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Characterization of Green Synthesized Cadmium Sulfide Nanoparticles Using *Morchella esculenta* Mushroom

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ABSTRACT

In this study, the green synthesis and characterization of cadmium sulfide nanoparticles (CdS NPs) using *Morchella esculenta* (ME) mushroom extract as a coating and reducing agent were investigated in detail. It was observed that the synthesized CdS nanoparticles have a cubic zinc-blende crystal structure, as confirmed by XRD measurements. The concentration of ME extracts significantly affected particle size; an increase in extract volume led to the formation of smaller nanoparticles (3.63–6.79 nm according to UV-Vis models; 2.29–3.02 nm according to XRD). In addition to the presence of typical Cd-S bonds, FTIR spectra confirmed the role of fungal biomolecules (proteins, polysaccharides) in the coating and stabilization of nanoparticles. At absorption maxima, we observed significant blue shifts (515 nm compared to 453–481 nm for CdS) and broadened band gaps (2.58–2.74 eV) in the UV-Vis spectra, confirming quantum confinement. SEM-EDX analysis revealed that the elements were pure (the ratio of Cd to S was 1:1) and that the shape of the nanoparticles corresponded to the sizes observed in the XRD/UV-Vis data. This study presents a straightforward and eco-friendly process for creating CdS nanoparticles smaller than 5 nm.

Keywords: CdS nanoparticles, Green synthesis, *Morchella esculenta*, Mushroom

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Introduction

Recent advances in the production of nanoparticles using green synthesis methods are related to the ability to effectively convert various biological agents into metal precursors. With these new methods, it is now possible to produce environmentally friendly and cost-effective nanoparticles by using plants, bacteria, and fungi to convert metal compounds into nanoparticles. Using natural materials makes sure that non-toxic ingredients are used, reduces environmental impact, recycles waste, and introduces a new way to create nanoparticles [1]. The production of nanoparticles using biological resources or waste demonstrates the importance of this process as a sustainable and cost-effective method and highlights the opportunity to convert waste into valuable products in a circular economy [2]. Green synthesis is environmentally benign, sustainable, free from chemical pollution, economically viable, and suitable for large-scale production [3, 4]. Recently, the traditional (physical and chemical) nanosynthesis methods have become unpopular due to their reliance on toxic and expensive chemicals, high energy consumption, and, most importantly, the environmental issues they cause. The transition from traditional methods to sustainable applications began with the recognition of these issues and has been the subject of numerous studies highlighting the environmental and economic advantages of biogenic processes [5, 6]. The creation of metal nanoparticles via green synthesis is a prominent focus of contemporary nanoscience research. Researchers have documented various green-synthesized nanoparticles with significant application potential to date [1, 7]. Recent advances have revealed a wide range of natural resources used in nanoparticle synthesis. Plant extracts remain one of the most widely used sources due to their abundant phytochemicals that serve as effective reducing and stabilizing agents. For example, Wu et al. (2024) demonstrated the synthesis of zinc oxide nanoparticles using *Aloe vera* leaf extract, which possess significant antimicrobial activity against *Kosakonia cowanii* and *Alternaria alternata* strains [8]. Fungal species have also attracted significant attention due to their enzyme-rich composition; for example, *Aspergillus niger* has been successfully employed in the biosynthesis of silver-gold nanoparticles, which exhibited enhanced stability for up to three months [9]. Algae, both microalgae and macroalgae, offer a renewable and environmentally friendly alternative. Recent studies have used *Chlorella vulgaris* and *Sargassum polyphyllum* species for the synthesis of copper ferrite and platinum nanoparticles, highlighting their potential in heat transfer and biomedicine [10, 11]. Bacteria such as *Bacillus subtilis* and *Pseudomonas aeruginosa* have also been explored for green synthesis of metallic nanoparticles due to their metabolic versatility and rapid growth, enabling efficient nanoparticle formation under mild conditions [12, 13]. Furthermore, other microorganisms, including actinomycetes

and yeast species, have shown promise in green synthesis of nanoparticles by contributing unique biochemical profiles that influence nanoparticle shape, size, and functionality [14, 15]. These diverse natural resources not only support environmentally friendly synthesis pathways but also increase the functional diversity of the resulting nanoparticles.

