Fabrication and Characterization of Cadmium Sulfide Nanoparticles via Laser Ablation Method

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In this work, cadmium sulfide (CdS) nanoparticles were prepared by pulsed laser ablation of CdS targets in distilled water (DW), which served as the solvent and reducing agent. Using 300 pulses and a repetition frequency of 6 Hz, an Nd:YAG laser (1064 nm, 480 mJ) was used. The x-ray diffraction (XRD), atomic force microscopy (AFM), field-emission scanning electron microscopy (FE-SEM), and UV-VIS spectroscopy were used to introduce and characterize the prepared samples. Plasmonic absorption was observed with discrete peaks using UV-Visible spectroscopy. The cubic structure of the CdS phase was validated using XRD patterns. Clusters ranging in size from 34.2 to 90.7 nm were formed with spherical particle dispersion, as shown by FE-SEM. The topography was studied by AFM showing a root mean square surface roughness of 2.833 nm, an average roughness of 2.354 nm, and an average diameter of 11.29 nm. These results validate the successful synthesis of materials for use in a variety of applied physics applications.

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1. Introduction

In recent years, an increasing number of studies have focused on the production and conceptualization of meticulously organized metal nanostructures motivated by their distinct and auspicious characteristics. Cadmium sulfide (CdS), a chemical comprising cadmium (Cd) and sulfur (S), has attracted considerable interest in the field of nanotechnology. Cadmium sulfide (CdS) nanoparticles exhibit unique optical characteristics such as adjustable bandgaps and effective light absorption [1]. These attributes render CdS nanoparticles extremely sought-after for optoelectronic applications, including solar cells, photodetectors, and light-emitting diodes (LEDs) [2,3].

The production and development of meticulously organized metal nanostructures encompass a range of synthetic techniques that enable meticulous manipulation of their dimensions, morphology, and chemical makeup [4]. The utilization of this control allows researchers to customize the characteristics of metal nanoparticles to suit specific applications. The distinctive characteristics exhibited by CdS nanoparticles possess significant potential for breakthroughs in various fields, such as electronics, energy, catalysis, sensing, and biomedicine [5,6].

As the field of nanotechnology advances, continued investigation and comprehension of metal nanomaterials is expected to result in new applications, thereby facilitating the advancement of cutting-edge technologies. Nanotechnology is an interdisciplinary domain that focuses on the manipulation and regulation of matter at the nanoscale, ranging from approximately 1 to 100 nm. This discipline involves the comprehension, conceptualization, and production of materials, devices, and systems that possess unique features and functionalities. The term "nano" denotes a unit of measurement equivalent to one billionth of a meter. At this size, the material characteristics can exhibit notable deviations from their macroscopic equivalents. Nanotechnology leverages these distinct qualities to advance novel materials, devices, and processes that are useful in diverse domains such as electronics, medicine, energy, materials science, and environmental science [7,8].

Cadmium sulfide (CdS) is composed of the elements cadmium (Cd) and sulfur (S). It functions as a crucial semiconductor material and is extensively used in optoelectronics and nanotechnology owing to its unique electrical and optical characteristics [9].

The aim of this study is to synthesize nanoparticles derived from the CdS and investigate their properties in light of their extensive applicability.

2. Materials and Methods

Pulsed-laser ablation (PLA) is a widely used technique for generating nanoparticles, thin films, and for surface modifications. The mechanism of pulsed laser ablation involves several steps: laser pulse absorption, where a high-energy laser pulse is focused onto the target material. The target material can be a solid, liquid, or gas. The laser typically used is a pulsed laser that emits short bursts of intense light energy [10]. Energy absorption and vaporization: Upon absorption of the laser pulse, the target material

