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Modifying the Surface of Silica-Coated Magnesium Cobalt Ferrite with Curcumin to Eliminate Pb(II) and Cd(II) from Different Environmental Water Samples

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Abstract

Water contamination is a crucial ecological concern impacting aquatic ecosystems and human health, particularly because of heavy metals entering water bodies from the industrial, agricultural, and mining activities. To address this, magnesium-doped cobalt ferrite nanoparticles ($\text{MgCoFe}_2\text{O}_4@\text{SiO}_2\text{-CPTMS-Cur}$) were expanded for effective heavy metal removal from wastewater. These nanoparticles were made initially through coprecipitation technique and then were coated with silica and modified with 3-chloropropyltrimethoxysilane (CPTMS) and curcumin (Cur) to improve the adsorption capabilities. The as-synthesized product was fully characterized by FTIR, EDX, XRD, TEM SEM, BET, TGA and VSM, showing a crystalline structure and a porous surface with a BET surface area of 24.176 m²/g. The adsorption experiments showed an effective removal of Lead Pb(II) and Cadmium Cd(II), with maximum abilities of 259.50 mg/g for Pb(II) and 208.35 mg/g for Cd(II). Kinetic testing revealed that the adsorption followed a second-order kinetic model, despite the Langmuir isotherm model accurately representing the equilibrium data. The adsorption process was endothermic, spontaneous, and beneficial, according to thermodynamic study. Research on regeneration demonstrated the durability and reusability of the composite over four cycles, highlighting its promise as a frugal and operative adsorbent for the extraction of heavy metals in environmental cleanup. The effective removal of Pb(II) and Cd(II) metal ions from tap, groundwater, and lake water was achieved utilizing this innovative adsorbent.

Keywords: Curcumin, Magnesium-doped cobalt ferrite nanoparticles, Metal ions, Adsorption, kinetics, isotherms, Real water treatment.

1 Introduction

Water is one of the most vital natural resources on Earth. It is possible for heavy metal ions to enter the food chain through biological sequestration in the environment. Consequently, the pollution of water due to industrial waste laden with heavy metals has a considerable impact on human life (Hawezy et al., 2025). The introduction of heavy metals into water bodies is a global concern. Heavy metals are common in the flow of waste water and form an important toxic combination (Iqbal et al., 2023). One of the most important Earth's natural resources is water. It is possible for heavy metal ions to enter the food chain through biological sequestration in the environment. Therefore, the contamination of water by heavy metal-laden manufacturing waste has a significant effect on human existence (ChizariFard et al., 2022).

On the basis of different classical heavy metals, cadmium (Cd^{2+}) and lead (Pb^{2+}) are considered highly toxic. Their contamination of soil, surface water, and groundwater could lead to environmental and health issues. The World Health Organization states that the acceptable levels of Pb^{2+} and Cd^{2+} in drinking water are 0.01 and 0.05 mg/L, respectively. For example, Pb^{2+} accumulation within the body causes adverse effects, including reduced male sperm production and cognitive repercussions, particularly for minors. It significantly impacts the gastrointestinal and hematopoietic systems and causes renal problems (Khorram Abadi et al., 2023).

Magnetic NPs (MNPs) form a rapidly advancing group of materials. The atypical attributes of MNPs, notably superparamagnetism, are vital for various uses in biology, environmental restoration, and electron imaging. With their elevated surface-to-volume ratios and quantum implications, they typically range in dimensions from 1 nm to 100 nm, opening up modern uses that are not possible with bulk materials (Chand & Vasquez-Guardado, 2025). Magnetic nanoparticles (NPs) are of considerable interest in a variety of fields of science, such as medicine, physics and biology are unique in their properties (Mokhosi et al., 2019).

Cobalt ferrites, a type of spine ferrite, are highly regarded in research due to their exceptional electrical and magnetic characteristics, making them ideal for many applications including information storage, sensors, telecommunications, and microwave technology (Mohanty et al., 2021). The introduction of non-magnetic magnesium ions (Mg(II)) into CoFe_2O_4 can profoundly alter its attributes, yielding remarkable features such as improved conductivity at grain boundaries, heightened porosity, superior magnetic properties, and captivating dielectric characteristics (Mondal et al., 2024).

Dendrimer polymer-modified $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles are produced. Subsequently, the synthesized nanoparticles were worked for the extraction of $\text{Cu}()$ ions in aqueous solutions. 99.7 mg/g was found to be the maximal adsorption capability (Zarabadipour et al., 2025). In a separate study, nickel (Ni^{2+}) ions were extracted from a liquid solution using the $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -DTPMP nano-adsorbent. The highest adsorption capacity recorded for this nano-adsorbent was 8.56 mg/g concerning (Ni^{2+}) ions (Donga et al., 2025).

Heavy metal ions have been extracted from water and wastewater samples in recent years using a range of methods, like biological absorption, membrane separation, filtration, adsorption, ion exchange, and reverse osmosis. The techniques of adsorption have received considerable focus owing to the affordability of adsorbent fabrication, the versatility of utilizing diverse biocompatible substances, and their effectiveness in extracting minimal amounts of metal ions (Zarabadipour et al., 2025). Furthermore, the use of magnetic adsorbents has appeared as a straightforward and efficient tactic without the production of secondary pollutants and with high efficiency (Elkholy et al., 2025).

The novelty of this paper is to synthesize CoFe_2O_4 nanoparticles with magnesium doped using a simple, cheap and friendly co-precipitation method. Then, the nanomagnetic particles are coated with a silica layer, resulting in the creation of a core-shell nanostructure. Subsequently, the nanostructure is functionalized with CPTMS. Subsequently, the magnetic material was modified with Curcumin (Cur). The isotherm for the adsorption model was ascertained through the assessment of the adsorption process utilizing isothermal models like Langmuir, Freundlich, and Temkin. Additionally, adsorption in batches trials were executed to identify the optimal circumstances for parameters like pH, temperature, contact time, nano adsorbent dosage, and starting concentration to maximize the elimination efficiency of Pb(II) and Cd(II) . The kinetics and the potential for reuse have been rigorously investigated. In conclusion, the synthesized $\text{MgCF@SiO}_2\text{-CPTMS-Cur}$ nano-adsorbent was utilized for the elimination of Pb(II) and Cd(II) from wastewater.

2 Experimental

2.1 Chemicals and reagents

The reagents procured for commercial use were Merck ferric chloride (FeCl_3), magnesium chloride (MgCl_2), cobalt chloride (CoCl_2), tetraethyl orthosilicate (TEOS), trichloropropyl trimethoxysilane (CPTMS), ammonium hydroxide (28%), ethanol, curcumin, dimethyl sulfoxide (DMSO), and triethylamine (TEA). Cadmium Cd(II) and lead Pb(II) standards were procured from Sigma, and all materials and reagents were utilized as received. All substances were prepared utilizing deionized water.

2.2 Synthesis of $\text{MgCoFe}_2\text{O}_4$ (MgCF) NPs

The nanocrystalline $\text{MgCoFe}_2\text{O}_4$ was produced by the chemical co-precipitation method. The quantities of ferric chloride, cobalt chloride, and magnesium chloride were solubilized in 50 mL of deionized water with a precursor ratio of Fe:Co:Mg (1:0.5:0.1). The mixtures were agitated and the pH was incrementally modified with ammonia solution to a range of 11-12. The acquired solution was agitated and exposed to heat at 70-80 °C during one hour. The precipitate underwent washing with de-ionized water to eliminate contaminants and was subsequently dried overnight at 105 °C. The necessary phase formation was achieved by finely grinding and calcining the powders at 700 °C for four hours. The MgCF synthesis process using the coprecipitation approach is schematically represented in Fig. 1.

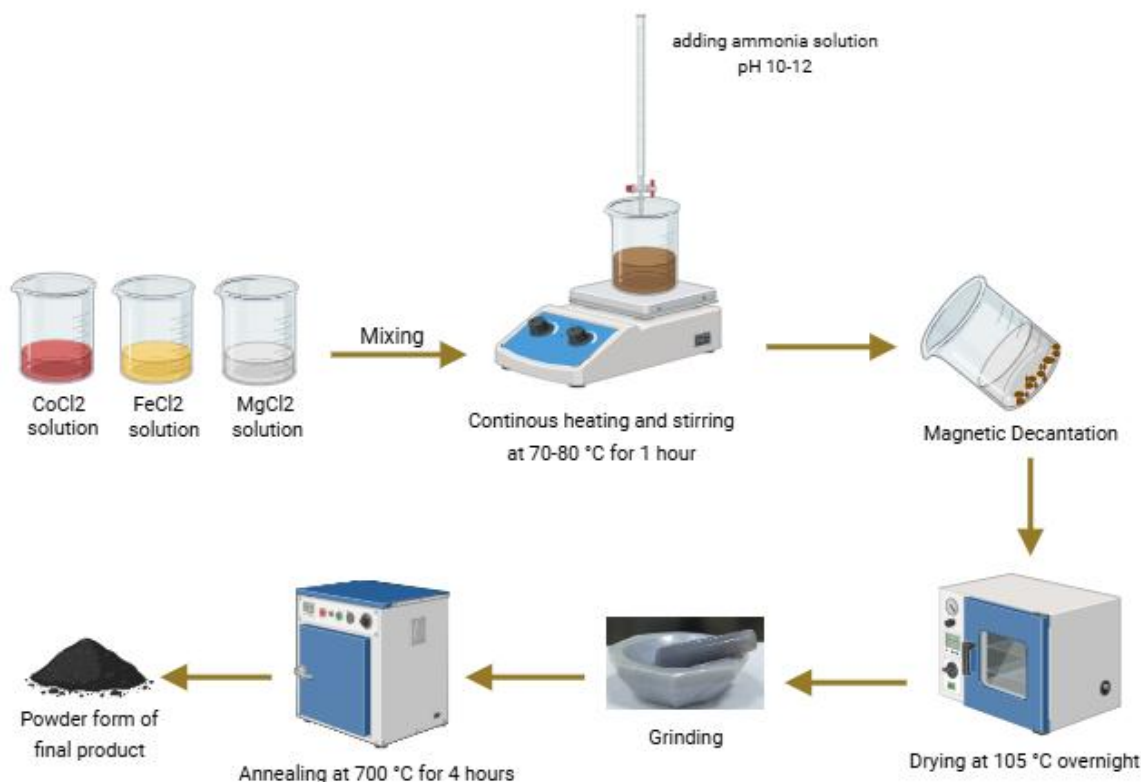


Fig. 1 Schematic illustration of the manufacturing process for magnesium-doped cobalt ferrite nanoparticles.

2.3 Synthesis of silica-coated MgCF (MgCF@SiO₂)

The magnetic nanoparticles coated with silica were synthesized using a modified Stober method, wherein the resultant nanoparticles were suspended in 80 mL of ethanol, 2 mL of 28% ammonia, and 50 mL of ionized water. The resultant mixture was sonicated in an ultrasonic bath during 30 minutes. One milliliter of Tetraethoxysilane (TEOS) was incrementally introduced to the nanoparticle solution. The resultant solution was agitated during 4 hours. The generated magnetic particles were isolated with an external magnet, properly cleaned many times with deionized water before being dried for 6 hours at 60 °C in an oven.

2.4 Functionalization of MgCF@SiO₂ NPs with CPTMS

0.5 g of MgCF@SiO₂ was blended with 40 mL of toluene. The blend underwent sonication for a duration of 30 minutes. During the following stage, the blend was introduced to the CPTMS and mixed for 18 hours at a temperature of 60 °C. The MgCF@SiO₂-CPTMS nanoparticles, after synthesized, were separated magnetically, carefully washed using toluene, ethanol, and water, and dried for 8 hours at 70 °C.

2.5 Surface modification of MgCF@SiO₂-CPTMS NPs with curcumin

Curcumin has been utilized for the functionalization of the nanoparticle surface architecture. To do this, 0.5 g of MgCF@SiO₂-CPTMS was suspended in 50 mL of ethanol using ultrasonic waves for 30 minutes. Subsequently, 0.5 gram of curcumin was dissolved in DMSO and added 3 drops of TEA after that the solution were included into the mixture and subjected to reflux at 70°C for 8 hours. Subsequently, the nanoparticles were extracted from the mixture utilizing external magnets, washed by ethanol and deionized water, then dried overnight at 65°C in an oven.

