

Green synthesis of multifunctional from cinnamon (cinnamomum verum) extract-functionalised CdS nanoparticles for In-vitro biomedical, photocatalytic degradation and photoelectrochemical applications

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Research Article

Keywords: CdS NPs, green synthesis, cinnamon extract, photocatalytic activity, photoelectrochemical, cytotoxicity assessment

Posted Date: October 31st, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-5129083/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at BioNanoScience on December 28th, 2024. See the published version at <https://doi.org/10.1007/s12668-024-01623-6>.

Abstract

Cadmium sulphide nanoparticles (CdS NPs), renowned for their tuneable bandgap, exhibit significant potential for photochemical applications. A simple, green, and cost-effective synthesis approach is quite desirable to harness their full potential. With this prospect, we present the green synthesis of CdS NPs using cinnamon extract which is rich in polyphenols and flavonoids, as a reducing and stabilizing agent. The as-synthesized NPs were characterized with the aid of diverse characterization techniques. The study also attempts to understand the role of CdS NPs as photocatalytic material for methylene blue (MB) dye degradation in both UV irradiation and natural sunlight. Notably, 91% degradation was achieved within 90 minutes under UV light in a self-fabricated photoreactor setup, and 70 minutes under direct sunlight. Tauc plot also revealed that the catalyst promoted an indirect electron transfer pathway. Further, the semiconductor properties were evaluated using photoelectrochemical (PEC) studies, demonstrating charge transport dynamics. Additionally, the cytotoxicity of the NPs was also explored using *in vitro* investigations on human breast cancer cell line, revealing promising anticancer properties. Biocompatibility test on normal cells, and antibacterial assays were also studies. This comprehensive investigation underscores the applicability of green-synthesised CdS NPs in diverse field.

1. Introduction

Semiconductors nanoparticles are nanoscale semiconductor crystals that exhibit unique optoelectronic properties due to quantum confinement effects, which occur when the particles size falls below the exciton Bohr radius [1, 2]. This confinement generates discrete electronic states, which result in size-dependent optical features such as tunable emission wavelengths, strong photostability, and enhanced charge transport [3, 4]. Among various semiconductor nanoparticles cadmium sulphide (CdS-NPs) is one of the most extensively studied catalyst due to its optimal bandgap energy, strong absorption in the visible spectrum and high charge carrier mobility [5, 6]. This makes it ideal for a variety of applications, including photocatalysis, photoelectrochemical (PEC) devices, and biomedical fields. However, traditional synthesis methods for CdS nanoparticles often involve hazardous precursors and require high-energy input which raising substantial environmental and health concerns (Parihar, 2023 and Sekar et al., 2019) [7, 8]. To address these concerns, there is a rising interest for developing sustainable and eco-friendly synthesis methods that can enhance the functional properties of these nanoparticles while reducing their environmental footprint.

Green synthesis of NPs using plant extracts has gained considerable attention due to its eco-friendly alternative and the biofunctionalization of the synthesized nanoparticles. Extracts from various plants, including aloe vera, papaya peels, and tea leaves were effectively used to synthesize nanoparticles due to their rich content of phytochemicals such as polyphenols, flavonoids, and antioxidants that function as reducing and stabilizing agents [9]. In this study, cinnamon sticks extract was specifically selected for its strong reducing capabilities, high antioxidant properties and inherent anticancer activity which enhance the stability and biocompatibility of the produced CdS NPs [10]. The use of cinnamon extract not only facilitates the eco-friendly synthesis of CdS NPs through a green approach compared to the

conventional methods, but also introduces functionality enhancements that make the NPs ideal for multifunctional applications.

The multifunctional potential of green synthesis of CdS NPs using cinnamon extract was explored in a range of applications, including photocatalytic dye degradation, PEC study, and biomedical applications. The potential of CdS NPs to break down harmful toxic dye such as methylene blue (MB) under natural visible light irradiation and artificial UV light irradiation were systematically evaluated. The catalytic properties of synthesized NPs were examined under both conditions to evaluate their performance. Research studies reported by Khodamorady et al. (2023) and Liu and Sun (2023) showed that CdS NPs displayed enhanced photocatalytic activity and stability, which makes them effective for dye degradation in both light conditions [11, 12]. This is especially important considering the widespread problem of water pollution caused by the indiscriminate discharge of industrial effluents, which contain complex aromatic dyes that are difficult to breakdown and represent serious health concerns to both aquatic and human life [13, 14]. Photocatalysis, which employs semiconductor-based photocatalysts and light energy, provides an effective pathway for the complete mineralization of these pollutants into harmless byproducts, addressing one of the most significant environmental problems [15–17]. The photoelectrochemical performance of green-synthesized CdS NPs were tested using Linear sweep voltammetry (LSV) and chopped light voltammetry (CLV) under light-on-off conditions to determine charge separation and recombination kinetics. Demonstrated the applicability of green-synthesized CdS nanoparticles for solar water splitting applications. Jia et al. (2024) reported the utilization of CdS NPs for water splitting [18].