rapidly absorbs the laser energy, causing localized heating. This intense energy absorption can lead to vaporization of the target material, turning it into plasma [11] and plasma formation, which causes the target material to rapidly heat up and expand, leading to the formation of a plasma plume. The plasma is a high-energy, ionized gas consisting of ions, electrons, and neutral species, and rapidly expands outward from the target surface owing to the pressure generated by laser-induced vaporization. As the plasma expands, it cools and condenses into nanoparticles and clusters. During the cooling and condensation processes, the atoms and molecules in the plasma aggregate and nucleate, forming nanoparticles or nanoclusters. The size and morphology of nanoparticles can be influenced by various factors, including the laser parameters, target material, and surrounding gas environment. After the nanoparticle collection, the generated nanoparticles were collected on a substrate or in a collection chamber. The substrate can be placed in close proximity to the target material, allowing the nanoparticles to deposit directly onto their surface to form thin films or coatings. Pulse laser ablation offers several advantages for nanoparticle synthesis and thin film deposition. This provides a simple and versatile method for producing nanoparticles of various materials. This process can be used to generate nanoparticles from a wide range of materials including metals, semiconductors, ceramics, and polymers. This allows precise control over the size and shape of the nanoparticles by adjusting the laser parameters and target properties. The process can be conducted in controlled environments, such as vacuum or specific gas atmospheres, to modify the properties of the generated nanoparticles and films. Pulsed laser ablation is widely used in materials science, nanotechnology, and surface engineering for various applications including catalysis, sensors, electronics, and biomedical devices. However, safety considerations are important when working with lasers and high-energy plasmas to avoid potential hazards and ensure the proper handling of the generated nanoparticles, as shown in Fig. (1) [12,13].

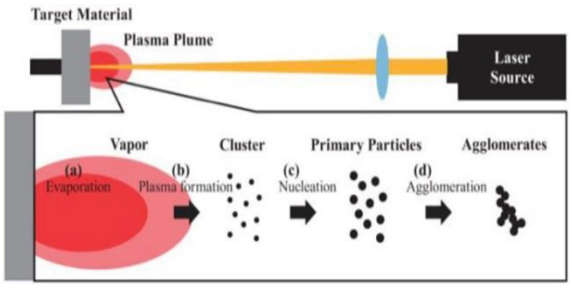

Fig. (1) Schematic diagram of nanoparticles synthesis by pulsed laser ablation [14]

The laser ablation method was chosen because of its simplicity and cost-effectiveness, making it one of the most accessible approaches for preparing nanoparticles. This method yields a substantial quantity of the material.

The manufacture of Cadmium Sulfide (CdS) nanoparticles involves the use of CdS powder as the initial substance. The procedure involved the utilization of a neodymium YAG (Nd:YAG) laser, which operated at a wavelength of 1064nm, an energy of 480 mJ, and a separation frequency of 5 Hz. The synthesis procedure involved the utilization of a precisely measured quantity of CdS powder (5g), which was subjected to compression using a specialized apparatus comprising many components.

The compression apparatus consisted of a base that was thoroughly cleansed with ethanol to achieve a purity of 99% to facilitate precise measurements. The base of the object was 2 cm in diameter and 3 cm long. The second component is situated above the initial component and is utilized to apply compression to the underlying substance (powder). The last component in question was the press apparatus, with a weight of 5 tons, responsible for compressing the material for a period of 12 min.

This technique guarantees a regulated and accurate compression procedure, which is essential for the effective production of CdS nanoparticles. The utilization of a giraffe and a 5-ton press ensures the effective application of the requisite force and duration, thus yielding the desired properties of the nanomaterial.

To commence the dish preparation process, it is advisable to begin by collecting the necessary materials to be utilized. The position of the electronic balance on a flat and even surface, taking care to verify its calibration, is accurate. Prior to placing the material in the dish, it was imperative to ascertain its weight by employing an electronic balance to ensure an accurate measurement of precisely 5g. After confirming the weight, the material must be transferred to a press or an appropriate container to initiate meal preparation. Upon introduction of the substance into a convection oven, it is imperative to subject it to a controlled thermal environment, namely, within the temperature range of 60 to 70 °C, for a duration of one hour, while ensuring that the upper limit of this temperature range is not surpassed. Upon removal from the oven, it was recommended to allow the object to cool for 60 min.