2.6 Instrumental characterization techniques

To fully analyze the MgCF@SiO₂-CPTMS-Cur nano-sorbent, a suite of analytical methods was employed to confirm its critical properties. X-ray diffraction analysis (XRD) The Philips PW1730 (Amsterdam, Netherlands) was the foremost approach for studying material crystallization and ascertaining the structure of materials at room temperature. The binding and functional groups of the materials were analysed using FT-IR spectra of the generated specimens, registered at room temperature over the range of 4000-400 cm⁻¹ utilizing KBr pellets with a WQF-510 FTIR (Rayleigh, Beijing, China). The particles' size and form were delineated by Philips CM120 TEM instrumentation (Amsterdam, Netherlands). The morphology of the nano-sorbents has been analysed with an FE-SEM system, QUANTA FEG650 (USA). Energy-dispersion X-ray spectroscopy (EDX) (Oxford Instruments, UK) was used for the elemental and chemical analysis of samples. The BET model and N₂ adsorption technique utilizing the BELSORP II analyzer (BELPREP-vac II, BEL Japan) were employed for determining the pore diameter, pore volume, and specific surface area. The specimens underwent thermal evaluation with a PerkinElmer Pyris Diamond (Yokohama, Japan), being heated at a rate of 10 °C min⁻¹ between 100 °C and 1000 °C (thermogravimetric analysis (TGA-DTA)). The synthesized nanocomposites underwent magnetic characterization at ambient temperature utilizing a Lake Shore 7404 series vibrating sample magnetometer (VSM; Westerville, OH, USA). The examination was conducted using a flame atomic absorption spectrometer (Varian SpectrAA 220 FS; Mulgrave, Victoria, Australia), featuring automatic hollow-cathode lamp switching and a corrector for deuterium background. The hollow-cathode lamps for lead and cadmium were utilized according to the manufacturer's recommended operational parameters existing 4 and 10 mA. Spectrum of wavelength from 228.8 to 217.0 nm, slit width of 0.5 and 1.0 nm, and a height of the burner 13.5 mm. The combustion mixture consisted of acetylene at a flow rate of 1.5 L min⁻¹ and 13.5 L min⁻¹ for air. The aspiration flow rate of the nebulizer ranges from 5.0 to 6.0 mL min⁻¹.

2.7 Determination of the point of zero charge

The pH_{pzc} of MgCF@SiO₂-CPTMS-Cur MNPs was ascertained by the solid addition approach (Gürsoy et al., 2025). A 50 mL volume of KCl solution (0.1 mol L⁻¹) was adjusted to nine varying pH levels (from 2 to 10) with the use of NaOH and HCl solutions (0.1 mol/L), and then, 50 mg of MgCF@SiO₂-CPTMS-Cur MNPs were incorporated into each solution. The blends were preserved at 300 K for a span of 24 hours. The initial pH (pH_i) and final pH (pH_f) were measured using a pH meter. The variation between these values was computed as ΔpH= pH_f – pH_i and represented in relation to pH_i. The pH_{pzc} was established as the pH_i value corresponding to ΔpH being zero.

2.8 Experiments on batch adsorption

Batch adsorption analyses were executed in 250 mL Erlenmeyer flasks, maintaining a shaking 200 rpm of speed and 300 K of temperature. The Erlenmeyer container was charged with 20 mg of magnetic nanoparticles and 100 mL of a solution featuring 50 mg L⁻¹ of Pb(II) and Cd(II) metal ions, respectively. The combination was shaken and the analysis was executed for 240 minutes at 300 degrees Kelvin. Following adsorption, the samples' individual concentrations of residual Pb(II) and Cd(II) metal ions were measured by FAAS at predefined intervals. The original pH was investigated within the limits of 2 to 10. Evaluations were carried out under the revised pH and specified conditions to explore the influence of sorption intervals between 10 and 360 minutes. The study explored the effects of multiple parameters to refine the testing variables by varying the Pb (II) and Cd (II) metal ion initial concentrations ranged from 5 to 300 mg L⁻¹, respectively. The quantity of adsorbent magnetic nanoparticles ranged between 5 and 30 mg, and the reaction was examined at 300, 310 and 320 K. The equilibrium adsorption uptake (q_e) and heavy metal removal efficiency (R_{metal})% have been ascertained using Eq. (1) and (2), respectively:

$$q_e = \frac{(C_i - C_e)V}{W} \dots \dots \dots (1)$$

$$R_{metal} \% = \frac{(C_i - C_e)}{C_i} \times 100 \dots \dots \dots (2)$$

C_i (mg L⁻¹) indicates for the initial concentration of the metal ion, C_e (mg L⁻¹) portrays for the concentration of the metal ion at balance, and q_e (mg g⁻¹) shows for the adsorption equilibrium capability. W (mg) denotes for the mass of the nano-adsorbent employed, while V (L) represents the metal solution's volume.

The adsorption isotherm of Pb(II) and Cd(II) metal ions on MgCF@SiO₂-CPTMS-Cur MNPs at temperatures of 300, 310, and 320 K was investigated using linearized versions of the Langmuir, Freundlich, and Temkin models.

The Langmuir isotherm model pertains to a single-layer adsorption on a surface with several available sites, positing ensures the adsorbent experiences uniform and homogeneous absorption. The Langmuir isotherm can be expressed by Eq. (3) (Abd Ali et al., 2024):

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{(q_m K_L)} \dots \dots \dots (3)$$

The equilibrium adsorption quantity is indicated by q_e (mg/g), while q_m (mg/g) signifies the monolayer coverage's maximum capacity for adsorption.

The adsorption process favorability can be assessed applying the separation factor (R_L) that is dimensionless, which is obtained from Langmuir isotherm. It is stated as:

$$R_L = \frac{1}{1 + K_L C_0} \dots \dots \dots (4)$$

where C_0 is the preliminary concentration of Pb(II) and Cd(II), and K_L is the Langmuir constant. The kind of adsorption is indicated by the R_L value; irreversible adsorption is represented by ($R_L = 0$), favourable adsorption by ($0 < R_L < 1$), linear adsorption by ($R_L = 1$) and unfavourable adsorption by ($R_L > 1$) (Olawale et al., 2025).

For heterogeneous surfaces and multilayer adsorption processes, the Freundlich adsorption isotherm is suitable. The Freundlich isotherm's linear form is described by Eq. (5) (Alam et al., 2025):

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e \dots \dots \dots (5)$$

The Freundlich parameters n and K_F describe the adsorption intensity and the isotherm capacity (mg g^{-1}), respectively.

According to the Temkin isotherm model, as the site occupied rises, the adsorption energy drops linearly rather than logarithmically. The engaged between the adsorbent and the adsorbate was studied using the isotherm. Eq. (6) provides the Temkin isotherm's linearized version (Dehghani et al., 2021; Yang et al., 2023):

$$q_e = A + B \ln C_e \dots \dots \dots (6)$$

A and B represent the variables of the Temkin isotherm.

2.9 Experimental kinetic studies

For the kinetic assays, 20 mg of MgCF@SiO₂-CPTMS-Cur MNPs were added to several 250 mL Erlenmeyer flasks holding 100 mL of Pb(II) and Cd(II) solutions at three initial concentrations (20, 50, and 100 mg L⁻¹, for Pb(II) at pH 6 and for Cd(II) at pH 7). Pb(II) and Cd(II) metal ions concentrations in the solution were measured at predetermined intervals using FAAS. The quantities of Pb(II) and Cd(II) metal ions adsorbed at various time intervals were computed utilizing Eq. (7):

$$q_t = \frac{(C_i - C_t)V}{W} \dots \dots \dots (7)$$

The variable q_t (mg g^{-1}) indicates the capacity for adsorption at a particular time $t(\text{min})$, while C_t (mg L^{-1}) represents the adsorbate's concentration at that specified time t (min).

The investigational data were modelled utilizing pseudo-first-order, pseudo-second-order, and Elovich techniques to clarify the adsorption kinetics of Pb(II) and Cd(II) metal ions on MgCF@SiO₂- CPTMS-Cur MNPs adsorbent (Adeoye et al., 2025), as indicated by Eqs. (8), (9) and (10), respectively:

$$\ln(q_e - q_t) = \ln q_e - K_{1t} \dots \dots \dots (8)$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \dots \dots \dots (9)$$

$$q_t = \frac{1}{\beta} \ln(\alpha\beta) + \frac{1}{\beta} \ln t \dots \dots \dots (10)$$

The pseudo-first-order kinetics model's rate constant represents by k_1 (1 min^{-1}), while the pseudo-second-order kinetics model's rate constant is indicated by k_2 ($\text{g mg} \cdot \text{min}^{-1}$). In conclusion, the primary rate of adsorption constant ($\text{mg g} \cdot \text{min}^{-1}$) is represented by α , and the rate of adsorption constant (g mg^{-1}), associated with the Elovich kinetics model, is denoted by β .

2.10 Study on regeneration and recycles

The ability of the nano-adsorbent to regenerate was evaluated using a set amount of heavy metal-loaded MgCF@SiO₂-CPTMS-Cur MNPs. A thermostatic shaker was used to shake the adsorbent and 50 mL of desorbing solution in a conical flask for 30 minutes at 180 rpm. To perform desorption tests, 0.5 g of the modified MgCF@SiO₂-CPTMS-Cur loaded with heavy metals (Pb/Cd) was mixed with 50 mL of deionized water that had been adjusted to pH 7 and shaken utilizing a VWR incubating orbital shaker for the entire night at ambient temperature. After desorption, the solution was separated, and until the pH was neutral, the nano-adsorbent was regularly washed with deionized water. Before being used once more in further adsorption cycles, the recovered adsorbent was dried at 105°C in an oven. FAAS was used to determine the amount of desorbed metal, and Eq. (11) was used to compute the desorption percentage:

$$Desorption \% = \frac{Amount\ of\ metal\ desorbed}{Amount\ of\ metal\ adsorbed} \times 100 \dots \dots \dots (11)$$

2.11 Application in the environmental samples

Water samples from taps, groundwater, and lakes were obtained from three distinct locations in the Kurdistan Region of Iraq: Koya, Erbil, and Dukan. Suspended particles were eliminated by filtering the samples over a Millipore cellulose acetate membrane with a pore width of 0.45 µm. Each sample's pH was regulated utilizing either 0.1 M HCl or 0.1 M NaOH.

2.12 Error Evaluations

In order to evaluate the quality of the fitting, chi-squared (χ^2) and sum of squared errors (SSE) tests were determined from, as expressed by Eqs. (12) and (13), respectively (Ojediran et al., 2021). This is linked to the fundamental bias originating from the linear approximation of the isotherm and kinetic models.

$$\chi^2 = \sum_{i=1}^n \frac{(q_{m(exp.)} - q_{m(cal.)})^2}{q_{m(calc.)}} \dots \dots \dots (12)$$

$$SSE = \sum_{i=1}^n (q_{m(exp.)} - q_{m(cal.)})^2 \dots \dots \dots (13)$$

The term $q_m(exp.)$ (mg/g) refers to the experimentally determined adsorption value, $q_m(cal.)$ indicates the predicted adsorption value based on the model (mg/g), and n represents the count of observations in the experiment (data points). Reduced SSE and χ^2 values in the analysed kinetic and isotherm models suggest enhanced curve conformity.