Furthermore, the biomedical applications of green fabricated CdS NPs were explored, focusing on their in vitro anticancer and antibacterial actions, as previous studies reported by Alireza et al., 2023 on leaf extract catalysed CdS NPs [19]. CdS NPs exhibited good antibacterial activity against both Gram-positive and Gram-negative bacteria due to ROS generation and membrane disruption [7]. In anticancer tests, demonstrated cytotoxicity against MCF-7 breast cancer cell lines, possibly due to phytochemicals in cinnamon extract, which disturb cellular metabolism and trigger cell death [20, 21].

This study not only addresses the environmental impact associated with traditional synthesis methods but also evaluates the fundamental performance of green synthesized nanoparticles for multifunctional applications, including the break-down of complex organic dye, photoelectrochemical performance for renewable energy, and biomedical properties. The synthesized NPs were comprehensively characterized using analytical techniques, including X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray (EDX) spectroscopy. The development of these sustainable, high-performance nanoparticles aligns with the growing demand for green technologies in advanced scientific field, significant step towards environmentally responsible and multifunctional nanomaterial design.

2. Experimental

2.1 Materials

Cadmium sulfate (CdSO_4 , 99.99% purity) and sodium sulphide (Na_2S , 98% purity) were obtained from Sigma Aldrich, USA. were purchased from Sigma-Aldrich, Loba Chemie and Alpha Chemicals. Methanol HPLC graded purity (99%), methylene blue dye was purchased from Merck. All solutions were made with fresh deionized water. All chemicals used in this work were of analytical grade and were used without further purification.

2.2.1 Preparation of Extract

The cinnamon sticks bought from a Dmart store in Maharashtra, India. After being kept in an oven at 50°C for one hours to remove any contaminants, it was grinded into a fine powder with an electric grinder. The extraction of active components is more effective when the dimension of the particles is small since it maximises surface area. Methanol: distilled water (DW) was employed in a 70:30 (volume/volume) ratio as a solvent for extraction [22, 23]. To a 10 mL extraction solvent system, approximately 1 g of cinnamon powder was added. To facilitate an efficient extraction of the active ingredients, the solvent-spice mixture was incubated for 24 hours at room temperature (RT) in dark conditions. The clear solution was obtained by filtering the extract through Whatman filter paper.

2.2.2 Green synthesis of Cinnamon extract catalysed cadmium sulphide NPs (CdS NPs):

To synthesize CdS NPs, a green approach was used. In a conical flask, 20 mL of cinnamon extract and 2 mL of an aqueous solution of CdSO_4 (0.25 M) were mixed. The mixtures were vigorously shaken for 30 minutes to ensure homogeneity. Following that, 2.0 mL of Na_2S aqueous solution (0.25 M) was added, and the resulting mixture was shaken for six hours. The reaction mixtures were then placed in the dark for four days. The phytochemicals present in cinnamon extract functioned as both reducing and capping agents, facilitating strong interactions with the NPs surfaces. The resultant suspension was centrifuged to extract the NPs precipitate, which was then washed with methanol and deionized water to eliminate contaminants. The purified NPs were oven-dried at 70°C then they were ground to a fine powder with a mortar and pestle.

2.3 Fabrication of the working electrode

To fabricate the working electrode, 20 mg of synthesized CdS NPS were dispersed in sonicated in 2 mL of ethylene glycol for 20 minutes. A 100 μL aliquot of the dispersion was spin-coated onto pre-cleaned FTO at 2000 rpm for 2 minutes and dried at 100°C on a hot plate for 10 minutes. This process was carried out eight times to achieve the appropriate thickness of the CdS NPs coating. Finally, the electrode was heated to 200°C for 60 minutes on a hot plate.

2.4.1 Characterization Technique

Characterization analytical technique including XRD, FTIR, SEM, HRTEM, EDX, and ultraviolet–visible (UV–vis) spectroscopy was employed to completely characterize and verify the formation of CdS NPs. A Shimadzu 1800 UV–vis spectrophotometer (Tokyo, Japan) was used to quantify absorbance, which allowed us to explore the optical characteristics of CdS–C NPs by determining how much the extract shifted between the conduction band and valence band in the 200–800 nm range. The XRD graph of the CdS NPs was acquired using a Rigaku Ultima IV X-ray diffractometer (Tokyo, Japan) and Cu K α radiation ($\lambda = 1.5418\text{\AA}$, 40 kV) to verify the crystallinity, phase structure, and purity of CdS NPs. Fourier Transform Infrared Spectroscopy (FTIR) was used using an (Perkin Elmer Spectrum One) in to analyse for chemical bond polymorphism of biomolecules within a cinnamon extract generated with NPs surface studying. The frequency range of $4000\text{--}400\text{ cm}^{-1}$ was used to record all the data.

