

Article

Structural and Surface Properties of CeO₂ Nanoparticles for Enhanced Lead Ion Removal

Bakheit Mustafa * and Ard Elshifa M. E. Mohammed 

Department of Chemistry, College of Science, Qassim University, Buraidah 51452, Saudi Arabia

* Correspondence: b.salih@qu.edu.sa

Abstract

In this study, cerium oxide (CeO₂) nanoparticles were successfully synthesized using a simple and cost-effective hydroxide-mediated precipitation method. Comprehensive characterization (XRD, SEM, TEM, FTIR, BET, and UV-Vis) confirmed the formation of uniformly distributed nanoparticles with an average size of ~100 nm, a well-defined crystalline structure, and a high specific surface area of 118.96 m²/g. The CeO₂ nanoparticles also exhibited a mesoporous framework with a pore volume of 0.39 cm³/g and an average pore radius of 2.27 nm, demonstrating favorable properties for adsorption applications. Adsorption experiments showed that CeO₂ nanoparticles effectively removed Pb²⁺ from aqueous solutions, achieving a maximum experimental adsorption capacity of 192 mg/g and a removal efficiency of 80% at pH 6 under the tested conditions. Kinetic analysis revealed that the pseudo-second-order model best described the adsorption process, suggesting chemisorption as the dominant mechanism, while equilibrium data were more accurately represented by the Langmuir isotherm model, which predicted a theoretical monolayer capacity (Q_m) of 714.2 mg/g. Overall, the findings demonstrate that CeO₂ nanoparticles possess a strong affinity toward Pb²⁺ ions and exhibit promising adsorption performance, indicating their potential applicability for the treatment of lead-contaminated wastewater and their suitability for reuse following regeneration.

Keywords: cerium oxide nanoparticles; lead removal; adsorption; Langmuir isotherm; wastewater treatment

1. Introduction

Heavy metal pollution from industrial activities poses serious threats to both environmental and human health [1,2]. Among these contaminants, lead (Pb²⁺) is one of the most toxic and persistent metals found in wastewater generated by battery manufacturing, mining operations, electroplating industries, and pigment production [3,4]. Even at trace levels, lead exposure can cause severe neurological, renal, cardiovascular, and developmental disorders [5,6]. The toxicity of lead is primarily attributed to its ability to generate reactive oxygen species (ROS), deplete antioxidants such as glutathione, and induce oxidative stress, ultimately causing lipid peroxidation, protein oxidation, and DNA damage [7]. In aquatic environments, Pb²⁺ disrupts membrane integrity and central nervous system function in marine organisms. Lead accumulates in fish gills during respiration, contributing to food-chain contamination and posing health risks to humans [7,8].

Lead naturally exists in human tissues at minimal levels (10 µg/dL for adults and 1.4 µg/dL for children), but concentrations beyond these limits are associated with significant health concerns, such as reproductive impairment and fetal development disor-



Academic Editor: Mingheng Li

Received: 4 November 2025

Revised: 18 December 2025

Accepted: 19 December 2025

Published: 9 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

ders [9,10]. At high exposure levels, lead can cause serious damage to the nervous system, kidneys, and skeletal tissues [7]. Regulatory agencies have established strict limits to minimize exposure: the U.S. Environmental Protection Agency (EPA) sets the permissible concentration for Pb^{2+} in wastewater at 50 $\mu\text{g/L}$ [11], while the maximum contaminant level (MCL) for drinking water is 0.03 $\mu\text{M/L}$ [7]. These constraints highlight the urgent need for efficient, economical, and environmentally safe technologies for lead removal.

Several conventional methods, such as chemical precipitation [12], ion exchange [13], membrane filtration [14], bioremediation [15], photocatalysis [16], electrocoagulation [17], and electrochemical treatments [18], have been used to remove lead from contaminated water. However, these techniques often suffer from high operational costs, low selectivity, the need for chemical additives, and limited effectiveness at low metal concentrations. In contrast, adsorption has emerged as a highly promising alternative due to its simplicity, cost-effectiveness, environmental compatibility, and ability to efficiently remove metal ions even at low concentrations [19–21].

A variety of adsorbents, including activated carbon [22], clays [23], algae-based biosorbents [24], and chitosan [25], have been studied for Pb^{2+} removal. Despite their advantages, many of these materials show limited adsorption capacity, poor regeneration ability, or insufficient selectivity. Recently, nanomaterials have gained significant attention as high-performance adsorbents owing to their large surface area, tunable surface chemistry, and enhanced reactivity. For instance, magnetic nanoparticles [26], silver nanoparticles [27], and zinc oxide nanoparticles [28] have demonstrated exceptional lead removal efficiency and improved reusability. Functionalization of nanomaterials with specific chemical groups can further enhance selectivity in complex water matrices.

Among various nanomaterials, cerium oxide nanoparticles (CeO_2 NPs) have attracted increasing attention due to their unique physicochemical properties, including high oxygen storage capacity, redox activity, thermal stability, and surface reactivity [29,30]. These characteristics make CeO_2 a promising material for catalysis, sensing, biomedical applications, and environmental remediation. However, despite growing interest, the use of CeO_2 specifically as an adsorbent for Pb^{2+} ions remains relatively underexplored. Reported adsorption capacities vary widely, likely due to differences in synthesis methods and resulting surface properties. For example, $\text{CeO}_2/\text{CuFe}_2\text{O}_4$ nanofibers achieved a maximum Pb^{2+} adsorption of 972.4 mg/g [31], whereas CeO_2 nanoparticles alone showed a significantly lower capacity of 128.1 mg/g [32].

Cerium oxide (CeO_2) nanoparticles have attracted considerable attention in environmental remediation due to their high chemical stability, strong redox activity associated with the $\text{Ce}^{3+}/\text{Ce}^{4+}$ couple, and abundant surface oxygen vacancies. These physicochemical properties promote strong interactions with heavy metal ions, making CeO_2 nanoparticles promising adsorbents for wastewater treatment applications. In the present study, pristine CeO_2 nanoparticles were intentionally selected as a model material to systematically investigate their adsorption performance toward Pb^{2+} ions and to establish fundamental structure–adsorption relationships under controlled experimental conditions. The insights gained from this work are expected to provide a reliable reference for the future design of modified or composite CeO_2 -based materials with enhanced efficiency and environmental safety.

Various synthesis methods have been developed for the preparation of cerium oxide nanoparticles, including hydrothermal and solvothermal processes, sol–gel techniques, combustion synthesis, and precipitation methods. Each route produces CeO_2 with distinct structural and surface properties. Hydrothermal and solvothermal methods typically yield highly crystalline nanoparticles but require high temperatures, long processing times, and pressurized equipment. Sol–gel and combustion synthesis allow for composi-

tional control but may lead to residual impurities and broad particle size distributions. In contrast, hydroxide-mediated precipitation is simple, cost-effective, and easily scalable, producing well-dispersed nanoparticles with tunable particle size, high oxygen-vacancy concentrations, and reactive surface sites. These defect-rich surfaces significantly enhance the adsorption affinity toward metal ions such as Pb^{2+} . For these reasons, the precipitation method was selected in the present study to obtain CeO_2 nanoparticles optimized for high surface reactivity and efficient heavy-metal removal.

Given these gaps, this study focuses on the synthesis of CeO_2 nanoparticles via a simple, low-cost hydroxide-mediated precipitation method capable of producing well-dispersed nanomaterials. The synthesized CeO_2 nanoparticles were comprehensively characterized to evaluate their structural, morphological, and physicochemical properties. Their adsorption performance toward Pb^{2+} ions in aqueous media was systematically investigated under varying operational parameters. Additionally, adsorption kinetics and isotherm models were analyzed to better understand the mechanism and efficiency of lead removal. This work aims to demonstrate the potential of CeO_2 nanoparticles as an effective, sustainable adsorbent for treating lead-contaminated water and to provide a foundation for the future development of advanced nanomaterials for environmental remediation.

2. Materials and Methods

2.1. Reagents

Cerium nitrate hexahydrate [$\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$], ammonium hydroxide (NH_4OH), Lead Nitrite ($\text{Pb}(\text{NO}_3)_2$) and methanol were purchased from Sigma-Aldrich (St. Louis, MO, USA).

2.2. Instrumentation

2.2.1. UV–Visible Spectroscopy

UV–visible absorption spectra were recorded using a PerkinElmer Lambda 950 UV–Vis spectrophotometer between 200 and 800 nm. The CeO_2 nanoparticle samples were dispersed in distilled water and analyzed at room temperature.

2.2.2. FT-IR Spectroscopy

The FTIR spectra of the synthesized cerium oxide nanoparticles (CeO_2 NPs) were obtained using a FTIR spectra were recorded using a PerkinElmer Spectrum FTIR spectrometer (PerkinElmer Inc., Waltham, MA, USA). The measurements were carried out in the spectral range of $4000\text{--}400\text{ cm}^{-1}$ to identify the functional groups and metal–oxygen vibrations associated with Ce–O bonding.

2.2.3. Transmission Electron Microscopy (TEM)

High-resolution transmission electron microscopy (HRTEM) was performed using JEOL JEM-2100F transmission electron microscope (JEOL Ltd., Tokyo, Japan) (or equivalent) running at a higher speed voltage of 200 kV. To prepare the samples, a small amount of the nanoparticle dispersion was placed on a copper grid coated with a thin carbon film and allowed to dry under ambient conditions.

2.2.4. Scanning Electron Microscopy (SEM)

SEM imaging was performed using a JEOL JCM-5100 scanning electron microscope (JEOL Ltd., Tokyo, Japan) operated via a dedicated computer workstation. This provided morphological characterization of the synthesized nanomaterials.

2.2.5. X-Ray Diffraction Analysis

Powder X-ray diffraction (PXRD) measurements were performed using a Bruker D8 Advance diffractometer (Bruker AXS SE, Karlsruhe, Germany) fitted with a Cu K α radioactive source ($\lambda = 1.5406 \text{ \AA}$), running at 40 mA and 40 kV in Bragg–Brentano geometry.

