different techniques were developed by researchers for the dye removal from the wastewater including membrane [6], photodegradation [7, 8], oxidation [9], electrochemical [10] ion exchange [11], and adsorption methods [12–14]. Among these techniques, adsorption is a successful, effective, and economical technique that is used to eliminate dyes from the polluted water as compared to other techniques [15, 16].

Many adsorbent materials were obtained from natural materials such as chitosan [17] and alginate beads [18]; wastes of agricultural activities, for example, almond shell [19], garlic peel [20], coffee waste [21], sugarcane bagasse
The prepared adsorbent was applied for removal of dyes via chemical activation and in situ coprecipitation methods. Recently, it has been reported that biosorbent treated with H₂O₂ improved the capacity of dye adsorption from the solution since the H₂O₂ could increase oxygen-containing functional groups on the surface of the adsorbent and thus augment its capability to remove dyes from aqueous media [30, 31]. As we know, nonmagnetic material adsorbents suffer from the difficulty of isolation of adsorbate-loaded absorbents from aqueous media after the adsorption process due to their small particle size. To overcome this problem, the use of magnetism has been proposed by several researchers. Magnetite nanoparticles (Fe₃O₄) attract significant attention due to their unique large surface area, and these possess high saturation magnetization and can easily isolate toxic pollutants from aqueous solutions by using a magnet without using centrifugation and filtration compared to conventional adsorbents [32]. New economical, highly effective, and locally available biosorbents are still under development. Juniperus procera leaves are the most abundant plant in Saudi Arabia and many countries such as Lebanon, Bosnia, and Turkey [33–36]. Magnetic modification of low-cost absorbents such as Juniperus procera leaves (JPL) could lead to materials appropriate for environmental applications. After a thorough literature survey, we have concluded that there are no previous studies reporting the activation of Juniperus procera leaves with H₂O₂ to increase the oxygen-containing functional groups on its surface. To our best knowledge, this is the first work to report the synthesis of a Fe₃O₄-activated Juniperus procera leaf nanocomposite.

This study was aimed at synthesizing a new Fe₃O₄-activated Juniperus procera leaf nanocomposite (Fe₃O₄@AJPL) via chemical activation and in situ coprecipitation methods. The prepared adsorbent was applied for removal of dyes from aqueous media. The Fe₃O₄@AJPL adsorbent was characterized by SEM, EDX, TEM, XRD, TGA, FTIR, and BET surface area analysis. The impact of various parameters on the MG dye adsorption onto Fe₃O₄@AJPL adsorbent such as solution pH, adsorbent dosage, contact time, initial MG concentrations, and temperature was achieved. The isotherm and kinetic data were analyzed by applying nonlinear equation models. Thermodynamic factors were also calculated.

2. Experiments

2.1. Chemicals and Instrumentation. Malachite green (MG), hydrogen peroxide (H₂O₂, 30%), ferric chloride (FeCl₃·6H₂O, 97%), ethanol (C₂H₅OH, 99.8%), and ferrous chloride (FeCl₂·4H₂O, 98%) were procured from Sigma Aldrich. Nitric acid (HNO₃, 68.0–70.0%) sodium hydroxide (NaOH, ≥97%), and hydrochloric acid (HCl, 36%) were procured from BDH, England. Solutions were prepared using deionized water. The crystalline structures of AJPL, Fe₃O₄, and Fe₃O₄@AJPL were determined using an XRD-6000 (Shimadzu, Kyoto, Japan). The morphological properties of AJPL, Fe₃O₄, Fe₃O₄@AJPL, and Fe₃O₄@AJPL-MG were evaluated using a transmission electron microscope (TEM) and scanning electron microscope (SEM) (JEOL 200 kV, Tokyo, Japan). Fourier transform infrared spectra of activated Juniperus procera leaves (AJPL), Fe₃O₄@AJPL, and MG-saturated Fe₃O₄@AJPL (Fe₃O₄@AJPL-MG) were recorded using a Nicolet iS50, Thermo Scientific (Madison, WI, USA). The elemental composition of adsorbents was detected by energy-dispersive X-ray (EDX) (JEOL 7600F, Tokyo, Japan). The surface area of Fe₃O₄@AJPL was evaluated through the determination of N₂ adsorption-desorption isotherms at −196°C by Micromeritics (USA). The concentration of MG was determined using a UV-visible spectrophotometer (Shimadzu 2450) at 616 nm.