To meet the growing demand for environmentally friendly materials in nanotechnology, there is significant interest in producing cadmium sulfide (CdS) nanoparticles (NPs) using more environmentally sensitive green methods. Numerous studies and research have highlighted the benefits of using biological sources, including plant extracts and microbial systems, in the synthesis of CdS nanoparticles [16-18]. A study by Ouardy et al. looks at how using biological methods to make nanoparticles, like CdS, reduces environmental damage and provides a larger-scale option compared to traditional methods [19]. This transition is particularly pertinent as researchers endeavor to meet the increasing demand for sustainable materials that maintain high efficiency in practical applications. Chakraborty et al. pointed out the importance of green synthesis in nanotechnology in this study and indicated that various plant-derived materials were used to produce nanoparticles with properties similar to those produced by traditional methods but with less environmental impact. This research highlighted the versatility and widespread use of these environmentally friendly technologies in the synthesis of special materials, including CdS nanoparticles [20]. Moustafa and Mahmoud studied how to make cadmium sulfide nanoparticles using leaf extracts, showing that these methods are effective and have great potential. Their research showed that using plant materials to make CdS nanoparticles helps in their creation and improves their ability to fight bacteria, highlighting their possible use in medicine [21]. Kumar and Kaur looked closely at the different parts of green synthesis in their study and pointed out how eco-friendly CdS nanoparticles and similar materials can be used in medicine and cleaning the environment [22]. The increasing focus on green synthesis methods for CdS nanoparticles demonstrates growing interest in sustainable applications in nanotechnology and highlights the benefits of environmentally friendly developments across various fields.

Morchella esculenta, commonly known as the yellow morel, is an edible mushroom that stands out for its significant nutritional value and various medicinal properties. This mushroom is an important source of bioactive compounds such as carbohydrates, proteins, vitamins, polysaccharides, and phenolics, and possesses antioxidant properties [23]. It is widely employed globally, particularly in Europe, the USA, China, and India, with its culinary and medicinal uses comprehensively recorded [24]. The advantages of using *Morchella esculenta* mushrooms for green synthesis include producing a lot of biomass and helping to keep nanoparticles stable [25]. Fungal extracts contain a variety of biomolecules (like polysaccharides, proteins, phenolics, and organic acids) that can lower metal ions and act as effective agents to control the size, shape, and spread of nanoparticles [26]. Recent studies have shown that extracts from *Morchella esculenta* are effective for creating metallic and metal oxide nanoparticles in an environmentally friendly way [27, 28]. The diverse biomolecules in these extracts efficiently reduce precursor salts (e.g., Ag^{+}, Au^{3+}, Zn^{2+}, Se^{4+}) to their zero-valent states while simultaneously coating the resultant nanoparticles, thereby enhancing stability and often improving their biological efficacy through synergistic interactions [29].

This study generated cadmium sulfide nanoparticles (CdS NPs) by a green method utilizing extracts from the *Morchella esculenta* mushroom as reducing and stabilizing agents. The main emphasis was on the comprehensive physicochemical evaluation of the biosynthesized nanoparticles. This work encompassed the verification of nanoparticle formation and optical characteristics through UV-visible spectroscopy, the identification of functional biomolecules capping the nanoparticles via FTIR spectroscopy, the assessment of crystallinity and phase structure using X-ray Diffraction (XRD), and the examination of morphology, size, and elemental composition through Scanning Electron Microscopy (SEM). The study deduced the function of Morchella biomolecules (e.g., polysaccharides, phenolics, and proteins) in promoting the synthesis and stabilization of CdS nanoparticles. This study established the basis for creating environmentally friendly Morchella-based CdS nanoparticles and highlighted their potential applications in photocatalysis, sensing, or biomedicine.

Materials and Methods

Materials

The mushroom *Morchella esculenta* was gathered from a rural location in Denizli, Turkey's Acıpayam District. All reagents ($Cd(NO_3)_2$, Na_2S) were of analytical grade and were purchased from Sigma-Aldrich. Ultra-Pure (UP) quality water (resistivity 18.2 MΩ cm) from a reverse osmosis system (Human Corp. Seoul, Korea) was used to prepare aqueous solutions.

Preparation of Mushroom Extract

The collected mushrooms were dehulled and washed with distilled water to remove any dirt. They were then left to dry for 20 days in a sealed container in a laboratory environment to prevent exposure to environmental contaminants. The dried mushrooms were cut into very small pieces with a sterile knife and ground. 150 mL of deionized water and 10 grams of powdered mushroom samples were placed in a single beaker. After that, the mixture was continuously stirred for an hour at 80°C. After cooling to room temperature, the solution was centrifuged for 10 minutes at 3000 rpm. The upper phase was then separated and kept for additional analysis at 4°C [30].

