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Isotherm Analysis of Ismate Violet 2r Dye Adsorption onto Cadmium Sulfide Nanoparticles

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Abstract:

This research endeavors to examine chemically synthesized cadmium sulfide nanoparticles (CdS-NPs) via exhaustive characterization and assesses their efficacy in the adsorption processes aimed at the removal of IV2R dye from aqueous solutions. Cadmium sulfide nanoparticles (CdS-NPs) were prepared and characterized in this study. CdS-NPs prepared through the chemical perfusion technique as a pure nanostructure. The synthesized CdS-NPs were characterized by XRD technique, UV-Visible spectroscopy, and FTIR. The energy gap for the prepared CdS-NP films was (2.6) eV, and absorbance measurements were very high for wavelengths greater than 600 nm. The nanoparticles appeared to be spherical in shape and (20) nm in size, which is considered a good size for achieving the highest dye removal efficiency. The surface area of CdS nanoparticles was 37.5 m² g⁻¹ by using BET method. Applications were made for dye degradation, and CdS-NPs were used for the degradation, removal, and decoloration of the highly hazardous Ismate Violet 2R (IV2R) dye using an adsorption technique. The effects of pH, contact time, and dose mass were optimized. The optimum conditions for removal were selected, with a pH of 7 and an exposure time of 180 minutes. The study also found that the zeta potential value was (-25) mV, which confirmed the presence of an electrostatic interaction between the surface of the Cds and the Dye. This study found that the size of cadmium sulfide nanoparticles (CdS-NPs) strongly influences their physicochemical properties.

Keyword: Adsorption, Heavy metal, XRD, CdS-NPs, (IV2R) dye.

Introduction

Cadmium sulfide nanoparticles that (CdS NPs): Small particles (1–100 nm) of CdS that have special electronic and optical characteristics because of quantum size effects. They are semiconductors with a lot of surface area, possess powerful luminous properties, and are employed in LEDs, solar energy sensors, and photocatalysis (Hadi et al 2021). Group II–VI semiconductors consist of a group II element (the metal cadmium, Cd) alongside the group VI element (the element sulfur, S. It has many physical and chemical properties (Al-Salman et al 2023; Refat et al 2023). It is a polycrystalline compound with hexagonal in structure or a diamond-like cube in its composition or mixes (Bukhtiar & Zou 2024). Cadmium sulfide has widely studied among semiconductors due to its wide energy gap of 2.42 eV at room temperature. Also, it is an important material in lasers, solar cells and photo detectors. CdS possesses have a variety of advantages such as easy fibrosis process, chemical stability, and band gap tenability (Abbas 2025). CdS-NPs are the most important nanoparticles of metal oxides, due to the unique physical and chemical properties. These possess are increases their susceptibility to applications such as the disposal of pollutants in the environment (Ghasempour et al 2023). It was found that CdS has great potential in adsorption techniques. The adsorption property of CdS nanoparticles was also evaluated as in study (Fouda-Mbanga et al 2020). It was proved that CdS-NPs has the ability in adsorption of H₂S gas, which is considered a highly toxic gas due to corrosion and a colorless gas, and contributes significantly to air pollution (Azamuddin et al 2021). The researcher investigated the adsorption efficiency of CdS-NPs in removing of an amount of potassium permanganate. CdS-NPs are the most benefit particles in the application of adsorption (Elia et al 2014). As they are used in the disposal of pollutants in the environment. CdS which has great potential in adsorption of dyes effectively in a different environments (Yu et al 2015). The IV2R with molecular formula (C₂₂H₁₄N₄O₁₁S₃CuCl) has a molecular weight (700 g/mole), it is hazardous to both the environment and human health because of its toxicity and resistance to degradation, highlighting the importance of its removal from water (Al-Arjan 2022). Previous studies have used CdS-NPs to get rid of H₂S gas that pollutes the air, which effectively affects the environment, in addition to studying the efficiency of CdS-NPs as an absorbent material for removing dye from aqueous solutions.

This study aim to use CdS-NPs in degradation, removal, decoloration of IV2R from water in addition to optimization study of different parameters affect the adsorption process.

Material and method

Materials

CdCl₂, thiourea, IV2R, were purchased from sigma Aldrich, alqifaf, (Baghdad, Iraq). In this study, the new clean glass slide with dimensions (1, 10 and, 50 mm) was used.

Preparation of CdsNPs

CdsNPs particles were prepared by dissolving 0.1 M CdCl₂ and 0.2 M thiourea in 50 ml distilled water. The solutions were mixed at 80 °C for 60 min. with stirring for 3 hour, then rinsed and dried at 60 °C.

Preparation of dye solution

The stock solution of (IV2R) was prepared by dissolve (1 g) of dye in (1 Liter) of distilled water and stored at 4 °C.

Characterization of Adsorbent

Detailed structural characterization of chemically synthesized cadmium sulfide nanoparticles before adsorption studies. UV spectrophotometric measurements (UV-Cary 60 - Agilent) it has been performed on materials that are dispersed in glycerin and suspensions in the water. Powder X-ray diffraction patterns were recorded on a Bruker apparatus D8 Advanced X-ray diffractometer with CuK α radiation, at 40 keV and 40 mA at two theta Range from 5-70 S. The crystal phases was matched by comparing the XRD patterns of with those reported in the literatures. Effective functional aggregates were identified through FTIR measurements (IRTracer-100, Shimadzu, Japan).

Adsorption package study

The ability of CdS-NPs to remove (IV2R) dye from aqueous solutions was investigated using batch adsorption tests in a shaking shaker, The ideal conditions for adsorption was determined, These experiments investigated that the ability of the prepared CdS-NPs in removing the (IV2R) dye from aqueous solutions in various conditions include pH value of 3-9, contact time of 15-180 min., and adsorbent dose on (IV2R) dye adsorption efficiency (10 -100 mg in 25 ml).

For all experiments, 100 mg of CdS-NPs were combined with 25 ml of solutions containing various amounts of IV2R dye.

Centrifugation of samples was accomplished at 5000 rpm for 10 min, in order to remove any suspended residual material especially after shaken using shaker water bath. the shaker water bath was run at 100 rpm to ensure the presence of adsorbent material in addition to confirm the binding of dsorbate and adsorbent.