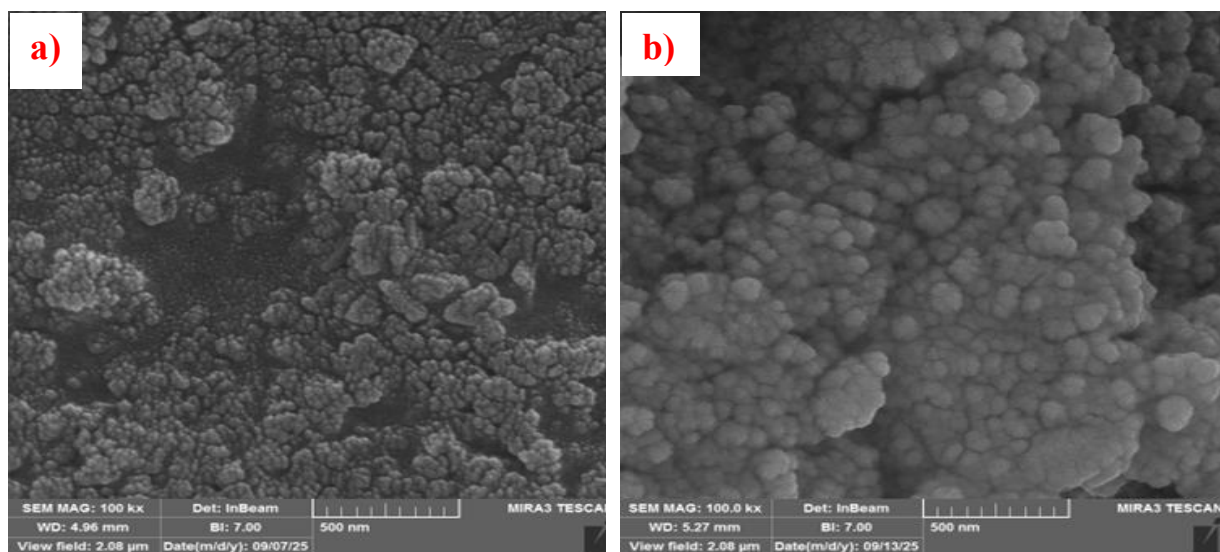
3 Results and Discussion

3.1 Characterization of morphology and structure

3.1.1 Surface Morphology

The morphology of MgCF NPs and MgCF@SiO₂-CPTMS-Cur MNPs adsorbent was analysed by FE-SEM, as illustrated in Figs. 2a and b. The MgCF nanoparticles possessed spherical shapes and a regular, uniform morphology, as shown in Fig. 2a. Some of the shapes are 10 nm across to 500 nm across, and they support the nanostructure of the Magnesium-doped cobalt ferrite nanoparticles (MgCF). FE-SEM examination clearly demonstrates that curcumin was successfully changed on the surfaces of magnesium-doped cobalt ferrite nanoparticles (MgCF) following the synthesis of MgCF@SiO₂-CPTMS-Cur MNPs adsorbent Fig. 2b. Furthermore, the surface of the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent exhibits a porous architecture, characterized by a greater free volume compared to Magnesium-doped cobalt ferrite nanoparticles (MgCF). This porosity is crucial for the adsorbent's efficacy in heavy metal adsorption, as it enhances the mass transfer rates of ions. Furthermore, the TEM picture in Fig. 2c corroborates the nanostructure shape of MgCF@SiO₂-CPTMS-Cur MNPs adsorbent. It can be inferred that the curcumin-modified magnesium-doped cobalt ferrite nanoparticles (MgCF) produced better surface characteristics, porosity, and surface area (Fig. 7), as well as increased heavy metal ion adsorption by the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent, as shown in further research.

The quantitative evaluation of MgCF@SiO₂-CPTMS-Cur magnetic nanoparticles indicates that the associated histogram in Fig. 2d reveals a particle size range ranging between 4 to 16 nm, with an average diameter of approximately 9 nm.



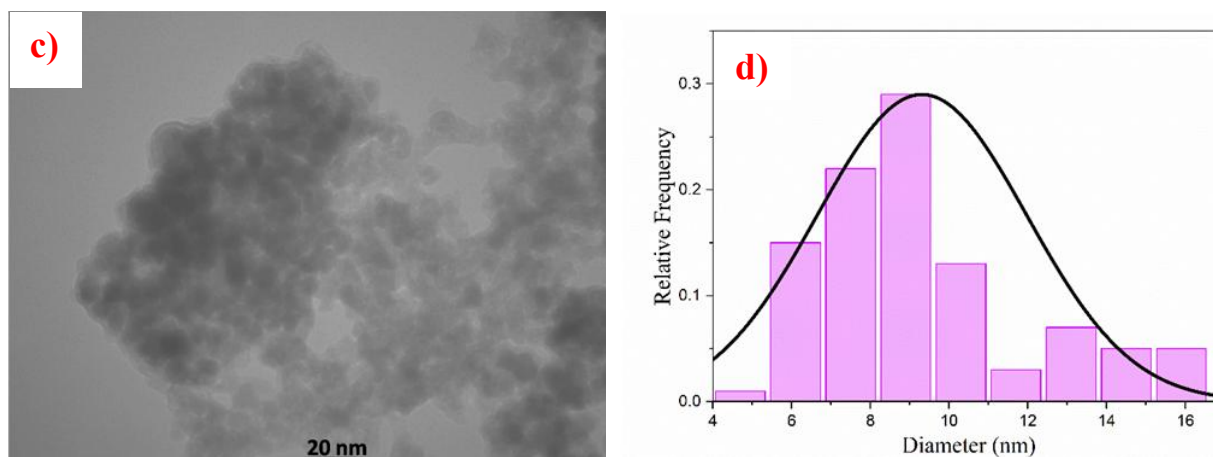


Fig. 2 FE-SEM images of MgCF (**a**) and the MgCF@SiO₂-CPTMS-Cur MNPs (**b**). (**c**) TEM image of the MgCF@SiO₂-CPTMS-Cur MNPs and histogram plot of the MgCF@SiO₂-CPTMS-Cur MNPs related with its TEM image (**d**).

The elemental examination of the adsorbent was performed using EDX before to and subsequent to adsorption to verify Pb(II) and Cd(II) metal ions the acceptance on the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent's surface. Fig. 3 (a, b, and c) illustrates the existence of Fe, Co, O, Mg, Si, Cl, and C within the composition of the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent. The EDX spectrum illustrated in Fig. 3b and c displayed two additional peaks corresponding to Pb and Cd following the adsorption of Pb(II) and Cd(II) metal ions by the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent, thereby validating the adsorption of Pb(II) and Cd(II) metal ions over to the adsorbent's surface.

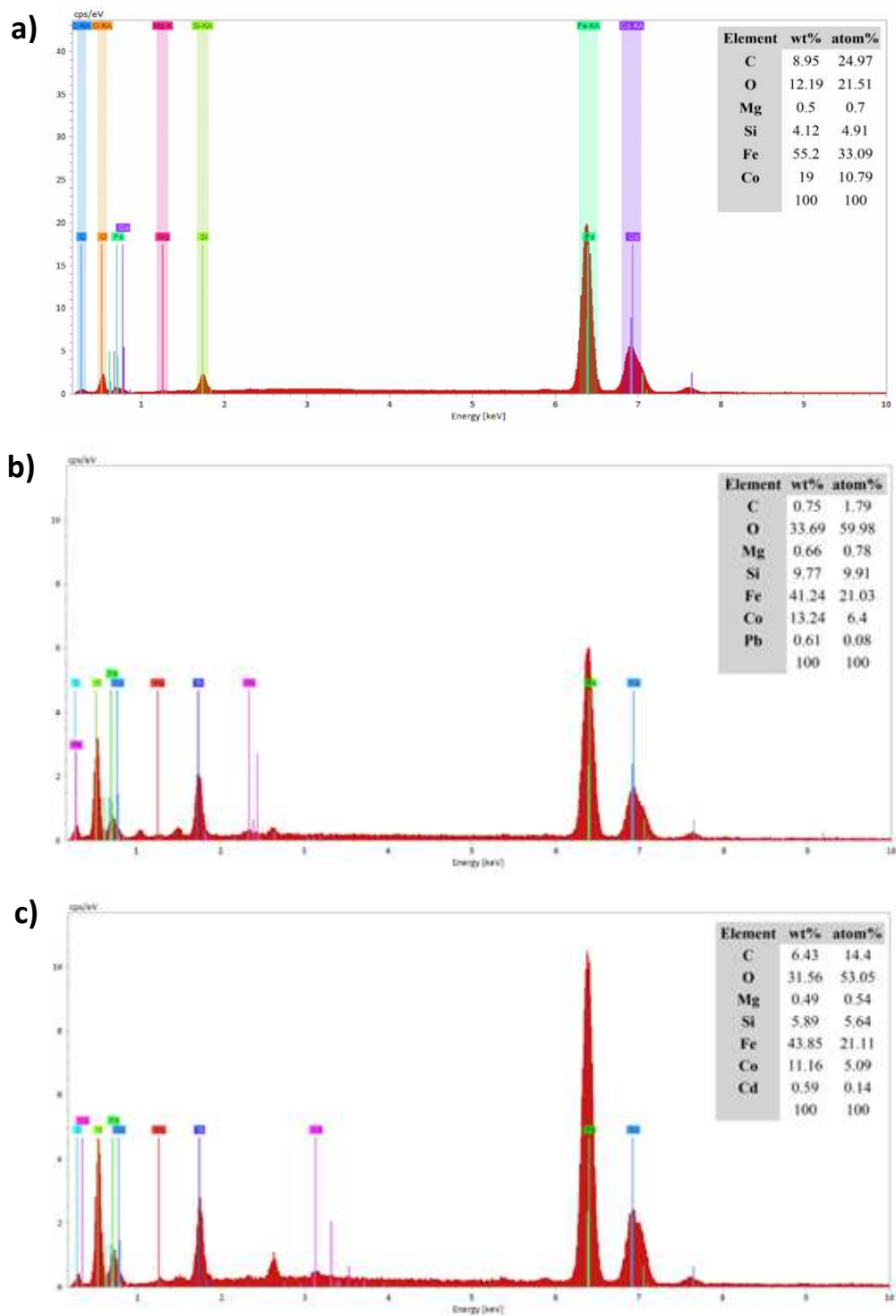


Fig. 3 MgCF@SiO₂-CPTMS-Cur EDX analysis (a) before adsorption (b) after Pb ion adsorption and (c) after Cd ion adsorption.

3.1.2 FTIR analysis

The FTIR spectra for MgCF, MgCF@SiO₂, MgCF@SiO₂-CPTMS, and MgCF@SiO₂-CPTMS-Cur are obtained from 400 to 4000 cm⁻¹. A wide absorption band at 3400 cm⁻¹ was visible in the spectra MgCF. This can be attributed to adsorbed water molecules and surface hydroxyl groups' O-H stretching vibrations, while H-O-H bending vibrations are linked to the band at about 1630 cm⁻¹. The formation of MgCF nanoparticles is validated by the unique bands observed between 500–600 cm⁻¹, which match the metal–oxygen vibrations characteristic of the spinel ferrite structure Fig. 4 (Rekaby et al., 2026).

Subsequent to silica coating, effective silica deposition is signified by a notable band in the MgCF@SiO₂ spectra at around 1080–1100 cm⁻¹, which relates to Si–O–Si stretching vibrations. Surface functionalization is validated by the emergence of additional bands between 2850 and 2950 cm⁻¹ in the MgCF@SiO₂-CPTMS spectra, which match the C–H stretching vibrations of the chloropropyl moiety (Valipour et al., 2025). The C–Cl bond, expected in the range of 700–800 cm⁻¹, appears weak owing to interference from metal–oxygen vibrations, as showed in Fig. 4. Finally, the spectra of MgCF@SiO₂-CPTMS-Cur reveals novel bands in the 1500–1600 cm⁻¹ and 1200–1300 cm⁻¹ ranges, connected with the aromatic C=C and C–O stretching vibrations of curcumin. This signifies that curcumin was effectively anchored onto the modified magnetic nanoparticles. as illustrated in Fig. 4 (Mosaffa et al., 2024).