2.2. Chemical Treatment of Juniperus procera Leaves. Juniperus procera leaves (JPL) were collected from Al Baha Province, Saudi Arabia. The leaves were washed with distilled water and dried for 7 days at room temperature (22–27°C) and ground using an electrical grinder. To increase oxygen-containing functional groups on the JPL surface, the JPL was treated with H₂O₂ by using the reported methods [30, 31]. Briefly, 50 g of the obtained JPL powder was immersed in 200 mL of 10% H₂O₂ and stirred for 24 h. Then, the sample was filtered off and was washed several times with deionized water. Following, 20 g of the AJPL powder was added into 200 mL of 1 M NaOH for removal of the impurities from the surface of JPL powder, resulting in improvement of the surface roughness of particles, formation of a pore structure, and opening of more hydroxyl groups and other reactive functional groups on its surface. Therefore, the removal of surface impurities can improve the adsorption properties of the JPL powder [37, 38]. The JPL powder was stirred for 24 h at 25°C. The resulting AJPL powder was washed with D.I. water and dried at 25°C for 3 days. Finally, the AJPL-obtained material was ground again to obtain a uniform particle size (Figure 1).

2.3. Magnetization of Juniperus procera Leaves (Fe₃O₄@AJPL). The magnetization of AJPL powder was performed using the in situ coprecipitation method. Briefly, in a three-necked round bottom flask containing 90 mL D.I. water, 1.5 g of AJPL powder was suspended. To this mixture, 0.71 g of FeCl₃·6H₂O, and 2.15 g of FeCl₂·4H₂O (Fe²⁺:Fe³⁺=1:2 molar ratio) were added and mechanically stirred for 20 min and heated to 80°C, and then, 10 mL of NH₃·OH was added dropwise over a period of 2 hrs. The obtained
black precipitate (termed Fe₃O₄@AJPL) was collected by external magnetic field and washed with ethanol and D.I. water. Finally, the Fe₃O₄@AJPL was dried at 60 °C for 24 h. Figure 1 demonstrates the preparation scheme of the Fe₃O₄@AJPL nanocomposite.

2.4. Adsorption Studies. The batch experiment method was conducted to select the best parameters for the adsorption process. The impact of adsorption parameters on MG dye adsorption by Fe₃O₄@AJPL adsorbents including adsorbent dosage (10–100 mg), pH (3–8), temperature (25–45 °C), contact time (5–240 min), and initial MG dye concentration (20–350 mg/L) was achieved. The general procedure was as follows: the desired quantity of Fe₃O₄@AJPL adsorbents was taken in a 250 mL Erlenmeyer flask containing a 50 mL solution of MG with a given concentration, and then, the sample solution pH was adjusted using a 0.1 M HCl or 0.1 M NaOH to the desired pH. Then, the sample solution was shaken at 100 rpm for a specific time. After that, the sample was separated using a magnet, and the residual MG concentration was measured using a UV/Vis spectrophotometer at 616 nm. The adsorption efficiency (Rₑ, %) and adsorbent capacity (qₑ, mg/g) were determined according to the following equations, respectively:

\[ Rₑ (%) = \frac{C₀ - Cₑ}{C₀} \times 100, \]  
\[ qₑ = \frac{(C₀ - Cₑ)}{m} \times V, \]

where \( C₀ \) (mg/L) and \( Cₑ \) (mg/L) represent the initial and equilibrium concentrations of MG, respectively; \( m \) is the amount of Fe₃O₄@AJPL adsorbents (g); and \( V \) (L) is the solution volume. For the desorption study, the separated adsorbent was placed into 50 mL of 90% ethanol or HCl (0.1 M) and HNO₃ (0.1 M) solution. Then, the sample solution was shaken at 100 rpm for 120 min. After that, the MG dye concentrations of the sample isolated with a magnet were determined using a UV/Vis spectrophotometer at 616 nm. The % desorption was calculated by using the following equation:

\[ \% \text{desorption} = \frac{\text{Concentration of MG desorbed by the ethanol}}{\text{Initial concentration of MG adsorbed on Fe₃O₄@AJPL}} \times 100. \]

3. Results and Discussion

3.1. Synthesis and Characterization of Fe₃O₄@AJPL. Juniperus procera leaves (JPL) were activated by using H₂O₂ and NaOH reagent. H₂O₂ is a strong oxidant, inexpensive, and clean. The use of H₂O₂ and NaOH is important to increase oxygen-containing functional groups on the JPL surface and improve the adsorption properties of JPL powder by removing the impurities from the surface of the JPL powder. AJPL carries hydroxyl, carboxyl, and carbonyl groups. Activated Juniperus procera leaves were successfully converted to the magnetized activated Juniperus procera leaves (Fe₃O₄@AJPL) via in situ coprecipitation. Fe₃O₄@AJPL has the ability to separate MG dye from aqueous solutions by using an external magnetic field, and it has a large surface area (116.9517 m²/g) and pore size (9.48 nm). It can easily separate the MG dye from aqueous solutions by using an external magnetic field. The Fe₃O₄@AJPL nanocomposite contains different functional groups (COOH, HOOC, COO–) as shown in the schematic diagram.
OH, C=O) which can adsorb MG ions by for π-π stacking, H-bonding, and electrostatic attraction (Figure 1).