2.2.6. Energy-Dispersive X-Ray Spectroscopy

The evaluations were conducted using a JEOL JED-2200 energy-dispersive X-ray (EDX) system coupled with a scanning electron microscope (JEOL Ltd., Akishima, Tokyo, Japan). The evaluations were conducted in high vacuum with an enhanced charge of 20 kV. Characteristic X-ray emissions were analyzed to identify the elemental composition. The resulting spectra were processed using standard ZAF (atomic number, absorption, and fluorescence) corrections for semi-quantitative analysis.

2.2.7. Brunauer–Emmett–Teller (BET) Surface Area Analysis

The Micrometrics ASAP 2020 surface space and pore analyzer was used to determine particular surface areas and pore properties. The nitrogen adsorption–desorption isotherms were studied at 77 K ($-196 \text{ }^{\circ}\text{C}$) after specimens had been degassed at $120 \text{ }^{\circ}\text{C}$ under vacuum for 12 h. The BET surface area was approximated from the adsorption values within the corresponding pressure band $P/P_0 = 0.05\text{--}0.30$ using the BET equation. The total volume of pore space was computed at $P/P_0 \approx 0.99$, and pore size distribution was derived from the desorption branch using the Barrett–Joyner–Halenda (BJH) method.

2.2.8. Thermogravimetric Analysis (TGA)

Thermal resistance was determined using a NETZSCH TG 209 F1 thermogravimetric analyzer (TGA) (NETZSCH-Gerätebau GmbH, Selb, Germany). A catalytic powder sample weighing 6.575 mg was put in a vessel made of alumina and subjected to heating from ambient temperature to $800 \text{ }^{\circ}\text{C}$. at a constant heating speed of 10 K/min in an air atmosphere. Mass loss was monitored to evaluate thermal degradation behavior.

2.3. Synthesis of Cerium Oxide Nanoparticles

A hydroxide-mediated precipitation method was employed due to its effectiveness in producing uniformly dispersed CeO_2 nanoparticles, as reported in previous studies [1,2]. First, a 0.2 M solution of cerium nitrate hexahydrate [$\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$] and a 0.6 M ammonium hydroxide (NH_4OH) solution were prepared by dissolving the respective reagents in 100 mL of distilled water in separate 200 mL beakers. The NH_4OH solution was transferred to a clean burette, positioned above a beaker containing the cerium nitrate solution, and placed on a magnetic stirrer. Under continuous stirring, the ammonium hydroxide was added slowly and dropwise to the cerium nitrate solution until complete precipitation was achieved.

The resulting suspension was centrifuged at 6000 rpm for 20 min, and the supernatant was decanted. The precipitate was washed three times with distilled water and once with methanol to remove remaining ions and soluble impurities. The purified solid was then dried in a vacuum oven at $110 \text{ }^{\circ}\text{C}$ for 12 h. After drying, the material was gently ground using a mortar and pestle to obtain a fine powder. Finally, to ensure complete dehydration and improve crystallinity, the powder was calcined at $500 \text{ }^{\circ}\text{C}$ for 3 h in air, which improves dehydration, crystallinity, and removal of organic residuals commonly associated with precipitation methods, yielding the final CeO_2 nanoparticles.

2.4. Adsorption Experiments

Batch experiments were performed to investigate the efficient elimination of lead ions from sewage. Several factors influencing adsorption performance were investigated.

A model Pb^{2+} solution was prepared by dissolving an accurately measured amount of $\text{Pb}(\text{NO}_3)_2$ in distilled water, followed by ultrasonic treatment for 30 min to ensure complete dissolution and homogenization. Cerium oxide (CeO_2) was used as the adsorbent to assess the consequences of various parameters, including interaction time, dosage, temperature, and pH. In addition, after analyzing the experimental data, the kinetics and mechanism of the adsorption process were explored. R represents the removal efficiency (%), indicating the proportion of Pb^{2+} removed from the solution, and the adsorption capacity (q_e) was determined using the following formulas:

$$R = \frac{(C_0 - C)}{C_0} \times 100\% \quad (1)$$

$$q_e = \frac{(C_0 - C)}{C_0} \times \frac{V}{m} \quad (2)$$

In this context, R reflects the speed of removal (%), q_e denotes the adsorption capacity (mg/g), C_0 is the initial concentration of the wastewater sample (mg/L), C is the final concentration of the wastewater after adsorption (mg/L), and V refers to the volume of the wastewater sample.

2.5. Kinetic Adsorption Studies

To investigate the adsorption kinetics and determine the equilibrium time, a fixed amount of CeO_2 was added to Pb^{2+} solutions and agitated over various time intervals at a constant temperature ($^{\circ}\text{C}$).

3. Results and Discussion

3.1. Nanoparticle Characterization

3.1.1. Chemical Structural Investigation

The chemical structure of the synthesized CeO_2 nanoparticles was thoroughly investigated using a variety of analytical techniques, including UV-visible (UV-Vis) spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, and X-ray photoelectron spectroscopy (XPS). In the ultraviolet region, cerium atoms within the CeO_2 lattice are capable of absorbing photons, which excite outer electrons to higher energy states. As a result, the UV-Vis absorption spectrum was examined to probe these electronic transitions. Figure 1a presents the UV-visible optical absorption spectra of the synthesized CeO_2 nanoparticles across the electromagnetic wavelength range from 200 to 600 nm. The UV-Vis spectrum of CeO_2 nanoparticles reveals a distinct absorption band at 269 nm, a feature in line with the standard electrical structure of CeO_2 . This absorption profile confirms the successful synthesis of CeO_2 nanoparticles, in agreement with previous reports [33,34]. FTIR spectroscopy is a powerful analytical method used to identify the chemical composition and functional groups in organic, polymeric, and occasionally inorganic materials. The FTIR spectrum of the synthesized CeO_2 nanoparticles, shown in Figure 1b, was captured over the entire range of $400\text{--}4000\text{ cm}^{-1}$, providing insights into the characteristic chemical bonds and functional arrangements found in the substance. The observed peaks in the FTIR spectrum of the CeO_2 nanoparticles (2370 , 2171 , 2090 , 1973 , 1003 , 868 , and 500 cm^{-1}) correspond to typical vibrational modes of CeO_2 . The peaks at 2370 cm^{-1} and 2171 cm^{-1} are attributed to surface adsorption of atmospheric CO_2 or residual carbon-containing species, as well as O–H vibrations associated with moisture or surface hydroxyl groups. Such features are standard in nanoparticle samples, which are susceptible to environmental exposure. The 2090 cm^{-1} and 1973 cm^{-1} peaks are attributed to oxygen vacancies or surface defects, a hallmark characteristic of CeO_2 nanoparticles. These peaks are indicative of the presence of Ce^{3+}

defects or local vibrational modes associated with oxygen vacancies, which are essential for the catalytic function of CeO₂. The 1003 cm⁻¹ and 868 cm⁻¹ peaks correspond to the well-known F2g and T2g vibrational modes of the CeO₂ lattice, reflecting the symmetric stretching of oxygen ions and lattice vibrations, respectively. These are key features of the CeO₂ fluorite structure and confirm the material's crystallinity. Lastly, the 500 cm⁻¹ peak is attributed to low-frequency lattice vibrations or defect-related modes, commonly observed in nanoparticles since they are smaller than bulk and have a different surface-to-volume relationship than CeO₂ [35].

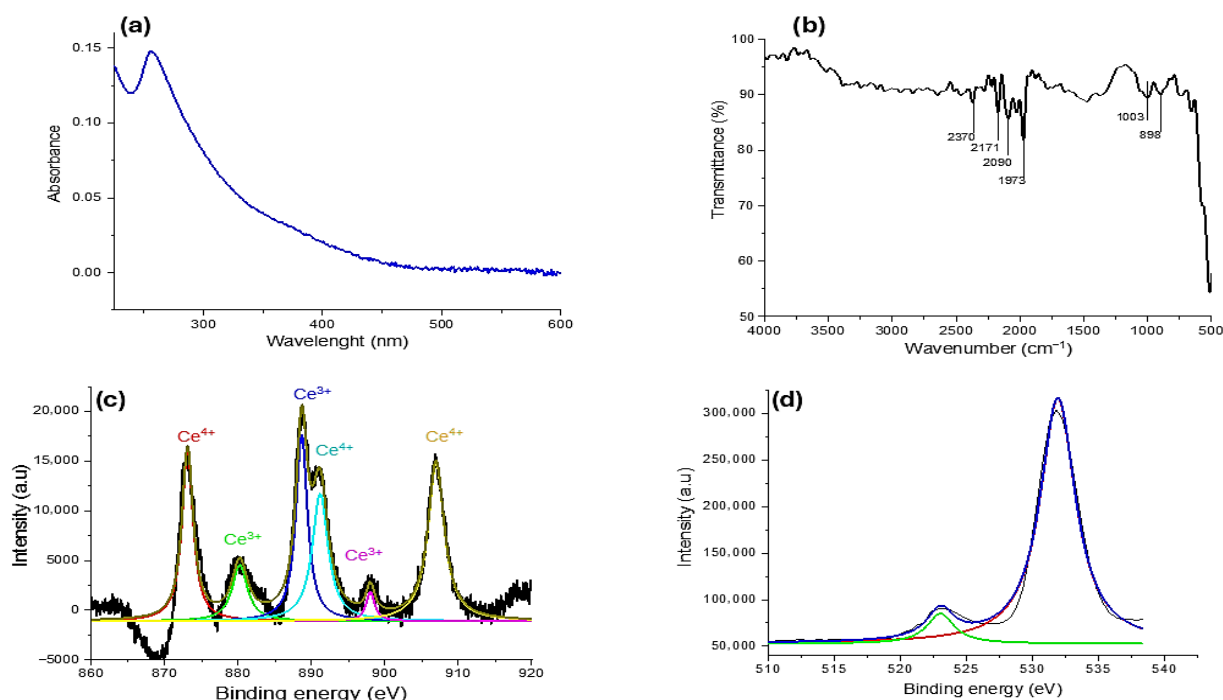


Figure 1. (a) UV spectra of CeO₂; (b) FTIR spectra of CeO₂; (c) high-resolution XPS spectra of Ce (3d); and (d) high-resolution XPS spectra of O (1 s) of CeO₂.