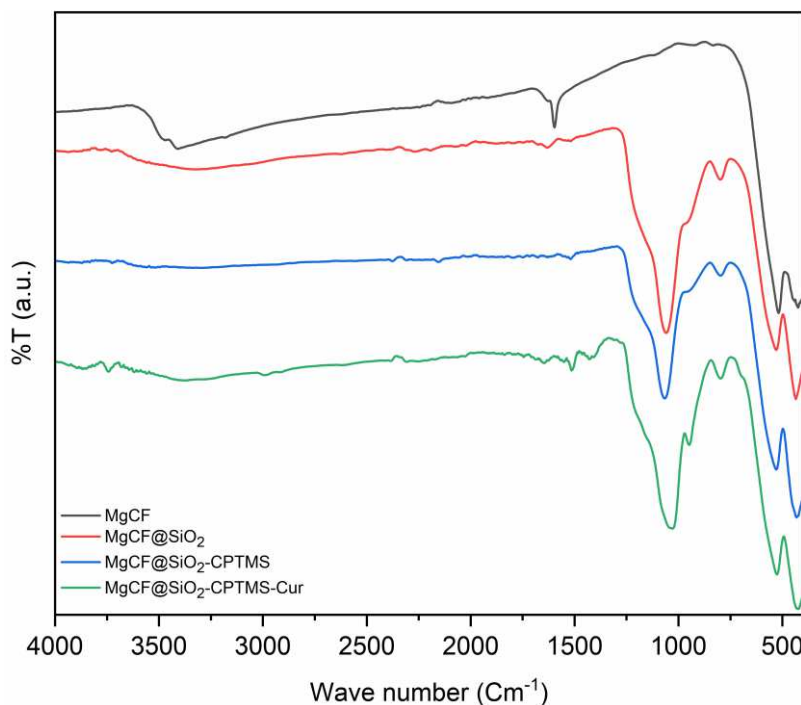


Fig. 4 FT-IR Curves of MgCF, MgCF@SiO₂, MgCF@SiO₂-CPTMS and MgCF@SiO₂-CPTMS-Cur nanoparticles

3.1.3 VSM (Vibrating magnetometer sample)

The magnetic characteristics of MgCF and MgCF@SiO₂-CPTMS-Cur NP were examined at ambient temperature utilising vibrating sample magnetometer (VSM) analysis, as illustrated such as Fig. 5. For practical applications, it is crucial to preserve adequate magnetic characteristics following surface alteration, especially for magnetic separation procedures. MgCF and MgCF@SiO₂-CPTMS-Cur nanoparticles were found to have saturation magnetization (Ms) values of 63.80 and 42.84 emu/g respectively. Following each modification step, a gradual decline in the saturation magnetization values is seen. This reduction is mostly credited to the existence of non-magnetic constituents on the nanoparticle surfaces, including SiO₂ shells and organic functional groups, which augment the overall mass of nanocomposites without contributing to the magnetic moment (Iacovita et al., 2021). As a result, after coating and functionalization, the total magnetization per unit mass decrease.

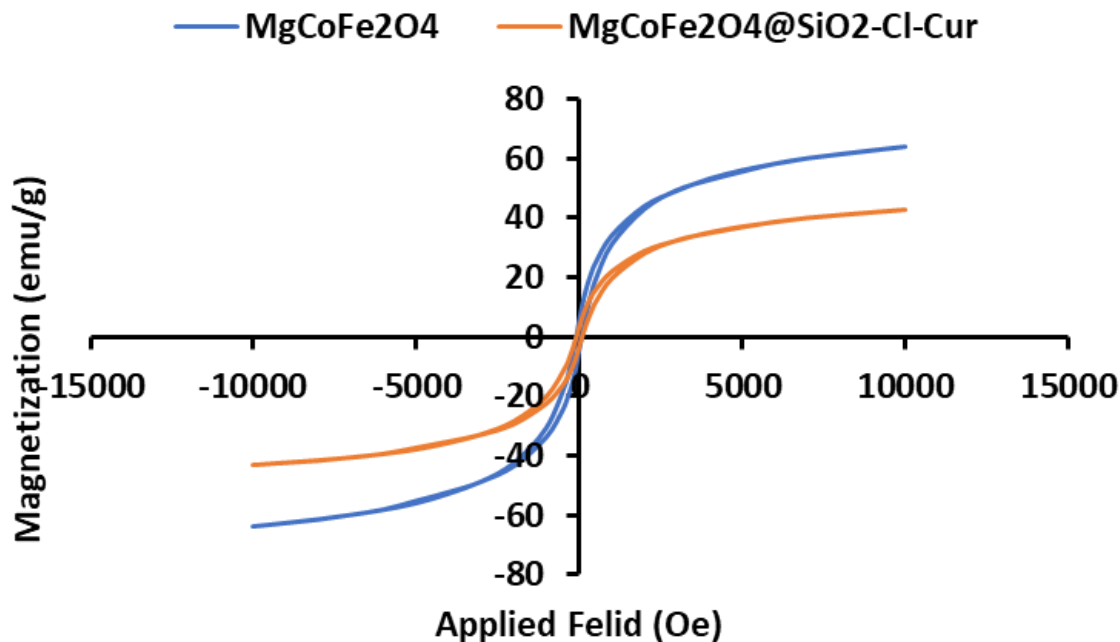


Fig. 5 Magnetic hysteresis loops of MgCF and MgCF@SiO₂-CPTMS-Cur nanoparticles.

3.1.4 Nitrogen adsorption-desorption studies

The isotherms of nitrogen adsorption and desorption for both synthesized MgCF and MgCF@SiO₂-CPTMS-Cur nanoparticles samples are presented in Fig. 6a and 6b. Both materials display a prototypical Type IV isotherm with a noticeable hysteresis loop of the H2 type, indicative of mesoporous formations. This phenomenon is marked by a quick spike in nitrogen uptake under high relative pressures ($P/P_0 = 0.990$), corroborating the development of mesopores measuring between 2 and 50 nm. The first sample's BET surface area and the total volume of pores were assessed to be 19.573 and 0.186, respectively. In comparison, the second sample showed a higher surface area of 24.176 and a pore volume of 0.1336. Furthermore, the distribution curves of pore sizes displayed in the insets reveal that both samples possess well-defined mesoporous, with average diameters centered around 38.021 nm and 22.103 nm, respectively. These results indicate that the modification process successfully maintained the mesoporous framework while significantly altering the textural properties, making them suitable for high-performance adsorption applications.

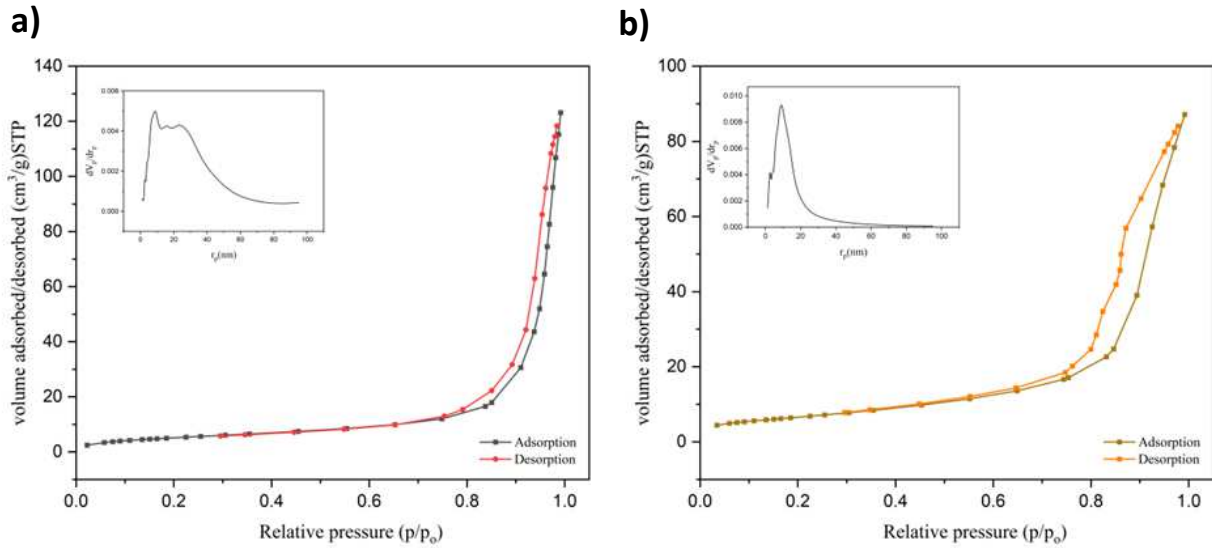


Fig. 6 BET Patterns of MgCF(a) and the MgCF@SiO₂-CPTMS-Cur MNPs (b).

3.1.5 TGA (Thermogravimetric analysis)

The thermogravimetric analysis (TGA) graphs depicted in Fig. 7 were employed to examine thermal stability of MgCF nanoparticles and MgCF@SiO₂-CPTMS-Cur nanoparticles within the temperature between 25–1000 °C. The overall weight reduction for MgCF NPs is 48.72% in relation to the adjusted sample, suggesting relatively low thermal stability. The reduction in weight at temperatures under 200 °C is ascribed to the elimination volatile substances and of physically water adsorbed. Significant weight reduction is observed at elevated temperatures, especially over 500 °C. This results from the stabilization of the spinel ferrite configuration and the complete removal of residual impurities (Atarod et al., 2021). The modified MgCF@SiO₂-CPTMS-Cur NPs, in contrast, exhibit a reduced overall weight loss of 29.21%, suggesting enhanced thermal stability following modification. There are several stages to the degradation, starting with a loss of weight below 200 °C, which is associated with the elimination

of moisture. This is followed by progressive weight losses in the middle temperature span of (200–500) °C due to the grafted organic functions' disintegration. The elimination of residual surface groups is linked to an additional weight drop at higher temperatures (>500 °C). As has been extensively documented for silica-modified materials, the decreased total weight loss and stepwise degradation behavior indicate that the silica-based coating increases structural integrity and improve resistance to thermal degradation (Crucho, 2024).

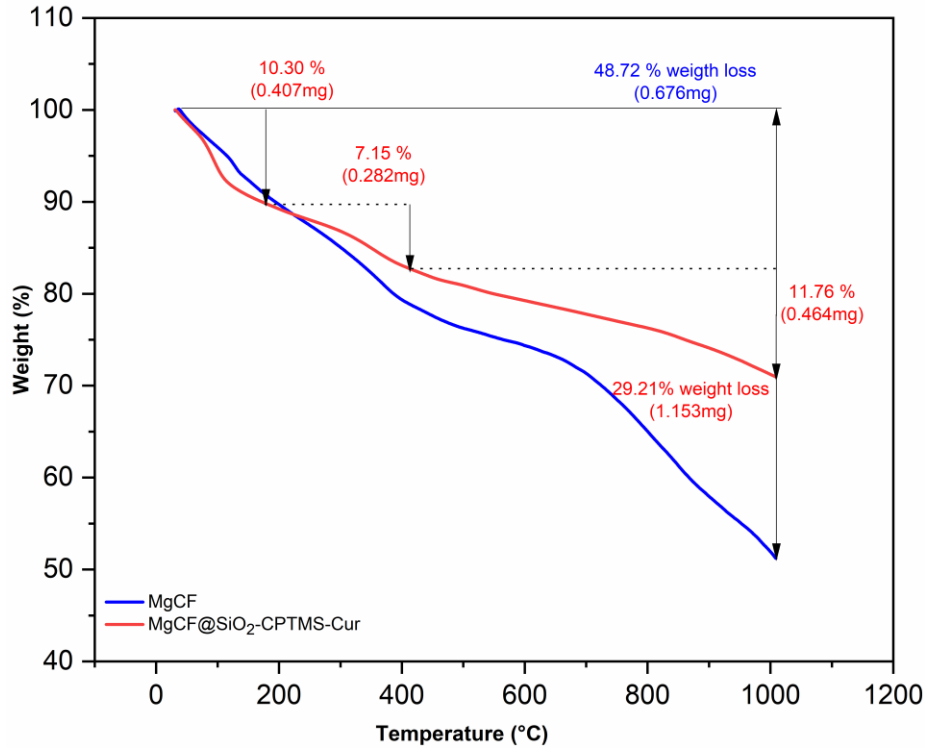


Fig. 7 TGA Curves of MgCF and MgCF@SiO₂-CPTMS-Cur nanoparticles

3.1.6 X-ray diffraction analysis

X-ray diffraction (XRD) was employed to examine the phase purity and crystalline organization of both unaltered MgCF and modified nanoparticles, as shown in the Fig. 8. The standard JCPDS information indicates (card no. 22-1086), The diffraction pattern acquired aligns with a cubic spinel configuration characterized by the space group Fd3m. The synthetic samples are phase-pure and free of secondary crystalline impurities, as no additional diffraction peaks are observed. These findings are consistent with formerly reported studies, corroborative the successful synthesis of MgCF and its modified form (Abdelrahman et al., 2024).