Figure 2(a) displays the FTIR of AJPL, Fe₃O₄@AJPL before adsorption, and MG-saturated Fe₃O₄@AJPL (Fe₃O₄@AJPL-MG) adsorbent. In the spectrum of AJPL, the broad band centered at 3320 cm⁻¹ is attributed to the OH group, suggesting the presence of a phenolic group [39]. The bands at 1731 and 1606 cm⁻¹ ascribed to C=O and the one at 1026 cm⁻¹ corresponding to C-O-C groups indicate the existence of carboxylic acid derivatives. Furthermore, the observed band of C=C stretching vibration at 1549 cm⁻¹ as well as the C-H out-of-plane bending vibrations at 776 cm⁻¹ is possibly characterizing the aromatic rings. Additional peaks of CH modes were also identified, e.g., at about 2943 cm⁻¹. In the spectrum of Fe₃O₄@AJPL, a new band at 560 cm⁻¹ assigned to the distinctive band of Fe-O stretching vibration was observed, confirming the presence of Fe₃O₄ nanoparticles [40, 41]. Moreover, it is observed that the modification of AJPL with Fe₃O₄ nanoparticles has resulted in intensity reduction of some characteristic peaks including the OH and C-O-C peaks. The spectra of the MG-loaded Fe₃O₄@AJPL showed shifts in the bands of
some functional groups such as C=O, OH, and C-O-C from 1731, 3320, and 1026 cm$^{-1}$ to 1721, 3329, and 1023 cm$^{-1}$, respectively, due to adsorptive interaction.

Figure 2(b) shows the XRD pattern of AJPL, Fe$_3$O$_4$ nanoparticles, and Fe$_3$O$_4$@AJPL nanocomposite. As implied in Figure 2(b), the characteristic peaks of Fe$_3$O$_4$ nanoparticles and the Fe$_3$O$_4$@AJPL nanocomposite perfectly matched the face-centered cubic crystalline which was confirmed by 2θ values of 30.24°, 35.56°, 43.22°, 57.11°, and 62.76° to (220), (311), (400), (511), and (440) planes, respectively [42]. The diffraction peaks for AJPL are 13.45°, 14.83°, 21.2°, 24.29°, 30.02°, 35.8°, and 38.15°. After modification of magnetite nanoparticles with AJPL, new peaks appeared at 2θ = 14.9° and 27.02° which matched to the strong peaks in the XRD pattern of leaves [43]. Therefore, these results indicated that the Fe$_3$O$_4$@AJPL nanocomposite was successfully synthesized.

Figure 2(c) displays the N$_2$ adsorption/desorption isotherms of Fe$_3$O$_4$ nanoparticles and the Fe$_3$O$_4$@AJPL nanocomposite. The surface area, pore volume, and pore size were found to be 116.9517 m$^2$/g, 0.322 cm$^3$/g, and 9.48 nm for Fe$_3$O$_4$ nanoparticles and 38.44 m$^2$/g, 0.136 cm$^3$/g, and 10.6 nm for the Fe$_3$O$_4$@AJPL nanocomposite. The N$_2$ adsorption/desorption curve of both adsorbents exhibited a type IV isotherm, suggesting the presence of mesopores in both adsorbents.

Figure 2(d) shows thermogravimetric analysis (TGA) of Fe$_3$O$_4$ and Fe$_3$O$_4$@AJPL. In the case of Fe$_3$O$_4$, about 10% is the total weight loss in the temperature range from 25°C to 1000°C due to the removal of the adsorbed water and conversion of hydroxide to oxide [44]. In the case of the Fe$_3$O$_4$@AJPL nanocomposite, it is a three-stage thermal degradation. The first stage from 25–180°C (3%) is related to the loss of moisture and adsorbed water. 7% and 50% weight loss were observed between the temperature ranges 180–320°C and 320–800°C in the second and third stages, respectively, due to decomposition of molecular organic compounds such as flavonoids of JPL in Fe$_3$O$_4$@AJPL [45]. The total weight losses of Fe$_3$O$_4$@AJPL and pure magnetite nanoparticles were 60% and 10%, respectively, which confirmed the formation of the Fe$_3$O$_4$@AJPL nanocomposite.