To ensure the integrity of the X-ray diffraction (XRD) measurements, it is vital to cleanse the previously utilized beaker, which contains ion-free water, by employing ethanol. This precautionary procedure was used to avert the presence of contaminants that may interfere with the accuracy and reliability of the XRD analysis. It is recommended to iterate this cleaning procedure several times to achieve comprehensive elimination of contaminants. The specimens were submerged in a beaker containing approximately 8 mm of water.

The laser, referred described as a "laser gun" in the field of physics, is aimed towards the flask that

contains the CdS sample. It was imperative to position the laser gun at a precise distance of 12 cm from the sample. Additionally, it is crucial to maintain a separation of 8 mm between the liquid surface and the target. The establishment of this configuration is crucial for subsequent experimental procedures. Adhering to these steps with painstaking attention guarantees the attainment of precision and accuracy in the preparation and subsequent laser ablation of the CdS sample.

It is imperative to ensure that the temperature of the laser remains within the prescribed range of 29–32°C during pressure application. The laser emitted a pulse, and the procedure entailed observing the alteration in the color of the liquid within the beaker. The number of laser pulses was recorded by measuring this change. For the copper sample, the pulse counter displayed a total of 300 pulses, as shown in Fig. (2).

To obtain the results shown in Fig. (3), it was necessary to reproduce the procedures employed for the synthesis of CdS.