The unadulterated MgCF specimen displays diffraction peaks at 2θ angles of approximately 30°, 35°, 44°, 53°, 57°, 62°, and 72°. The diffraction peaks can be correlated with the crystallographic planes (220), (311), (400), (422), (511), (440), and (533). These factors also support the development of a cubic spinel ferrite configuration devoid of any

discernible secondary phases. The primary diffraction peaks for MgCF are still present in the functionalized sample's XRD pattern, suggesting that the core crystal structure is unaffected by surface alteration. Nevertheless, a reduction in peak intensity along with a slight peak expanding is noticed, which can be credited to the presence of an amorphous SiO₂ layer and organic groups CPTMS and curcumin coated on the nanoparticle surface. Furthermore, according to earlier research, curcumin may be linked to the weak and broad patterns seen at lower diffraction angles about (18°–27°) (Moradi et al., 2020). After functionalization, there is no discernible change in peak positions, suggesting that the lattice structure is essentially unchanged.

By examining the strongest (311) diffraction peak, the Debye-Scherrer an equation was utilized to calculate the average crystallite size.

The computed crystallite size for functionalized sample is 13.03 nm; these results approximately near with the result from TEM analysis.

Furthermore, the interplanar distance (*d*) and lattice constant (*a*) were computed using Eq. (14) and Eq. (15), respectively:

$$d = \frac{n\lambda}{2 \sin \theta} \dots \dots \dots (14)$$

$$a = d\sqrt{h^2 + k^2 + l^2} \dots \dots \dots (15)$$

where *a* is the lattice constant, *λ* is the Xray wavelength, *θ* is the diffraction angle, and *h*, *k*, and *l* are the Miller indices of each plane set. For the pristine and functionalized samples, the computed lattice constants are 8.41 Å and 8.36 Å, respectively. Surface interactions and induced lattice strain may be responsible for the modest drop in lattice parameter following modification.

Using the relation *V*= *a*³, the unit cell volume (*V*_{cell}) for the pristine and changed samples was determined to be 595 Å³ and 584 Å³, respectively. Table S1 provides a summary of the computed structural parameters. These findings verify that MgCF crystal structure is maintained during functionalization, with only slight changes brought about by surface modification effects.

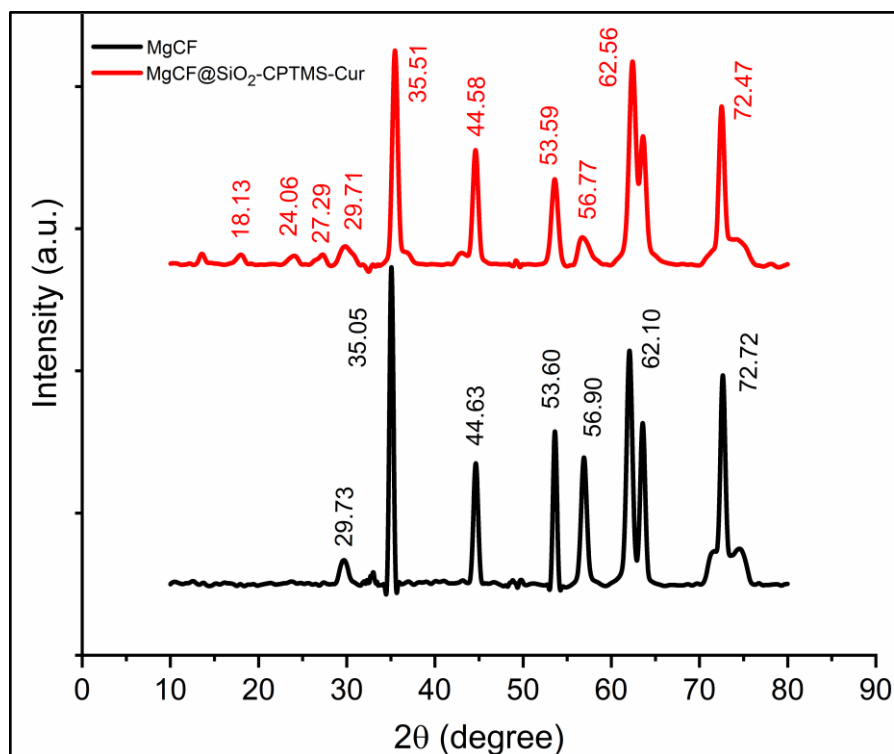


Fig. 8 The X-ray diffraction patterns of of MgCF and MgCF@SiO₂-CPTMS-Cur nanoparticles

3.2 Utilization of MgCF@SiO₂-CPTMS-Cur Nanoparticles for Optimization of Metal Ion Adsorption Parameters

The experimental variables (pH, amount of adsorbent, period of contact, initial concentration, as well temperature) were refined to assess the efficacy of the MgCF@SiO₂-CPTMS-Cur nanoparticles technique for the quantitative extraction of Pb(II) and Cd(II) metal ions.

3.2.1 The pH effect

The pH of solution directly effects the behavior of the metal ions and their interactions with nano-adsorbent (MgCF@SiO₂@CPTMS-Cur) at solid-liquid interface, which is crucial for the method of adsorption heavy metals. The pH at which the surface of the adsorbent shows no overall charge is known as the zero charge point (pH_{pzc}). The electrostatic interaction among the adsorbate and adsorbent is a crucial parameter to regulate. Based on the ΔpH vs pH_i graph (Fig. 9 A), the pH_{pzc} of the synthesized MgCF@SiO₂-CPTMS-Cur nanoparticles was approximated to be around 4.9. Consequently, there is a positive charge on the composite surface at pH values lower than the pH_{pzc} (pH

< 4.9) with a pH-negative charge above it. The surface charge characteristics of the metal ions being examined greatly influence their adsorption efficacy.

Within the pH range between 2–10, the impact of pH on the removal of Pb(II) and Cd(II) metal ions(MI) by magnetic nano adsorbent was examined (Fig. 9B). The data revealed that optimal removal effectiveness for Pb ions occurred in pH 6, with a rate of 96.28%, while Cd ions demonstrated their optimal removal effectiveness in pH 7, at 95.62%.

The capacity to adsorb both metal ions diminished markedly at low pH levels due to protonation of active functional groups on the adsorbent's surface and elevated concentration of H_3O^+ ions in the solution. In these circumstances, the accessibility of adsorption sites diminishes, and contestation between H_3O^+ ions and metal ions for these binding sites intensifies. Consequently, the positive charge of the adsorbent surface exhibits diminished attraction in order to adsorption of the positively charged Pb(II) and Cd(II) ions (Li et al., 2024; Zhang et al., 2021). The efficacy of adsorption was seen to diminish when pH levels rose. This decline may result from the formation and subsequent precipitation of $Pb(OH)_2$ and $Cd(OH)_2$ in alkaline conditions, which lowers the concentration of free metal ions ready for adsorption. Moreover, the surplus OH^- ions could influence the adsorption mechanism by altering the charge on the surface of the nano-adsorbent and diminishing the reaction between metal ions and the adsorbent (Li et al., 2024; Zhang et al., 2021).

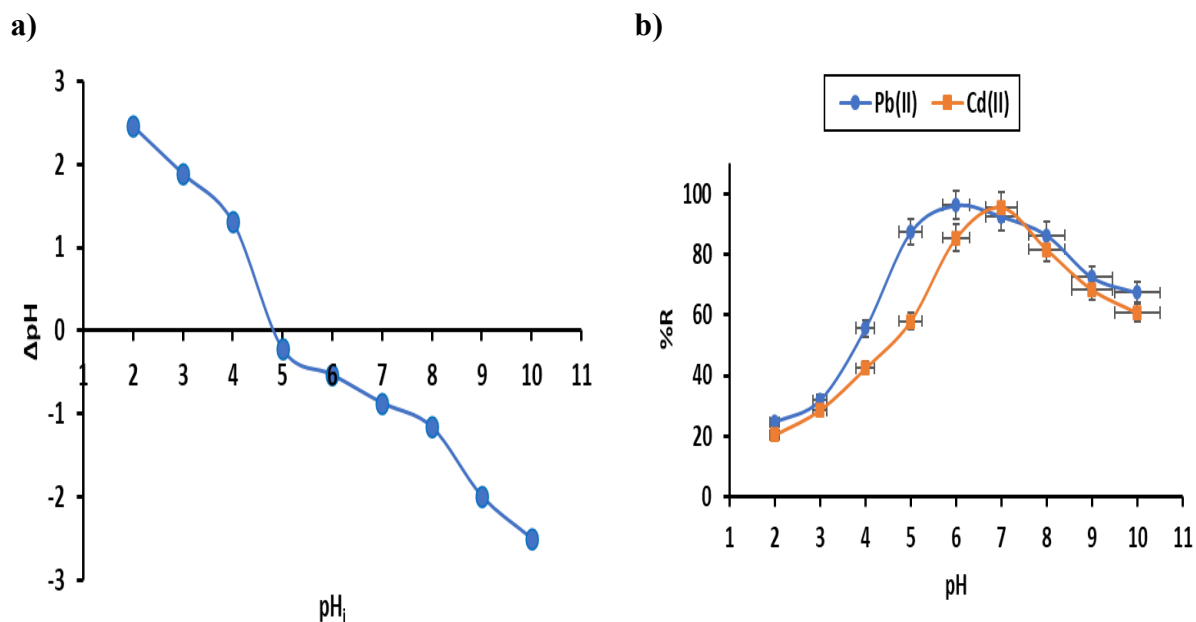


Fig. 9 The pH_{pzc} analysis of the $MgCF@SiO_2-CPTMS-Cur$ nanoparticles. **(a)** and Impact of pH on heavy metals (Pb and Cd) adsorption onto $MgCF@SiO_2-CPTMS-Cur$. while keeping every other parameter (circumstances: Conc. of metal= 50 mg/L, contact time= min, adsorbent dosage= mg) **(b)**.

3.2.2 Impact of magnetic nano-adsorbent quantity

Various quantities of MgCF@SiO₂-CPTMS-Cur magnetic nano-adsorbent (5–45 mg) were assessed to optimize the adsorbent dosage at an elementary metal ion 50 mg/L concentration, with pH 6 for Pb(II) with pH 7 for Cd(II) at ambient temperature. As illustrated in Fig. 10, the elimination rates of both metal ions markedly rose with the augmentation of adsorbent mass from 5 mg to 20 mg, indicating that a greater quantity of adsorbent offers extra active sites for adsorption of metal ion. The highest removal efficiency is 98.35% for Pb and 97.14% for Cd at an adsorbent mass of 20 mg. Subsequently, the removal efficiency stabilized, indicating that adsorption equilibrium or surface saturation had been attained, and additional increments in adsorbent dosage did not significantly enhance the elimination of metal ions. Consequently, the ideal adsorbent dosage for the proficient extraction of Pb(II) and Cd(II) beneath evaluated circumstances was established to be 20 mg.