Figure 1c displays the high-quality X-ray photoelectron spectroscopic (XPS) spectrum of cerium (Ce), which clearly reveals the 3d spin-orbit splitting states: 3d_{5/2} and 3d_{3/2}. The highest values observed at binding forces (BE) of 906.6 eV and 891.9 eV correspond to the Ce⁴⁺ 3d_{3/2} and Ce⁴⁺ 3d_{5/2} states, respectively. These peaks are characteristic of the Ce⁴⁺ oxidation state in the CeO₂ lattice. Furthermore, the peaks at 897.2 eV and 886.7 eV are ascribed to the Ce³⁺ 3d_{3/2} and Ce³⁺ 3d_{5/2} states, indicative of Ce³⁺ species, which typically arise due to the presence of oxygen vacancies in the material. These findings are consistent with previous reports in the literature [36–38], confirming the coexistence of Ce⁴⁺ and Ce³⁺ species in CeO₂ nanoparticles. Furthermore, the deconvoluted peaks at 874.0 eV and 880.1 eV are allocated to the ‘shake-up’ remote functionalities of Ce, which are characteristic of the Ce³⁺ oxidation state. These satellite peaks are often observed due to strong electron-electron interactions within the cerium 3d orbitals. The presence of these features suggests that the CeO₂ nanoparticles contain a significant number of Ce³⁺ species, which can be explained by vacant oxygen spaces in the structure, facilitating the transformation between Ce³⁺ and Ce⁴⁺ states. Figure 1d displays the O 1s XPS spectrum of the CeO₂ nanoparticles, which was deconvoluted into two distinct peaks. The central peak at 532.5 eV (O_a) is ascribed to lattice oxygen (O²⁻), a characteristic feature of the cubic fluorite structure of CeO₂ [36–38]. The peaks at 522.5 eV (O_β) and (O_c) are attributed to oxygen vacancies and adsorbed oxygen species on the cerium surface. The presence of these surface oxygen species further supports the idea that oxygen vacancies play an

essential part in the transformation of Ce^{3+} to Ce^{4+} and may influence the material's catalytic properties. These results are consistent with earlier investigations. [36–38], which highlight the significance of oxygen vacancies in the structural and electronic properties of CeO_2 nanoparticles.

3.1.2. Elemental and Structural Analyses

The elemental composition and structural characteristics of the synthesized CeO_2 nanoparticles were thoroughly studied. Figure 2a displays the X-ray diffraction pattern of the as-produced CeO_2 nanoparticles. The diffraction peaks observed at 2θ values of 28° , 32.5° , 47° , 56° , 59° , and 69° correspond to the (111), (200), (220), (311), (222), and (400) lattice planes, respectively. These well-defined peaks confirm the crystalline nature of the CeO_2 nanoparticles, indicating that the material adopts a highly ordered structure. The results are consistent with the standard cubic fluorite structure of CeO_2 [39,40]. These values align well with the literature-reported data for cerium oxide (JCPDS 43-1002), further validating the crystalline structure of the synthesized nanoparticles. The agreement between the experimental results and the standard references highlights the successful fabrication of crystalline CeO_2 nanoparticles with a well-defined cubic structure.

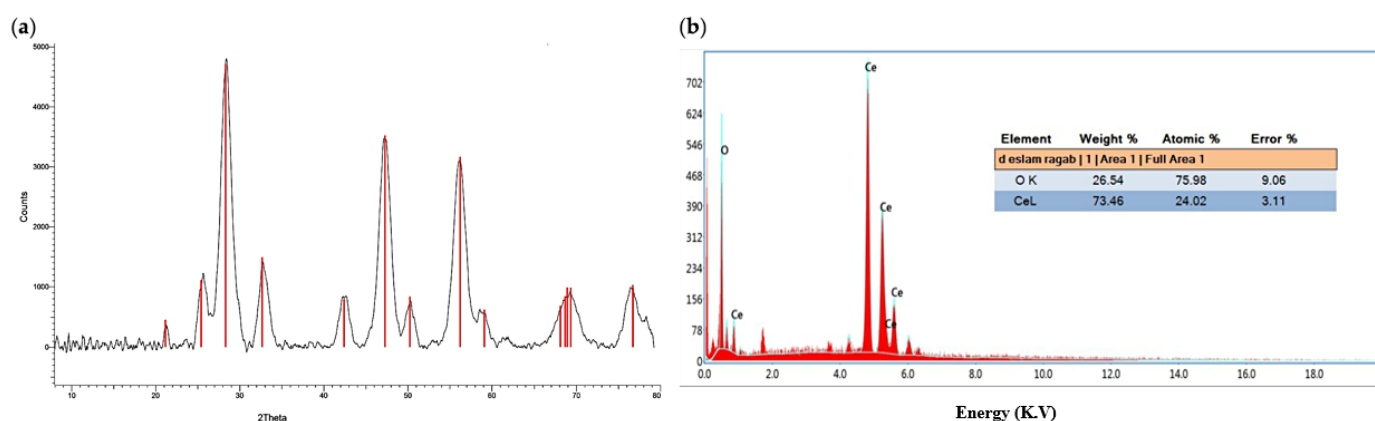


Figure 2. (a) XRD spectra of CeO_2 ; (b) EDX spectra of CeO_2 .

The energy-dispersive X-ray spectroscopy provides further confirmation of the elemental composition of the synthesized CeO_2 nanoparticles, specifically the presence of cerium (Ce) and oxygen (O). Figure 2b illustrates the elemental composition of the CeO_2 sample, as established by EDX. The spectrum shows a prominent peak corresponding to the Ce $L\alpha$ X-ray emission, accompanied by a smaller but distinct peak for O $K\alpha$ X-ray emission, indicating the successful incorporation of both cerium and oxygen in the material. These findings confirm the presence of Ce and O as the primary constituents of the annealed CeO_2 sample. The observed peaks are consistent with the expected stoichiometric composition of CeO_2 , further validating the synthesis process and the elemental purity of the nanoparticles.

3.1.3. Microscopy Techniques

The morphology and structural features of the synthesized CeO_2 nanoparticles were examined using high-resolution TEM (HRTEM) and SEM (Figure 3). The updated HRTEM images (Figure 3a–c), recorded at nanometer-scale magnifications (50–100 nm), clearly reveal the crystalline nature of the nanoparticles, with well-defined lattice fringes visible in the magnified insets. These fringes confirm the formation of CeO_2 with distinct interplanar spacing. The nanoparticles appear moderately dispersed with limited agglomeration, which is commonly observed in metal oxide systems.

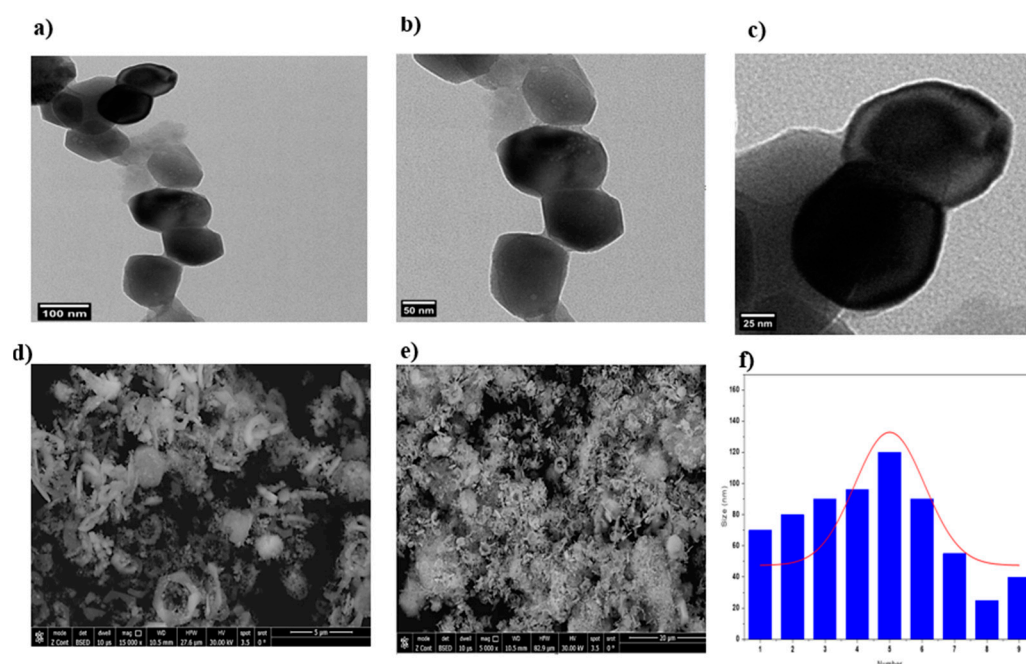


Figure 3. HRTEM images: (a) 100 nm; (b) 75 nm; (c) 50 nm; SEM images at: (d) 100 nm; (e) 50 nm; and (f) particle size distribution histogram of CeO₂ nanoparticles.

The high-magnification SEM micrographs (Figure 3d,e) provide additional visualization of the particle morphology and surface texture. The nanoparticles exhibit a predominantly spherical shape with a noticeably rough surface, which may contribute to enhanced surface reactivity and adsorption capability. The particle size distribution histogram (Figure 3f) indicates a relatively uniform distribution, with an average particle diameter of approximately 100 nm.

