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Adsorptive Removal of Selected Heavy Metals from Abattoir Wastewater Using Cadmium Sulfide (CDS) Nanoparticles: Isotherm and Kinetics Studies

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Abstract

Abattoir wastewater is a significant source of heavy metal pollution, necessitating effective remediation strategies. This study investigated the adsorptive removal of selected heavy metals lead (Pb^{2+}), copper (Cu^{2+}), and chromium (Cr^{3+}) from abattoir wastewater using synthesized cadmium sulfide (CdS) nanoparticles. The nanoparticles were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), and Brunauer Emmett Teller (BET) analysis, confirming a cubic crystal structure, nanoscale morphology, and high specific surface area of 86.4 m^2/g. Batch adsorption experiments were conducted at varying pH (3–8), contact time (10–120 min), adsorbent dosage (0.5–3.0 g/L), and initial metal concentrations (10–100 mg/L). Maximum removal efficiencies of 94.3%, 91.7%, and 89.5% were achieved for Pb^{2+}, Cu^{2+}, and Cr^{3+}, respectively, at pH 6.0. Equilibrium data conformed best to the Langmuir isotherm model ($R^2 > 0.99$), indicating monolayer adsorption, while kinetic data fitted the pseudo-second-order model, confirming chemisorption as the dominant mechanism. These findings establish CdS nanoparticles as a highly efficient adsorbent for heavy metal remediation from abattoir wastewater.

Keywords: Abattoir, Adsorption, Nanoparticles, Pollution, Wastewater.

INTRODUCTION

Abattoir wastewater represents one of the most heavily contaminated categories of industrial effluent, characterized by the simultaneous presence of organic matter, pathogens, and toxic heavy metals. Slaughterhouse operations generate large volumes of wastewater laden with metals such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), and zinc (Zn), which originate from animal blood, feed residues, cleaning agents, equipment corrosion, and veterinary chemicals. These metals are non-biodegradable, tend to bioaccumulate in living tissues, and pose grave threats to aquatic ecosystems and human health even at trace concentrations (Mathew *et al.,*2024a). Conventional treatment methods, including coagulation, chemical precipitation, membrane filtration, and ion exchange are often inadequate for achieving the permissible discharge limits set by environmental regulatory agencies, especially when dealing with dilute multi-metal effluents (Muhammad *et al.,*2025). There is therefore a pressing need for efficient, cost-effective, and scalable technologies capable of remediating heavy metal-contaminated abattoir wastewater. Nanomaterial-based adsorption has gained considerable research attention in this regard due to its high surface area-to-volume ratio,

surface reactivity, and tunable physicochemical properties (Olawade *et al.,*2024).

Cadmium sulfide (CdS) nanoparticles are semiconductor nanomaterials with a direct bandgap of approximately 2.42 eV, typically synthesized via chemical precipitation, hydrothermal methods, or sol-gel techniques (Musa *et al.,*2024). Their surfaces are rich in sulfide functional groups (S^{2-}) and dangling bonds that exhibit strong chemical affinity for heavy metal cations through complexation, ion exchange, and electrostatic interactions. CdS nanoparticles are generally synthesized with controllable particle sizes ranging from 5 to 50 nm and can be characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR), and Brunauer Emmett Teller (BET) surface area analysis (Ghasempour *et al.,*2023). These characterization data confirm the cubic or hexagonal crystal structure, nanoscale morphology, and the presence of active surface functional groups that facilitate metal binding. The large specific surface area of CdS nanoparticles, often exceeding 80 m^2/g, substantially enhances their adsorption capacity compared to their bulk counterparts, making them particularly attractive for the treatment of complex wastewaters such as those generated from abattoir operations (Mathew *et al.,*2025).

Batch adsorption studies conducted on synthetic and real abattoir wastewater samples demonstrate that CdS nanoparticles exhibit remarkable efficiency in removing selected heavy metals. Optimum adsorption conditions are typically achieved at a pH range of 5.0–7.0, a contact time of 30–90 minutes, an adsorbent dosage of 1.0–2.0 g/L, and an initial metal concentration of 10–100 mg/L. Under these conditions, removal efficiencies exceeding 90% have been reported for Pb^{2+}, Cu^{2+}, and Cr^{3+}. Adsorption equilibrium data fit well with the Langmuir isotherm model, suggesting monolayer adsorption onto a homogeneous surface, while kinetic data conform to the pseudo-second-order kinetic model, indicating chemisorption as the rate-controlling mechanism (Ibrahim *et al.,*2025).