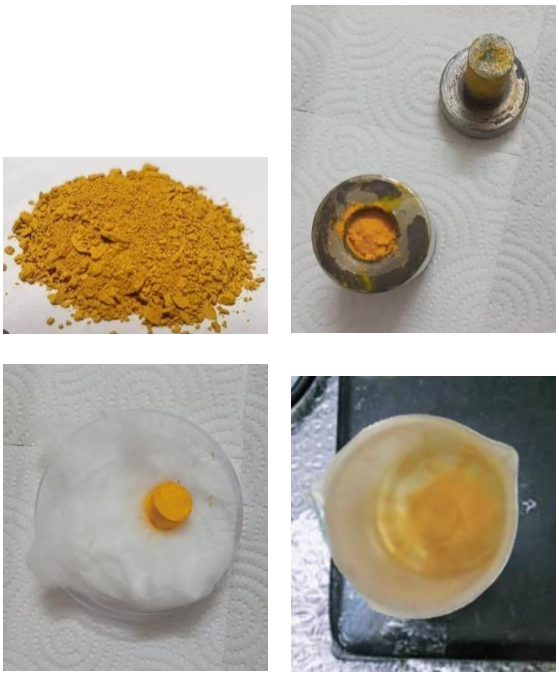

Fig. (2) Steps of synthesis of CdS samples in this work

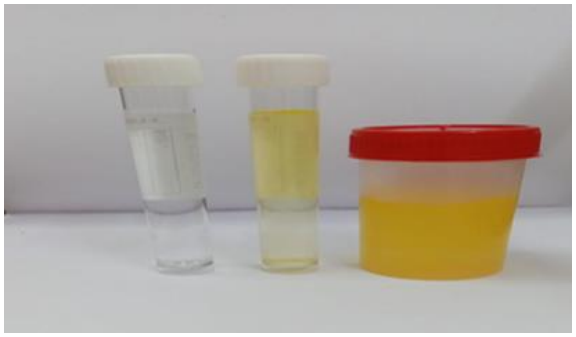

Fig. (3) Nano-liquid materials for CdS substance

3. Results and Discussion

Nanoparticles are characterized by many techniques to study their structure, surface morphology, optical properties, etc. This technique can be classified as x-ray diffraction (XRD), energy-dispersive x-ray spectroscopy (EDX), UV-Visible spectroscopy, atomic force microscopy (AFM), and field-emission scanning electron microscopy (FE-SEM). Figure (4) shows the XRD patterns of nanoparticles prepared by pulsed laser ablation. Diffraction peaks were observed for the CdS NPs, confirming that the synthesized product had pure (cubic) CdS nanocrystals, according to JCPDS card no 75-0581. The diffraction planes of (111) and (200) correspond to the diffraction angles of 24.94°, 27.0°, 30.4°, 43.94°, 47.79°, 54.44° crystal lattice planes of CdS, respectively. These peaks confirm the formation of nanomaterials with high crystallization. The diffraction peaks of the prepared samples show sharp (111) and (200) peaks at approximately 27.04° and 30.75°, respectively, ascribed to a cubic phase structure with a lattice parameter equally 5.81 nm and the same angle. The XRD patterns also showed that there were no peaks of other materials, which means that the samples were very pure when they were made, which was mostly the same, but there were some changes because the membrane had some impurities or empty spaces. It is important to note that the granular level increased as the thickness increased and decreased as the width of the center peak, which represents x-ray diffraction, increased. This shows that the width of the center peak and the x-ray diffraction are related in opposite directions, as shown in table (1) [15-17].

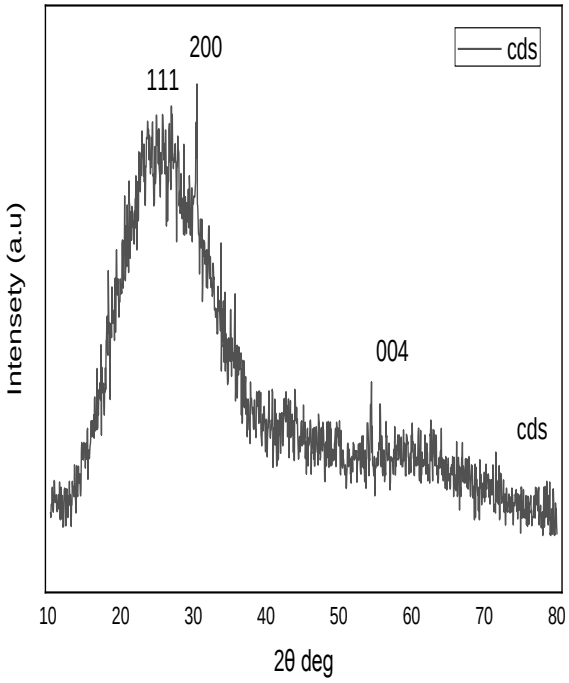

Fig. (4) XRD pattern of the CdS nanoparticles prepared in this work

Figure (5) displays a 3D AFM image of CdS nanoparticles prepared by pulsed laser ablation. They are distributed uniformly on the sample surface and cover it well with CdS nanoparticles. The image clearly shows that the nanoparticles made with 480mJ laser energy have small, well-ordered particles that are half-spherical and tapered, and they are spread out evenly with some monopod rods.

Using the software, the average particle size was found to be 11.29 nm. The particle size was greater than that found using the XRD analysis. The reason for this is that XRD looks at the size-defect free volume, whereas AFM looks at the grain itself, not the level of crystal flaws [17].When the laser energy was 480mJ, the root-mean-square of the surface roughness of the CdS particles was 2.833 nm. The average roughness was 2.354 nm and the average diameter was 11.29 nm [17].

The sizes of the grains matched the XRD data. The granular size, surface roughness, and square root value of the mean roughness of all films are listed in table (2).