2.4.2 SEM-EDS, HRTEM & SAED Analysis

SEM was used for structural characterisation to determine particle size and shape, and energy-dispersive X-ray (EDX) spectroscopy was used to estimate the elemental composition. HR-TEM through examination, important morphological details as well as details regarding the dimensions, form, and structural characteristics of the produced CdS NPs were examined. The JEOL JEMCXII HR-TEM apparatus, which operated at an acceleration voltage of 200 kV, was used in the investigation. The HR-TEM investigation (Fig. 3) was performed with the use of Soft Imaging Systems iTEM software, FEI, Tecnai G2, F30 TEM, an accelerating voltage of 300 kV, and a Megaview III camera. A small fraction of the synthesised material was deposited onto an appropriate substrate, such as a copper grid coated in carbon, to create CdS NPs. HR-TEM images and electron diffraction patterns revealed important details about the overall shape, lattice spacing, and crystal structure of the CdS NPs.

2.5 Photocatalytic degradation experiments

The photocatalytic effectiveness of green-synthesized CdS semiconductor NPs has been investigated for enhancement to improve the removal efficiency of the widely used organic textile dyes, MB. 100 mL of an aqueous dye solution were mixed with 30 mg of CdS NPs in each study set. The surface area was then increased by ultrasonication for five minutes. MB were prepared at concentrations of 20 ppm, respectively. To reach the adsorption/desorption equilibrium, the mixture was then agitated for 30 minutes at RT under dark environments [24]. Subsequently, the photocatalytic reaction was initiated in one set under direct sunlight. Additionally, CdS NPs were stirred in a self-designed photoreactor with a UV lamp serving as the light source in a parallel series of studies. The catalyst efficiency to degrade the dye under both natural sunlight and artificial UV light conditions was evaluated. The absorbance was measured using a Shimadzu 1800 UV–vis spectrophotometer after a 5 mL aliquot was extracted and centrifuged to remove catalyst particles at specific time intervals. The percentage of dye degradation was calculated using the obtained UV spectra.

$$\text{Photocatalytic efficiency (\%)} = \frac{(A_0 - A_t)}{A_0} \times 100 \quad (1)$$

where absorbance at time t (A_t) and initial absorbance (A_0) exist Eq. 1. The pseudo-first-order kinetic model (Eq. 2) was utilized to calculate the degradation rate. In this equation, k stands for the apparent

rate constant, while C_0 and C_t denote the initial and final analyte concentrations, respectively.

$$\ln \frac{C_0}{C_t} = -k_1 t$$

2

2.6 Photoelectrochemical (PEC) measurements

The PEC properties of the prepared NPs were assessed using a standard three-electrode configuration in an H-type cell. An Ag/AgCl (3.0 M KCl) reference electrode, a Pt wire counter electrode, and a catalyst-coated FTO working electrode were all used. The CHI 920D potentiostat was used to measure PEC under simulated 1 sun illumination (AM 1.5 G) under back illumination conditions. Photocurrent generation was assessed using linear sweep voltammetry (LSV) at 10 mV s⁻¹ and chopped light voltammetry (CLV) at 10 mV s⁻¹. The electrolyte was a pH 8.5 borate buffer containing 0.5 M Na₂SO₄, which was chosen over phosphate buffer due to its corrosive nature towards CdS NPs.

2.7 *In-Vitro* cytotoxicity MTT

The cytotoxic activity of green synthesized CdS NPs against Michigan Cancer Foundation-7 (MCF-7) breast cancer cells was determined using the MTT test. Cells were seeded at a predetermined density in 96-well plates (Table 1) and incubated for 24 hours at 37°C with 5% CO₂. Subsequently, different concentrations of QDs were introduced, followed by another 48-hour incubation under identical conditions. The MTT reduction assay was then carried out according to the protocol [25]. Briefly, cells were lysed, and the absorbance of the formazan product was measured at 570 nm. The results were displayed as log% viability versus log concentration of CdS NPs. The IC₅₀ value, which represents the concentration of NPs that inhibits 50% cell viability, was calculated using regression analysis.