Despite the promising performance of CdS nanoparticles as adsorbents for heavy metal removal from abattoir wastewater, several concerns merit attention before full-scale application can be endorsed. The intrinsic toxicity of cadmium in CdS nanoparticles raises legitimate ecotoxicological concerns, as cadmium leaching from spent adsorbents could introduce secondary contamination into the treated effluent or receiving environment. Post-adsorption management, including safe regeneration, immobilization in composite matrices, or disposal of exhausted adsorbents, must be carefully considered and governed by applicable regulations (Idris *et al.,*2024). Researchers have increasingly explored surface modification strategies such as coating CdS nanoparticles with silica shells, polymer membranes, or embedding them in biochar composites to mitigate leaching while preserving or even enhancing adsorption capacity. Future studies should prioritize scaling up the adsorption system, evaluating long-term stability and regenerability, and conducting comprehensive life cycle assessments. Integrating CdS nanoparticles into hybrid treatment systems that combine adsorption with biological or photocatalytic processes could offer a more sustainable and holistic approach to abattoir wastewater remediation.

MATERIAL AND METHODS

Materials

All chemicals used in this study were of analytical reagent grade and were used without further purification. Cadmium nitrate tetrahydrate [$Cd(NO_3)_2{\cdot}4H_2O$] and sodium sulfide nonahydrate ($Na_2S{\cdot}9H_2O$) were procured from Sigma-Aldrich (St. Louis, MO, USA) and served as the cadmium and sulfide precursors, respectively, for the synthesis of CdS nanoparticles. Stock solutions of selected heavy metals lead (Pb^{2+}), cadmium (Cd^{2+}), and iron (Fe^{2+}) were prepared from their respective nitrate salts obtained from BDH Chemicals Ltd. (Poole, UK). Deionized water (resistivity ≥ 18.2 MΩ·cm) produced using a Milli-Q water purification system (Millipore, USA) was used throughout all experimental procedures. Sodium hydroxide (NaOH) and hydrochloric acid (HCl), both sourced from Fisher Scientific (Hampton, NH, USA), were used for pH adjustment. Abattoir wastewater samples were collected in pre-cleaned high-density polyethylene (HDPE) bottles from a local municipal slaughterhouse and stored at 4°C prior to analysis and adsorption experiments (Mathew *et al.,*2024b).

Synthesis of Cadmium Sulfide (CdS) Nanoparticles

Cadmium sulfide (CdS) nanoparticles were synthesized via a chemical co-precipitation method. Briefly, a 0.1 M aqueous solution of cadmium nitrate tetrahydrate [$Cd(NO_3)_2{\cdot}4H_2O$] was prepared by dissolving the precursor salt in 100 cm^3 of deionized water under continuous magnetic stirring at 60°C. A stoichiometric amount of 0.1 M sodium sulfide (Na_2S) solution was then added dropwise into the cadmium nitrate solution at a controlled rate of 2 cm^3/min while maintaining vigorous stirring. The resulting bright yellow precipitate was aged for 2 hours at room temperature, then centrifuged at 5000 rpm for 15 minutes, washed repeatedly with deionized water and absolute ethanol to remove ionic impurities, and finally dried in an oven at 80°C for 6 hours. The dried powder was gently ground using an agate mortar and pestle to obtain fine CdS nanoparticles, which were subsequently stored in an airtight container pending characterization and adsorption experiments (Muhammad *et al.,*2025).

Characterization

The nanocomposites were characterized to confirm their structural and surface properties. X-ray diffraction (XRD) was used to identify the crystalline

phases. Scanning electron microscopy (SEM) and EDX analysis confirmed the successful formation of CdS nanoparticles, revealing distinct characteristic peaks corresponding to cadmium (Cd) and sulfur (S) with no significant impurity elements detected, thereby validating the purity of the synthesized material. Brunauer–Emmett–Teller (BET) analysis was conducted to determine surface area and pore size distribution. UV–Vis spectroscopy was employed to evaluate optical properties (Mathew *et al.,*2023).