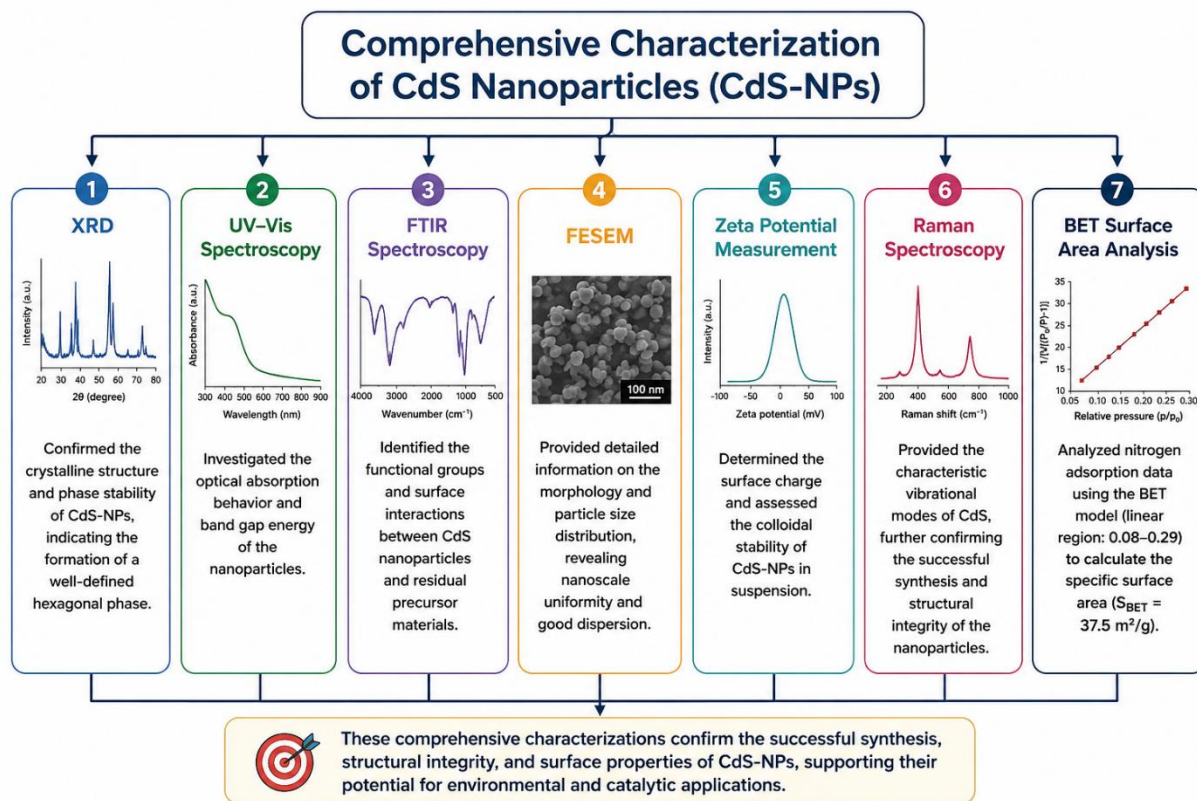
The experiments temperature were conducted at room temperature. The removal efficiency ratio (%R) and the adsorptive capacity (qe) of dye, respectively were determined. equations 1 and 2 were used after the evaluation of concentration of final dye concentration (Ce), initial concentration Co (Pandian et al 2011) .

$$\%R = \frac{(Co - Ce)}{Co} \times 100 \dots \dots \dots \text{Equation (1)}$$

$$q_e = \frac{(Co - Ce) \times V}{m} \dots \dots \dots \text{Equation (2)}$$

Results And Discussions

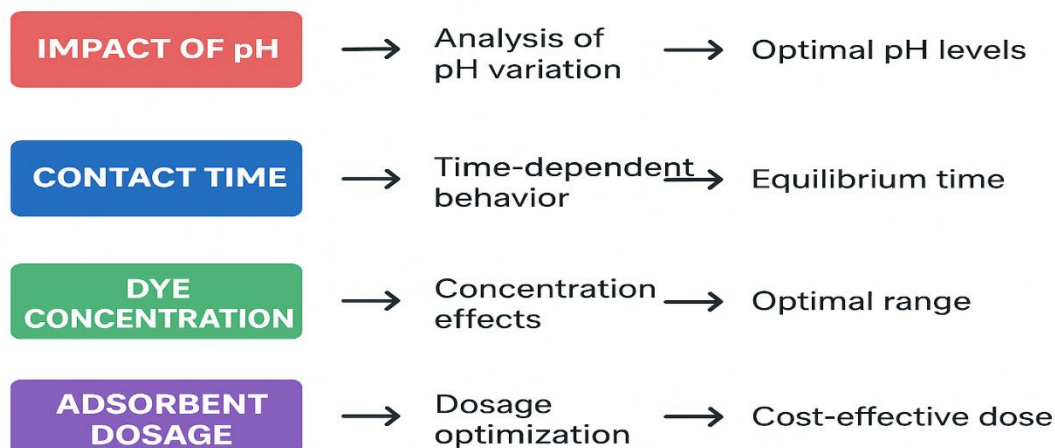
The investigation was executed in two principal segments. Initially, the characterization of Cadmium Sulfide nanoparticles (CdS-NPs) was conducted comprehensively to ascertain their structural, morphological, and surface attributes. Ultraviolet–Visible (UV–Vis) spectrum analysis was utilized to examine the optical absorption characteristics and band gap phenomena of the nanoparticles. X-ray diffraction (XRD) analysis substantiated the crystalline architecture and phase integrity of the nanoparticles. Fourier Transform Infrared (FTIR) spectroscopy facilitated the identification of significant functional groups and surface interactions, while Field Emission Scanning Electron Microscopy (FESEM) elucidated the morphology and particle size distribution. Zeta potential assessments revealed the surface charge and colloidal stability, and Raman spectroscopy yielded a vibrational signature, further corroborating the synthesis of CdS-NPs.



Scheme 1 Schematic illustration of the thorough characterization of the synthesized CdS nanoparticles (CdS-NPs) employing X-ray diffraction (XRD), UV-Visible (UV-Vis) spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, Field Emission Scanning Electron Microscopy (FESEM), zeta potential assessment, Raman spectroscopy, and Brunauer–Emmett–Teller (BET) surface area evaluation. The characterisation methods yield insights into the crystalline architecture, optical attributes, functional groups, morphology, surface charge, vibrational traits, and specific surface area of the CdS-NPs

Subsequently, the efficacy of CdS-NPs for the remediation of IV2R dye from aqueous media was scrutinized under diverse conditions. The impact of pH on dye removal efficacy was analyzed, revealing optimal performance at designated pH levels. The effect of contact time (shaking) was investigated to ascertain the duration necessary for maximal adsorption.