Figure 3 shows the SEM-EDX image results of the AJPL powder, Fe$_3$O$_4$, Fe$_3$O$_4$@AJPL, and MG dye-saturated Fe$_3$O$_4$@AJPL adsorbents. The surface structure of the AJPL powder is rough with the existence of some pore and crack sites (Figure 3(a)). After modifying the AJPL powder with magnetite nanoparticles, the magnetite nanoparticles are dispersed in the surface of AJPL (Figure 3(c)). The surface of Fe$_3$O$_4$ nanoparticles shows a spherical shape with diameters in the range of 12–25 nm (Figure 3(e)). The SEM image of the Fe$_3$O$_4$@AJPL loading MG showed a different morphology than before adsorption, which was well occupied with the MG dye as implied in Figure 3(g), indicating that the MG dye was successfully adsorbed on the Fe$_3$O$_4$@AJPL adsorbent. The EDX of the AJPL powder (Figure 3(h)) revealed the presence of mainly C (30.68%) and O (30.50%) and small amounts of Ca, Al, K, and Si. After modifying AJPL with magnetite nanoparticles, it was clearly observed that a new peak from iron (45.33%) appeared and increased in the intensity of oxygen (38.27%), confirming the synthesis of Fe$_3$O$_4$@AJPL successfully (Figure 3(d)). 65.32% of iron and 34.68% of oxygen were observed in the EDX spectrum of pure magnetite nanoparticles (Figure 3(e)). After MG dye was saturated on the Fe$_3$O$_4$@AJPL nanocomposite, a new peak of nitrogen was observed, indicating the successful adsorption of MG dye on the Fe$_3$O$_4$@AJPL adsorbent Figure 3(h). Figure 4(a) displays the TEM images of Fe$_3$O$_4$@AJPL nanocomposite. A small degree of agglomeration with a spherical shape was observed. The particle size was found to be 9 nm Figure 4(b). Figure 4(c) displays the lattice fringe spacing of the crystalline part (Fe$_3$O$_4$) of the Fe$_3$O$_4$@AJPL nanocomposite. The d spacing values were 0.291 nm and 0.252 nm, which are attributed to the (311) and (220) planes of Fe$_3$O$_4$ nanoparticles which were confirmed by the XRD results for the cubic structure of Fe$_3$O$_4$ nanoparticles. The selected area electron diffraction (SAED) analysis shows a ring pattern which confirms the presence of crystalline Fe$_3$O$_4$ nanoparticles in the nanocomposites (Fe$_3$O$_4$@AJPL) (Figure 4(c)).

3.2. Adsorption Studies

3.2.1. Adsorbate Selectivity. The prepared adsorbents AJPL and Fe$_3$O$_4$@AJPL nanocomposite were examined for elimination of different cationic dyes such as MG, CV, and MB from aqueous solutions as implied in Table 1. It was noticed that, at the adsorption conditions of adsorbent dose 50 mg, initial adsorbate concentration (C$_0$) of 50 mg/L, and temperature of 25°C, the maximum removal efficiency of MG, CV, and MB dyes on both AJPL and Fe$_3$O$_4$@AJPL nanocomposite adsorbent were 98.76%, 94.81%, and 93.20% and 99.15%, 95.61%, and 73.11%, respectively. Accordingly, the removal of MG by the Fe$_3$O$_4$@AJPL adsorbent is considerably favored due to the high performance, easy separation, and recovery of the adsorbent using external magnetism. Thus, the adsorption parameters were further studied.