2.7.1 Biocompatibility studies

The hemolytic effect of CdS NPs on human red blood cells (RBCs) was investigated. Phosphate-buffered saline (PBS, pH 7.4) was used as the negative control (no lysis), and water as the positive control [26]. To isolate RBCs, fresh blood (5 mL) was centrifuged with EDTA anticoagulant. The separated RBCs were then washed with PBS (pH 7.4) to remove any remaining EDTA. The washed RBCs were diluted 1:10 with PBS. Aliquots of the diluted RBC sample were incubated with various concentrations of CdS QDs for 3 hours at RT [26]. After incubation and centrifugation, the supernatant absorbance was measured at 540 nm. The percentage of hemolysis was determined using the standard equation shown following.

$$\text{Hemolysis (\%)} = \frac{(\text{Sample absorbance} - \text{negative control})}{(\text{Positive control} - \text{negative control})} \times 100 \quad (3)$$

Phosphate-buffered saline (PBS) served as the negative control, demonstrating minimal haemolytic activity (0% lysis), whereas distilled water (DW) was used as the positive control which result in total haemolysis (100% lysis).

2.7.2 Antimicrobial activity assay:

A disc diffusion assay was used to assess CdS NPs antibacterial activity against Gram-positive bacteria (*Staphylococcus aureus* and *Bacillus subtilis*) and Gram-negative bacteria (*Pseudomonas aeruginosa* and *Escherichia coli*). Bacterial cultures were cultivated in sterile broth media overnight. Using a sterile L-shaped spreader, aliquots (100 µL) of each culture were evenly spread onto Luria-Bertani (LB) agar plates. Following that, sterile paper discs (5 mm diameter) loaded with varying quantities of CdS NPs in DMSO (0.06 mg/mL, 0.08 mg/mL, and 0.1 mg/mL) were placed on the inoculated agar plates. The plates were then incubated at 37°C for 24 hours to allow for bacterial growth and for the detection of inhibition zones. CdS QDs with larger inhibition zone diameters have higher antibacterial efficacy.

3. Result and discussion

The phase purity, composition and structure of the green synthesized CdS NPs were determined using XRD measurements which demonstrated the crystalline nature of the synthesized CdS NPs (Fig. 1a). The diffraction peaks corresponded to the (JCPDS No. 001-0780), with position at 2θ values of 26.69°, 44.12°, and 51.40°, corresponding to the (002), (110), and (112) lattice planes, respectively as shown in Fig. 3a [27]. The average crystallite size calculated from the Scherrer equation was found to be about 5 nm with broad peaks as observed in Fig. 1a. This peak broadening is attributed to the decrease in crystallite size, further supported by the crystallite size estimated using the Debye-Scherrer equation [27, 6]:

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

4

where D is the average particle size, K is a dimensionless factor close to unity, λ is the wavelength of X-ray radiation, β is the full width at half-maximum (FWHM) of the highest intensity diffraction peak, and θ is the X-ray Bragg angle. Furthermore, the presence of C and O indicated the incorporation of phytochemicals from the spice extract. To further validate the role of biomolecules in synthesis of NPs, their surface examination was carried out using FTIR spectroscopy. Peaks at 3150–3350 cm⁻¹ and 1594 cm⁻¹ were attributed to O-H stretching vibrations, confirming the presence of surface water molecules. The peak at 658 cm⁻¹ indicates the formation of Cd-S bonds and the existence of CdS NPs [29]. Following peaks revealed details on organic functional groups. Peaks at 2924 cm⁻¹ and 2853 cm⁻¹ related to C-H stretching vibrations, whereas those at 1611 cm⁻¹, 1447 cm⁻¹, and 1520 cm⁻¹ related to C = O stretching vibrations of aldehydes, C = C stretching vibrations of alkenes, and aromatic rings. The peak at 1062 cm⁻¹ indicates C-O stretching vibrations, while the peak at 1283 cm⁻¹ could be attributable

to C-H bending vibrations of aromatic rings. These peaks indicated the presence of biomolecules on the surface of CdS NPs, including flavonoids, and aldehydes, which were most likely derived from the spice extract.

The optical characteristics of the prepared CdS QDs were investigated using UV-Vis absorption spectroscopy shown in Fig. 1c. In comparison to bulk CdS, QDs showed a blue shift in the absorption edge, indicating quantum confinement effects within the smaller NPs [11]. Tauc plot analysis indicated an indirect allowed electron transition with a calculated bandgap energy of 2.91 eV, indicating the synthesis of very small size CdS NPs with modified electronic characteristics.

3.1 Structure characteristics

The morphology of the as-prepared NPs was investigated by the electron microscopy technique. SEM and HR-TEM-SAED analysis shown in NPs Figs. 2a, and c clearly depict the formation of production of nanosized, spherical CdS NPs. EDX assessment revealed the presence of cadmium (Cd) and Sulphur (S) indicating that the CdS nanoparticles were successfully synthesized (Fig. 2c).