Furthermore, the repercussions of both the dye concentration and the dosage of the adsorbent were assessed, culminating in an optimized condition for efficient decolorization, degradation, and removal of IV2R from aqueous environments.



Scheme 2 A schematic illustration of the experimental variables examined for the elimination of IV2R dye utilizing CdS nanoparticles (CdS-NPs), encompassing the influences of pH, contact duration, dye concentration, and adsorbent quantity, resulting in the identification of the ideal pH, equilibrium contact time, appropriate dye concentration range, and economical adsorbent dosage.

X-ray diffraction Analysis

Figure (1) displays the X-ray diffraction (XRD) layout of the synthesized CdS nanoparticles (CdS-NPs). The diffraction results verify that the CdS films possess a polycrystalline structure featuring a hexagonal phase, aligning well with prior research [9]. The XRD pattern shows five significant diffraction peaks currently $2\theta = 24.50^\circ$, 26.66° , 37.55° , 43.20° , and 52.50° . These peaks correspond with the (100), (002), (102), (110), and (112) crystallographic planes, respectively.

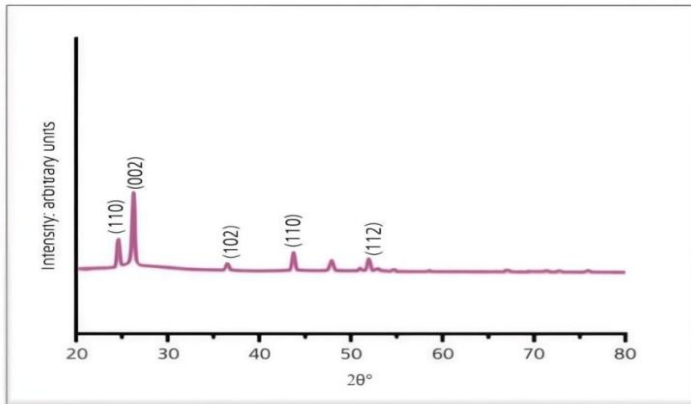


Fig. 1. The X-ray diffraction (XRD) pattern of CdS-NPs shows clear peaks that match the hexagonal crystalline structure.

The findings indicate that the synthesized CdS-NPs possess a polycrystalline characteristic with a hexagonal crystal configuration. This finding corresponds with the conventional hexagonal structure phase of CdS documented in earlier research

The crystal size (D) of the CdS crystal was estimated using Debye Scherer equations.

$$D = \frac{K\lambda}{B \cos \theta}$$

K . it is the Scherer constant whose value for spherical crystals is (0.9)

λ =XRD wavelength (1.540 Å)

B = is the full width at the midpoint of the diffraction peak.

θ . Bragg diffraction angle.

Uv-visible Spectroscopy

Measurement of absorbance as a function of wavelength was accomplished. The absorbance of CdS-NPs thin films on glass substrates was measured as a function of wavelength to see how they behaved in the 320–900 nm range. The absorbance spectrum showed a clear peak around 325 nm, which means that the material reacted strongly to ultraviolet light. Also, the absorbance values stayed pretty high at wavelengths over 600 nm, which means that the CdS-NPs films can precisely absorb and discriminate light with longer wavelengths. These results show that the films could be sensitive to UV radiation along with would work well for optoelectronic as well as photo-detection uses (Pandian et al 2011; Salim & AL-Mammar 2023; Farhan et al 2018)

The gap in the energy band (E_g) of the produced CdS-NPs films was found to be about 2.6 eV. The value of the band gap was discovered to depend on a number of factors, such as the type of substances used and the method used to make them. This value is significantly greater than the standard typical CdS-NPs band gap (2.42 eV), and it's likely because the particles are tiny enough (~20 nm) that they are confined to a quantum state. As the particle size gets smaller, the energy gap gets bigger. This means that CdS nanoparticles have successfully formed in the quantum dimension range (Figure 2).

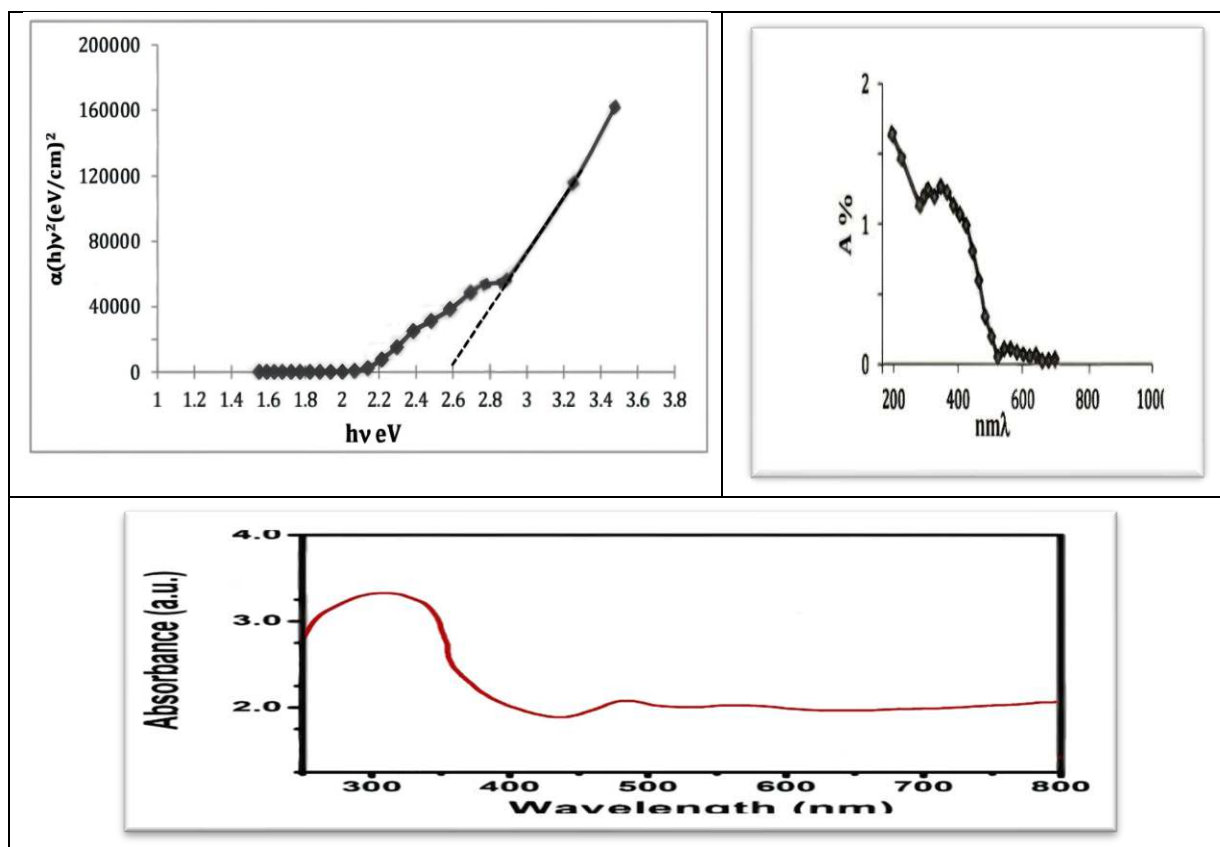


Fig. 2: Show a. Energy gap of CdS nanoparticles b. absorbance. C.UV-Visible spectra of CdS nano