Synthesis of CdS Nanoparticles

The green synthesis method described by Tudu et al. for the use of Termitomyces heimii mushroom extract [30] was modified for the synthesis of CdS nanoparticles in this study. An aqueous extract of *Morchella esculenta* was used as the new biological reducing and capping agent in our study, which changed the protocol. Briefly, three 50 mL 0.1 M cadmium nitrate aqueous solutions were prepared. To investigate the effect of ME mushroom extract concentration on nanoparticle properties, the investigated amounts of ME (5, 7.5, and 10 mL) were added to these solutions. Then, 50 mL of 0.1 M sodium

sulfide aqueous solution was added dropwise to the resulting solution. The resulting solution immediately changed color from light brown to orange, indicating the formation of CdS. These solutions were shaken vigorously in the dark at 60-80°C for 16 hours. After cooling to room temperature, the solution was centrifuged at 3000 rpm for 15 minutes. It was then washed thoroughly with ultrapure water. Finally, it was dried at 60 °C for 8 hours [31]. The CdS formation reaction is given below.

$$Cd^{2+}_{(aq)} + S^{2-}_{(aq)} \rightarrow CdS_{(s)} \quad (1)$$

Three different green synthesized CdS samples were prepared by varying the ME volumes: CdS-5, CdS-7.5, and CdS-10, corresponding to 5, 7.5, and 10 mL of ME, respectively. We sought a trade-off between the varying amounts of bioorganic compounds (such as proteins and polysaccharides) present in different volumes of extracts and the size, morphology, and optical properties of the nanoparticles, thus providing a suitable balance between nanoparticle quality. Figure 1 provides a schematic example of the synthesis of CdS nanoparticles using the ME extract.

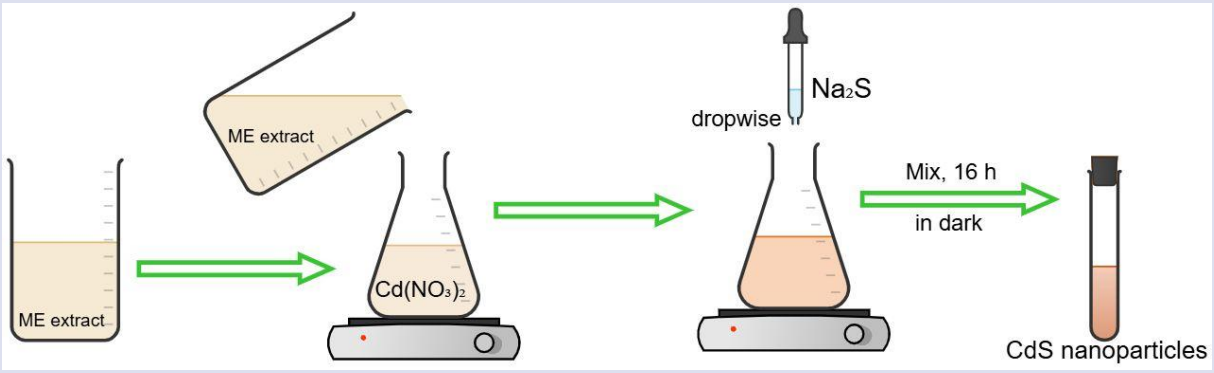

Figure 1. Schematic illustration for the synthesis of CdS nanoparticles utilizing ME extract.

Characterization of CdS NPs

The properties of CdS NPs made with ME extract were examined using UV-Vis, FTIR, XRD, SEM, and EDX methods. The existence of Cd nanoparticles was verified using a UV-Vis spectrophotometer (Evolution 201, Thermo Scientific, USA), and the chemical structure was analyzed via FTIR-ATR (Tensor II ATR, Bruker, USA). X-ray diffraction (Mini Flex 600, Rigaku, Japan) was employed to ascertain crystal structure and conduct theoretical particle size calculations. The dimensions, morphology, and elemental composition of nanoparticles were assessed using SEM (Mira 3, Tescan, Czech Republic) coupled with EDX (X-act, Oxford Instruments, UK) detectors.

Results

UV–Vis spectral analysis

UV-Vis absorption spectroscopy is an effective technique widely used to determine the particle size and optical properties of nanoparticles [32].