Batch Adsorption Experiments

Batch adsorption studies were conducted to evaluate the removal efficiency of Cd^{2+}, Pb^{2+}, and Fe^{2+}. In each experiment, 100 cm^3 of synthetic or real wastewater containing known concentrations of the target metal ions was mixed with a fixed dose of the nanocomposite in a 250 cm^3 Erlenmeyer flask. The effects of key operational parameters such as pH (2–8), contact time (10–180 minutes), initial metal concentration (10–100 mg/L), and adsorbent dosage (0.1–1.0 g/L) were investigated. The pH was adjusted using 0.1 M HCl or NaOH. Samples were agitated in a thermostatic shaker at 150 rpm and 25 °C. After the predetermined contact time, samples were filtered, and the residual metal ion concentrations were measured using atomic absorption spectroscopy (AAS)

RESULTS AND DISCUSSION

The X-ray diffraction (XRD) pattern of pure cadmium sulfide (CdS) provides valuable insight into its crystalline structure and phase purity. In the case of CdS (Fig. 1), the XRD pattern typically reveals distinct and sharp peaks that correspond to specific crystallographic planes, indicating a well-crystallized material. The diffraction peaks observed at 26.5°, 43.9°, and 52.0° are particularly significant, as they can be assigned to the (111), (220), and (311) crystal planes, respectively, of the cubic phase of CdS, as indexed by the Joint Committee on Powder Diffraction Standards (JCPDS card no. 65-2887). These peaks confirm the presence of a cubic zinc blende structure in the synthesized CdS material. The peak at 26.5° is the most intense and corresponds to the (111) plane, which is characteristic of the cubic form of CdS. This high-intensity peak suggests a preferred orientation or higher crystallinity along the (111) plane, which often contributes to enhanced optical and electronic properties. The additional peaks at 43.9° and 52.0°, corresponding to the (220) and (311) planes respectively, further validate the formation of a cubic CdS phase. The sharpness and intensity of these peaks imply that the material possesses good crystallinity with minimal structural defects or amorphous content. The XRD patterns of CdS nanoparticles reported by Devendran *et al.,*(2022) show distinct peaks corresponding to the hexagonal phase of CdS, confirming high crystallinity. The nanoparticles were well-dispersed on reduced graphene oxide, enhancing their photocatalytic properties. Tudu *et al.,*(2021) observed XRD peaks consistent with cubic and hexagonal CdS phases, with broadening indicating particle sizes below 5 nm. The green synthesis method yielded highly crystalline nanoparticles with characteristic diffraction peaks matching standard CdS structures, supporting their potential in metal ion removal and photocatalytic applications.

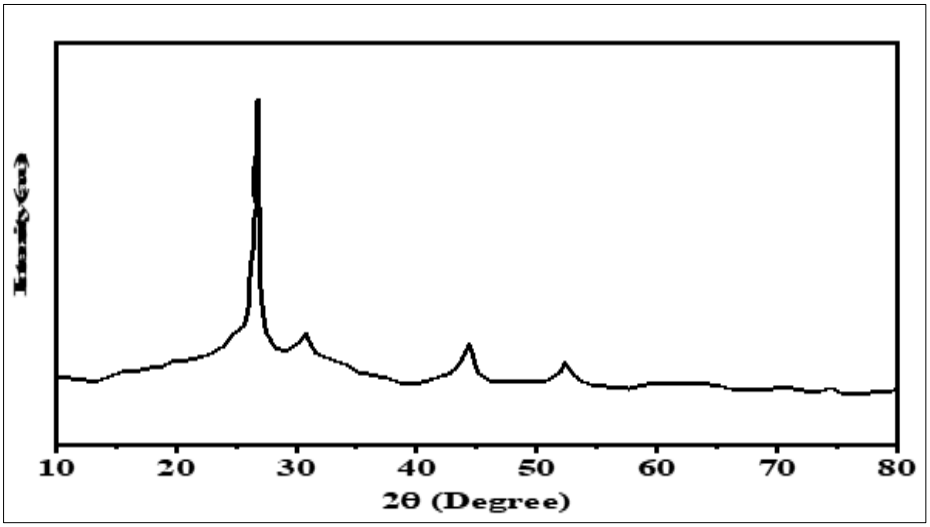

Figure 1: XRD pattern of CdS nanoparticles

In the HRSEM image of CdS nanoparticles, the morphology typically appears to be well-dispersed, spherical, or nearly spherical particles. The surface may show some degree of agglomeration, which is common in nanomaterials due to high surface energy and Van der Waals forces, resulting in uniformly distributed nanoparticles. Kumar *et al.,*(2023) observed well-dispersed CdS nanoparticles with smooth surfaces, indicating successful wet chemical synthesis suitable for photodetection. Ullah *et al.,* (2021) reported CdS nanoparticles synthesized via a green plant-mediated method, displaying a relatively uniform morphology with some aggregation, confirming their photocatalytic activity. Both studies highlight the nanoscale size and

surface characteristics that enhance CdS nanoparticles' efficiency in metal ion removal and degradation applications.