FTIR measurement

The FTIR measurement used to study the composition of composite materials, to know the functional group and types of bonds. The interpretation of FTIR spectra of CdS-NPs shown with different peaks. The FTIR spectroscopy technique of CdS-NPs employs distinctive peaks to ascertain the material's structure, including the principal peak depicted below 700 cm^{-1} indicates the intrinsic Cd-S bond vibration, and other common peaks between 1000 and 3600 cm^{-1} show that there is water (O-H) and remaining organically functional groups (C-H, C=O, C-N) from the creation procedure or capping agents (A.B et al 2012; Kumar & Sharma 2016; RamKumar Pandian et al 2011).

The study finding peaks was as follows: 3250 cm^{-1} may attributed to the (O-H) group, which confirms the presence of water. While a peak at 3450 cm^{-1} , may related to (N-H), peak at 2460 cm^{-1} the (C=N), peak at 1700 cm^{-1} may belong to (C=O), peak at 1500 cm^{-1} is due to (-CH₂-), and peak at 1160 cm^{-1} is related to (C-N). The appearance of peak at 1050 cm^{-1}

which may come from existence of (C-O) expansion vibration of the adsorbed methanol (Farhan et al 2022; Ali et al 2025; Amer et al 2020) (Figure 3).

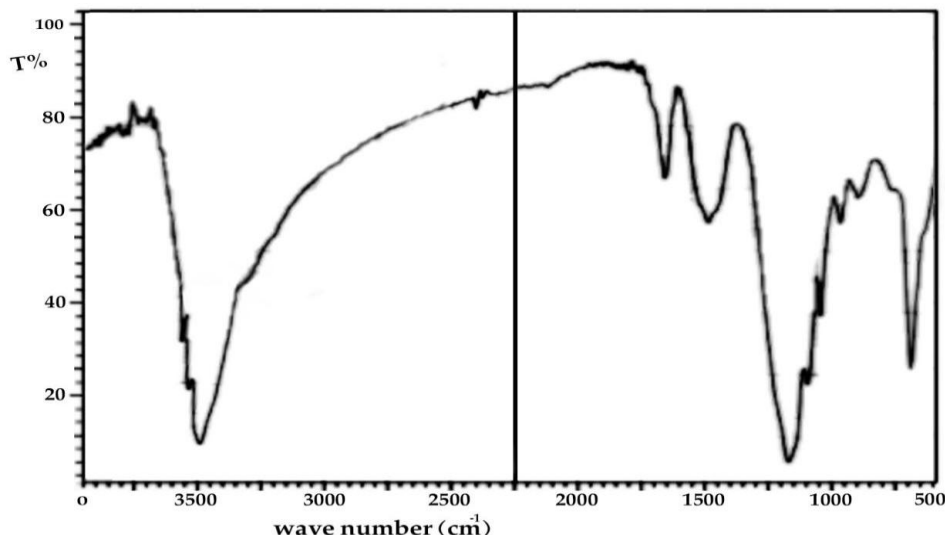


Fig. 3: FTIR spectra of CdS nanoparticles

Field Emission Scanning Electron Microscopy (FESEM)

Field emission scanning electron microscopy, also known as FESEM, is a high-resolution imaging method used for studying at the surface structure and shape of nanomaterials. A field source of emission creates a narrow electron beam that scans the surface of the sample in FESEM. The electrons interact with the material to create detailed images. Compared to regular SEM, this method gives you a lot more detail, greater depth on field, and a clearer image. The FESEM assessment of CdS nanoparticles shows their dimension, distribution of dimensions, and surface texture. This lets us accurately estimate the size and shape of particles at the nanoscale level (Gnanamoorthy et al 2013; Havrdova et al 2014).

Figure (4) displays the scanning electron microscope (SEM) visualization of CdS NPs. The micrograph shows that most of the nanoparticles are spherical and have an average size of about 20 nm. The small size of the particles gives them a more extensive surface area, which means there are more places for the dye to stick to and be removed from. Also, the nano scale size makes the energy band gap wider because of the quantum confinement effect. This helps absorb light and makes reactive radicals that break down dyes.

Specific surface area calculated using the following relationship for spherical nanoparticles:

$$S_{BET} = \frac{6}{\rho \times D}$$

SBET = Theoretical specific surface area (m²/g)

P = Density of CdsNPS (4.82 g/cm³)

D= Average particle diameter (nm)

SBET = 6/4.82×20 ×1000= 62.24 m²/g.

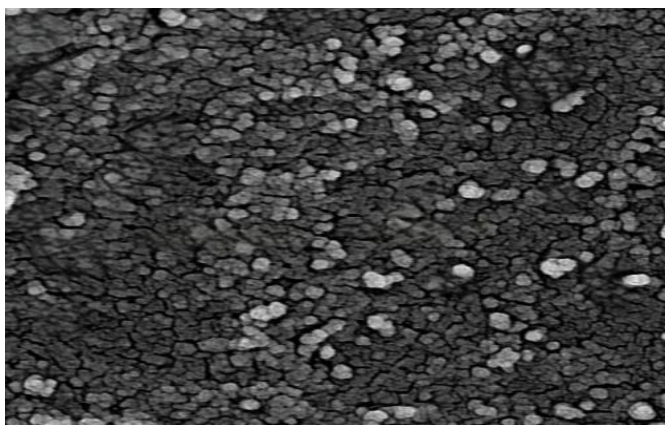


Fig 4. The scanning electron microscope (SEM) images of CdS nanoparticles shows spherical grains with a mean particle size of about 20 nm. The small size of the particles raises the surface area that can be used to remove dye and broadens the band gap of energy, which helps absorb more light and makes more reactive radicals that break down dye.