3.1.4. Thermal Assessment

The thermal durability of the produced CeO₂ nanomaterials was evaluated utilizing thermogravimetric analysis, which exhibited distinct weight-loss stages across different temperature regions (Figure 4). In the low-temperature range, a noticeable endothermic event was observed around 110 °C, accompanied by a mass loss of approximately 1.58%, as evident from the TGA profile. This initial weight reduction is primarily attributed to the dehydration of the nanoparticles, linked to the removal of physically adsorbed and surface-bound water molecules. This mass loss corresponds to the removal of physically adsorbed water and the decomposition of residual hydroxyl groups on the surface of the CeO₂ nanoparticles, consistent with the thermal behavior expected for CeO₂ prepared by hydroxide-mediated precipitation [41]. A second modest weight-loss area exists between 150 °C and 250 °C, related to the disintegration of residual hydroxyl groups and traces of organic species originating from the precursor or synthesis route. Beyond 250 °C, the TGA curve exhibited negligible weight loss (less than 1%), indicating the formation of a stable CeO₂ crystalline structure. The total weight loss recorded was approximately 5–6% up to 500 °C, confirming the high thermal stability and predominantly inorganic nature of the nanoparticles, which is advantageous for practical applications in water treatment and adsorption processes.

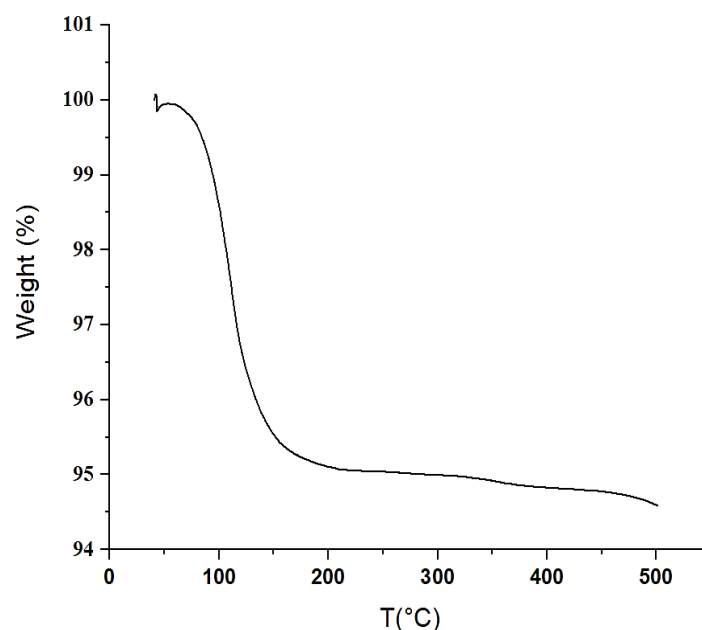


Figure 4. TGA spectra of CeO₂ nanoparticles.

3.1.5. Surface Area and Porosity Analysis

The outcomes of the surface area and porous dimensions assessment of CeO₂ particles are summarized in Table 1. The results indicate that the material possesses a well-developed and accessible surface. The BET method provides a moderate surface area of 118.96 m²/g, suggesting a significant amount of surface available for adsorption. This is complemented by a pore volume of 0.3962 cc/g, indicating that the material can adsorb and store gases effectively. The Langmuir technique, predicated on the assumption of single-layer adsorption, provides an elevated surface area of 205.62 m²/g, which suggests that CeO₂ has a highly ordered surface with minimal multilayer adsorption, making it potentially useful in applications requiring high surface interactions, such as catalysis.

Table 1. Textural properties of CeO₂ nanoparticles based on BET, Langmuir, BJH, and DFT methods.

Method	Specific Surface Area (m ² /g)	Pore Volume (cc/g)	Pore Radius (m)
BET (Multipoint)	118.96	0.3962	2.27
Langmuir	205.62	N/A	N/A
BJH Adsorption	85.67	0.3962	2.27
BJH Desorption	105.93	0.4028	5.69
DFT Method	118.98	0.3890	6.28
Total Pore Volume	N/A	0.4229	N/A
Average Pore Size	N/A	N/A	7.11

The BJH adsorption and desorption methods provide further insights into the material's pore structure. The surface area obtained by BJH adsorption (85.67 m²/g) and desorption (105.93 m²/g) is somewhat lower than that from the Langmuir method. However, it aligns with the presence of mesopores (pores with diameters between 2 and 50 nm), which is consistent with the pore radius of 2.27 nm in adsorption and 5.69 nm in desorption. This suggests that the material has a mix of small and slightly larger pores, which are beneficial for various catalytic and adsorptive processes. The DFT analysis further supports the porous characteristics of CeO₂, revealing a surface area of 118.98 m²/g and a mean porous radius of 6.28 nm, which highlights the material's well-defined pore structure and

large surface area, both of which are crucial for effective interactions in catalytic processes. Additionally, the overall pore volume of 0.4229 cc/g. The mean pore dimension is 7.11 nm confirm that CeO₂ particles are primarily mesoporous. Overall, the mixture of an extensive surface area, significant pore volume, and a well-defined mesoporous structure makes CeO₂ particles highly suitable for lead adsorption and removal.

3.2. Lead Ion Removal

3.2.1. Effect of Initial Pb²⁺ Concentration on Adsorption Performance

The effect of varying initial Pb²⁺ ion concentrations on adsorption performance was examined under consistent experimental conditions, using 0.01 g of CeO₂ added to 50 mL of Pb²⁺ solution, an interval of communication of 30 min, and agitation at 150 rpm. A range of initial Pb²⁺ concentrations (5, 15, 30, 45, 60, 100, and 200 mg/L) was employed to evaluate changes in both adsorption capacity and removal efficiency. As depicted in Figure 5a, the adsorption capacity (q_e) exhibited a rising trend with increasing initial metal ion concentration, spanning from 10 to 350 mg/g. This behavior is likely due to the intensified concentration gradient at higher Pb²⁺ levels, which promotes an intensified impetus for transferring mass, consequently augmenting the interaction between Pb²⁺ ions and the active sites available on the CeO₂ surface.

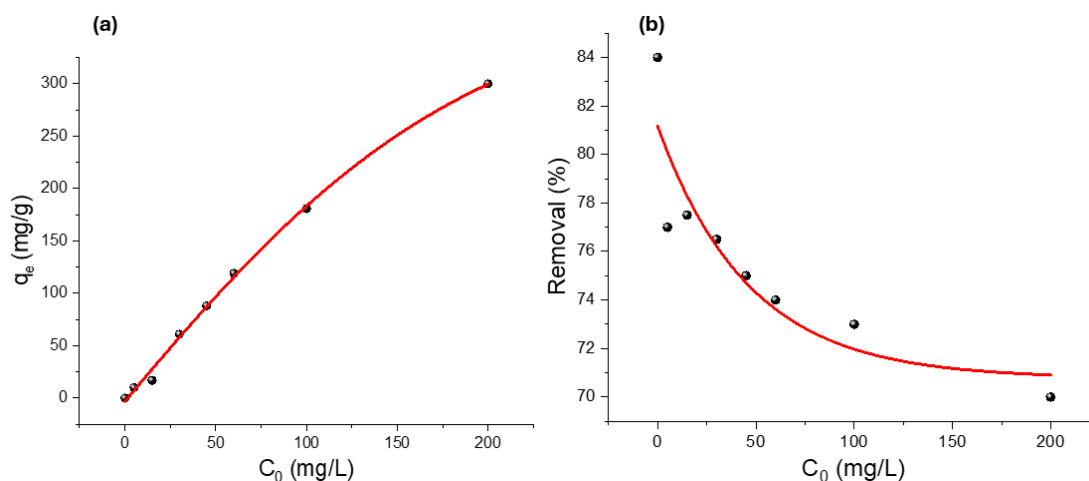


Figure 5. (a) Effect of Pb²⁺ concentration on the amount adsorbed (q_e) and (b) removal percentage (R%).

Conversely, the removal efficiency (R%), shown in Figure 5b, decreased from 84.18% to 70% with increasing initial concentrations. This inverse relationship is commonly observed in adsorption systems and is primarily owing to the depletion of available adsorption sites at higher solute concentrations. Once the adsorbent surface becomes saturated, typically at lower concentrations, further increases in Pb²⁺ concentration do not proportionally increase the amount removed from solution.

3.2.2. Influence of Adsorption Time on Pb²⁺ Removal

The influence of interface time for elimination efficiency of Pb²⁺ ions was examined by altering the adsorption time from 15 to 1440 min at a fixed temperature of 298 K. The experiments were conducted using 0.01 g of CeO₂ and an initial Pb²⁺ concentration of 45 mg/L. The effects of contact time on both the adsorption capacity (q_e) and removal effectiveness (R%) are presented in Figure 6a,b. As illustrated in the figures, the adsorption capacity (q_e) increased from 58.5 to 107.25 mg/g as the contact time increased. Notably, the removal efficiency (R%) rose sharply during the initial adsorption phase, reaching 52.18% within the first 10 min, and continued to increase more gradually thereafter, stabilizing around 90% by 1440 min. This fast initial adoption can be attributable to the quantity of

unoccupied active locations on the CeO_2 surface, which enhances the absorption of Pb^{2+} ions. As the adsorption process progressed, these active sites gradually became occupied, and the system approached equilibrium. The observed stabilization of removal efficiency suggests that most accessible binding sites were saturated. The slight increase in q_e over time, despite the plateau in the effectiveness of elimination, can be ascribed to the diffusion of Pb^{2+} ions into mesopores or microporous regions within the CeO_2 structure, allowing for continued but slower adsorption beyond the external surface.