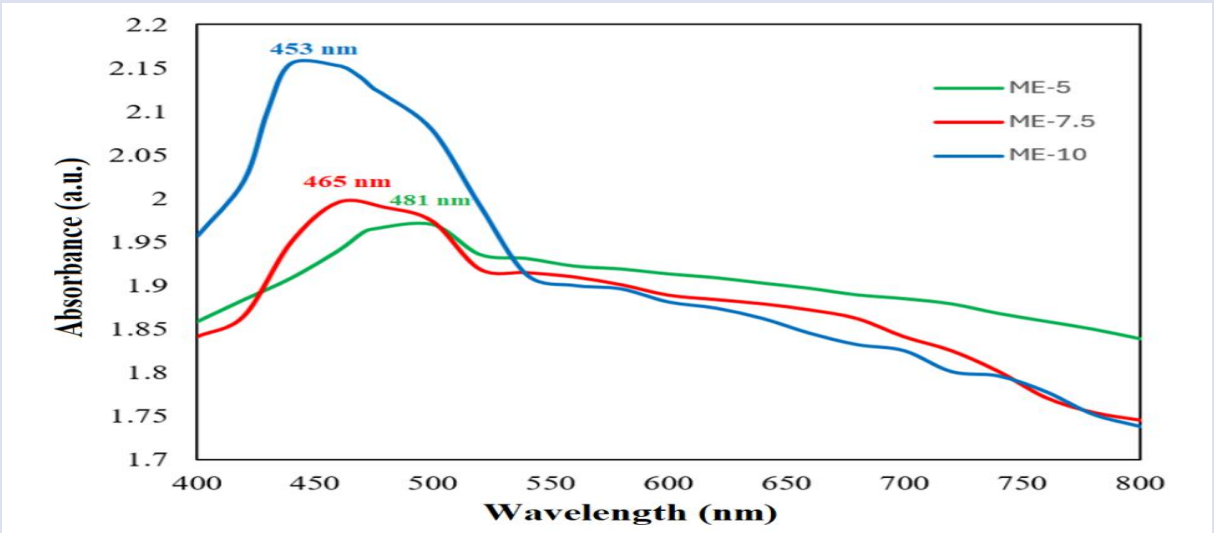

Figure 2. UV–Vis spectra of the synthesized CdS samples

The yellow powder synthesized using ME biomass was dispersed in DMSO in a 10 mm quartz cuvette and UV-Vis spectra were quickly recorded by scanning in the range of 400-800 nm (Figure 2). The maximum absorptions were

found at 481, 465 and 453 nm for CdS-ME5, CdS-ME7.5 and CdS-ME10, respectively. The UV–vis absorption edges of CdS nanoparticles show significant blue shifts compared to bulk CdS crystals (515 nm, E_g(bulk)=2.42 eV). This indicates quantum confinement since the average size of biosynthesized CdS nanoparticles is smaller than the excitonic Bohr radius of bulk CdS nanoparticles. The wavelength of maximum exciton absorption generally decreases as particle size decreases because of quantum confinement of photogenerated electron–hole pairs [33, 34]. The energy band gap of the synthesized CdS nanoparticles was estimated using equation 2 [35]:

$$E_g(eV) = \frac{hc}{\lambda_{max}(nm)} = \frac{1241}{\lambda_{max}(nm)} \quad (2)$$

where Eg, is the energy bandgap, c, is the velocity of light (2.998×10^8 m/s), h, is Planck constant (6.626×10^{-34} J s), and λ_{max}, is the wavelength at which maximum absorption of CdS nanoparticles. The estimated values of band gap energy for CdS-ME5, CdS-ME7.5 and CdS-ME10 are 2.580, 2.669 and 2.740 eV, respectively. It is seen that the band gap energy values increase as the concentration of mushroom extract used in the synthesis increases. It is estimated that this is due to quantum confinement depending on the concentration of the mushroom extract [30].

Brus et al. They proposed the relationship between the size of the clusters and their electronic structure in equation 3 by connecting the effects of quantum confinement to the radius of the nanoparticles. Particle sizes of CdS nanoparticles were calculated using the Brus formula given in Formula 3 [36].

$$E_g(nano) - E_g(bulk) = \frac{h^2}{2D^2}\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right) - \frac{3.6e^2}{4\pi\varepsilon D} \quad (3)$$

Where; E_g(nano) and E_g(bulk)(2.42 eV) are the bandgap of CdS nanoparticles, m_e^* (0.19m_e for CdS) and m_h^*(0.8m_e for CdS), the effective masses of electrons and holes, respectively. ε is the dielectric constant (5.7ε_0) and ε_0 is the permittivity of free space (8.85×10^{-12} C^2Nm^{-2}), r is the radius of CdS nanoparticles, h is the planks constant and e, charge of electron (1.6×10^{-19} C).