The size of CdsNPS is considered a good size to achieve the highest dye removal efficiency because of the availability of a very high surface area and high optical activity

Zeta potential measurement

Zeta potential is an approach to measure the surface charge of nanoparticles and see how stable their suspension is. You can find out by measuring how fast particles move through an electric field using methods like electrophoretic light scattering. High absolute zeta values of potential (above ±30 mV) mean that the particles are strongly repelled by each other and that the colloid is stable. Values close to zero mean that the particles are likely to stick together

It is one of the basic concepts in surface chemistry and colloidal physics. It is the electric potential difference at the shear plane between the surrounding liquid such as water and the

charged particles or surfaces immersed in it. It gives an understanding of the mechanism of adsorption of the IV2R dye by CdS NPS nanoparticles, and it is indicator of the stability of the particles in the solution.

Figure 5 When we measured the zeta potential of CdS NPs at pH 6.8, we got a value of -25 mV. This means that the dispersion was moderately stable and that there were electrical charges between the positively charge CdS surface and the negatively charged dye molecules. This behavior of the surface charge helps with effective adsorption by attracting particles through electrostatic forces. The FTIR spectrum also shows these interactions. The peaks at 3250 cm^{-1} and 3450 cm^{-1} represent $-\text{OH}$ and $-\text{NH}$ stretching vibrations, respectively. This means that there are functional groups that can absorb protons in acidic media and help the dye stick to the surface of the nanoparticles. (Bukhtiar & Zou 2024; Almagviva et al 2022).

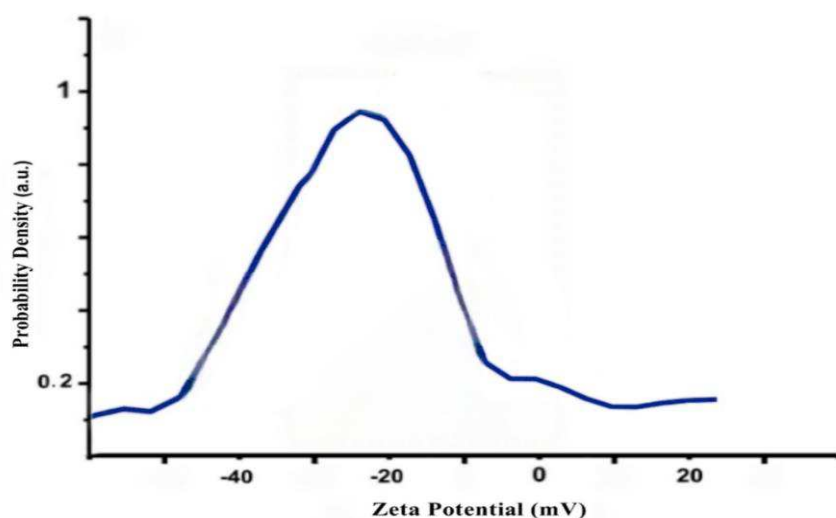


Fig. 5. The zeta potential of CdsNPS at pH 6.8 is -25 mV, which means that the positively charged CdsNPS surface and the negatively charged dye molecules are attracted to each other by electrostatic forces. FTIR peaks at 3250 cm^{-1} as well as 3450 cm^{-1} ($-\text{OH}$ and $-\text{NH}$ groups) show that the surface works and can absorb protons in acidic environments

The figure (5) showed a peak at (-25mV) with a moderate spread between (-10 and -40) confirming the interaction of the dye with the surface of CdsNPS, and measurement carried out at a temperature of $25\text{ }^{\circ}\text{C}$ using a zeta Malvern device.

Raman Spectroscopy measurement

Raman spectroscopy characterized nanoparticles by examining alterations in inflexibly scattered light, functioning as a robust, non-destructive method that elucidates the composition, crystal structure, dimensions, and defects of nanomaterials.

Raman Spectroscopy measurement provide variation information about the interactions in the analyzed material, which provides of the composition and chemical structure (Farhan et al 2022).

The molecular interactions between IV2R dye and CdsNPS were investigated. The investigation findings were ($\lambda_{\text{ex}} = 532\text{ nm}$, 5Mv power, 10s integration time).

The increase in the Raman intensity in figure (6-b) is because the nanoparticles are separated, so they provide a larger surface area for the absorption of dye molecules, which increase the interaction of light with the dye on the surface, also, the good and regular distribution of the CdS-NPs particles reduces the phenomenon of light scattering, which weakens the Raman intensity, we note that the CdS peaks do not appear clearly because the surface enhancement effect of the dye is especially dominant if the particles are small and regularly distributed.

Table 1 shows the precise Raman shifts (wavenumbers) seen in the spectra regarding Figure 6 and links them to the dye's molecular functional groups. By connecting the observed peaks to the dye's particular chemical composition and confirming its identity, this table helps make sense of the data.

Table 1. shows Raman spectroscopy for Dye solution before and after adding CdS-NPs

Sample	Peak wave number (cm^{-1})	Intensity (a.u)	Function group
Dye solution in distilled water	1130.03	194.90	S=O
	1100.88	175.10	C-H

	1440.90	500.11	N=N
	1500.10	250.30	C=C
	2900.39	100.52	O-H
Dye solution after adding CdS-NPs	1200.03	198.91	S=O
	1142.88	178.80	C-H
	1440.90	515.20	N=N
	1550.10	295.75	C=C
	2998.30	110.70	O-H