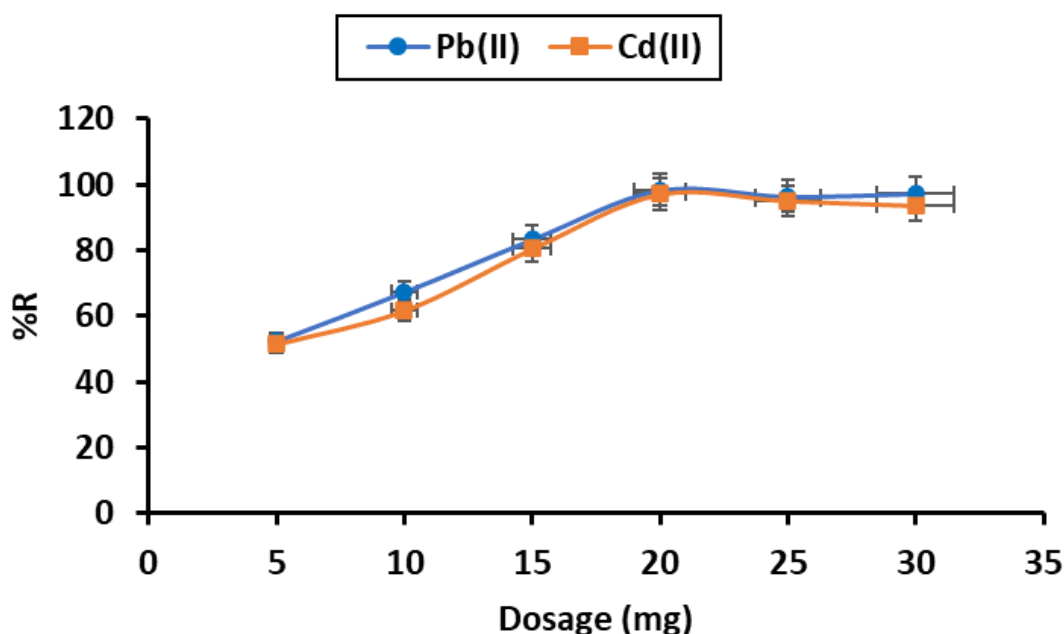


Fig. 10 Impact of MgCF@SiO₂-CPTMS-Cur magnetic nano-adsorbent dosage on heavy metals (Pb and Cd) adsorption.

3.2.3 Adsorption kinetic analysis

The prompt adsorption is significant for discovering a comparatively effective adsorbent material. In Figure 11, the impact of adsorption time on the adsorbent is depicted to identify the duration that yields the highest adsorption capacity. The rate of adsorption was somewhat rapid in the early phases and thereafter declined until an equilibrium state was attained.

The findings in Table 1 reveal that the correct kinetic model for Pb(II) and Cd(II) metal ions adsorption on the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent was established based on the computed values (q_e cal. (mg/g)) and the linear correlation coefficients (R^2) in relation to experimental value (q_m exp. (mg/g)) and error functions (SSE and χ^2). The pseudo-second-order kinetic model reveals a high correlation coefficient (R^2) for every tested initial concentration of Pb(II) and Cd(II), implying a more robust correlation with the adsorption process than the pseudo-first-order and Elovich models when utilizing the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent, showcasing exceptional linearity ($R^2 > 0.99$) (Table 1). Furthermore, every assessed initial concentration of Pb and Cd metal ions demonstrated a decline in the SSE and χ^2 values according to the kinetic model of pseudo-second-order. The experimental data is most suitably represented by the kinetic model of pseudo-second-order. As a result, it was inferred that the adoption of Pb(II) and Cd(II) ions by MgCF@SiO₂-CPTMS-Cur MNPs adsorbent conformed to the model of pseudo-second-order kinetics. Consequently, it can deduced that chemical adsorption serves as the rate-limiting phase in the adsorption procedure of Pb and Cd metal ions utilizing MgCF@SiO₂-CPTMS-Cur MNPs (Salehi et al., 2021). A portion of the chemical adsorption was accomplished through various techniques, including the formation of covalent connections between Pb and Cd metal ions and active sites via electron exchange (Seo et al., 2020). The adsorption kinetics of Pb(II) and Cd(II) were examined utilizing pseudo-first-order, pseudo-second-order, and Elovich kinetic models, as shown in Figs. S1, S2, and S3, respectively (Supplementary Information).

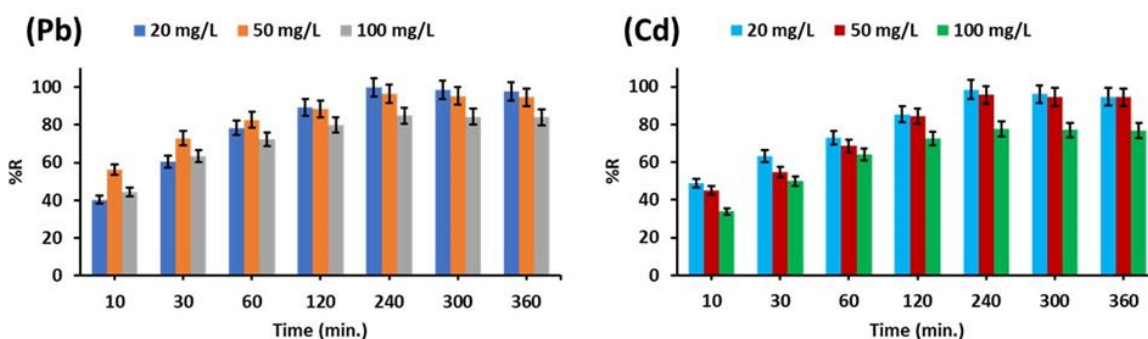


Fig. 11 Removal percentages versus time of Pb(II) and Cd(II) with three initial concentrations of (20, 50, and 100 mg/L) for Pb at pH 6 and for Cd at pH 7; adsorbent dosage 20 mg.

Table 1

Adsorption PFO, PSO, and Elovich kinetics factors for Pb(II) and Cd(II) ions adsorption by the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent (conditions: pH 6 for Pb and pH 7 for Cd; dosage = 20 mg; initial Pb, Cd conc.= 20, 50, 100 mg/L).

Kinetic models	Factors	Initial Pb concentration			Initial Cd concentration		
		20 mg/L	50 mg/L	100 mg/L	20 mg/L	50 mg/L	100 mg/L
PFO	q_m (exp.) (mg/g)	49.901	120.35	212.02	49.252	119.52	193.85
	k_1 (1/min)	0.0102	0.0096	0.0116	0.0080	0.0114	0.0120
	q_e (cal.) (mg/g)	23.81	37.761	72.327	21.498	65.437	82.822
	R^2	0.9374	0.9231	0.9300	0.9312	0.9729	0.9418
	SSE	61.163	362.46	2006.7	127.49	662.04	1955.4
	χ^2	0.5231	0.2996	0.6042	0.3792	0.5493	0.6593
PSO	k_2 (mg/g.min)	0.0010	0.0008	0.0004	0.0012	0.0003	0.0004
	q_e (cal.) (mg/g)	52.083	121.95	217.39	50.251	126.58	200.00
	h (mg/g min)	2.8288	12.658	20.790	1.0000	5.9417	13.531
	R^2	0.9990	0.9995	0.9998	0.9977	0.9980	0.9995
	SSE	0.0470	0.0342	0.0302	0.0004	5.6E-05	0.0343
	χ^2	0.00013	2.8E-05	9.1E-06	1.2E-06	4.6E-08	1.1E-05
Elovich	q_e cal. (mg/g)	48.355	117.71	209.54	46.706	114.37	190.85
	α (mg/g.min)	11.071	327.27	238.76	22.238	30.075	63.543
	β (g/mg)	0.1190	0.0735	0.0364	0.1419	0.0517	0.0325
	R^2	0.9679	0.9617	0.9415	0.9766	0.9717	0.9496
	SSE	0.1585	0.5690	0.2977	0.5149	0.6597	0.4307
	χ^2	0.0004	0.0004	8.9E-05	0.0015	0.0005	0.0001

3.2.4 Isotherms analysis of adsorption

Adsorption isotherms were examined for varying initial adsorbed concentrations Pb(II) and Cd(II) metal ions between 5 and 300 mg/L at 300, 310, and 320 K to identify the highest adsorption capacity and analyze the relation among the nano adsorbent and the adsorbed Pb(II) and Cd(II) metal ions.

The adsorption capabilities of MgCF@SiO₂-CPTMS-Cur MNPs augmented with rising ion concentrations, reaching peak adsorption capacity as illustrated in Fig. 12. Figures S4, S5, and S6 illustrate Langmuir, Freundlich, and Temkin isotherm models pertaining the adsorption of Pb(II) and Cd(II) over MgCF@SiO₂-CPTMS-Cur MNPs adsorbent, respectively (Supplementary Information). Table 2 displayed the fitting findings.

Figure 12 demonstrates that equilibrium adsorption capacity augmented with a higher starting concentration of Pb(II) and Cd(II) metal ions. The peak capacity for adsorption of the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent for metal ions of Pb and Cd were recorded between 258.15 to 323.15 mg/g and 204.22 to 274.21 mg/g, respectively, at a starting concentration 150 mg/L for each metal ion. The enhancement of capacity for adsorption from the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent at a certain constant dosage is anticipated to be the primary driver of mass movement between the phases of liquid and solid. This procedure is optimized at elevated concentrations due to the increased accessibility of Pb and Cd metal ions for reaction with the MgCF@SiO₂-CPTMS-Cur active sites of magnetic nanoparticle adsorbents.

Fig. S4 shows the Langmuir model's linear graphs (C_e/q_e against C_e) based on the temperature scrutinizes (300, 310, and 320 K) for P(II) and Cd(II) metal ions. The anticipated q_m and KL values for the examined temperatures are displayed within Table 2. The theoretical adsorption capacities were found to be 256.41, 303.03, and 322.58 mg/g for Pb, and 204.08, 256.41, and 270.27 mg/g for Cd at the examined temperatures.

The experimentally confirmed adsorption capabilities were (259.50, 309.50 and 329.57 mg/g) for Pb and (208.35, 257.10 and 277.90 mg/g) for Cd at same temperatures. RL values were computed for the Pb(II) and Cd(II) metal ions within this experiment, producing ranges of 0.0007–0.1264 and 0.0003–0.1299, respectively, at the designated temperatures. According to the data, Pb(II) and Cd(II) metal ions are favorably adsorbed on the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent at all investigated temperatures.

The linear graphs of the Freundlich model pertaining to temperature investigations at 300, 310, and 320 K for Pb and Cd metal ions are presented within (Fig. S5). The values of K_f with n are likewise displayed in Table 2. The Freundlich isotherm graphs indicated peak capacity of adsorption for Pb metal ions at 326.01, 406.63, and 435.90 mg/g, respectively. The metal ions of Cd exhibited maximal adsorption capacities at 280.20, 362.51, and 382.98 mg/g at the investigated temperatures.

The graphs of the Temkin isotherm for Pb(II) and Cd(II) metal ions at a temperature of 300, 310, and 320 K are illustrated in (Fig. S6). A and B were identified utilizing the intercept and slope obtained from the linear Temkin isotherm graph. The parameters A, B, and R^2 are displayed within Table 2. The Temkin model demonstrated maximal adsorption capacities q_m of 245.77, 291.71, and 309.64 mg/g for Pb metal ions, also 215.18, 263.91, and 289.57 mg/g for Cd metal ions in specified temperatures.

The Langmuir, Freundlich, and Temkin models exhibit determination coefficients (R^2) of (0.9994–0.9999), (0.8644–0.9441), also (0.9111–0.9659) for Pb(II) and Cd(II) metal ions at the designated temperatures, respectively. The isotherm adsorption analysis indicates that the model of Langmuir isotherm exhibits the highest correlation ($R^2 = 0.999$), with the estimated and observed adsorbed quantities being closely aligned. Furthermore, the SSE and χ^2 metrics of the Langmuir isotherm model for all assessed starting concentrations of Pb and Cd metal ions exhibited a decline. The adsorption of Pb(II) and Cd(II) metal ions over MgCF@SiO₂-CPTMS-Cur MNPs adsorbent was shown to conform most accurately to the model of Langmuir isotherm. Prior investigations and adsorption findings demonstrated significant promise for utilizing MgCF@SiO₂-CPTMS-Cur MNPs as an effectual adsorbent for environmental materials, specifically Pb and Cd metal ions. To evaluate the effectiveness of MgCF@SiO₂-CPTMS-Cur MNPs as an adsorbent, a comparison with different magnetic nanoparticle adsorbents in order to extraction of Pb and Cd metal ions is presented in Table 3. The MgCF@SiO₂-CPTMS-Cur MNPs adsorbent demonstrated a substantial effectiveness in achieving maximum capacity for adsorption for raised concentrations of Pb(II) and Cd(II) metal ions, smallest amount of adsorbent dosage, and optimal performing at the neutral pH used in this investigation.