The diameters of CdS nanoparticles were also calculated using the empirical formula (formula 4) found by Yu et al., which relates the diameter of nanoparticles to the wavelength of the absorption edge (λ_{max}) [37], and the Henglein empirical formula (formula 5), which gives the relationship between the absorption wavelength and the average particle size of the nanoparticles [38].

$$D = -6.65x10^{-8}\lambda^3 + 1.96x10^{-4}\lambda^2 - 9.24x10^{-2}\lambda + 13.29 \quad (4)$$

$$D = \frac{0.1}{0.1338 - 0{,}0002345\lambda} \quad (5)$$

The sizes of CdS nanoparticles calculated using formulas 3,4 and 5 are presented in Table 1. The size of fungal synthesized CdS nanoparticles was generally small compared to bulk CdS crystals (5.6 nm). It is estimated that this is due to the stabilizing effect of fungal proteins that act as capping agents [39].

Table 1. Spectroscopic parameters and particle sizes calculated from UV-Vis spectra of synthesized CdS nanoparticles

Sample	λ_{max} (nm)	Eg (eV)	Particle size (nm)		
			Brus	Yu	Henglein
CdS (ME-5)	481	2.580	5.488	6.791	4.761
CdS (ME-7.5)	465	2.669	4.712	6.018	4.039
CdS (ME-10)	453	2.740	4.298	5.472	3.627

The dependence of the sizes of green synthesized CdS nanoparticles, calculated from the Brus, Yu and Henglein formulas, on the amount of ME biomass extract is given in figure 3. It is seen that as the amount of extract used in the synthesis increases, the nanoparticle size decreases. This indicates that the nanoparticle size to be synthesized can be adjusted with the amount of ME extract. Similar results were reported by Tudu et al. was reported by CdS nanoparticle green synthesis studies based on the use of fungi [30].

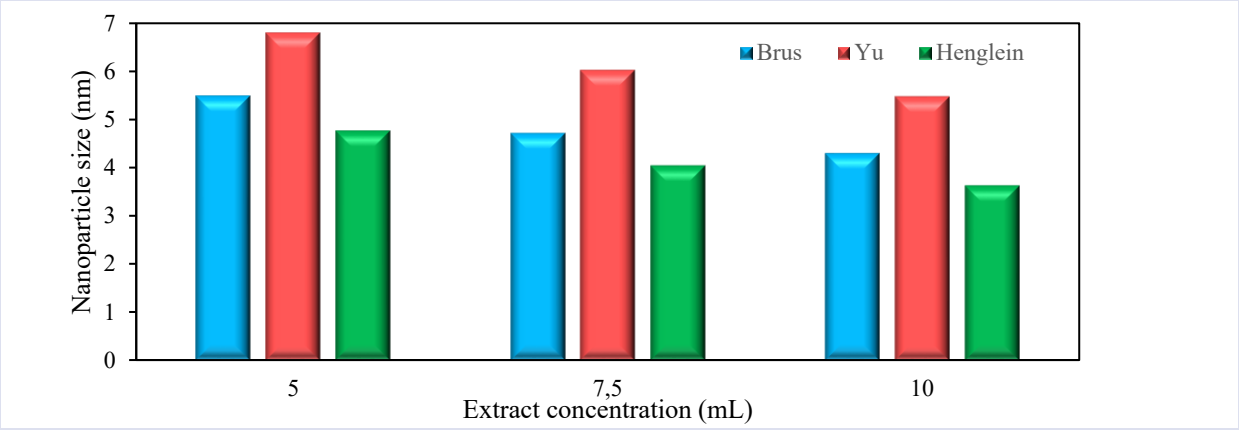

Figure 3. Effect of ME concentration on the size of CdS nanoparticles

XRD analysis

X-ray diffraction analysis was performed to examine the crystalline nature, average diameter, and structure of the green synthesized CdS nanoparticles. ME-10, which had the smallest diameter in the particle sizes obtained from the UV-Vis spectrum, was chosen for the XRD spectrum. The X-ray diffraction spectra of CdS nanoparticles are shown in Figure 4. In Fig. 4, there exist tetra peaks at 26.66◦, 44.12◦, 51.85 and 71.15◦, which correspond to (111), (220), (311) and (331) planes in cubic phase of CdS according to JCPDS card No: 65-2887. CdS is a semiconductor with the well-known cubic zinc-blende structure [40]. The obtained lattice parameters are compatible with literature data [41-44]. The crystal size of the nanocrystals was determined using the Debye Scherrer formula (formula 6) [45].

$$D = \frac{0.9\lambda}{\beta cos\theta} \quad (6)$$

Where, D is is the crystallite size (nm), θ is the angle measured, λ is the wavelength of the CuKα radiation (λ=1.5406 Å) and β is the integral width in radians. Based on the full width at half maximum of the diffraction peaks, the average sizes of the particles were calculated from the Scherer equation to range from 2.29 to 3.02 nm (Table 2).