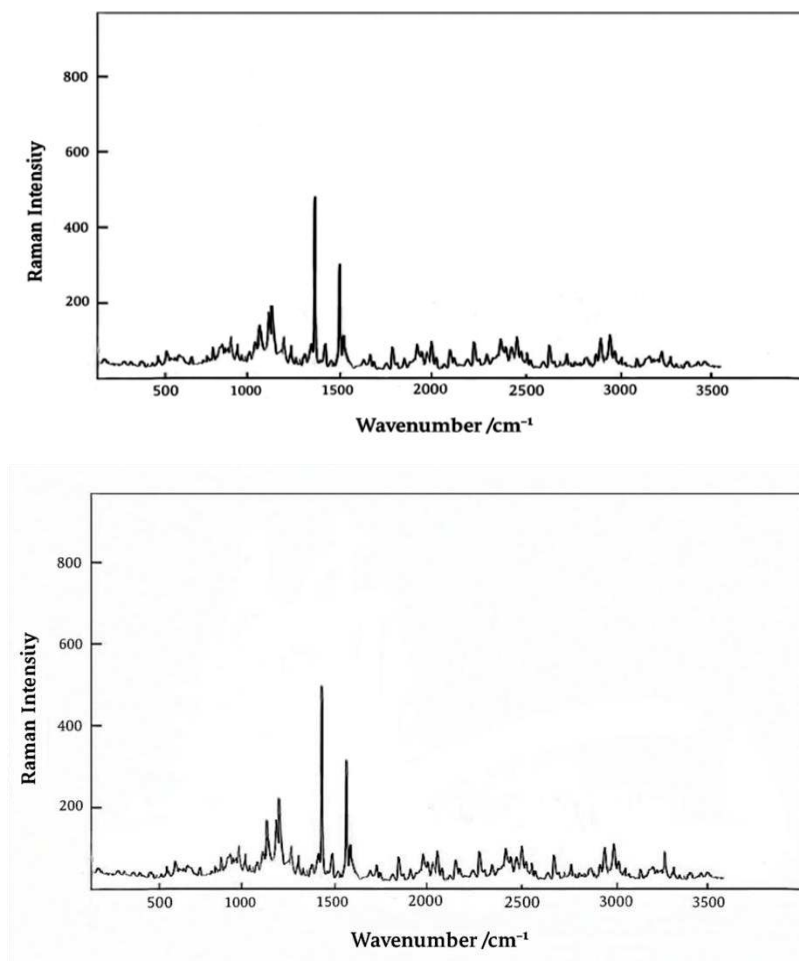


Fig. 6. Raman of Dye (a) before treatment with CdSNPS (b) after treatment with CdS-NPs

The more significant Raman resonances in Figure (6-b) show that the dye molecules are strongly interacting with and efficiently sticking to the outer layer of the CdS-NPs. The "SERS" (surface-enhanced Raman scattering) influence is mostly responsible for this increase in signal strength. It shows that the CdS-NPs are good at holding dyes.

Surface area analysis using the BET method :

The prepared CdS nanoparticles' (CdS-NPs) specific surface area (SBET) was ascertained utilizing the Brunauer–Emmett–Teller (BET) technique based on the subsequent equation:

$$SBET = \frac{V_m \times N_A \times \sigma}{22414 \times W}$$

where V_m is the monolayer adsorption volume, N_A is Avogadro's number ($6.022 \times 10^{23} \text{ mol}^{-1}$), σ is the cross-sectional area of a nitrogen molecule (0.162 nm^2), and W is the mass of the analyzed sample.

The nitrogen adsorption data were evaluated by the BET model. The BET plot illustrated in Figure 7 demonstrates a remarkable linear correlation over the relative pressure (P/P_0) interval of 0.08–0.29, suggesting that nitrogen adsorption adheres to the BET theory and that monolayer adsorption transpires within this range. The determined specific surface area of the CdS nanoparticles was $37.5 \text{ m}^2 \text{ g}^{-1}$. This comparatively elevated surface area results from the nanoscale size of the produced particles and the effective preparation technique that created several available surface-active sites. The augmented surface area is anticipated to improve the adsorption capability and catalytic efficacy of the CdS nanoparticles, rendering them viable candidates for environmental remediation, especially for the effective extraction of organic contaminants from water solutions (Figure 7).

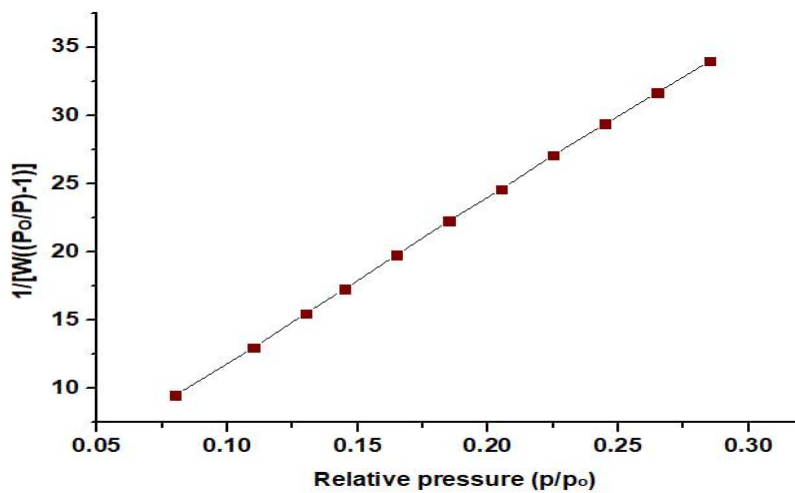


Fig. 7: BET figure illustrating nitrogen adsorption for chemically produced CdS nanoparticles, highlighting the linear segment within the relative pressure (P/P_0) interval of 0.08–0.29 utilized for calculating the specific surface area ($SBET = 37.5 \text{ m}^2 \text{ g}^{-1}$).

Application of using CdS-NPs in removing IV2R

Effect of pH

The impact of altering the pH of a solution on elimination of IV2R dye was examined. The pH of the solution being used is very important to get remove of IV2R dye because it regulates the ionization along with charge of both the molecules of dye and the outer layer of the CdS nanoparticles. Adjusting the pH to the optimum level enhance the dye and nanoparticles to bound and attract each other as much as possible (Badr et al 2016; Gonsalvesh et al 2016). The solution pH was studied in range of 3 to 9 in the presence of constant dye concentration of 25 mg/L.

The percentage of dye removal raised up as the pH of the solution raised up. The highest amount of dye was adsorbed at $\text{pH} = 6.8$ within the conditions given. The surface charge properties of CdS-NPs are responsible for this behavior. When the pH is low, the outer layer of CdS NPs gets highly protonated, which gives them an intense positive charge that makes them more attracted to the negative-charged dye molecule. The equilibrium between surface charged particles along with dye ionization, on the other hand, leads to the best electrostatic attraction and surface binding when the pH is close to neutral (around pH 6.8). This is how maximum adsorption efficiency is reached (Arab et al 2022; Majhi & Patra 2020; Alkhabbas et al 2023; Senasu et al 2018). At lower pH levels, the rise in H^+ concentration in CdS-NPs leads to the generation of a positive charge via H^+ adsorption, increasing the adsorption of IV2R dye.

CdS nanoparticles (CdS-NPs) have a positively charged outer layer in acidic environments, which makes them very attracted to anionic dye molecules. This makes them more effective at adsorbing dye and, in some cases, almost completely removing it. When the pH rises up, the number of sites with negative charges on the CdS surface increases up as well. This causes electrostatic repulsion in between the negative charged surface of the adsorbent and the anionic dye molecule. So, the ability to adsorb goes down as the pH increases up. These observations indicate that electrostatic interaction is the primary mechanism of dye adsorption at lower pH levels, whereas at elevated pH values, alternative mechanisms involving cation

exchange along with surface complexation may also influence the overall adsorption process (Senasu et al 2018; Anoop Krishnan et al 2011).