HR-TEM examination revealed the spherical morphology of CdS NPs, which is comparable with SEM results (Fig. 3a, b). The size distribution of the NPs was uniform, with an average diameter of around 5 nm as assessed by HR-TEM (Fig. 3b). The crystalline nature of the as-synthesized nanodots was further affirmed from selected area electron diffraction (SAED) patterns revealed ring-like structures, indicating the creation of a hexagonal crystal phase [6]. Smaller NPs were identified by the appearance of bright rings rather than discrete spots in the SAED pattern.

3.2 Photocatalytic dye degradation

Study of dye degradation properties of green synthesised CdS NPs. The MB dye served as a model contaminant with a concentration of 20 ppm. The photocatalytic experiment comprised four different conditions. Without the photocatalyst in light (Blank), with the photocatalyst in darkness (Dark), along with the photocatalyst in natural sunlight and a UV photoreactor. The observation reveals that the dye degrades faster at the initial phase of the reaction, achieving 65% degradation within the first 10 minutes of UV light exposure. This rapid initial degradation demonstrates that the photocatalyst is efficiently generating reactive oxygen species (ROS), resulting in the rapid oxidation of dye molecules [30]. Spectral measurements show that the degradation kinetics slower trend towards the end. As the reaction progresses, the reaction rate may slow down as the catalyst active sites become saturated over time. This saturation may reduce the catalyst efficiency, causing a slower degradation rate in the later phases of the process. Notably, even with constant light intensity, the reaction rate can reach certain levels.

Under direct exposure to sunlight, an opposite trend was observed and based on absorption spectrum analysis, the reaction kinetics were assessed to be the slowest in the initial 30 minutes of exposure. The reaction mixture was exposed to direct sunlight under static conditions, which may have resulted in insufficient contact between the catalyst and dye, causing the decreased rate. This static exposure could

cause the dye compound to degrade at a slower rate. As the reaction develops, the reaction rate accelerates, and it was found that the temperature of the reaction beaker increased from 26°C to 32.7°C under natural conditions. This temperature increase could indicate an increased possibility of photon activation on the catalyst surface, resulting in a higher photocatalytic rate. The degrading reaction could have a complex kinetic profile, and the rate-limiting step could change as the reaction develops. These differences can affect the total reaction rate [31].

3.3 Photocatalytic degradation mechanism of the MB dye

CdS NPs absorb light during the photocatalytic dye degradation process, resulting in the formation of electron-hole pairs within the semiconductor [31]. The photoexcited electrons in the conduction band (CB^{e-}) and hole (VB^{h+}) pairs are required to initiate redox reactions with dye adsorbed on the photocatalyst surface. The nanomaterial band gap impacts the efficacy of spectrum absorption, have become a focus of substantial research [32, 33]. Given that sunlight consists of approximately 95% visible light and 5% UV radiation [34]. CdS bandgap is predominantly in the visible light range, allowing for efficient sunlight absorption in dye degradation process.

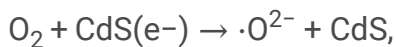


Generation of electron hole pairs:



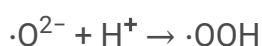
The degradation process comprises both direct and indirect pathways. Tauc plot calculation revealed an indirect bandgap transition, implying that electron-hole pair formation is followed by indirect charge transfer mechanisms. As a result, oxygen and water molecules adsorbed on the photocatalyst's surface react with these charge carriers to form highly reactive species such as hydroxyl radicals ($\cdot OH$) and superoxide ions ($\cdot O^{2-}$) [35, 36]. These species are primarily responsible for the oxidation of organic contaminants to inorganic byproducts.

Trapping Charge Carriers:

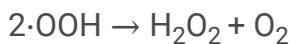


These reactive molecules ($\cdot O^{2-}$) and ($\cdot OH$) are effective, short-lived oxidizing agents that initiate photocatalytic oxidation of MB. The degradation process involves several phases, such as producing peroxy radicals ($\cdot OOH$), recombining free radicals, and converting MB to inorganic chemicals [36, 37].

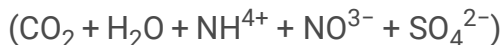
Formation of peroxy radicals:



Recombination of free radicals to produce hydroxyl radicals



Dye degradation.



This process results in noticeable spectrum changes in MB during the degradation process, such as color changes and a hypochromic shift in the UV absorption band at 665 nm, indicating the breakdown of auxochromes inside the MB structure. The kinetics measurements revealed spectrum changes in MB under natural sunlight and UV light, including color transition and a hypochromic shift in the UV absorption band at 665 nm. This comprehensive study demonstrates CdS NPs versatility as highly efficient photocatalysts for the degradation of organic dyes under various light conditions, improving their potential for a wide range of environmental remediation applications.