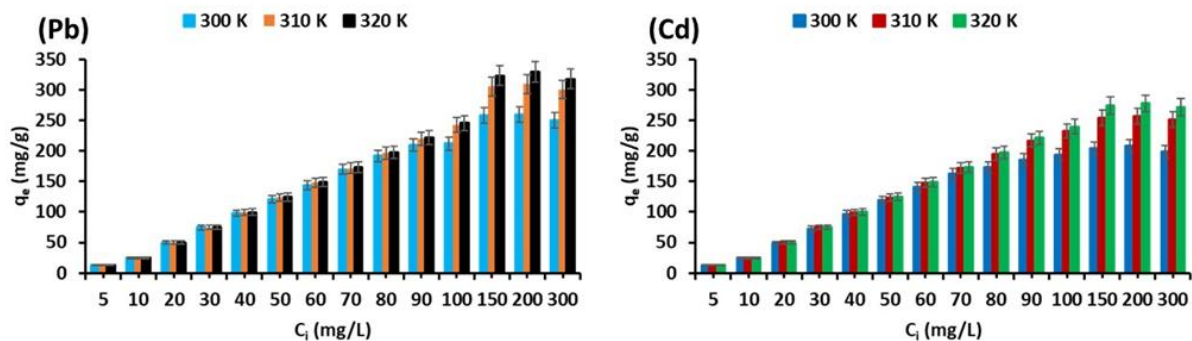


Fig. 12 The adsorption properties of MgCF@SiO₂-CPTMS-Cur MNPs were evaluated at initial concentrations among 5–300 mg/L of Pb(II) and Cd(II) at three temperatures (300, 310, and 320 K); Pb at pH 6 and Cd at pH 7; with dosage of 20 mg.

Table 2

The Langmuir, Freundlich, and Temkin isotherm parameters for the process of adsorbing of Pb(II) and Cd(II) ions utilising MgCF@SiO₂-CPTMS-Cur MNPs as the adsorbent (Pb at pH= 6 and Cd at pH=7; dosage = 20 mg; temperature = 300, 310, 320 K).

Adsorption models	Factors	Pb(II) metal ions			Cd(II) metal ions		
	Temp.	300 K	310 K	320 K	300 K	310 K	320 K
Langmuir	$q_m\ (exp.)\ (mg/g)$	259.50	309.50	329.57	208.35	257.10	277.90
	$q_m\ (mg/g)$	256.41	303.03	322.58	204.08	256.41	270.27
	$K_L(L/mg)$	1.1818	2.5384	4.4285	1.1395	3.5454	9.2500
	$R_L\ range$	0.0028-	0.0013-	0.0007-	0.0029-	0.0009-	0.0003-
		0.1264	0.0680	0.0414	0.1299	0.0506	0.0207
	R^2	0.9994	0.9998	0.9998	0.9994	0.9999	0.9999
	SSE	9.5465	41.856	48.920	18.218	0.4757	58.212
	χ^2	0.0372	0.1381	0.1516	0.0892	0.0018	0.2153
Freundlich	$q_m\ (mg/g)$	326.01	406.63	435.90	280.20	362.51	382.98
	$K_F\ (mg/g$						
	$(L/mg)1/n)$	103.48	135.38	153.05	72.486	119.88	151.97
	n	3.9793	3.9401	4.0338	3.5198	4.1356	4.8543
	R^2	0.9441	0.9347	0.9198	0.8931	0.8644	0.8773
	SSE	4424.2	9434.5	11307	5162.5	11112	11042
	χ^2	13.570	23.201	25.938	18.424	30.653	28.832
Temkin	$q_m\ (mg/g)$	245.77	291.71	309.64	215.18	263.91	289.57
	A	141.17	176.63	193.84	103.25	156.19	184.23
	B	22.907	26.557	27.430	22.889	23.540	21.251
	R^2	0.9111	0.9169	0.9255	0.9178	0.9396	0.9659
	SSE	188.42	316.44	397.02	46.714	46.478	136.41
	χ^2	0.7666	1.0847	1.2821	0.2170	0.1761	0.4710

Table 3

Comparison with various nanoparticle adsorbents utilized to remove of Pb(II) and Cd(II) metal ions.

Metal Ions	Adsorbent	pH	Time (min)	Adsorption capacity (mg/g)	Ref.
Pb	Fe ₃ O ₄ @TCA@CS (magnetic nanocomposite)	5.5	180	204.9	(Algamdi et al., 2023)
Pb	Fe ₃ O ₄ -GO/Ch beads	6	125	187.0	(Mishra & Tripathi, 2022)
Pb	ZnO NPs (Ocimum tenuiflorum)	7	20	25.00	(Elsamra et al., 2024)
Pb	MNPSS	6	60	277.7	(el Amine Zennaki et al., 2026)
Pb	Magnetic k-carrageenan/N-doped carbon dots (MMCG)	6	360	114.6	(Rahmani et al., 2022)
Pb	Fe ₃ O ₄ /SiO ₂ /PANI-SDBS	7	120	72.20	(Youssif & Wojnicki, 2025)
Pb	IONPs	6	60	128.0	(Rehman et al., 2023)
Pb	MgCF@SiO ₂ -CPTMS-Cur MNPs	6	240	259.5	Current study
Cd	tGO-Zeo (thiourea reduced GO/ NaA zeolite composite)	7	720	196.0	(Liu et al., 2020)
Cd	Fe ₃ O ₄ + Si-AN	8	60	65.00	(Younes et al., 2024)
Cd	Fe ₃ O ₄ @SiO ₂ -(TCT) ₂ -(NH ₂) ₂ NPs	7	20	115.7	(Zarabadipour et al., 2025)
Cd	nSiO ₂ -(TCT) ₂ -(NH ₂) ₂	7	28	69.00	(Zarabadipour et al., 2026)
Cd	ZnFe ₂ O ₄ NPs	6	15	152.4	(Zhao et al., 2022)
Cd	[NiFe ₂ O ₄ @BMSI]Br	7	180	106.0	(Naushad et al., 2023)
Cd	Fe ₃ O ₄ -CS (magnetic chitosan nanocomposite)	6	120	12.38	(ŞAHİN et al., 2023)
Cd	MgCF@SiO ₂ -CPTMS-Cur MNPs	7	240	208.35	Current study

3.2.5 Effect of thermodynamic evaluation and reaction temperature

The findings in Fig. 13 illustrate the impact of reaction temperature on the elimination proportion of metal ions Pb(II) and Cd(II). The proportion of removal escalates with rising reaction temperature, ascribed to the enhanced mobility

of Pb and Cd particles and the sufficient energy of ions to engage with the available sites on the modified nanoparticles' surface, peaking at 320 K.

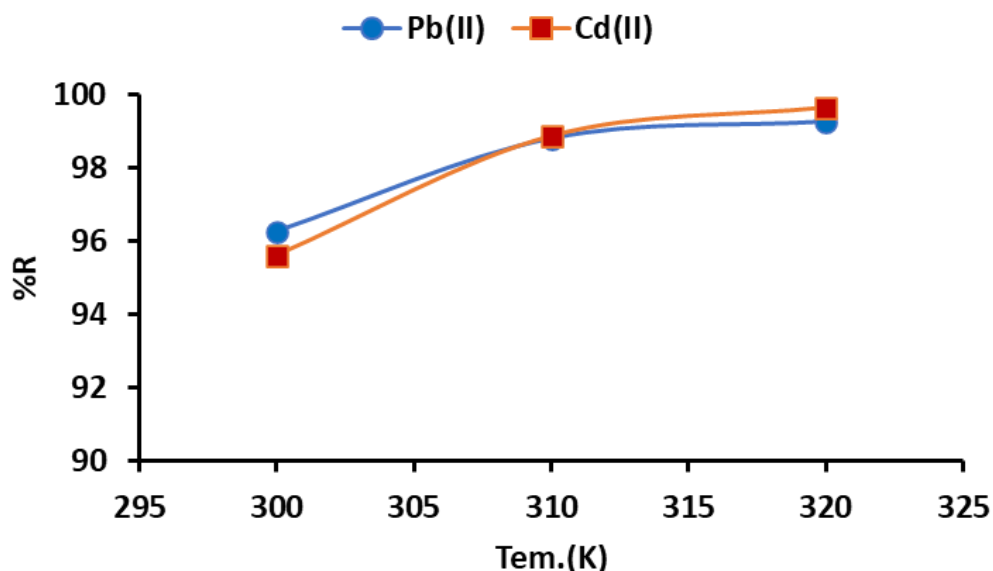


Fig. 13 Impact of temperatures on heavy metals Pb(II) and Cd(II) adsorption by MgCF@SiO₂-CPTMS-Cur magnetic nano-adsorbent

The thermodynamic parameters for Pb(II) and Cd(II) adsorption onto the MgCF@SiO₂-CPTMS-Cur magnetic nanoparticles adsorbent were determined using Eqs. (16) and (17) (Avrilia et al., 2025):

$$\ln(K_L) = -\frac{\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R} \dots \dots \dots (16)$$

$$\Delta G^\circ = -RT\ln(K_L) \dots \dots \dots (17)$$

Where T denotes temperature (K), R and K_L represent the gas constant (8.314 J mol⁻¹ K⁻¹) and the Langmuir constant (L mg⁻¹), respectively. The standard enthalpy change (ΔH°, J mol⁻¹), standard entropy change (ΔS°, J mol⁻¹ K⁻¹), and standard Gibbs free energy change (ΔG°, J mol⁻¹) are presented.

The values of ΔH° and ΔS° were derived based on the intercept and slope of the linear graph of ln K_L against 1000/T (Fig. S7). The standard Gibbs free energy change (ΔG°) at the designated temperatures of 300, 310, and 320 K was determined utilizing Equation (16). In Table 4 displays the computed thermodynamic parameters. The elevated figures

indicated an effective sorption system. The ΔG° values ranged from -0.4166 to -3.9589 and -0.3257 to -5.9185 (kJ/mol), affirming the spontaneous adsorption of Pb(II) and Cd(II) metal ions onto the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent at the designated temperatures.

The favourable values of ΔH° (52.788 and 83.613 kJ/mol) suggest that the adsorption of Pb(II) also Cd(II) metal ions onto the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent at the designated temperatures is an endothermic process. Additionally, the sorption process may be either chemisorption or physisorption based on ΔH° values for sorption energy. The usual energy values of van der Waals forces and hydrogen bonds are 4 to 8 KJ mol⁻¹ and 8 to 40 KJ mol⁻¹, respectively. The enthalpic demand for chemisorption should therefore possess energies about 40 kJ mol⁻¹, considered the threshold for transition energy (Omar et al., 2026). Thus, it can be deduced that the adsorption of Pb(II) and Cd(II) metal ions on the MgCF@SiO₂-CPTMS-Cur MNPs adsorbent transpires through chemisorption. The elevated ΔS° values (177.57 and 279.94 kJ/mol) at the designated temperatures reflect the disorder at the solid-liquid interface, hence promoting the adsorption of Pb and Cd metals correspondingly.

Table 4

Thermodynamic characteristics for the adsorption of Pb(II) and Cd(II) metal ions onto the MgCF@SiO₂-CPTMS-Cur magnetic nanoparticle adsorbent at varying temperatures. (Nanoparticle dosage set at 20 mg; volume equals 100 mL; pH maintained for Pb at 6 and Cd at 7).