When the pH of the solution was raised above pH = 8, the percentage of dye removal was reduced. This phenomenon can be explained by the formation of soluble hydroxyl complexes at higher pH levels, resulting in a shift in the sorption behavior (Senasu et al 2018).

Previous research investigations have demonstrated the same mechanism to earn the adsorption of different metal ions via bio sorbents that where attraction by electrostatic force, ions exchange, as well as surface complexation play essential roles in the uptake mechanism (Chanda et al 2021; Sud et al 2008) (Figure 8).

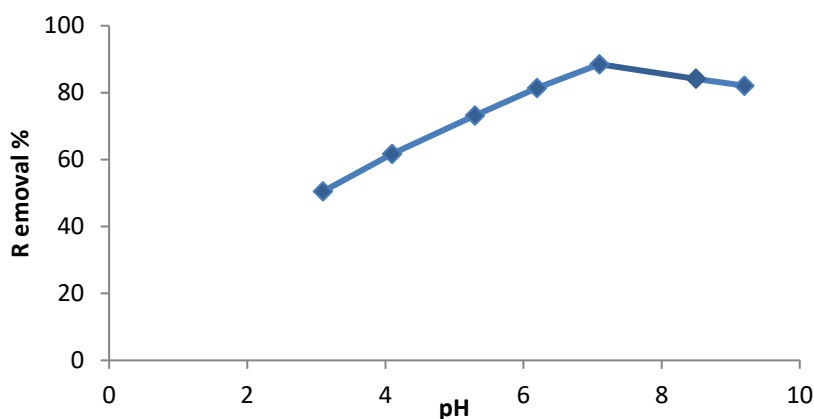


Fig. 8: Effect of pH on dye adsorption

Effect of (shacking) Contact

Another important factor that affects how well CdS nanoparticles (CdS-NPs) adsorb IV2R dye is shaking or contact time, which is the amount of time it takes to reach adsorption balance. So, choosing the right contact time is important for getting the most out of adsorption. Figure 9 shows that the IV2R dye stuck to the CdS-NPs quickly at first and then slowly reached equilibrium. The adsorption tests were done with contact times of 10 to 180 minutes, and the best time for equilibrium was determined to be about 120 minutes. There were two distinct stages

of adsorption: a quick first phase that lasted 10 minutes, and a slower phase that lasted until equilibrium was reached approximately 180 minutes. The fast adsorption at the beginning is because there are a lot of binding sites located on the CdS-NP outer layer, which lets dye molecules bind quickly. The adsorption rate dropped down as these sites filled up because the sites were full and the dye molecules couldn't move as easily near the surface. After three hours (180 minutes), the maximum effectiveness of removal was about 95%. These results show that adsorption efficiency goes up with contact time till equilibrium is reached. This is because there are more chances for dye molecules to hit and interact with the active sites of adsorption on CdS-NPs (Chanda et al 2021; Farhan et al 2023a; Ananta et al 2015).

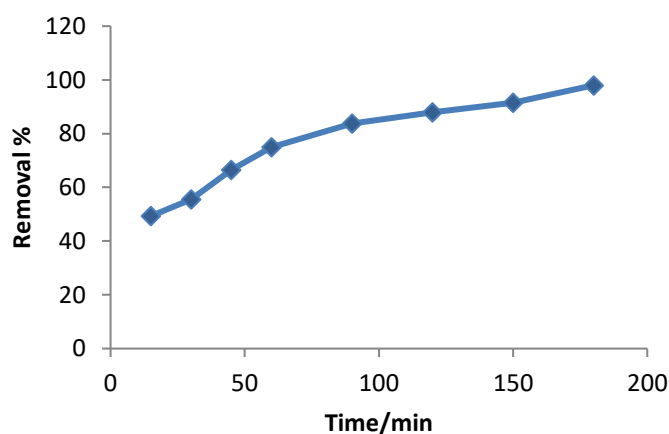


Fig. 9 shows how the amount of time that the IV2R dye is in contact with CdS-NPs currently 25 °C along with pH 6.8 affects its adsorption. In the first 10 minutes, adsorption happens quickly and then slows down until it achieves equilibrium at 120–180 minutes, when it is 95% effective at removing the substance.

Dose of IV2R dye

The experimental study examined the influence of the initial concentration of dye (10–100 mg/L) on adsorption efficacy of CdS nanoparticles (CdS-NPs). The adsorbent dosage was maintained a constant currently 100 mg under regulated conditions of a pH 6.8, temperature of 25 °C, along with contact time 180 min. Figure 10 shows that the dye removal rate was about 99% at its lowest concentration (10 mg/L). This shows that CdS-NPs can strongly adsorb under these conditions.

But as the initial amount of dye raised up, the percentage of dye that was removed slowly went down. This decrease is because the CdS-NP surface has too many active sites, which means there are fewer places for dye molecules to stick to than there are dye compounds in solution.

The same phenomenon has been documented in prior studies, wherein an elevation in dye concentration resulted in a decrease in removal efficiency attributed to outer site saturation and diminished mass transfer forces (Adeoye et al 2025; Tareq & Al-Hyali 2022; Elkhaleefa et al 2021).

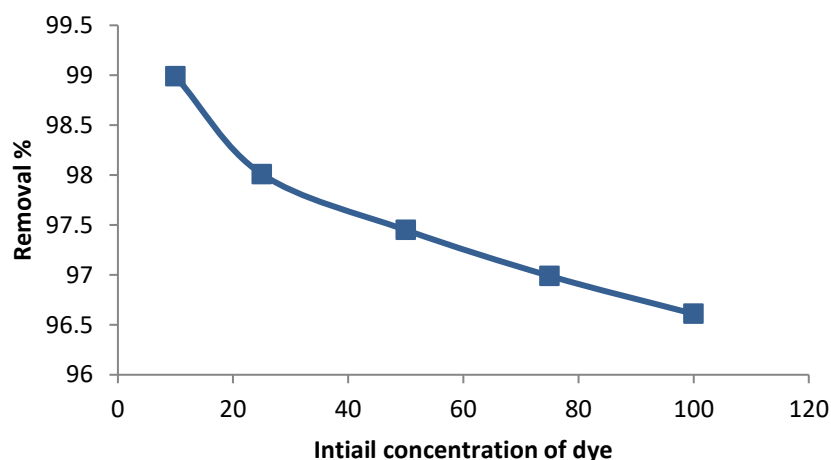


Fig. 10. Effect of initial concentration of dye

The results confirm that the adsorption efficiency decreased with increasing dye concentration. This can be explained by the low number of the active places available on the surface from the adsorbent material , in order to bind to the ions present on IV2R dye in the solution (Elkhaleefa et al 2021).