3.2.2. Effect of pH. The impact of the solution pH on MG adsorption onto Fe$_3$O$_4$@AJPL was tested over a range of pH values from 3 to 8 (MG: 20 mg/L, contact time: 24 h, adsorbent dose: 50 mg, temperature: 25°C, and agitation: 100 rpm) as shown in Figure 5(a). The results indicate an increase in the adsorption capacity and removal percentage with increase in pH up to pH 7. This increase in adsorption capacity was due to the surface charge of Fe$_3$O$_4$@AJPL nanocomposites becoming more negative and having strong electrostatic attraction with the cationic MG dye, resulting in higher adsorption efficiency. On the contrary, under an acidic medium, the excessive protonation of the Fe$_3$O$_4$@AJPL nanocomposite surface hindered the binding of cationic MG ions on the Fe$_3$O$_4$@AJPL nanocomposite surface, resulting in a lower adsorption efficiency [46]. Similar trends have been reported by Asfaram et al. for the removal of MG using biosorbent Yarrowia lipolytica ISF7 [47]. Compared with pH 7, an almost similar performance was observed at pH 8 above which the solution becomes colorless due to the reaction occurrence between the MG and...
Figure 3: (a) SEM image, (b) EDX analysis of activated Juniperus procera leaves (AJPL), (c) SEM image, (d) EDX analysis of Fe\textsubscript{3}O\textsubscript{4}@AJPL, (e) SEM images, (f) EDX analysis of magnetite nanoparticles, (g) SEM image, and (h) EDX analysis of MG adsorption onto Fe\textsubscript{3}O\textsubscript{4}@AJPL.
3.2.3. Effect of Contact Time. The impact of the contact time on the MG adsorption by Fe$_3$O$_4$@AJPL was achieved over the time interval of 5–240 min under fixed conditions (MG: 20 mg/L, pH: 7, temperature: 25°C dose: 50 mg, and agitation: 100 rpm) (Figure 5(b)). At an initial period of 15 min, the adsorption rate was high with $R_e$ (%) and $q_e$ values of 85.7% and 17.14 mg/g, respectively. The initial rapid rate may indicate the existence of available active sites on the Fe$_3$O$_4$@AJPL surface. After 15 min, the adsorption was gradually increased with time, reaching the equilibrium, after 120 min, at which the $q_e$ and $R_e$ (%) were 18.32 mg/g and 91.6% at 120 min, respectively. Thus, the optimized equilibrium time for the work was 120 min. Compared with the literature, this equilibrium time is better than the ones previously reported by Pan et al. [48] and Gao et al. [50].

3.2.4. Effect of Dosage. The impact of the adsorbent dosage on the removal efficiency and adsorption capacity was tested in the range 10–100 mg under the following conditions: MG: 20 mg/L, pH: 7, contact time: 120 min, agitation: 100 rpm, and temperature: 25°C. As shown in Figure 5(c), the $R_e$ (%) value was slightly improved from 94.3% to 99.1% with the gradual rise in the amount of Fe$_3$O$_4$@AJPL adsorbent from 10 to 50 mg; however, the capacity ($q_e$) was reduced. These results can be assigned to increased active sites at a
high adsorbent dose [51, 52]. However, no significant increase in the adsorption efficiency above the 50 mg dose was observed. Moreover, the drop in the adsorption capacity is due to the aggregation events at a high dosage which lead to a decrease in the total surface area of the Fe₃O₄@JPL adsorbent. These outcomes are consistent with the results of the literature reported in [53]. As a result, under the examined condition, the optimal adsorbent dose was 50 mg.

3.2.5. Effect of Initial Concentration and Temperatures. The adsorption capacities of the Fe₃O₄@AJPAL adsorbent at different initial MG concentrations (20–350 mg/L) and temperatures (25, 35, and 45°C) were also studied, keeping other factors (time: 120 min, pH: 7, dose: 50 mg, and agitation: 100 rpm) as given in Figure 5(d). The outcomes show that the adsorbed amount of MG dye by Fe₃O₄@AJPAL was linearly increased while the initial MG concentration increased, e.g., as Cₒ was augmented from 20 to 350 mg/L, the adsorption capacity improved from 18.5 to 201.2 mg/g at 25°C. Such results can be ascribed to the increment in the driving force of the adsorbate concentration, resulting in a high diffusion rate of the MG dye from the liquid phase to the solid phase. At the higher Cₒ and at 45°C, the archived qₑ value was 258.6 mg/g. Also, the adsorption capacity was increased from 18.5 to 20 mg/g with increasing temperature from 25°C to 45°C at 20 mg/L. This increase in adsorption capacity is possibly due to diffusion enhancement of MG molecules to the surface and pores of Fe₃O₄@AJPAL which is driven by
3.3. Adsorption Modeling

3.3.1. Adsorption Isotherm. The adsorption isotherm studies were accomplished over a range of MG initial concentrations of 20–350 mg/L and at temperatures of 25, 35, and 45°C, keeping the other factors constants (i.e., adsorbent dose: 50 mg, pH: 7, contact time: 120 min, and agitation speed: 100 rpm). Nonlinear isotherm adsorption models such as Langmuir (Equation (4)) [56] and Freundlich (Equation (5)) [57] were applied to describe the behavior of the MG adsorption onto Fe₃O₄@AJPAL.