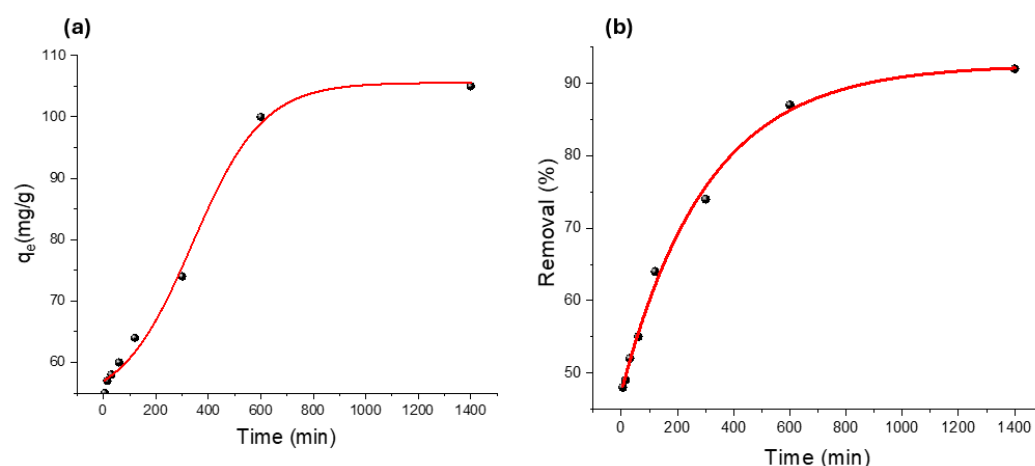


Figure 6. The impact of adsorption time on (a) the amount adsorbed (q_e) and (b) removal percentage (R%).

Equilibrium was effectively achieved around 1400 min, indicating this duration as optimal under the given experimental conditions.

3.3. Influence of Initial pH on Pb^{2+} Adsorption

The pH is a significant aspect in adsorption investigations, as it influences both the chemical form of the solute and the surface characteristics of the adsorbent. To evaluate its effect on Pb^{2+} ion removal, the pH was systematically varied from 1 to 8 at a constant temperature of 298 K. The experiments were conducted using a CeO_2 concentration of 45 mg/L, with an adsorbent mass of 0.01 g and a contact time fixed at 30 min. Figure 7a,b illustrate the relationship between pH and both the adsorption capacity (q_e) and removal efficiency (R%). Results showed that the quantity of extractable increased from 9.25 mg/g at pH 1 to 60 mg/g at pH 6, while the removal efficiency improved from 12.33% to 80%. These trends underscore the pivotal role of pH in regulating the adsorption process, particularly through its impact on the adsorbent surface charge and Pb^{2+} speciation in solution. At low pH levels, the CeO_2 surface becomes heavily protonated, acquiring a positive charge that repels Pb^{2+} ions and thus reduces adsorption. As the pH increased, the deprotonation of surface functional groups reduced the positive charge on the CeO_2 surface, possibly resulting in a neutral or even negatively charged surface that enhanced the electrostatic attraction between the adsorbent and Pb^{2+} ions. However, the available figures do not show detailed adsorption behavior for pH values above 6, and therefore, the claim that adsorption ‘no longer increases significantly’ beyond this point cannot be confirmed from the presented data and the impact of pH solution on Figure 7.

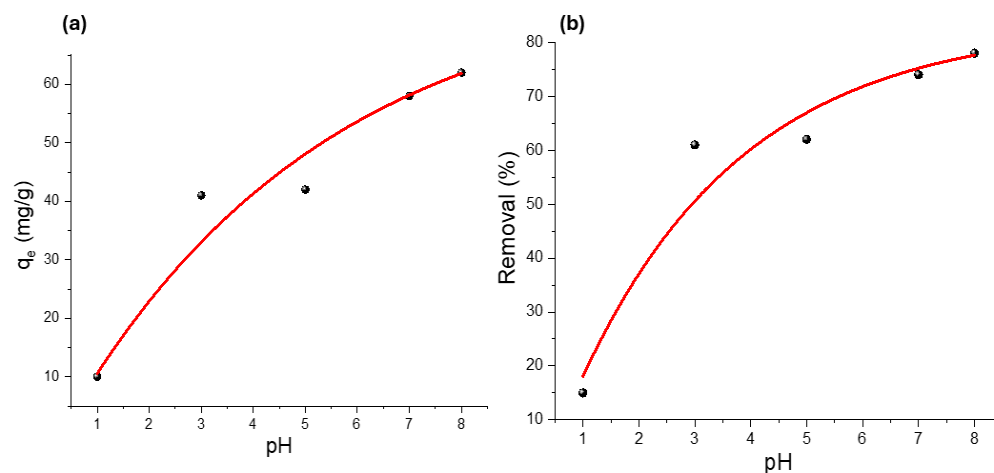


Figure 7. The impact of pH solution on (a) the amount adsorbed (q_e) and (b) removal percentage (R%).

Thus, pH 6 represents the highest pH value for which complete experimental data are provided, and under these conditions, the adsorption capacity and removal efficiency reached their maximum observed values in this study.

3.4. Adsorption Isotherm Models

The Langmuir isotherm implies optimal single-layer adsorption onto an evenly distributed surface with a restricted number of similar, energetically comparable sites [42]. It further presumes that each site accommodates only one adsorbate molecule and that there are no interactions between adsorbed species. This model is often applied to describe systems where surface saturation is attainable. The following equation represents the Langmuir model's linear equation:

$$\frac{C_e}{q_e} = \frac{1}{Q_m \cdot b} + \frac{1}{Q_m} \times C_e \quad (3)$$

Here, C_e represents the equilibrium concentration of lead ions in solution (mg/L), q_e denotes the quantity of Pb^{2+} adsorbed per unit mass of CeO_2 at equilibrium (mg/g), the parameter Q_m refers to the theoretical maximum adsorption capacity assuming single-layer coverage (mg/g), and b is the Langmuir constant relating to the attraction of binding sites (L/mg). The parameters Q_m and b were determined from the linearized Langmuir graph of C_e/q_e versus C_e (as shown in Figure 8a).

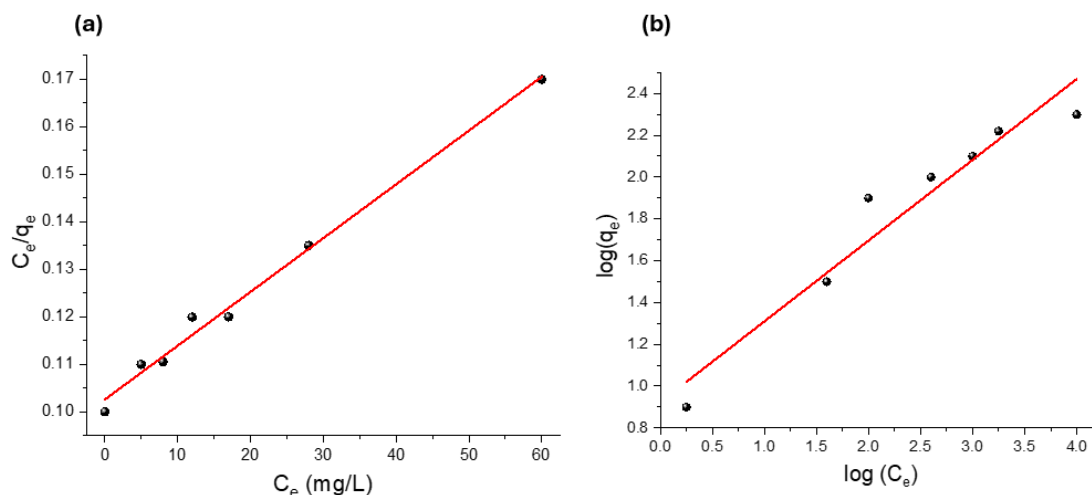


Figure 8. (a) Langmuir; and (b) Freundlich model simulations on isotherm curves.

The efficiency of the adsorption process was further evaluated by applying the non-dimensional separation factor, R_s , which was determined utilizing the following formula:

$$R_L = \frac{1}{b_{CI}} \quad (4)$$

C_i designates the initial concentration of CeO_2 in the solution (mg/L). The dimensionless separation factor, R_s , gives insights into the functioning of the adsorption process. Depending on its value, adsorption can be classified as irrevocable ($R_s = 0$) and positive ($0 < R_s < 1$), linear ($R_s = 1$), or unfavorable ($R_s > 1$). The parameters b , Q_m , and R_s are consolidated in Table 2. The fact that R_s parameters fall within the range of 0 to 1 confirms that Pb^{2+} adsorption onto CeO_2 is favorable under the tested conditions. Among the evaluated models, the Langmuir isotherm demonstrated the greatest fit to the data obtained from experiments, as demonstrated by a higher correlation coefficient ($R^2 = 0.97$) in contrast to the Freundlich model ($R^2 = 0.89$). The Langmuir model yielded a theoretical monolayer adsorption capacity of 714.28 mg/g, suggesting a high potential adsorption capability under idealized conditions.

Table 2. Adsorption isotherm models' constants.

Isotherm Model	R_L	Evaluated Parameters of Isotherm		
		Q_{max} (mg/g)	b (L/mg)	R^2
Langmuir	0.06	714.28	0.50	0.97
Freundlich	-	n	K_f	R^2
	-	2.88	4.22	0.89

It is important to note that the Q_m value is theoretical and derived from model extrapolation; the highest experimentally measured adsorption capacity in this study was $q_{e,exp} = 192$ mg/g. This discrepancy reflects the ideal assumptions of the Langmuir model compared to real experimental limitations such as incomplete site accessibility, surface heterogeneity, and kinetic constraints.

Overall, the Langmuir model indicates a strong affinity between Pb^{2+} ions and CeO_2 surface sites, while the experimental data provide a more realistic measure of actual adsorption performance.