Temperature (K)	ΔH° (KJ/mol)		ΔS° (J/mol K)		ΔG° (KJ/mol)	
	Pb(II)	Cd(II)	Pb(II)	Cd(II)	Pb(II)	Cd(II)
300					-0.4166	-0.3257
310	52.788	83.613	177.57	279.94	-2.4009	-3.2620
320					-3.9589	-5.9185

3.3 Potential mechanism of adsorption

The elemental compositions of MgCF@SiO₂-CPTMS-Cur prior to and subsequent to the adsorption of Pb(II) and Cd(II) were assessed via EDX analysis (Fig. 3a, b, and c). The EDX spectrum prior to adsorption indicated the existence of C, O, Mg, Si, Fe, and Co, confirming the elemental makeup of the synthesised adsorbent. Subsequent to Pb(II) adsorption, a novel Pb signal was identified at a concentration of 0.61 wt%, whereas no Pb signal was observed before to the adsorption. A novel Cd signal with a concentration of 0.59 wt% was detected following the adsorption of Cd. The emergence of Pb(II) and Cd(II) signals post-adsorption and the spatial distribution of Pb and Cd in the elemental mapping (Fig. S8) validate the existence of these metal ions on the surface of the adsorbent in the time of adsorption process.

Additionally, to ascertain the surface charge of MgCF@SiO₂-CPTMS-Cur at different initial pH values, an examination of the point of zero charge (pHpzc) was conducted in accordance with the experimental study (section 3.2.1: Impact of pH). The adsorbent exhibited a negative surface charge for Pb at pH and for Cd at pH 7 under the

experimental adsorption conditions applied in this research. The adverse surface charge may be associated with the deprotonation of oxygenated functional groups on the superficie of the modified adsorbent. Consequently, the electrostatic interactions can draw the positively charged Pb(II) and Cd(II) entities toward the negatively charged superficie. Curcumin's oxygen-containing moieties may also participate to the adsorption process by interacting with metal ions or forming complexes. The β -diketo functional group of curcumin may serve as a binding site for Pb(II) and Cd(II). The findings suggest that the potential mechanisms for the adsorption of Pb and Cd onto MgCF@SiO₂-CPTMS-Cur involve complexation/coordination and electrostatic interactions, as depicted in Fig. 14.

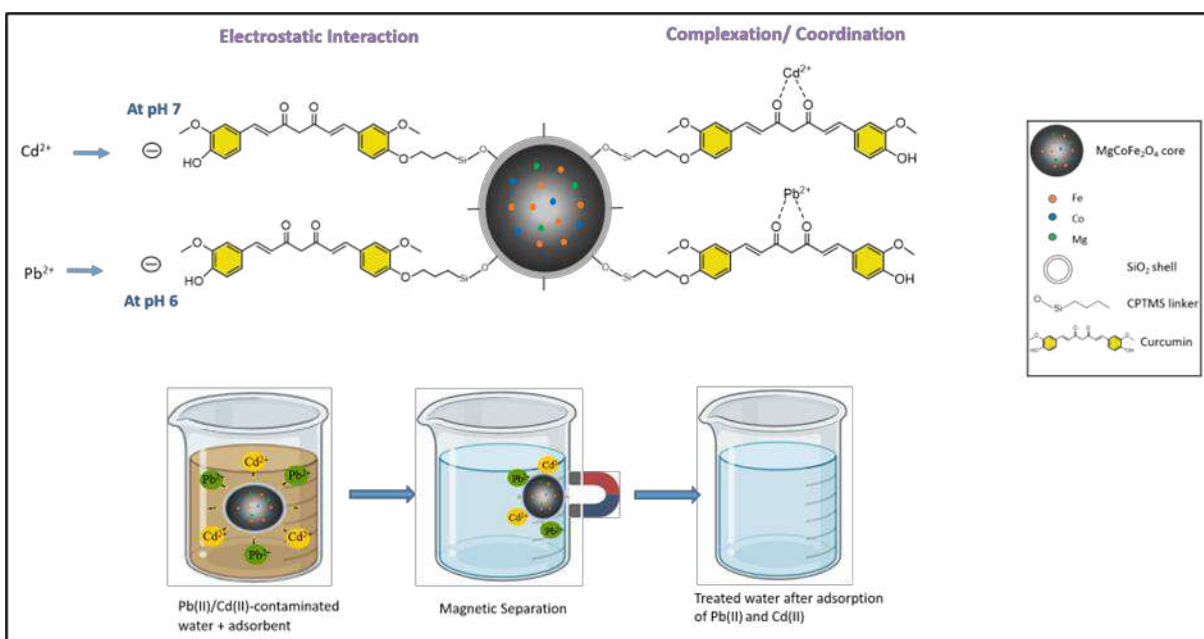


Fig. 14 Proposed adsorption mechanisms for Pb(II) and Cd(II) on the MgCF@SiO₂-CPTMS-Cur NPs and its magnetic separation from aqueous solution.

3.4 The adsorbents recyclability and regeneration

The capacity to regenerate and recycle adsorbents is crucial for their practical application, since these factors directly affect operational efficiency and economic viability. The potential for the reutilization of MgCF@SiO₂-CPTMS-Cur for the adsorption of Pb(II) and Cd(II) metal ions was investigated over four consecutive cycles to assess this property Fig. (15). After each round, the adsorbent was extracted out of the suspension using magnetic separation, completely cleaned with deionized water till achieving a neutral pH prior to reuse, and dried for five hours at 100 °C. The desorption efficiency diminished from 96.1% to 72.4%, whereas the efficiency of removal of Pb(II) metal declined

from 96.2% in the initial cycle to 75.8% in the fourth cycle. During the identical cycles, the desorption efficiency diminished from 95.5% to 70.6%, while the efficiency of removal of Cd(II) metal fell from 95.6% to 73.2%. The ongoing decline is ascribed to the partial retention of Pb or Cd metal ions on the adsorbent surface, which obstructs the active sites, along with minor loss or reorganization of active components during successive adsorption-desorption cycles. This reduction was coupled with a favourable regeneration capability of the MgCF@SiO₂-CPTMS-Cur, demonstrating suitable adsorption efficacy after four cycles.

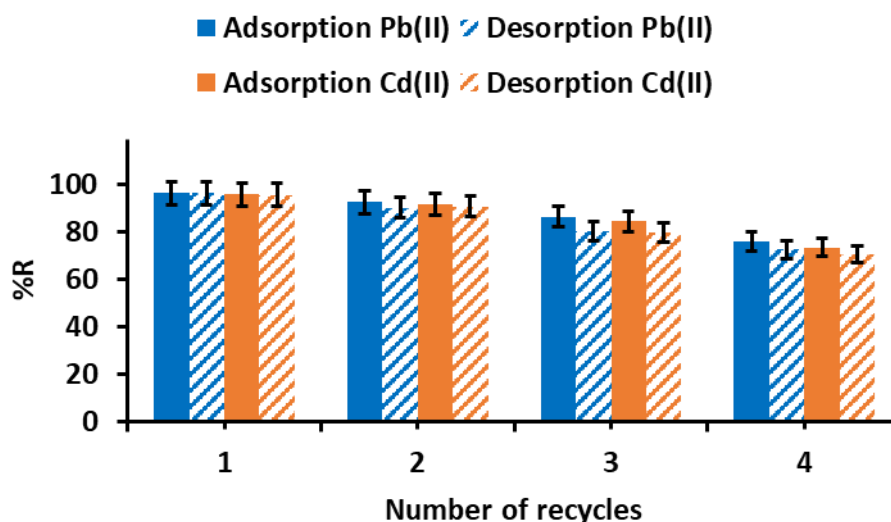


Fig. 15 Reusability of the MgCF@SiO₂-CPTMS-Cur NPs adsorbent for the removal of Pb(II) and Cd(II) over four consecutive adsorption- desorption cycles.

3.5 Use in samples of the environment

The actual water samples were revealed to include diverse anions and cations apart from Pb(II) and Cd(II) metal ions. Table S2 showcases the exact ionic profiles of real water samples from tap, groundwater, and lake sources. The MgCF@SiO₂-CPTMS-Cur magnetic nanoparticles were utilized to extract Pb(II) and Cd(II) metal ions from the three genuine water samples. According to Fig. 16, the three authentic water samples exhibited significant adsorption capabilities for Pb and Cd, with elimination efficiencies nearing 95%. As a result, the existence of alternative metal ions in various real-world water samples might improve the uptake of heavy metals.

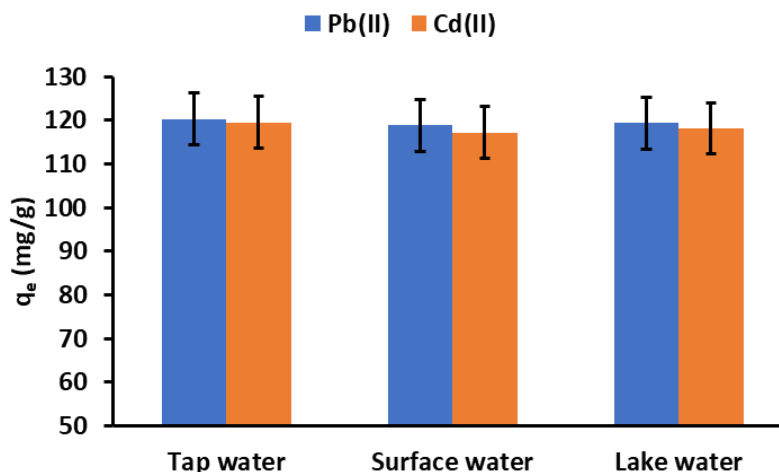


Fig. 16 Adsorption capacities of the MgCF@SiO₂-CPTMS-Cur NPs adsorbent for Pb(II) and Cd(II) ions in different real water specimens.

Conclusion

This investigation reveals a strategy for the remediation of designated heavy-metal pollutants (Pb and Cd) in wastewater with MgCF@SiO₂-CPTMS-Cur nanoparticles. In this investigation, magnetic magnesium-doped CoFe₂O₄ nanoparticles were effectively produced through the coprecipitation approach. The nanoparticles were encased in a silica layer and thereafter treated with chloropropyl groups utilizing 3-chloropropyltrimethoxysilane (CPTMS). Major treatment with curcumin (Cur) yielded a considerable augmentation of the nanoparticle's adsorption traits. Lead (Pb) and cadmium (Cd) were effectively removed from real-world water samples using the prepared MgCF@SiO₂-CPTMS-Cur nanoparticles revealed as a magnetic high nano-adsorbent. Modification of the surface augments the availability of active binding sites, which assists in the adsorption of Pb(II) and Cd(II) through the combined effects of (a) complexation/coordination and (b) electrostatic interaction. The Langmuir isotherm model provided an effective explanation for the equilibrium results. Moreover, the mechanism of adsorption was consistent along with the second-order kinetic model as indicated by the kinetic research. It denotes that the chief category of adsorption is chemisorption with a homogeneous monolayer. Furthermore, thermodynamic computations implied the process of adsorption was both endothermic and beneficial, occurring spontaneously. The maximum adsorption capabilities were established at 259.50 mg/g to lead and 208.35 mg/g to cadmium. In addition, the MgCF@SiO₂-CPTMS-Cur nanoparticles shown exceptional recyclability and retained significant adsorption-desorption efficiency across four repeated cycles. As a result, this paper reveals a budget-friendly and environmentally benign adsorbent with remarkable capabilities for wastewater treatment and the extraction of the heavy metals. The performance of this exceptional adsorbent for Pb and Cd metal ions removal from three authentic water samples (tap, groundwater, and lake water) has been confirmed. The findings obtained demonstrate the potential of the synthesized substance for practical application in water treatment, particularly for the elimination of Pb(II) and Cd(II), and as a preliminary analytical process for heavy metals extraction from genuine aqueous samples.

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Author Contributions

Hawar J. Sadiq Hawezy: Investigation, Writing – original draft, Methodology, Validation, Software, Data curation, and Resources. **Layth I. Abd Ali:** Investigation, Formal analysis, conceptualization, Writing – review & editing, Project administration, and supervision.

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Data Availability

All data that support the findings of this study are included within the article.

Declarations

Competing Interest

The authors declare no competing interests.

Consent to Participate

The research does not involve human subjects, therefore "Consent to Participate" is not applicable.

Consent to Publication

The research does not involve human subjects, therefore "Consent to Publish" is not applicable.

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