Dose of Adsorbent

The adsorbent dose is one of the most important factors that affects the extent to which IV2R dye reacts to low-cost adsorbents. Batch testing for adsorption were carried out at 25 °C to find the best dose of CdS nanoparticles (CdS-NPs). The adsorbent dose was changed from 10 g/L to 100 g/L while keeping the pH constant. Figure 11 shows that the percentage of dye removed rose up from 36% towards 88% as the amount of adsorbent rose up from 10 g/L into 100 g/L. This trend is due to the fact that higher amounts of adsorbent increase both the total surface area along with the number of active sites, which makes the molecules of the dye and the CdS-NP layer interact more (Adeoye et al 2025).

But when the amount of adsorbent was more than about 15 g/L, the rate of adsorption tended to level off. This meant that adding more adsorbent mass did not significantly improve removal efficiency. This behavior is probably because the adsorption sites overlap or group together at higher doses, which makes the effective surface area smaller and limits the interaction between the dye and the adsorbent. The results of this study align with prior literature, indicating that a rise in adsorbent dosage initially improved removal efficiency until reaching a saturation threshold (Rafiq et al 2020; Farhan et al 2023b; Mahmoud & Hsu 2025; Pant et al 2014).

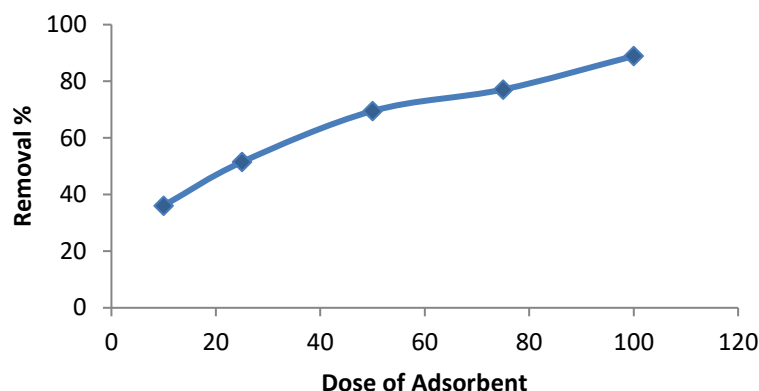


Fig. 11. The impact of adsorbent dosage on the removal effectiveness of IV2R dye using CdS-NPs at a temperature of 25 °C and a pH that is constant. The adsorption percentage rose up from 36% to 88% when the dose rose up from 10 g/L to 100 g/L. After that, it stayed about unchanged because the surface sites were full.

Sorption isotherms

The Langmuir model, Freundlich, and Temkin isotherm approaches were used to look at the adsorption equilibrium data and explain how IV2R dye and CdS-NPs interact. The Freundlich and Langmuir models both fit the experimental data very well, with the coefficients of correlation ($R^2 > 0.997$) showing that the dye elimination process happens mostly through adsorption and not a catalytic reaction. The results from the Temkin model also supported these findings, showing that the molecules of the dye have a strong attraction to the CdS-NP outer layer. The linearity of adsorption isotherms shown in table 2.

Table 2. the Langmuir, Freundlich, as well as Temkin established isotherm parameters for the adsorption of IV2R dye onto CdS-NPs. The Temkin model shows that the sorbent and dye have a strong affinity for each other, which supports the idea that adsorption is the main mechanism.

Freundlich	Linear equation	R ²	1/n	KF
IV2R_CdS-NPs	y = 0.871x + 0.9739	R ² = 0.999	0.7493	7.368
Langmuir	Linear equation	R ²	qm, (mg/g)	KL (L/mg)
IV2R_CdS-NPs	y = 0.01381x + 0.005	R ² = 0.9997	204.0816	0.00862
Temkin	Linear equation	R ²	BT (J/mol)	KL (L/mg)
IV2R_CdS-NPs	y = 22.616x + 0.7475	R ² = 0.9955	22.616	1.026

Mechanism of IV2R removal using CdS-NPs

Based on the research findings, CdS-NPs demonstrated a high dye removal efficiency of 95% within over 180 min. The mechanism of dye removal involves both electrostatic and chemical interactions between the nanoparticles' surface and dye molecules. The IV2R contains negatively charged sulfonate groups (SO₃⁻) that are strongly attracted to the positively charged CdSNPS surface at pH = 6.8, as evidenced by zeta potential measurements (-25 mV). FTIR measurements showed that new chemical bonds were made (C=O at 1700 cm⁻¹ and C=N at 2460 cm⁻¹), which proved that both chemisorption and physical adsorption were happening. The significant increase in Raman signal intensity post-adsorption further supports enhanced surface interactions, attributed to the nanoparticles' high surface area (20 nm diameter) and uniform distribution, as shown by FESEM. The optical properties of CdSNPS particles, including a 2.6 eV band gap and a strong UV absorption peak at 325 nm, suggest potential photocatalytic activity that may contribute to dye degradation through free radical generation. The excellent fit of experimental data for both the Langmuir and the Freundlich isotherm models (R² > 0.997) indicates a predominant chemical adsorption process.

Conclusion

In this study, the particles for CdS were synthesized by chemical deposition, which was inferred and examined through the visible spectrum, XRD, and ultraviolet rays. The absorbance and the value of the energy gap in the sample were also determined. This study indicated that the cadmium sulfide membrane has a polycrystalline structure of the hexagonal type. The expansion and bending of the molecular functional groups in the sample were studied through the FTIR spectrum. This method of preparation is characterized that it is simple and easy. The surface area of CdS nanoparticles was measured to be found 37.5 m² g⁻¹ by BET method. This

study found that CdS-NPs have many critical applications, the most important of which is their ability to absorb toxic dyes (such as IV2R dye) and heavy metals from water. This conclusion was confirmed by Raman, zeta potential, and FESEM measurements, which demonstrated the strong absorption efficiency of the nanoparticles due to their small size of 20 nm, which provides a high surface area for absorption.

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CONFLICT OF INTEREST

I affirm that there exists no conflict of interest pertaining to my manuscript. All information and data utilized in the book were sourced from credible origins, aiming just to deliver precise and beneficial scientific material devoid of any external influence or personal bias.

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