3.4 Photoelectrochemical properties

Photoresponsivity is an important parameter for semiconductor nanoparticles in renewable energy applications since it impacts light absorption, charge carrier generation, recombination, and total energy conversion efficiency. To assess the photoresponse of the synthesized semiconductor NPs, a CdS NP-fabricated photoelectrode was evaluated employing the PEC test. The photoanode PEC performance was measured by plotting photocurrent density vs applied potential. Charge separation efficiency was determined using CLV testing, and the results revealed a photocurrent response consistent with semiconductor behaviour. Following illumination, an initial current spike was detected, which was attributed to the rapid formation and separation of electron-hole pairs. Electrons moved towards the FTO and counter electrodes, whereas holes accumulated at the photoanode-electrolyte interface [37]. The resulted drop in photocurrent following light interruption indicated fast charge carrier recombination, exhibited by a pronounced spike-and-decay CLV plot.

Transient photocurrent studies Fig. 5a at a constant potential of 0.8 V against Ag/AgCl showed an initial photocurrent density of 0.42 mA cm⁻². This pattern was consistent with the rapid formation and separation of electron-hole pairs upon illumination. Holes at the photoanode-electrolyte interface contribute to water oxidation, whereas electrons move to the FTO. The transient figure shows that current spikes occur in the initial pulse but not in subsequent pulses, demonstrating that almost all generated electrons and holes were efficiently utilized during the process. LSV tests revealed similar anodic spikes of photocurrent under illumination. The fabricated working electrode anodic curve exhibited n-type semiconductor characteristics. The highly reactive S²⁻ ions contribute electrons to the photoanode, causing the formation of oxidation products that inhibit charge transfer [38]. Several

reactions, such as charge accumulation, oxygen evolution reaction (OER), and S²⁻ oxidation, occur simultaneously during CLV [39]. Despite the observed OER activity, the overall performance of the synthesized photoanodes was inferior to reported literature, possibly caused by the intrinsic instability of CdS nanomaterials.

3.5 MTT assay

The cytotoxicity of CdS NPs on human breast cancer MCF-7 cell lines was assessed using the MTT test, which is a reliable indicator of cell viability [40]. This assay assesses the ability of metabolically active cells (with healthy mitochondria) to transform a yellow MTT dye into a purple formazan [41]. Cisplatin, a well-known chemotherapy drug, was used as a positive control. While cinnamon extract has been demonstrated to up-regulate peroxisome proliferator-activated receptor (PPARG), a gene associated with decreased proliferation and enhanced apoptosis in breast cancer cells [42, 43]. The cinnamon extract contains bioactive components, specifically cinnamaldehyde and polyphenols, which could interact with the NPs surface [43]. These interactions, depending on the synthesis factors and affinity, could include adsorption or even biolayer formation. Such a surface modification may affect the NPs targeting capacity and overall anti-cancer efficacy [44]. The MTT experiment results in Fig. 6a show that CdS NPs inhibited MCF-7 cell proliferation in a dose-dependent manner. The IC₅₀ values (concentration needed for 50% inhibition) were 110 µg/mL for CdS NPs whereas 31.63 µg/mL for cisplatin.

Table 1
Cell viability (%) of CdS NPs with standard cisplatin drug obtain against drug concentration ((µM)

Drug concentration (µM)	Viability (%)	
	Cisplatin	CdS NPs
10 ⁻³ M	0.39766	17.2398
(10 ⁻⁴ M	51.5789	82.5029
10 ⁻⁵ M	92.3977	98.2924
10 ⁻⁶ M	92.2573	103.392

3.6 Biocompatibility studies

The hemolytic activity of CdS NPs was determined using a red blood cell (RBC) lysis assay. This test measures the release of haemoglobin, a component of red blood cells, after exposure to NPs. The degree of hemolysis indicates possible cytotoxicity to erythrocytes [26]. NPs that cause more than 2% hemolysis are considered as non-hemolytic, 2–5% as slightly hemolytic, and more than 5% as hemolytic [45]. According to Fig. 5d, the synthesized NPs cause less hemolysis even at high concentrations, demonstrating their biocompatibility. The CdS NPs showed slight hemolysis at the highest dose tested (120 µg/mL). The addition of cinnamon extract during the fabrication process may enhance the

biocompatibility of CdS NPs [42]. Several extract components, especially polyphenols, have antioxidant and anti-inflammatory activities [42,46]. These characteristics may serve to stabilise the NPs and reduce their contact with the RBC membrane leading to decreased hemolysis.