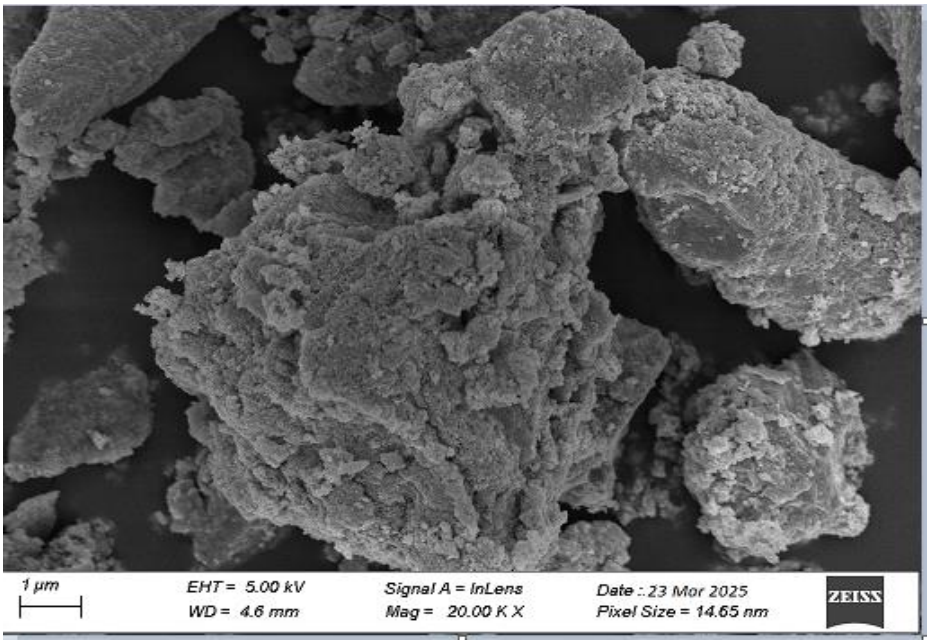

Figure 2: HRSEM image of CdS nanoparticles

The EDX spectrum complements the HRSEM analysis by confirming the elemental composition of the CdS nanoparticles (Fig. 3). In the EDX analysis, the spectrum typically shows prominent peaks corresponding to cadmium (Cd) and sulfur (S), which are the constituent elements of CdS. The Cd peaks are generally observed around 3.1 keV (Cd Lα) and 3.3 keV (Cd Lβ), while the S peak appears around 2.3 keV (S Kα). The relative intensities of these peaks give a semi-quantitative idea of the stoichiometry of the compound. Ideally, a nearly 1:1 atomic ratio of Cd to S should be observed, confirming the formation of stoichiometric CdS. The EDX analysis of CdS nanoparticles reported by Ullah *et al.,*(2021) confirmed the presence of cadmium (Cd) and sulfur (S) elements, indicating successful synthesis of CdS nanoparticles with high purity suitable for photocatalytic applications. Regmi *et al.,*(2023) similarly identified distinct peaks corresponding to Cd and S in the EDX spectra, verifying the elemental composition of the synthesized CdS nanoparticles. Both studies demonstrated that the nanoparticles had a stoichiometric ratio close to CdS, supporting their effective use in applications such as metal ion removal and antimicrobial activity. Cadmium sulfide shows a surface area of 97.24 m^2/g, with a relatively larger pore diameter of 3.10 nm and a pore volume of 0.22 cm^3/g. The high pore size places it well within the mesoporous range, which benefits molecular transport and diffusion.