In contrast, the Freundlich isotherm is an experimental model that is suitable for diverse surfaces, where adsorption sites possess varying affinities and energies. Unlike the Langmuir model, the Freundlich model does not anticipate a point of saturation and is thus applicable to multilayer adsorption processes. The Freundlich equation includes a heterogeneity factor ($1/n$), which indicates the degree of surface heterogeneity and adsorption intensity; values of $1/n$ closer to zero reflect more substantial heterogeneity and higher adsorption affinity. Together, these models provide a comprehensive framework for knowing the Adsorption Behavior and capacity of the synthesized nanocomposite under equilibrium conditions. The linear representation of the Freundlich equation is articulated as follows:

$$\log q_e = \log K_f + \frac{1}{n} \log C_e \quad (5)$$

where k_f is the Freundlich factor proportional to adsorption capacity (mg/g), and n_f is the adsorption intensity. These results were calculated using the slope and intercept of the linear relationship between $\ln q_e$ and $\ln C_e$ Figure 8b. Table 2 displays the values that were obtained. The Freundlich model demonstrates a heterogeneity factor ($1/n$) of 0.35 ($n = 2.88$), indicating moderately favorable adsorption on a heterogeneous surface. The Freundlich constant K_f was calculated to be 4.22, suggesting a reasonable adsorption capacity but

less predictive power compared to the Langmuir model. The kinetic results, together with the surface characterization, suggest that Pb^{2+} adsorption onto CeO_2 nanoparticles proceeds predominantly through chemisorption. This process may involve several chemical interactions, including electron transfer between Pb^{2+} ions and $\text{Ce}^{3+}/\text{Ce}^{4+}$ redox sites, the formation of inner-sphere surface complexes, and coordination bonding with surface oxygen atoms or hydroxyl groups ($-\text{OH}$) present on CeO_2 . Oxygen vacancies and Ce^{3+} sites on the nanoparticle surface can serve as active sites where Pb^{2+} ions form stable interactions, further supporting the chemisorption nature of the process. To better highlight the novelty of the present work, a comparative analysis of various nanocomposite adsorbents for lead (Pb^{2+}) removal reveals a broad spectrum of performance efficiencies based on Factors such as adsorbent quantity, pH value, interaction duration, and adsorption capacity (Q_m) (Table 3). Most studies employed slightly acidic to neutral pH conditions (pH 4–8), which are favorable for lead ion adsorption due to minimal competition from hydrogen ions. The adsorption capacities varied considerably, with $\text{CeO}_2/\text{CuFe}_2\text{O}_4$ (972.4 mg/g) and UiO-66-NH_2 (692.8 mg/g) exhibiting the highest Q_m values, although the latter lacked complete operational data. The Langmuir model predicted a theoretical monolayer capacity (Q_m) of 714.2 mg/g for the CeO_2 nanocomposite; however, the highest experimentally measured adsorption capacity was 192 mg/g, with a maximum removal efficiency of 80% at pH 6 under the tested conditions. Although the contact time was long (1440 min), the results still indicate a strong affinity of the CeO_2 surface for Pb^{2+} ions. Other notable materials include hydroxyapatite nanostructures and silica spheres, which also achieved high adsorption capacities (322.6 and 266.89 mg/g, respectively) at low dosages and short contact times. Low-dosage, high-efficiency materials, such as $\text{La}_2\text{S}_3/\text{MGO}$ and CeO_2 (as identified in previous studies), further highlight the role of material surface chemistry and morphology in performance. Although some materials achieved 100% removal (e.g., magnetite oxide and starch/cellulose-capped MNPs), their adsorption capacities were comparatively lower, indicating possible rapid surface saturation. Overall, the CeO_2 nanocomposite reported in this work compares favorably with existing adsorbents and offers a promising avenue for efficient lead remediation, especially where high adsorption capacity is prioritized.

Table 3. Comparative illustration on nanocomposites for lead removal.

Adsorbent	Quantity of Adsorbent (g/L)	pH	Contact Time (min)	Speed (rpm)	Q_m (mg/g)	Removal (%)	Ref.
Orange-peel@ Fe_3O_4	0.2	5.5	90	-	-	95	[43]
Cellulose nanoparticles (CN)	2	6.5	120	-	221.1	94	[44]
Alg@MgS	-	4	60	-	84.74	90	[45]
Hydroxyapatite nanostructures	0.01	7	20	-	322.6	-	[46]
Silica spheres	-	-	40	-	266.89	99.6	[47]
$\text{La}_2\text{S}_3/\text{MGO}$	0.02	5	40	-	98.03	95	[11]
Magnetite Oxide	-	6	60	400	1.45	100	[48]
MXene	0.4	6	120	-	43.86	97	[49]
UiO-66-NH_2	0.2	-	-	-	692.80	-	[50]
Silica/klucel nanocomposite	0.05	-	60	-	63.938	95	[51]

Table 3. Cont.

Adsorbent	Quantity of Adsorbent (g/L)	pH	Contact Time (min)	Speed (rpm)	Qm (mg/g)	Removal (%)	Ref.
ZnO	-	-	4320	-	-	94	[52]
Manganese ferrite (MNPs) capped with starch or cellulose	2	5.5	30	-	46	100	[53]
CeO ₂ /CuFe ₂ O ₄	0.03	7	150	180	972.4	92	[31]
γ-Fe ₂ O ₃ /CeO ₂ /cellulose nanofibril (CNF)	0.5	-	240	-	42.6	77.6	[54]
CeO ₂	0.01	5	-	130	128.1	-	[32]
CeO ₂	0.2	6	1440	150	714.2	90	The present work

3.5. Adsorption Kinetics Model

The kinetics of adsorption elucidate the rate and mechanisms by which adsorbate molecules engage with the adsorbent's surface. Acquiring a comprehensive understanding of these dynamics is crucial for assessing the efficacy and feasibility of adsorption systems, particularly in environmental applications such as the elimination of heavy metals. Commonly applied kinetic models include the pseudo-first-order and pseudo-second-order models, which help elucidate whether physical or chemical interactions govern the process. The pseudo-first order (Lagergren equation) is written as follows:

$$\ln(q_e - q_t) = \ln q_e - k_1 \times t \quad (6)$$

where q_t , q_e are the quantity adsorbed at time t and at equilibrium (mg.g^{-1}), respectively. For the adsorption process, t is the time (min), and k_1 is the PFO rate constant (min^{-1}). PFO rate constants k_1 and q_e were estimated using the slopes and intercepts of the charts between $\ln(q_e - q_t)$ against t in Figure 9a. Table 4 provides a summary of these values. The lack of fitting alignment between the values of $q_{e, \text{cal}}$ and $q_{e, \text{exp}}$ is evident from the data, showing that this model is not as suitable for elucidating the adsorption processes. The following is the expression for the pseudo-second order (PSO) kinetics equation:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} \cdot t \quad (7)$$

Table 4. Kinetic variables and correlation coefficients for Pb²⁺ adsorption.

Pseudo-First Order		Pseudo-Second Order		Experimental q_e
$q_{e, \text{cal}} (\text{mg.g}^{-1})$	4.92844	$q_{e, \text{cal}} (\text{mg.g}^{-1})$	109.69 (mg.g^{-1})	192 (mg.g^{-1})
$K_1 (\text{min}^{-1})$	2.77	$K_2 (\text{g mg}^{-1} \text{min}^{-1})$	0.016	
R^2	0.98	R^2	0.99	

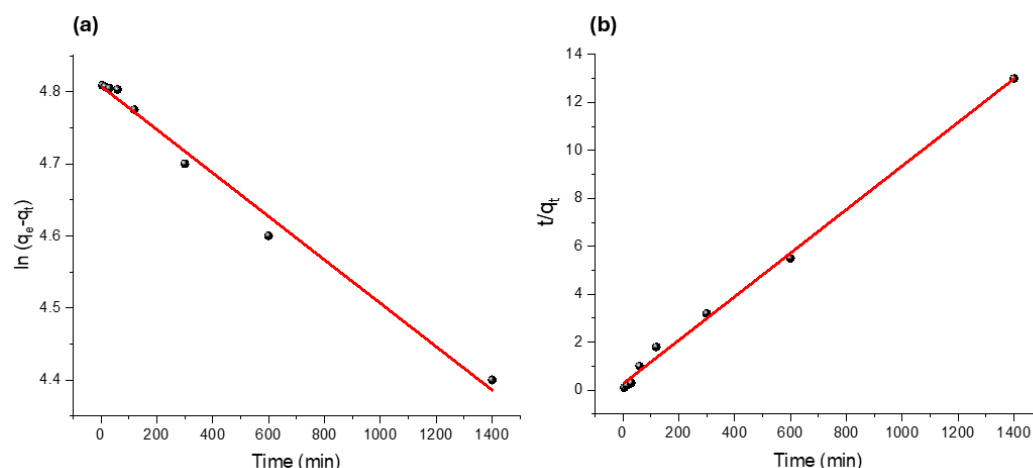


Figure 9. Kinetic graphs of adsorption for (a) the PFO model and (b) the PSO model.

In this model, k_2 represents the rate constant of the pseudo-second order (PSO) kinetic equation ($\text{g} \cdot \text{mg}^{-1} \cdot \text{min}^{-1}$). The values of k_2 and the theoretical adsorption capacity (q_e , cal) were derived from the slope and intercept of the linear plot of t/q_t vs. t (illustrated in Figure 9b), with corresponding data summarized in Table 4. The results indicate that the correlation coefficients (R^2) for the PSO model were persistently superior to those for the pseudo-first order (PFO) model.

Although the PSO model exhibited a higher correlation coefficient than the PFO model, the calculated adsorption capacity (q_e , cal) differed significantly from the experimental value (q_e , exp), indicating that the PSO model captures the kinetic trend but does not precisely predict the absolute adsorption capacity. This suggests that the rate-limiting step may involve chemisorption, characterized by electron transfer or exchange between adsorbent and adsorbate.