\[
q_e = \frac{q_m K_L C_e}{1 + K_L C_e}, \quad (4)
\]

\[
q_e = K_F C_e^{1/n}, \quad (5)
\]

where \(q_m\) is the maximum adsorption capacity (mg/g), \(n\) is the adsorption intensity, \(K_F\) is the Freundlich isotherm constants, and \(K_L\) is the Langmuir constant. According to the isotherm data shown in Figure 6(a) and Table 2, it is clear that the Langmuir model \(R^2 = 0.989\) provided a better fit than the Freundlich one \(R^2 = 0.929\), suggesting monolayer coverage. The adsorbent capacity corresponding to the maximum monolayer coverage \(q_m\) mg/g was 318.3 mg/g at 45°C. The separation factor \(R_L\) values during the work were found in favorable adsorption \(R_L < 1\) (i.e., 0.026, 0.040, and 0.052 at 298, 308, and 318 K). Moreover, the increase in the values of the \(K_F\) and \(K_L\) constants with temperature confirmed endothermic adsorption [58, 59].

3.3.2. Kinetic Adsorption. The adsorption mechanism was achieved using the nonlinear kinetic models and pseudo-first-order (PFO) and pseudo-second-order models described by the following equations:

\[
q_t = q_e \left( 1 - e^{-k_1 t} \right), \quad (6)
\]

\[
q_t = \frac{q_e^2 k_2 t}{1 + q_e k_2 t}, \quad (7)
\]

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where $q_c$ (mg/g) is the adsorption capacity at time $t$ (min) and $k_1$ and $k_2$ are the rate constants of PFO and PSO, respectively. Figure 6(b) displays the kinetic plots for the MG adsorption onto Fe$_3$O$_4$@AJPAL. It was observed that adsorption was fast in the first stage of the adsorption period (20 min), then slowly developed until equilibrium (120 min). The calculated kinetic parameters are given in Table 3. On the basis of $R^2$ values, the adsorption kinetics fit PSO ($R^2 = 0.998$) better than the PFO ($R^2 = 0.991$), suggesting that the adsorption of MG onto Fe$_3$O$_4$@AJPAL occurred by the chemisorption mechanism. Moreover, the $q_{e,\text{cal}}$, calculated according to the PSO kinetic model ($q_{e,\text{cal}} = 18.36$ mg/g), was closer to the experimental
value ($q_{\text{exp}} = 18.35 \text{ mg/g}$), supporting the PSO model. Similar trends have been reported by other adsorbents [60, 61].

### 3.3.3 Adsorption Thermodynamics

The adsorption thermodynamic factors such as the Gibbs free energy ($\Delta G^\circ$), entropy ($\Delta S^\circ$), and enthalpy ($\Delta H^\circ$) for the removal of the MG dye onto the Fe$_3$O$_4$@AJPL nanocomposite were calculated using Equation (8) and the van’t Hoff equation (Equation (9)) [62]:

$$
\Delta G^\circ = -RT \ln K_c,
$$

(8)

$$
\ln K_c = \frac{-\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R},
$$

(9)

where $R$ is gas constant (8.314 J/mol·K) and $K_c$ represents the equilibrium constant and its equal $q_c / C_c$ [63]; the other notations have the same meaning as above.

Figure 7(a) and Table 4 summarize the data obtained. The value of $\Delta G^\circ$ obtained was negative, indicating that the adsorption of MG onto Fe$_3$O$_4$@AJPL is spontaneous. The positive values of $\Delta H^\circ$ and $\Delta S^\circ$ indicate the endothermic process and increase in randomness during the adsorption process, respectively. The temperature-dependent $\Delta G^\circ$ revealed favorable adsorption at higher temperature; however, the effect of the initial concentration of MG suggests better adsorption at a lower concentration. Additionally, the value of $\Delta H^\circ > 40 \text{ kJ/mol}$ at a low concentration means that the mechanism of MG adsorption is chemisorption. Therefore, at the examined adsorption conditions, the obtained $\Delta G^\circ$ and $\Delta H^\circ$ values suggest physical and chemical adsorption mechanisms, respectively [64]. Similar trends have been reported by Arabkhani et al. for the removal of MG using the GO/MMT polymer nanocomposite [65].