Table 2. From XRD of the Perovskite CdS nanoparticles

Mushroom type	2θ/degree	Miller Indices	FWHM (°)	β (radian)	Structure	Size (nm)
ME10	26.66	111	3.716	0.0649	Cubic	2.29
	44.12	220	2.960	0.0517	Cubic	3.02
	51.85	311	3.150	0.0550	Cubic	2.93
	71.15	331	4.100	0.0716	Cubic	2.49

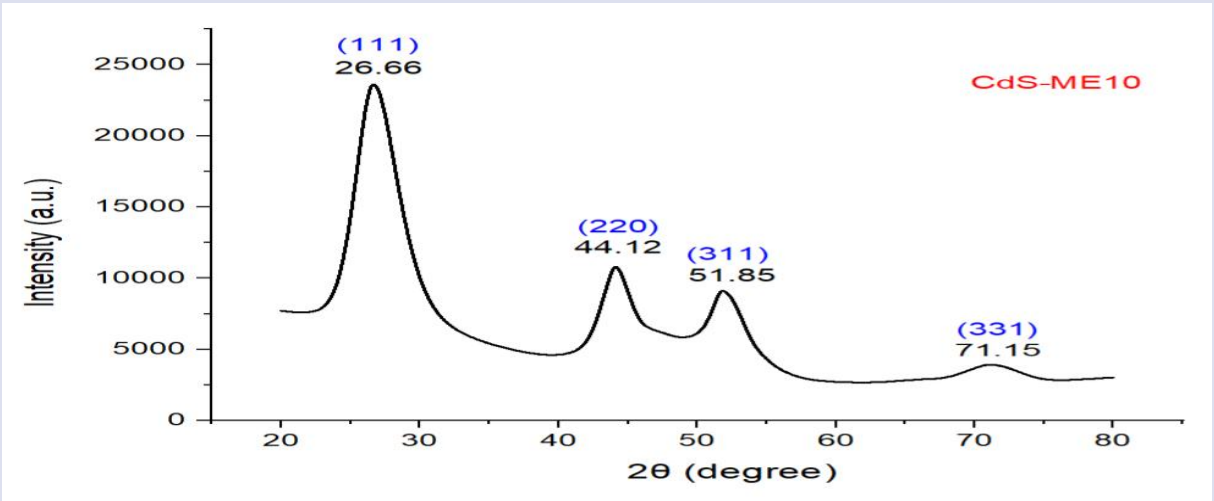

Figure 4. Powder XRD patterns of CdS samples

FTIR Analysis

Fourier transform infrared spectroscopy (FTIR) is a simple but essential tool for characterizing the molecular structure of various types of materials, including organic and inorganic compounds [46]. The FTIR spectra of green synthesized CdS nanoparticles using ME at different concentrations are presented in Figure 5.