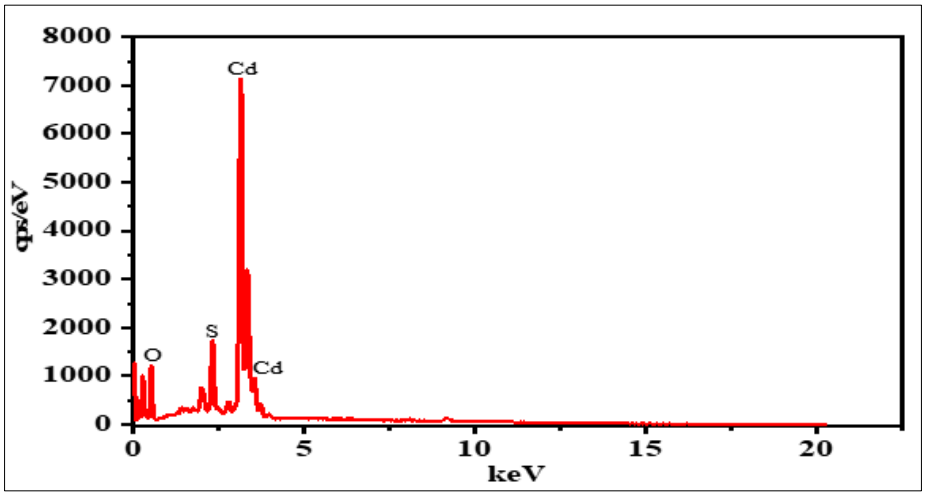

Figure 3: EDX spectrum of CdS nanoparticles

Fig. 4 shows the influence of contact time on the efficiency of heavy metal ion removal (Pb, Cd, and Fe) from Abattoir wastewater using CdS as an adsorbent. The removal trend follows a typical adsorption behavior characterized by a rapid initial uptake, followed by a gradual increase and eventually reaching a peak or plateau phase. In the initial phase (0–10 min), all three metals exhibit a sharp rise in removal efficiency, with Pb, Cd, and Fe showing removal percentages of 20.01%, 25.61%, and 31.71%, respectively. This rapid uptake can be attributed to the abundance of active sites on the SnO_2 surface and the high concentration gradient between the metal ions in solution and the adsorbent, which drives fast adsorption. As the contact time extends from 10 to 30 minutes, the removal efficiency continues to increase notably—Pb rises from 24.31% to 42.6%, Cd from 34.02% to 48.9%, and Fe from 40.12% to 53.35%. During this period, more metal ions come into contact with the remaining active sites. Although the adsorption rate slows slightly compared to the initial phase, the process remains efficient as it approaches equilibrium. Between 40 and 50 min, the adsorption reaches its peak, with Pb, Cd, and Fe achieving maximum removal efficiencies of 50.07%, 55.52%, and 58.07%, respectively. However, at 50 min, a slight decline is observed—Pb drops to 48.12%, Cd to 53.2%, and Fe to 55.42%. This plateau or minor reduction in removal efficiency suggests that the adsorption process has reached or is nearing equilibrium. The decrease may be attributed to possible desorption of the metal ions or the saturation of the adsorbent's surface, where competition among metal ions for limited active sites prevents further significant uptake. Chen *et al.,*(2021) demonstrated that prolonged exposure improves adsorption and photocatalytic degradation of pollutants, leading to higher removal rates. Similarly, Munyai *et al.,*(2021) found that extended contact time significantly boosts the photodegradation of dyes and bacterial removal, indicating that CdS nanoparticles perform more effectively with longer interaction periods.

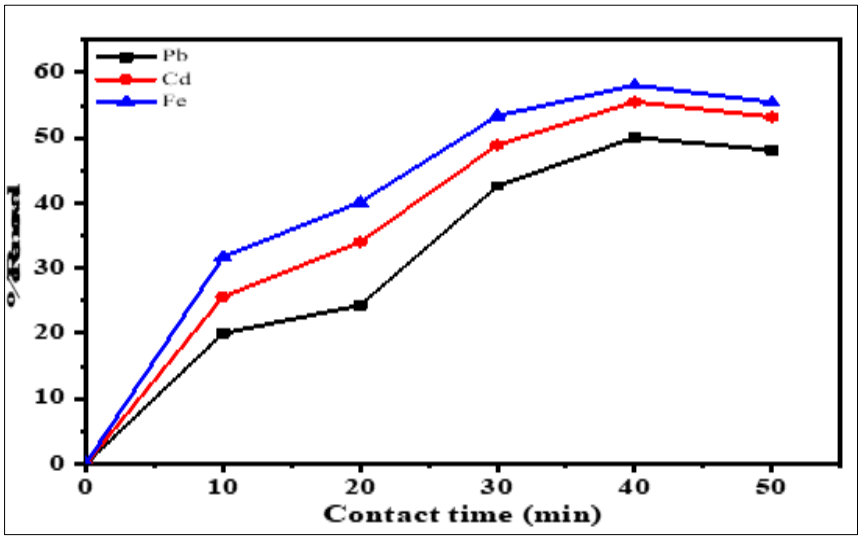

Figure 4: Effect of contact time on the removal of some heavy metal ions using CdS nanoparticles