The kinetic parameters show that the pseudo-second order (PSO) model provides a better description of Pb^{2+} adsorption onto CeO_2 nanoparticles than the pseudo-first order (PFO) model, as indicated by its higher correlation coefficient ($R^2 = 0.99$). However, the calculated adsorption capacity for the PSO model (q_e , cal = 109.69 mg/g) deviates noticeably from the experimental value (q_e , exp = 192 mg/g), demonstrating that although the PSO model accurately represents the kinetic trend, it does not precisely predict the equilibrium adsorption capacity. In contrast, the PFO model significantly underestimates adsorption capacity (q_e , cal = 4.93 mg/g), further confirming its unsuitability for describing this system. Overall, the kinetic analysis suggests that the adsorption process is likely governed by chemisorption, involving electron transfer or sharing between Pb^{2+} ions and the CeO_2 nanoparticle surface.

3.6. Regeneration and Disposal of Spent Adsorbent

Regeneration of CeO_2 -based adsorbents is performed using dilute HCl, which efficiently desorbs Pb^{2+} ions from the nanoparticle surface. After acid treatment, the material is thoroughly rinsed with distilled water and dried to restore its adsorption capability for reuse. In this study, regeneration testing showed that the CeO_2 adsorbent retained approximately 95% of its initial adsorption capacity after treatment with dilute HCl, demonstrating that the material maintains its integrity and remains suitable for subsequent adsorption cycles. For disposal, Pb^{2+} -loaded CeO_2 nanoparticles must be managed as hazardous waste and immobilized or solidified to prevent secondary contamination. These practices contribute to the safe and sustainable use of CeO_2 -based materials in water treatment applications.

4. Conclusions

In this study, CeO₂ nanoparticles were synthesized through a simple and cost-effective hydroxide-mediated precipitation method. Structural and physicochemical characterization (XRD, SEM, TEM, FTIR, BET, UV–Vis) confirmed well-crystallized, uniformly distributed nanoparticles with an average size of ~100 nm, a high surface area of 118.96 m²/g, and mesoporous features favorable for adsorption.

Adsorption experiments demonstrated effective Pb²⁺ removal, achieving an experimental capacity of 192 mg/g and 80% removal at pH 6. The process followed pseudo-second-order kinetics, indicating chemisorption, while the Langmuir model provided the best isotherm fit with a theoretical monolayer capacity of 714.2 mg/g. Overall, CeO₂ nanoparticles showed strong affinity for Pb²⁺ and promising performance as a low-cost and sustainable adsorbent for contaminated water. Regeneration with dilute HCl maintained about 95% of the initial adsorption capacity, supporting their potential for reuse. These findings offer a solid basis for developing CeO₂-based composites, improving regeneration cycles, and advancing safer disposal strategies for environmentally sustainable water treatment.

Author Contributions: Methodology, B.M.; Software, A.E.M.E.M.; Validation, B.M.; Formal analysis, A.E.M.E.M.; Investigation, B.M.; Data curation, B.M.; Writing—original draft, B.M.; Writing—review & editing, B.M.; Visualization, B.M.; Supervision, B.M. and A.E.M.E.M.; Project administration, B.M.; Funding acquisition, A.E.M.E.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The Researcher would like to thank the Deanship of Graduate Studies and Scientific Research at Qassim University for financial support (QU-APC-2026).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ali, H.; Khan, E.; Ilahi, I. Environmental Chemistry and Ecotoxicology of Hazardous Heavy Metals: And Ecotoxicology of Hazardous Heavy Metals: Environmental Persistence, Toxicity, and Bioaccumulation. *J. Chem.* **2019**, *2019*, 6730305. [\[CrossRef\]](#)
2. Kotnala, S.; Tiwari, S.; Nayak, A.; Bhushan, B.; Chandra, S.; Medeiros, M.; Coutinho, H.D.M. Impact of heavy metal toxicity on human health and the environment. *Sci. Total Environ.* **2025**, *987*, 17978541. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Jomova, K.; Alomar, S.Y.; Nepovimova, E.; Kuca, K.; Valko, M. *Heavy Metals: Toxicity and Human Health Effects*; Springer: Berlin/Heidelberg, Germany, 2024; Volume 99, p. 1.
4. Ondrasek, G.; Shepherd, J.; Rathod, S.; Dharavath, R.; Rashid, M.I.; Brtnicky, M.; Shahid, M.S.; Horvatinec, J.; Rengel, Z. Metal contamination—A global environmental issue: Sources, implications & advances in mitigation. *RSC Adv.* **2025**, *15*, 3904–3927.
5. Olufemi, A.C.; Mji, A.; Mukhola, M.S. Potential Health Risks of Lead Exposure from Early Life through Later Life: Implications for Public Health Education. *Int. J. Environ. Res. Public Health* **2022**, *19*, 16006. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Collin, M.S.; Venkatraman, S.K.; Vijayakumar, N.; Kanimozhi, V.; Arbaaz, M.S.; Stacey, R.G.S.; Anusha, J.; Choudhary, R.; Gabriel, V.L.; Tovar, I.; et al. Bioaccumulation of lead (Pb) and its effects on human: A review. *J. Hazard. Mater. Adv.* **2022**, *7*, 100094. [\[CrossRef\]](#)
7. Oladimeji, T.E.; Oyedemi, M.; Emeteri, M.E.; Agboola, O.; Adeoye, J.B.; Odunlami, O.A. Review on the impact of heavy metals from industrial wastewater effluent and removal technologies. *Heliyon* **2024**, *10*, e40370. [\[CrossRef\]](#)
8. Abera, B.D.; Adimas, M.A. Health benefits and health risks of contaminated fish consumption: Current research outputs, research approaches, and perspectives. *Heliyon* **2024**, *10*, e33905. [\[CrossRef\]](#)
9. Nag, R.; Cummins, E. Human health risk assessment of lead (Pb) through the environmental-food pathway. *Sci. Total Environ.* **2022**, *810*, 151168. [\[CrossRef\]](#)
10. Balachandar, R.; Bagepally, B.S.; Kalahasthi, R.; Haridoss, M. Blood lead levels and male reproductive hormones: A systematic review and meta-analysis. *Toxicology* **2020**, *443*, 152574. [\[CrossRef\]](#)

11. Rezania, S.; Mojiri, A.; Park, J.; Nawrot, N.; Wojciechowska, E.; Marraiki, N.; Zaghloul, N.S.S. Removal of lead ions from wastewater using lanthanum sulfide nanoparticle decorated over magnetic graphene oxide. *Environ. Res.* **2022**, *204*, 111959. [\[CrossRef\]](#)
12. Zitong, X.; Siwei, G.; Dipak, R.; Takeshi, M.; Christopher, Q.L. Chemical precipitation enabled UF and MF filtration for lead removal. *J. Water Process Eng.* **2021**, *41*, 101987.
13. Jasim, A.Q.; Ajjam, S.K. Removal of heavy metal ions from wastewater using ion exchange resin in a batch process with kinetic isotherm. *S. Afr. J. Chem. Eng.* **2024**, *49*, 43–54. [\[CrossRef\]](#)
14. Manawi, Y.; McKay, G.; Ismail, N.; Fard, A.K.; Kochkodan, V.; Atieh, M.A. Enhancing lead removal from water by complex-assisted filtration with acacia gum. *Chem. Eng. J.* **2018**, *352*, 828–836. [\[CrossRef\]](#)
15. Monica, R.; Paola, G.; Elisa, M.; Mery, F. Debora, Bioremediation methods for the recovery of lead-contaminated soils: A review. *Appl. Sci.* **2020**, *10*, 3528.
16. Shakir, H.A.; Alsaffar, M.A.; Mageed, A.K.; Sukkar, K.A.; Ghany, M.A.A. Optimizing Photocatalytic Lead Removal from Wastewater Using ZnO/ZrO₂: A Response Surface Methodology Approach. *Chem. Eng.* **2024**, *8*, 72. [\[CrossRef\]](#)
17. Aljaberi, F.Y.; Mohammed, W.T. Analyzing the removal of lead from synthesis wastewater by electrocoagulation technique using experimental design. *Desalin. Water Treat.* **2018**, *111*, 286–296. [\[CrossRef\]](#)
18. Liu, Y.X.; Yan, J.M.; Yuan, D.X.; Li, Q.L.; Wu, X.Y. The study of lead removal from aqueous solution using an electrochemical method with a stainless steel net electrode coated with single wall carbon nanotubes. *Chem. Eng. J.* **2013**, *218*, 81–88. [\[CrossRef\]](#)
19. Satyam, S.; Patra, S. Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. *Heliyon* **2024**, *10*, e29573. [\[CrossRef\]](#)
20. Asma, S.; Mehwish, S.; Muhammad, I. Application potential of grapefruit peel as dye sorbent: Kinetics, equilibrium and mechanism of crystal violet adsorption. *J. Hazard. Mater.* **2010**, *179*, 564–572. [\[CrossRef\]](#)
21. Akhtar, M.S.; Ali, S.; Zaman, W. Innovative Adsorbents for Pollutant Removal: Exploring the Latest Research and Applications. *Molecules* **2024**, *29*, 4317. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Futralan, C.C.; Diana, E.; Edang, M.F.A.; Padilla, J.M.; Cenia, M.C.; Alfeche, D.M. Adsorption of Lead from Aqueous Solution Using Activated Carbon Derived from Rice Husk Modified with Lemon Juice. *Sustainability* **2023**, *15*, 15955. [\[CrossRef\]](#)
23. Xie, S.; Huang, L.; Su, C.; Yan, J.; Chen, Z.; Li, M.; Du, M.; Zhang, H. Application of clay minerals as adsorbents for removing heavy metals from the environment. *Green Smart Min. Eng.* **2024**, *1*, 249–261. [\[CrossRef\]](#)
24. Oyebamiji, O.O.; Corcoran, A.A.; Edauri, N.P.; Matthew, O.I.; Olukayode, O.A.; Omar, F.H.; Wiebke, J.P. Lead tolerance and bioremoval by four strains of green algae from Nigerian fish ponds. *Algal Res.* **2021**, *58*, 102403. [\[CrossRef\]](#)
25. Ali, G.; Helally, M.; Alani, M.A.F.; Alardah, A.H.S.; Khataby, R.A.M.; Fazili, M.Y.; Al-Maki, J.H.A.; Mohamed, A.; Sliem, M.H.R.; Al-Qahtani, N. Green Innovation: Harnessing Chitosan Hydrogel Beads for Sustainable Lead Removal in Wastewater Treatment towards Qatar Vision. *Mater. Proc.* **2024**, *18*, 10.
26. Shahzad, A.; Aslibeiki, B.; Slimani, S.; Ghosh, S.; Voccianti, M.; Grotti, M.; Comite, A.; Peddis, D.; Sarkar, T. Magnetic nanocomposite for lead (II) removal from water. *Sci. Rep.* **2024**, *14*, 17674. [\[CrossRef\]](#)
27. Attatsi, I.K.; Nsiah, F. Application of silver nanoparticles toward Co(II) and Pb(II) ions contaminant removal in groundwater. *Appl. Water Sci.* **2020**, *10*, 152. [\[CrossRef\]](#)
28. Aruja, T.C.; Sharma, R.; Dhiman, V.; Chand, S.; Choudhary, P.; Kondal, N. ZnO based nanoadsorbents for purification of lead contaminated water. *Mater. Today Proc.* **2022**, *48*, 1320–1324.
29. Hadole, P.; Mondal, S.; Shingda, S.; Ahmed, M.Z.; Mule, A.; Rai, A.R.; Ayub, A.; Alone, H.; Mondal, A. Green and Biogenic Synthesis of Cerium Oxide (CeO₂) Nanoparticles: Heterogeneous Catalytic Synthesis of Isoxazol-5(4H)-one Derivatives and Assessment of Their Antibacterial Activity. *Chem. Select.* **2025**, *10*, e202406123. [\[CrossRef\]](#)
30. Mohajeri, M.; Momenai, R.; Karami-Mohajeri, S.; Ohadi, M.; Raeisi Estabragh, M.A. Cerium oxide nanoparticles, physical and chemical properties, applications and toxicological implications: A review. *Results Chem.* **2025**, *15*, 102302. [\[CrossRef\]](#)
31. Talebzadeh, F.; Zandipak, R.; Sobhanardakani, S. CeO₂ nanoparticles supported on CuFe₂O₄ nanofibers as novel adsorbent for removal of Pb(II), Ni(II), and V(V) ions from petrochemical wastewater. *Desalin. Water Treat.* **2016**, *57*, 28363–28377. [\[CrossRef\]](#)
32. Contreras, A.R.; Casals, E.; Puentes, V.; Komilis, D.; Sánchez, A.; Font, X. Use of cerium oxide (CeO₂) nanoparticles for the adsorption of dissolved cadmium (II), lead (II) and chromium (VI) at two different pHs in single and multi-component systems. *Glob. Nest J.* **2015**, *17*, 536–543.
33. Nurhasanah, I.; Safitri, W.; Arifin, Z.; Subagio, A.; Windarti, T. Antioxidant activity and dose enhancement factor of CeO₂ nanoparticles synthesized by precipitation method. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *432*, 3. [\[CrossRef\]](#)
34. Zamiri, R.; Ahangar, H.A.; Kaushal, A.; Zakaria, A.; Zamiri, G.; Tobaldi, D.; Ferreira, J.M.F. Dielectrical properties of CeO₂ nanoparticles at different temperatures. *PLoS ONE* **2015**, *10*, 4.
35. Farahmandjou, M.; Farahmandjou, M.; Zarinkamar, M.; Firoozabadi, T.P. Synthesis of Cerium Oxide (CeO₂) nanoparticles using simple CO-precipitation method. *Rev. Mex. Física.* **2016**, *62*, 496–499.