3.7 Antimicrobial action

Green synthesised CdS NPs show broad spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria. As demonstrated by their ability to inhibit the growth of all studied microorganisms during incubation showed in Fig. 7. Cinnamaldehyde, an important component in cinnamon, was responsible for its antibacterial properties [43]. The NPs were considered to have increased permeability to bacterial membranes because of their small size and large surface areas. This allows them to penetrate the microbial cell wall and interact with essential cellular components. Gram-positive microorganisms have a simpler cell wall structure than Gram-negative bacteria, making them more sensitive to the impact of CdS NPs. However, study results on comparative efficacy against strains such as *E. coli* might vary. The capacity to penetrate the Gram-negative cell wall, as well as the inherent resistance mechanisms associated with specific bacterial strains, can influence the reported results [47].

Conclusion

The present research effectively produced CdS NPs utilizing a green approach, using cinnamon extract acting as a capping and reducing agent. The synthesized CdS NPs demonstrated promising multifunctional applications. *In-vitro* anticancer experiments show substantial cytotoxicity against MCF-7 breast cancer cells, with an IC_{50} value of 110 μ g. The NPs determined to be biocompatible, as indicated by haemolysis tests. Furthermore, the NPs demonstrated considerable antibacterial action against *E. coli* when compared to other Gram-positive and Gram-negative pathogens. Notably, CdS NPs demonstrated superior photocatalytic degradation of MB dye under natural direct sunlight compared to artificial UV light. The improved charge transfer, reaction kinetics, and light absorption properties of the NPs contribute to their higher efficiency. PEC studies demonstrated that the semiconductor nature of the green synthesized NPs with efficient charge separation. LSV plots demonstrated that the working electrode exhibited an anodic shift, validating its function as a photoanode and facilitating the oxidation process. These findings underscore the versatility of greenly synthesized CdS NPs as an option for biomedical and environmental applications.

Declarations

Acknowledgement

It is a self-funded project. The authors want to extend their sincere gratitude to the Department of Microbiology from K. J. Somaiya College of Science and Commerce, Vidyavihar for providing the necessary facilities. We further thank SAIF-IIT Bombay, Tata Institute of Fundamental Research (TIFR) and the invaluable assistance of Dr. Maithili Athavale, Assistant General Manager, R&D Cancer Biology, Godavari Biorefineries Ltd. in conducting the MTT Assay for this research work.

Declaration of Interest Statement

The authors declare that they have no known conflicts of interest.

Ethical Approval

Human/Animal Studies

Not Applicable

Funding

It is a self-funded project. No funding was received from any institutions.