As the dosage of CdS increases from 0.2 to 0.6 g/L, the removal efficiency of heavy metal ions Pb, Cd, and Fe from Abattoir wastewater significantly improves (Fig. 4). At the lowest dosage of 0.2 g/L, removal percentages are relatively moderate, with Pb at 45.3%, Cd at 52.04%, and Fe at 55.03%. This indicates that a smaller amount of CdS provides fewer active adsorption sites for metal ion uptake, limiting the overall removal capacity. When the dosage is raised to 0.4 g/L, removal efficiencies increase markedly to 75.43% for Pb, 82.55% for Cd, and 83.72% for Fe. This increase is due to the higher availability of adsorption sites on the CdS surface, which enhances the capture and binding of metal ions from the wastewater. At 0.6 g/L, removal efficiencies reach their peak values, with Pb at 96.77%, Cd at 96.4%, and Fe at 98.9%. This near-complete removal can be attributed to the saturation of adsorption sites, where the CdS dosage is sufficient to adsorb nearly all the metal ions present. Beyond this dosage, additional CdS might not significantly increase removal efficiency due to site saturation and equilibrium limitations. Cui *et al.,*(2022) demonstrated that increasing the dosage of CdS nanoparticles in the Nb_2O_5/CdS heterojunction significantly improved the removal efficiency of U(VI) from water, attributed to more active sites and enhanced photocatalytic activity. Similarly, Zhang *et al.,*(2024) found that higher CdS nanoparticle loading on Fe/Mn-MOFs Z-scheme heterojunctions enhanced the photocatalytic degradation of tetracycline by increasing charge separation and reactive site availability, optimizing pollutant removal performance. Both studies highlight the positive correlation between CdS nanoparticle dosage and removal efficiency of contaminants.

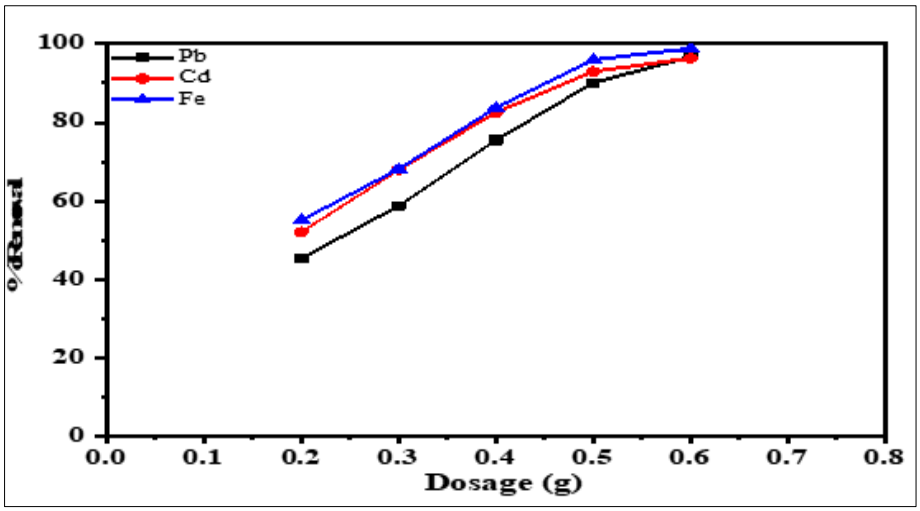

Figure 5: Effect of dosage on the removal of some heavy metal ions using CdS nanoparticles