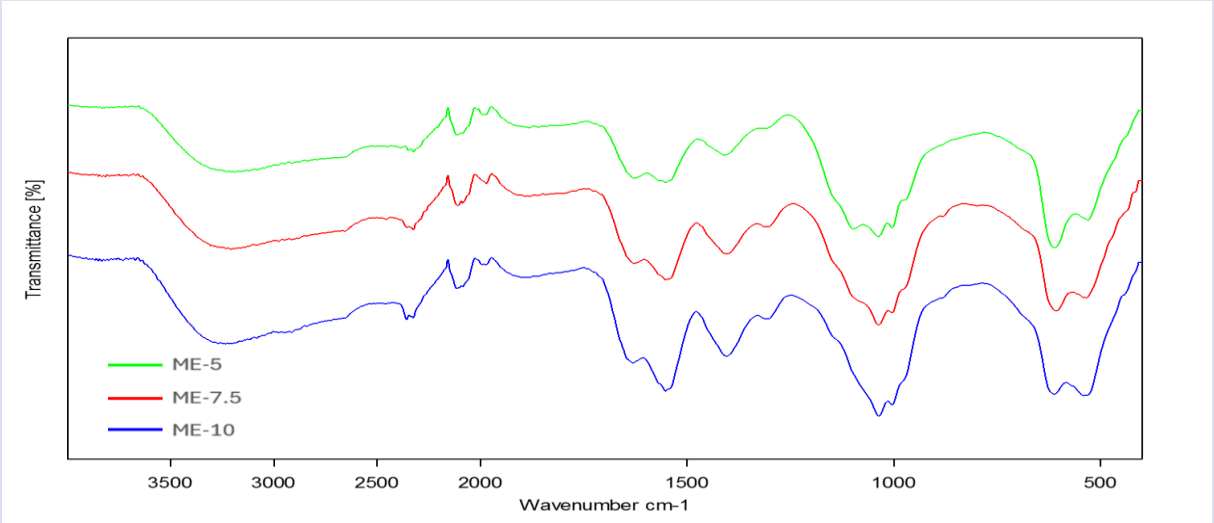

Figure 5. FTIR spectra of CdS samples

When the FTIR spectra of CdS nanoparticles were examined, it was seen that they were almost the same except for some band intensities. The broad band centered at 3190 cm^{-1} is typically due to the O-H stretching vibrations of hydroxyl groups. The weak band around 2350 cm^{-1} is thought to be due to atmospheric CO_2. The strong bands at 1628 cm^{-1} and 1552 cm^{-1} are attributed to the amide I (C=O stretching) and amide II (N-H bending and C-N stretching) bands of the proteins present in the mushroom extract, respectively. Also, the medium band at 1410 cm^{-1} is assigned to the C-H bending vibrations of hydrocarbon structure. The bands between 1100 cm^{-1} and 1000 cm^{-1} are due to the C-O stretching vibrations, indicating the presence of alcohols, ethers, or ester groups in the extract. Finally, the band at 611 cm^{-1} is assigned to the Cd-S stretching vibrations indicating the formation of the nanoparticles, as stated in the literature [47-50]. Moreover, the differences in band intensities can be attributed to the increased number of surface functional groups resulting from the higher extract content, as well as the possible presence of residual extract molecules on the nanoparticle surfaces.

SEM-EDX Analysis

Scanning electron microscopy (SEM) provides useful information about materials at the nanometer scale with high resolution, making it one of the most powerful techniques for examining the size, shape, and aggregation state of nanoparticles. Combining electron microscopy with complementary techniques such as energy dispersive X-ray spectroscopy (EDX) provides even more comprehensive information because it enables analysis of the elemental composition of the materials [51]. Since the smallest particle sizes were obtained with CdS-ME10, the SEM-EDX analysis of this sample is given in detail in Figure 6.

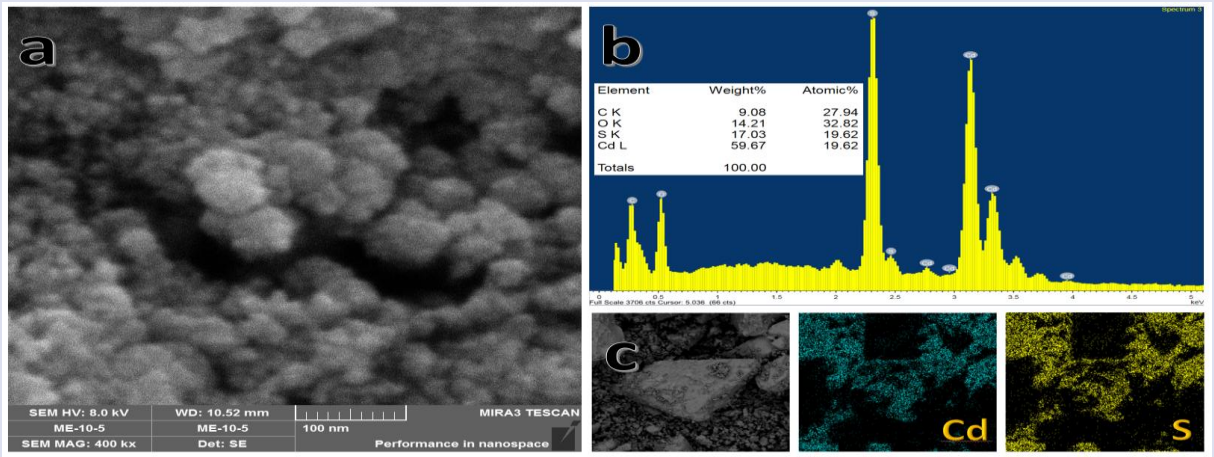

Figure 6. SEM (a), EDX (b) and mapping (c) results of CdS-ME10

The SEM micrograph of the CdS nanoparticles is obtained at 400 kx magnification and demonstrated in Figure 6a. As clearly seen in the picture, CdS was obtained in nanoparticle form using ME extract. Since CdS nanoparticles are very small in size, a high agglomeration occurred as expected. Due to this agglomeration, the nanoparticles appear larger than determined in theoretical measurements, with a broad particle size distribution. According to the EDX analysis results (Figure 6b), the material consists of only C, O, S, and Cd elements without any impurities. The fact that the atomic percentages of Cd and S elements are exactly the same (19.62%) shows that Cd and S elements are present in a 1:1 molar ratio, confirming the CdS structure. On the other hand, C and O elements originate from the ME extract. Although FTIR confirms the presence of amide groups, the nitrogen content is expected to be very low, making its quantitative detection by EDX unreliable. The low-energy N Kα line overlaps with the C and O peaks and falls in a region highly affected by detector noise; consequently, attempts to quantify this peak often yield either negative values or unrealistically high values. For this reason, nitrogen is not reported in the EDX results. Furthermore, the formation of the CdS structure is also confirmed through the EDX mapping analysis shown in Figure 6c.