### 3.4 Adsorption Mechanism

Figure 1 shows the stepwise preparation of the adsorbent Fe$_3$O$_4$@AJPL and the proposed adsorption mechanism. According to the FTIR spectrum, after MG dye adsorption on the Fe$_3$O$_4$@AJPL nanocomposite, there was a decrease and shift in the peak intensities of the functional groups, it was observed that the peaks at 3320 cm$^{-1}$, 1721 cm$^{-1}$, and 1026 cm$^{-1}$ decrease and shift to 3329 cm$^{-1}$, 1721 cm$^{-1}$, and 1023 cm$^{-1}$, respectively, due to adsorptive interaction between the MG dye and the COOH, OH, and C-O-C groups on the Fe$_3$O$_4$@AJPL surface by different mechanisms such as hydrogen bonding, $\pi-\pi$ stacking, and electrostatic interaction. The nonlinear isotherm and kinetic adsorption studies exhibited a better fit to P50 kinetic and Langmuir isotherm models, indicating chemisorption adsorption. Additionally, the weak desorption efficiency of MG from the Fe$_3$O$_4$@AJPL surface confirms the chemisorption mechanism. It was observed that adsorption of MG onto Fe$_3$O$_4$@AJPL was fast in the first stage of the adsorption period (15 min) then slowly developed until equilibrium (120 min). The initial rapid rate may indicate existence of available active sites on the Fe$_3$O$_4$@AJPL surface. Furthermore, the data indicate that more than 85.7% of MG molecules were adsorbed in the first stage, supporting the chemical adsorption mechanism. However, the first stage cannot be recognized, and the slow rate in the second adsorption phase suggests a physical mechanism, which is possibly controlled by the diffusion process. On the other hand, the thermodynamic data support the physisorption mechanism. Therefore, it could be concluded that the MG adsorption on Fe$_3$O$_4$@AJPL occurred by physical adsorption together with the chemisorption process. The EDX analysis clearly shows a new peak of nitrogen along with the peaks of elements of the Fe$_3$O$_4$@AJPL nanocomposite, indicating MG adsorption onto the whole surface of the Fe$_3$O$_4$@AJPL adsorbent.

### 3.5 Comparative Performance of Fe$_3$O$_4$@AJPL with Other Adsorbents

For comparative purposes, the maximum

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**Table 4: Thermodynamic factors for adsorption of MG on Fe$_3$O$_4$@AJPL (conditions: time—120 min, Fe$_3$O$_4$@AJPL—50 mg, volume—0.05 L, pH—7, and agitation—100 rpm).**

<table>
<thead>
<tr>
<th>Concentration MG dye</th>
<th>$\Delta H^\circ$ (kJ/mol)</th>
<th>$\Delta S^\circ$ (J/mol·K)</th>
<th>298 K</th>
<th>308 K</th>
<th>318 K</th>
<th>$\Delta G^\circ$ (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>40.12</td>
<td>151.2</td>
<td>5.095</td>
<td>6.192</td>
<td>8.139</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>50.10</td>
<td>180.7</td>
<td>3.998</td>
<td>5.065</td>
<td>7.646</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>27.69</td>
<td>106.0</td>
<td>3.716</td>
<td>5.342</td>
<td>5.811</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5: Comparison of the MG adsorption capacity of Fe$_3$O$_4$@AJPL nanocomposite with other magnetic adsorbents.**