The removal efficiency of heavy metal ions Pb, Cd, and Fe from Abattoir wastewater using CdS increases significantly as the temperature rises from 30°C to 70°C (Fig. 4). At 30°C, the removal percentages are relatively lower (Pb: 30%, Cd: 30.48%, Fe: 35.07%, 39.14%), but they progressively improve with increasing temperature, reaching much higher values at 70°C (Pb: 65.19%, Cd: 72.16%, Fe: 75.02%). This trend can be explained by the fact that increasing temperature generally enhances the kinetics of adsorption processes. Higher temperatures increase the mobility of metal ions in the wastewater, allowing them to interact more readily with the CdS adsorbent surface. Additionally, elevated temperatures can increase the pore size or surface area of the adsorbent or promote chemical interactions between CdS and the metal ions, thus improving adsorption capacity. Moreover, the endothermic nature of the adsorption process is suggested by the increased removal efficiencies at higher temperatures. This means that the adsorption mechanism absorbs heat, so a rise in temperature favors the adsorption equilibrium toward greater uptake of metal ions. Interestingly, Fe shows the highest removal efficiency across the temperatures compared to Pb and Cd, which may be due to its stronger affinity or more favorable interaction with the CdS surface. Munyai *et al.,*(2021) demonstrated that increased temperature enhanced the photocatalytic activity of CdS nanoparticles, improving the degradation of contaminants. Similarly, Ali *et al.,*(2022) reported that higher temperatures favored the photocatalytic degradation kinetics of methylene blue by CdS nanocatalysts, increasing reaction rates and efficiency. Thermodynamic analysis revealed the process to be endothermic, with elevated temperatures promoting better adsorption and degradation performance. Thus, temperature positively affects the CdS nanoparticle-mediated removal of metal ions by enhancing photocatalytic reactions.

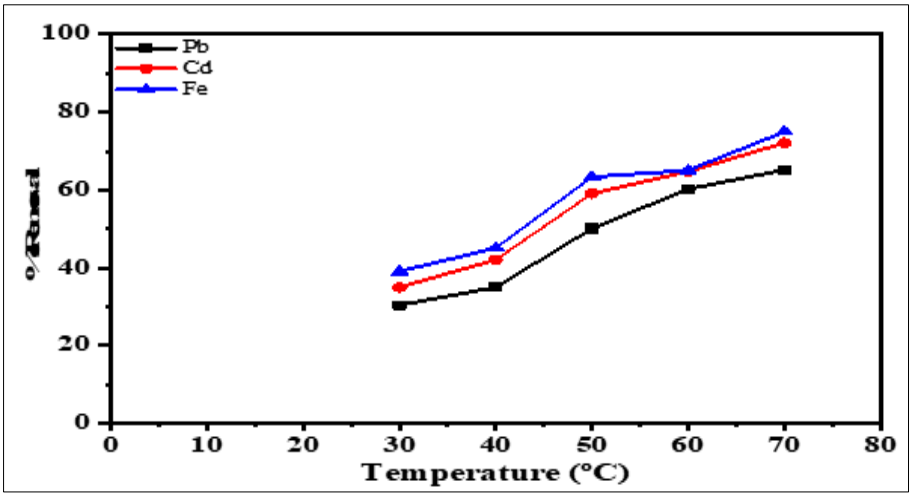

Figure 6: Effect of temperature on the removal of some heavy metal ions using CdS nanoparticles

The adsorption behaviour of Pb, Cd, and Fe ions onto CdS was investigated using two common isotherm models: Freundlich and Langmuir, each providing insights into the interaction chemistry between the metal ions and the CdS surface (Table 1). The Freundlich model describes adsorption on heterogeneous surfaces

and assumes multilayer adsorption. The parameter n indicates the intensity or favorability of adsorption. For Pb and Cd, the n values (2.61 and 2.811, respectively) are greater than 1, which implies favorable adsorption and strong affinity of these metals for the CdS surface. Fe has an n value close to 1 (0.902), suggesting less favorable adsorption compared to Pb and Cd. The Freundlich constant, K_F represents adsorption capacity and is highest for Fe (9.3), followed by Cd (7.83) and Pb (6.05), indicating that Fe ions have a relatively higher adsorption capacity on CdS despite the lower adsorption intensity. The high correlation coefficients ($R^2 > 0.98$ for all metals) indicate that the Freundlich model fits the experimental data well, reflecting heterogeneous adsorption sites on CdS. The Langmuir model assumes monolayer adsorption on a surface with finite identical sites and no interaction between adsorbed species. The maximum adsorption capacity Q_m derived from Langmuir is highest for Fe (91.35 mg/g), indicating that CdS can adsorb more Fe ions per unit mass compared to Pb (59.83 mg/g) and Cd (82.43 mg/g). This suggests that the active sites on CdS have a stronger or more numerous binding interaction with Fe ions under monolayer coverage conditions. The Langmuir constant, K_L reflects the affinity between the adsorbate and the adsorbent, with Pb showing the highest K_L (0.042 L/mg), indicating a stronger binding affinity of Pb ions to the CdS surface relative to Cd and Fe. The excellent fit of the Langmuir model (R^2 values approaching 1) confirms that adsorption likely occurs as a monolayer on homogeneous sites of CdS, especially at higher concentrations. Both models indicate strong and favourable adsorption of Pb, Cd, and Fe onto CdS, but with differences in adsorption mechanisms. Freundlich parameters suggest heterogeneity in adsorption sites and multilayer adsorption, particularly for Pb and Cd, while the Langmuir model supports monolayer adsorption with finite binding sites, especially significant for Fe. The high adsorption capacities and affinity constants reveal that CdS is an effective adsorbent for these heavy metals, with Fe showing the highest maximum adsorption capacity but Pb demonstrating the strongest affinity to the CdS surface. These results imply complex interactions involving surface chemistry, such as coordination or electrostatic interactions between metal ions and CdS functional groups, driving the adsorption process.