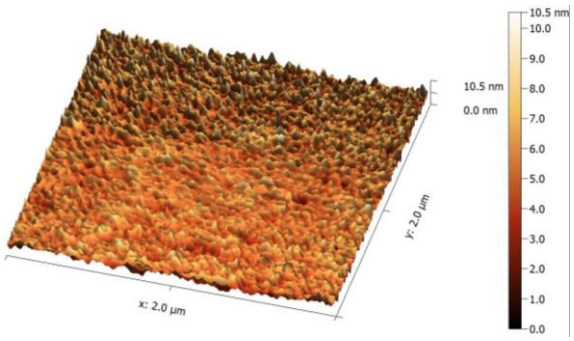

Fig. (5) 3D AFM image of CdS nanoparticles prepared in this work

Table (2) Roughness and average diameter of CdS nanoparticles prepared in this work

Sample	Root mean square S_q (nm)	Roughness average S_a (nm)	Average diameter
Cds	2.833	2.354	11.29

The surface morphologies of the produced samples were investigated using field-emission scanning electron microscopy (FE-SEM), as depicted in Fig. (6). The FE-SEM images depict the structural characteristics of the CdS samples with an energy of 480mJ. The images reveal that the samples exhibited a distribution of spherical particles, forming spherical clusters that were dispersed throughout various regions. The average diameter of these spherical clusters was 65.12 nm, as indicated in table (3). Upon closer examination of the FE-SEM images, it was confirmed that the CdS samples displayed a rough surface and possessed large pore sizes. Consequently, these features contribute to the high specific surface areas of the samples. This observation aligns well with the findings of the AFM analysis. In general, a direct correlation between pulsed laser ablation and particle size has been determined.

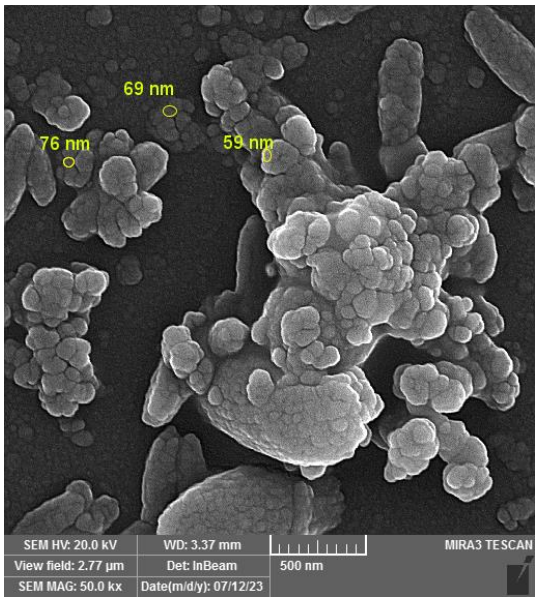

Fig. (6) FE-SEM image of CdS nanoparticles prepared in this work

Table (3) presents the recorded measurements of ten nanoscale particles, revealing that the mean diameter of these particles was 65 nm. The smallest observed diameter was 34 nm, whereas the largest measured diameter was 99 nm. The standard deviation formula was employed to analyze the collected measurements, revealing an average standard deviation of 11.7. This finding confirms that the particles under investigation were of nanoscale size.

Table (3) FE-SEM images of CdS nanoparticles prepared in this work

Label	Area	Mean	Min	Max
1	0.026	54.979	23.000	87.000
2	0.023	64.661	34.000	93.000
3	0.017	90.663	34.000	100.000
4	0.019	74.216	51.000	103.000
5	0.037	50.203	27.000	79.000
6	0.022	72.261	41.000	100.000
7	0.019	60.923	42.000	76.000
8	0.023	55.621	23.000	83.000
9	0.027	61.288	19.000	100.000
10	0.024	66.438	49.000	91.000
Mean	0.024	65.125	34.300	99.500
SD	0.006	11.719	11.265	36.909
Min	0.017	50.203	19.000	76.000
Max	0.037	90.663	51.000	100

Figures (7) and (8) depict the absorption and transmission spectra of CdS nanoparticles synthesized in this work using laser energy of 480mJ in the UV-visible region. Furthermore, as shown in Fig. (9), there was an increase in absorption as the wavelength increased from 196 to 260 nm, with a prominent peak observed at a wavelength of 210 nm.