36. Pandit, B.; Sankapal, B.R.; Koinkar, P.M. Novel chemical route for CeO₂/MWCNTs composite towards highly bendable solid-state supercapacitor device. *Sci. Rep.* **2019**, *9*, 5892. [\[CrossRef\]](#)
37. Tharani, D.S.; Sivasubramanian, R. CeO₂ nanocubes-based electrochemical sensor for the selective and simultaneous determination of dopamine in the presence of uric acid and ascorbic acid. *J. Chem. Sci.* **2023**, *135*, 93. [\[CrossRef\]](#)
38. Shi, Y.; Fu, J.; Hui, K.; Liu, J.; Gao, C.; Chang, S.; Chen, Y.; Gao, X.; Cao, T.; Xu, L.; et al. Promoting the electrochemical properties of yolk-shell-structured CeO₂ composites for lithium-ion batteries. *Microstructures* **2021**, *1*, 2021005. [\[CrossRef\]](#)
39. Bakkiyaraj, R.; Balakrishnan, M.; Subramanian, R. Synthesis, structural characterisation, optical studies of CeO₂ nanoparticles and its cytotoxic activity. *Mater. Res. Innov.* **2017**, *21*, 351–357. [\[CrossRef\]](#)
40. Latha, P.; Prakash, K.; Karuthapandian, S. Effective Photodegradation of CR & MO dyes by morphologically controlled Cerium oxide nanocubes under visible light illumination. *Optik* **2018**, *154*, 242–250. [\[CrossRef\]](#)
41. Pop, O.L.; Mesaros, A.; Vodnar, D.C.; Suharoschi, R.; Tabaran, F.; Magerusan, L.; Todor, I.S.; Diaconeasa, Z.; Balint, A.; Ciontea, L.; et al. Cerium oxide nanoparticles and their efficient antibacterial application in vitro against gram-positive and gram-negative pathogens. *Nanomaterials* **2020**, *10*, 1614. [\[CrossRef\]](#)
42. Salahshoor, S.; Fahes, M.; Teodoru, C. A review on the effect of confinement on phase behavior in tight formations. *J. Nat. Gas Sci. Eng.* **2018**, *51*, 89–103. [\[CrossRef\]](#)
43. Li, L.; Haziq, M.A.; Ullah, S.; Abdul Ghani, S.; Bibi, S.D.; Taqweem, U.H.; Muhammad, T.; Zihua, Y. Remediation of Lead-Contaminated Water Using Green Synthesized Iron-Oxide Nanoparticles: Performance and Mechanism. *Air Soil Water Res.* **2024**, *17*, 11786221241278517. [\[CrossRef\]](#)
44. Matter, E.A.; Hassan, A.F.; Elfaramawy, N.M.; Esmail, G. Enhanced adsorption of lead (II) ions onto cellulose nanoparticles/chitosan composite based on loofah sponge: Kinetic and thermodynamic studies. *Biomass Convers. Biorefinery* **2024**, *13*, 10961–10976. [\[CrossRef\]](#)
45. Bidhendi, M.E.; Parandi, E.; Meymand, M.M.; Sereshti, H.; Nodeh, H.R.; Joo, S.W.; Vasseghian, Y.; Mahmoudi Khatir, N.; Rezaia, S. Removal of lead ions from wastewater using magnesium sulfide nanoparticles caged alginate microbeads. *Environ. Res.* **2023**, *216*, 114416. [\[CrossRef\]](#)
46. Safatian, F.; Doago, Z.; Torabbeigi, M.; Shams, H.R.; Ahadi, N. Lead ion removal from water by hydroxyapatite nanostructures synthesized from egg shells with microwave irradiation. *Appl. Water Sci.* **2019**, *9*, 108. [\[CrossRef\]](#)
47. Milton, M.; Nyaradzai, M.H.C.; Narsaiah, T.B.; Chakra, C.S.; Gratitude, C.; Gwiranai, D.; Tirivaviri, A.M. Adsorption of lead ions from wastewater using nano silica spheres synthesized on calcium carbonate templates. *Heliyon* **2020**, *6*, e05309. [\[CrossRef\]](#)
48. Oana, S.; Covaliu, I.C.; Gigel, P.; Gina, A.C.; Mihai, N.L.; Ecaterina, M.; Sorin, S.B.; Paula, T. Magnetite oxide nanomaterial used for lead ions removal from industrial wastewater. *Materials* **2021**, *14*, 2831. [\[CrossRef\]](#)
49. Kagalkar, A.; Dharaskar, S.; Chaudhari, N. Development of MXene for removal of lead (Pb⁺) ions from wastewater. *Water Pract. Technol.* **2024**, *19*, 911–936. [\[CrossRef\]](#)
50. Hu, S.-Z.; Huang, T.; Zhang, N.; Lei, Y.-Z.; Wang, Y. Enhanced removal of lead ions and methyl orange from wastewater using polyethyleneimine grafted UiO-66-NH₂ nanoparticles. *Sep. Purif. Technol.* **2022**, *297*, 121470. [\[CrossRef\]](#)
51. El-Shafey, S.E.; Obada, M.K.; El-Shamy, A.M.; Mohamed, W.S. Silica/kluclen nanocomposite as promising durable adsorbent for lead removal from industrial effluents. *Sci. Rep.* **2024**, *14*, 26095. [\[CrossRef\]](#)
52. Kumari, P.; Gupta, G.; Saini, M.K.; Samanta, S.; Misra, K.P. Chat, S. ZnS Nanoparticles for Efficient Removal of Lead (II) Ions. *Nano-World J.* **2023**, *9*, 215–219.
53. Perez, T.; Pasquini, D.; Lima, A.d.F.; Rosa, E.V.; Sousa, M.H.; Cerqueira, D.A.; Morais, L.C.D. Efficient removal of lead ions from water by magnetic nanosorbents based on manganese ferrite nanoparticles capped with thin layers of modified biopolymers. *J. Environ. Chem. Eng.* **2019**, *7*, 102892. [\[CrossRef\]](#)
54. Yan, M.; Tan, Y.; Dong, H.; Xu, H.; Xiao, X.; Ling, Z.; Huang, C.; Yong, Q. Facilely constructing physical-linked γ-Fe₂O₃/CeO₂/cellulose nanofibril films for highly effective, recyclable, and multi-removal of heavy metals and dyes from wastewater. *Adv. Compos. Hybrid Mater.* **2025**, *8*, 2. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.