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Conditions</th>
<th>$q_m$ (mg/g)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNT-Fe$_3$O$_4$</td>
<td>$C_o$: 40-120 mg/L; $T$: 298 K; pH: 8; time: 240 min; dose: 150 mg</td>
<td>44.25</td>
<td>[49]</td>
</tr>
<tr>
<td>A litchi peel-based magnetic</td>
<td>$C_o$: 150 mg/L; $pH$: 6; $T$: 298 K; dose: 5.14 g/L; time: 66.69 min</td>
<td>70.42</td>
<td>[66]</td>
</tr>
<tr>
<td>PDA/CS/Fe$_3$O$_4$</td>
<td>$C_o$: 5-200 mg/L; $T$: 303 K; pH: 8; time: 40 min; dose: 100 mg</td>
<td>60.97</td>
<td>[67]</td>
</tr>
<tr>
<td>Magnetic pectin-Chlorella vulgaris</td>
<td>$C_o$: 5-100 mg/L; $T$: 303 K; dose: 50 mg; time: 30 min</td>
<td>247.2</td>
<td>[68]</td>
</tr>
<tr>
<td>3-MPA@PMNPs</td>
<td>$C_o$: 25 mg/L; $T$: 298 K; $pH$: 6; time: 120 min; dose: 500 mg</td>
<td>81.2</td>
<td>[69]</td>
</tr>
<tr>
<td>Fe$_3$O$_4$@AMCA-MIL-53 (Al)</td>
<td>$C_o$: 25-400 mg/L; $T$: 298 K; $pH$: 6.8; time: 210 min; dose: 20 mg</td>
<td>262.52</td>
<td>[70]</td>
</tr>
<tr>
<td>Fe$_3$O$_4$@AJPL</td>
<td>$C_o$: 25-350 mg/L; $T$: 318 K; $pH$: 7; time: 120 min; dose: 50 mg</td>
<td>318.3</td>
<td>This study</td>
</tr>
</tbody>
</table>
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adsorption capacity, \(q_m\), of some other adsorbents reported in the literature for the MG uptake are given in Table 5 [49, 66–70]; the adsorption conditions are also tabulated for easy comparison. Obviously, the \(q_m\) value of \(\text{Fe}_3\text{O}_4@\text{AJPL}\) (318.3 mg/g) for MG adsorption is greater than the other listed magnetic nanocomposite adsorbents. The difference in the efficiencies of various adsorbents is due to the diversity in the adsorbent’s structures and morphologies. Hence, the characteristics and performance of the investigated adsorbent, \(\text{Fe}_3\text{O}_4@\text{AJPL}\), support its being appropriate as a potential adsorbent for the removal of cationic pollutants such as MG from polluted aqueous systems.

3.6. Desorption and Reusability Studies. To recover the MG dye from the \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite, three eluents, 0.1 M HCl, 0.1 M HNO\(_3\), and ethanol (90%), were used (Figure 7(b)). From the results, it was observed that the recovery performance of ethanol was the highest (50.77%), while the acidic eluents (HCl and HNO\(_3\)) used showed only negligible efficiencies toward MG elution. The low recovery efficiency of MG from the \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite surface using ethanol indicates that most of the MG adsorption was probably by chemisorption. The outcomes of the kinetic and isotherm adsorption confirm the chemical adsorption mechanisms. The regeneration efficiency after two cycles was also examined. The result revealed that the adsorption efficiency of the MG dye on \(\text{Fe}_3\text{O}_4@\text{AJPL}\) was decreased from 89.5% to 58.2% as well as in the recovery percentage mostly due to incomplete desorption in the first cycle of the adsorption-desorption process as well as possible destruction of some active sites on the \(\text{Fe}_3\text{O}_4@\text{AJPL}\) surface.

4. Conclusion

In summary, a new magnetic nanocomposite (\(\text{Fe}_3\text{O}_4@\text{AJPL}\)) adsorbent was successfully synthesized via chemical activation of JPL and in situ coprecipitation with \(\text{Fe}_3\text{O}_4\). The \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite was applied for the removal of the MG dye from aqueous solutions. The \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite was analyzed using different analytical techniques, and the results confirmed that the \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite was successfully synthesized. The surface area of the \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite was identified via BET analysis, and it is found to be 38.44 m\(^2\)/g. The \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite was tested to thoroughly clarify the influences of the factors on the adsorption of MG onto \(\text{Fe}_3\text{O}_4@\text{AJPL}\). The optimized adsorption factors were found to be pH: 7, contact time: 120 min, adsorbent dose: 50 mg, temperature: 45°C, and initial MG concentration: 150 mg/L. The adsorption kinetic and isotherm were revealed to be a better fit to the PSO kinetic and Langmuir isotherm models. The maximum monolayer adsorption capacity was 318.3 mg/g at 45°C, which was greater than magnetic nanocomposite adsorbents reported previously. The thermodynamic studies indicated that the adsorption of MG onto \(\text{Fe}_3\text{O}_4@\text{AJPL}\) is a spontaneous and endothermic process. The interaction between the \(\text{Fe}_3\text{O}_4@\text{AJPL}\) nanocomposite and the MG dye occurred by chemisorption and physisorption that can be achieved by H-bonding, \(\pi-\pi\) interactions, and electrostatic attractions. The recovery results indicated that ethanol was the best eluent among the all the tested eluents. Overall, it could be concluded that the prepared \(\text{Fe}_3\text{O}_4@\text{AJPL}\) adsorbent will be a promising adsorbent for the elimination of MG dye from aqueous solutions.

Data Availability

Anyone who wants to request research article data can contact me directly via the following email: aalorabi@bu.edu.sa, Chemistry Department, College of Science, Al Baha University.

Conflicts of Interest

There are no conflicts to declare.

Acknowledgments

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