The transmittance of the CdS nanoparticles prepared using a laser energy of 480mJ exhibited its lowest value at a certain wavelength. Additionally, the absorption behavior of these nanoparticles started to decline beyond 210 nm, in contrast to the behavior observed in transmittance, which can be ascribed to the quantum size effect, and the dependence of both the laser energy and the number of laser pulses on the intensity and width of these plasmon peaks was observed. The observation of CdS sedimentation during ablation for multiple days aligns with the results documented by Anikin et al. [18].

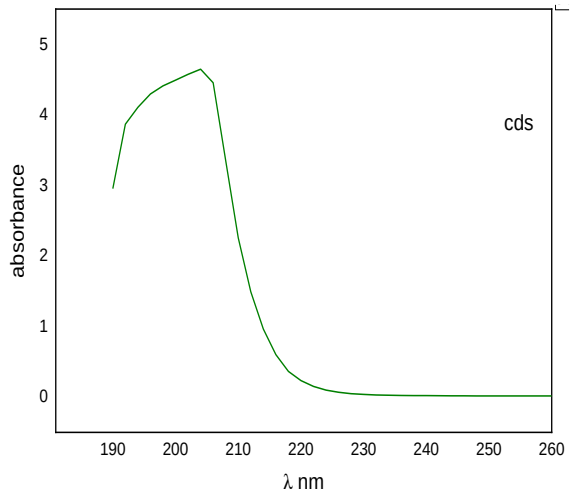

Fig. (7) UV-visible absorption spectrum of CdS nanoparticles prepared in this work

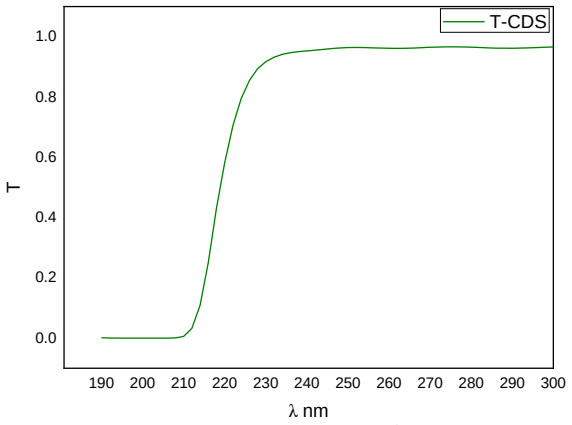

Fig. (8) UV-visible transmission spectrum of CdS nanoparticles prepared in this work

4. Conclusion

One-step synthesis of CdS rods and nanoparticles was demonstrated and studied using 10ns laser pulses for ablation of the CdS target in distilled water (DW). Structural characterizations showed that the nanoparticles were single-phase cubic CdS with morphology and size regulated by laser ablation with laser energy and lattice parameter identical to 5.81 nm and the same angle. Using 300 pulses with 480mJ laser energy, bipod and tripod CdS structures are produced. Highly agglomerated 50-90nm CdS particles were observed depending on the nanoparticle synthesis process (laser ablation). This study highlights the potential applications of these created nanoparticles due to their unique features, which are controlled by laser ablation in deionized water. Future study could focus on specialized nanoparticle uses, taking into consideration their unique properties and adaptability in numerous scientific and technological fields.

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Table (1) XRD results for the prepared CdS nanoparticles by pulse laser ablation

2Θ (deg) Standard	2Θ (deg) Observed	d(Å) Standard	d(Å) Observed	hkl	FWHM (deg)	Tip width [°2Th.]
24.837	24.944	3.5819	3.5810	(100)	4.000	4.8000
26.551	27.041	3.3544	3.294	(111)	1.840	2.2087
30.747	30.747	2.9055	2.93741	(200)	2.8725	3.4470
43.737	43.944	2.0680	2.0701	(110)	1.3050	3.7420
47.893	47.794	1.8978	1.8788	(103)	1.5980	2.8577
54.642	54.444	1.6782	1.6777	(004)	2.7141	3.56