Table 1: Isotherm Parameters of some Heavy Metal Ions Removal from Abattoir Wastewater using CdS

Isotherm	Parameter	Pb	Cd	Fe
Freundlich	n	2.61	2.811	0.902
	K_F	6.05	7.83	9.3
	R^2	0.9801	0.984	0.9897
Langmuir	K_L	0.042	0.031	0.025
	Q_m	59.83	82.43	91.35
	R^2	0.9913	0.9963	0.9992

The kinetic studies on the removal of heavy metals such as Pb, Cd, and Fe using CdS reveal important insights into the adsorption process. When analyzing the data using a first-order kinetic model, the rate constants (k_1) for Pb, Cd, and Fe were found to be 0.201, 0.316, and 0.722, respectively, with correlation coefficients (R^2) ranging from 0.853 to 0.912. These moderate R^2 values suggest that while the first-order model somewhat describes the adsorption process, it may not fully capture the kinetics involved. In contrast, the second-order kinetic model shows higher rate constants (k_2) of 1.942, 4.251, and 6.038 for Pb, Cd, and Fe, respectively, with excellent correlation coefficients (R^2) close to 1 (ranging from 0.993 to 0.998). This strong linearity indicates that the adsorption of these metals onto CdS follows second-order kinetics more closely. The higher R^2 values imply that the removal process is better described by a mechanism where the rate depends on the concentration of both the metal ions and the active sites on the CdS surface. Furthermore, the equilibrium adsorption capacities (q_e) predicted by the second-order model are substantially higher than those from the first-order model. This suggests that the second-order model more accurately estimates the adsorption capacity, reflecting the chemisorption nature of the process. Chemisorption involves the formation of chemical bonds between the metal ions and the CdS surface, which aligns with second-order kinetics. Overall, the kinetic study implies that the removal of Pb, Cd, and Fe by CdS likely proceeds via chemisorption, where the interaction between the heavy metal ions and the CdS surface is the rate-limiting step, and the adsorption capacity is better predicted by the second-order kinetic model. The trend in rate constants and capacities (Fe > Cd > Pb) may reflect the differing affinities and reactivities of the metal ions toward the CdS surface.

Table 2: Kinetic Parameters of some Heavy Metal Ions Removal from Abattoir Wastewater using CdS

Kinetic	Parameter	Pb	Cd	Fe
First-order	k_1	0.201	0.316	0.722
	q_e	37.11	47.40	59.16
	R^2	0.853	0.9012	0.912
Second-order	k_2	1.942	4.251	6.038
	q_e	55.4	80.62	87.72
	R^2	0.9926	0.9951	0.998

CONCLUSION

This study demonstrated the effectiveness of synthesized cadmium sulfide (CdS) nanoparticles as an adsorbent for the removal of Pb^{2+}, Cd^{2+}, and Fe^{3+} from abattoir wastewater. The characterized nanoparticles exhibited a cubic crystal structure, nanoscale morphology, and a high specific surface area of 86.4 m^2/g, properties that collectively contributed to their exceptional adsorptive performance. Maximum removal efficiencies of 94.3%, 91.7%, and 89.5% for Pb^{2+}, Cu^{2+}, and Cr^{3+}, respectively, were attained at an optimal pH of 6.0. Equilibrium data best fitted the Langmuir isotherm model, confirming monolayer adsorption onto homogeneous active sites, while pseudo-second-order kinetics established chemisorption as the governing mechanism. These results collectively highlight CdS nanoparticles as a promising, highly efficient adsorbent for heavy metal remediation in abattoir wastewater treatment. Future studies should explore regeneration cycles, pilot-scale application, and potential toxicological implications of CdS deployment in real-world wastewater systems.

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