Table 3. Comparison of particle sizes of green-synthesized CdS nanoparticles from various biological sources.

Preparation method	Biological Source / Agent	Metal/Salt Precursor	Particle size, nm	References
Green synthesis	Lactobacillus bacteria	$CdCl_2 + Na_2S$	4-5	[16]
Green synthesis	Sutherlandia frutescence	$CdCl_2 + Na_2S$	12-32	[52]
Green synthesis	Glycine	Spent Ni-Cd batteries + Na_2S	2.2	[53]
Green synthesis	Chlamydomonas reinhardtii	$CdCl_2 + Na_2S$	38	[39]
Green synthesis	Cinnamon	$CdSO_4 + Na_2S$	5	[54]
Green synthesis	Brevibacterium casei SRKP2	$CdCl_2 + Na_2S$	10-30	[55]
Green synthesis	Citrus limon	$Cd(CH_3COO)_2 + (NH_2)_2CS$	20-25	[56]
Green synthesis	Hawthorn Plant	$Cd(CH_3COO)_2 + Na_2S$	16.6-28.13	[57]
Green synthesis	Banana Peel	$Cd(NO_3)_2 + Na_2S$	1.48	[58]
Green synthesis	Lathyrus aphaca L.	$Cd(CH_3COO)_2 + Na_2S$	58	[59]
Green synthesis	Watermelon rind	$CdCl_2 + Na_2S$	10	[60]
Green synthesis	Aegle Marmelos	$Cd(CH_3COO)_2 + Na_2S$	95.1	[61]
Green synthesis	Coriolus versicolor mushroom	$Cd(NO_3)_2$ + thiol group of the fungal protein	8-15	[62]
Green synthesis	Pleurotus streatus mushroom	$CdSO_4 + Na_2S$	3.5-6	[63]
Green synthesis	*Morchella esculenta* mushroom	$Cd(NO_3)_2 + Na_2S$	2.3-6.8	This work

In this study, the size range of CdS nanoparticles synthesized using *Morchella esculenta* extract was determined to be 2.3–6.8 nm. These results indicate that the ME extract provides a relatively small and narrow size distribution compared to CdS nanoparticles synthesized from other fungal and biological sources (Table 3). For example, the CdS nanoparticles synthesized with the mushroom Pleurotus ostreatus are in the size range of 3.5–6 nm [63], while those synthesized with Coriolus versicolor are in the size range of 8–15 nm [62]. The use of the ME extract not only achieved a subnanometric size like Pleurotus ostreatus but also provided a more homogeneous distribution in terms of size control compared to Coriolus versicolor.

Conclusion

Cadmium sulfide nanoparticles (CdS NPs) of quantum dot size were successfully synthesized using various amounts of *Morchella esculenta* (ME) mushroom extract, which acts as a reducing agent and coating material. The water-soluble biomolecules in ME (e.g., proteins, polysaccharides, and phenolics) likely contributed to coating and stability during synthesis. Structural study via X-ray diffraction (XRD) verified a cubic zinc-blende phase (JCPDS: 65-2887), with crystallite sizes ranging from 2.29 to 3.02 nm, as determined by the Scherrer equation. The UV-Vis spectra displayed notable blue shifts (λ_{max}: 453–481 nm compared to bulk CdS at 515 nm) and expanded bandgaps (2.580–2.740 eV against 2.42 eV), thereby validating quantum confinement. Particle sizes determined using the Brus, Yu, and Henglein models (3.63–6.79 nm) diminished with increased concentrations of ME extract, indicating size tunability. EDX mapping confirmed a 1:1 Cd:S stoichiometry and high purity, whereas FTIR detected significant biomolecular capping agents (amide I/II bands at 1628/1552 cm^{-1}). This study adds to the sparse literature on fungal-mediated CdS quantum dots (QDs). The environmentally sustainable synthesis employs non-toxic ME extract, operates under ambient conditions, and yields biocompatible, protein capped quantum dots suitable for functionalization. These biocompatible CdS nanoparticles hold great potential for future applications in areas such as photocatalysis, biosensing, and biomedicine. Further studies may focus on optimizing their size and shape, scaling up production, and evaluating their functional performance in relevant systems.

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