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Figures

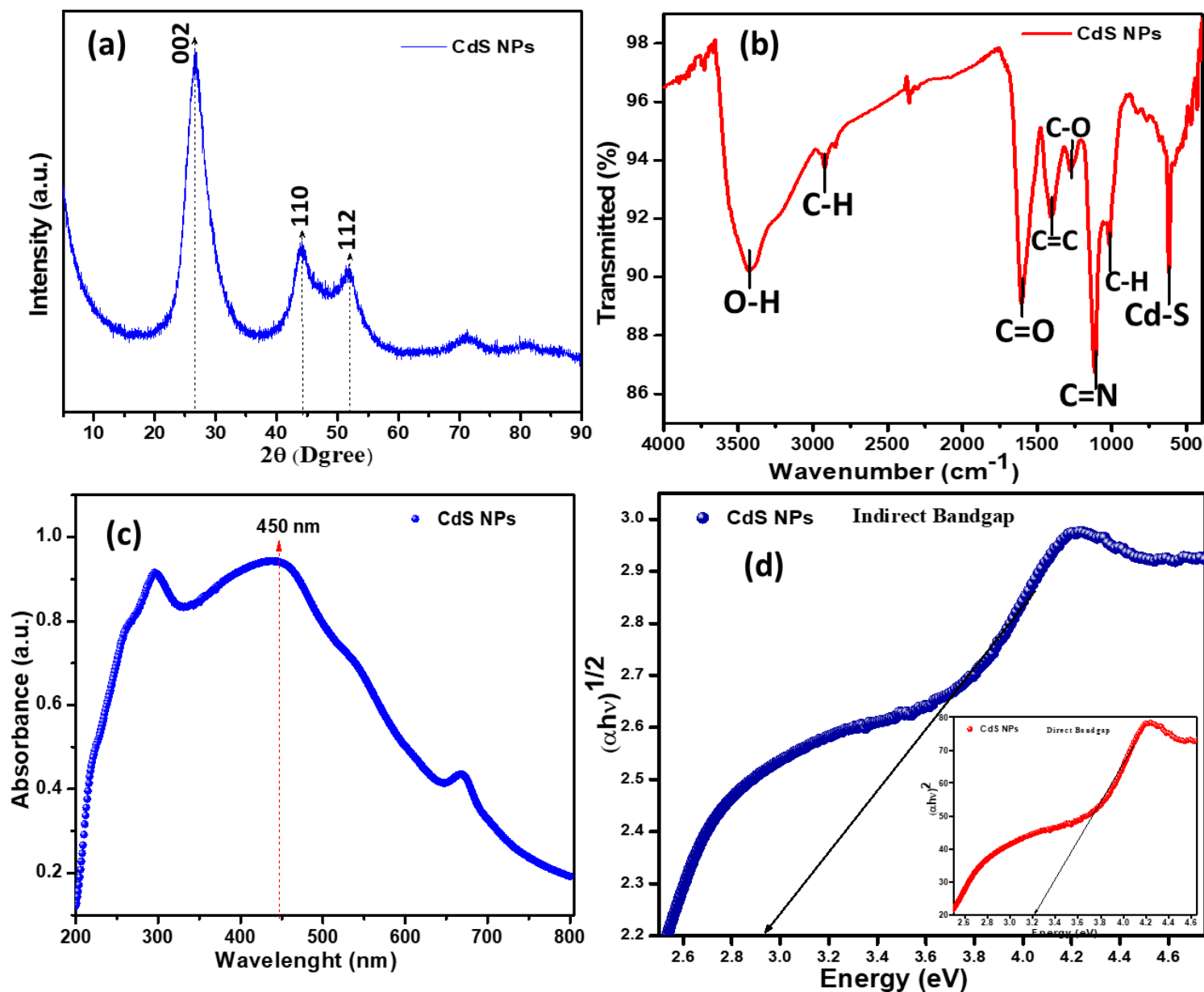


Figure 1

(a) XRD patterns green CdS NPs (b) FTIR spectra of synthesized CdS NPs. (c) UV-Vis absorption spectra, (d) Tauc plots of the direct and indirect bandgap energies for CdS NPs.

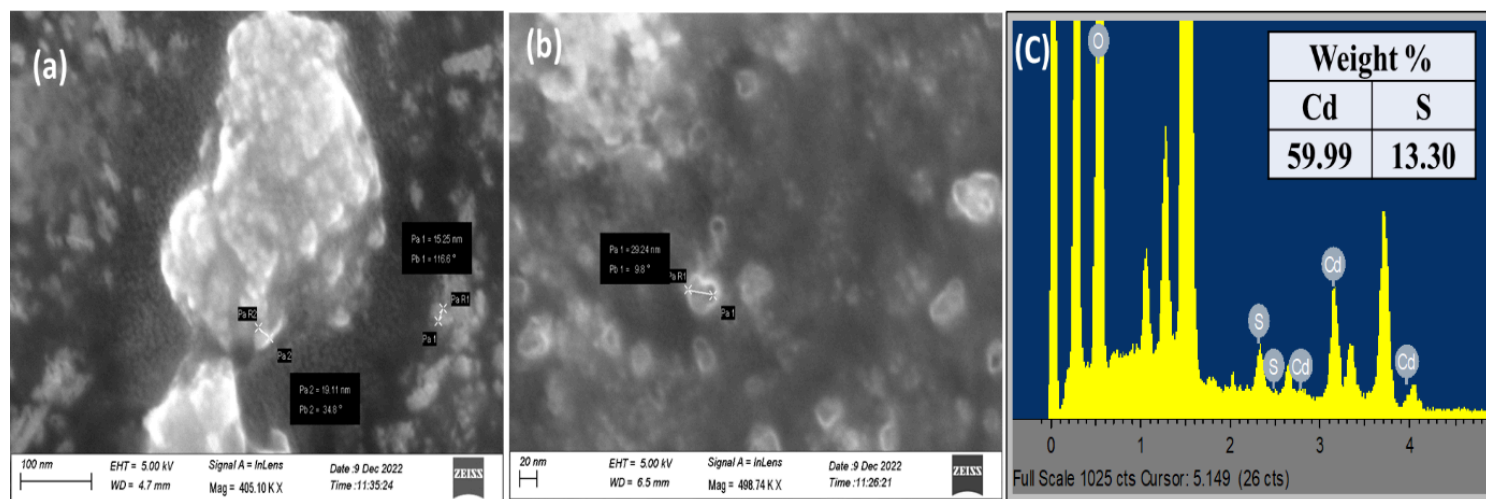


Figure 2

(a-b) SEM mapping image of green synthesized CdS nanoparticles. (c) EDX with corresponding weight percentage.

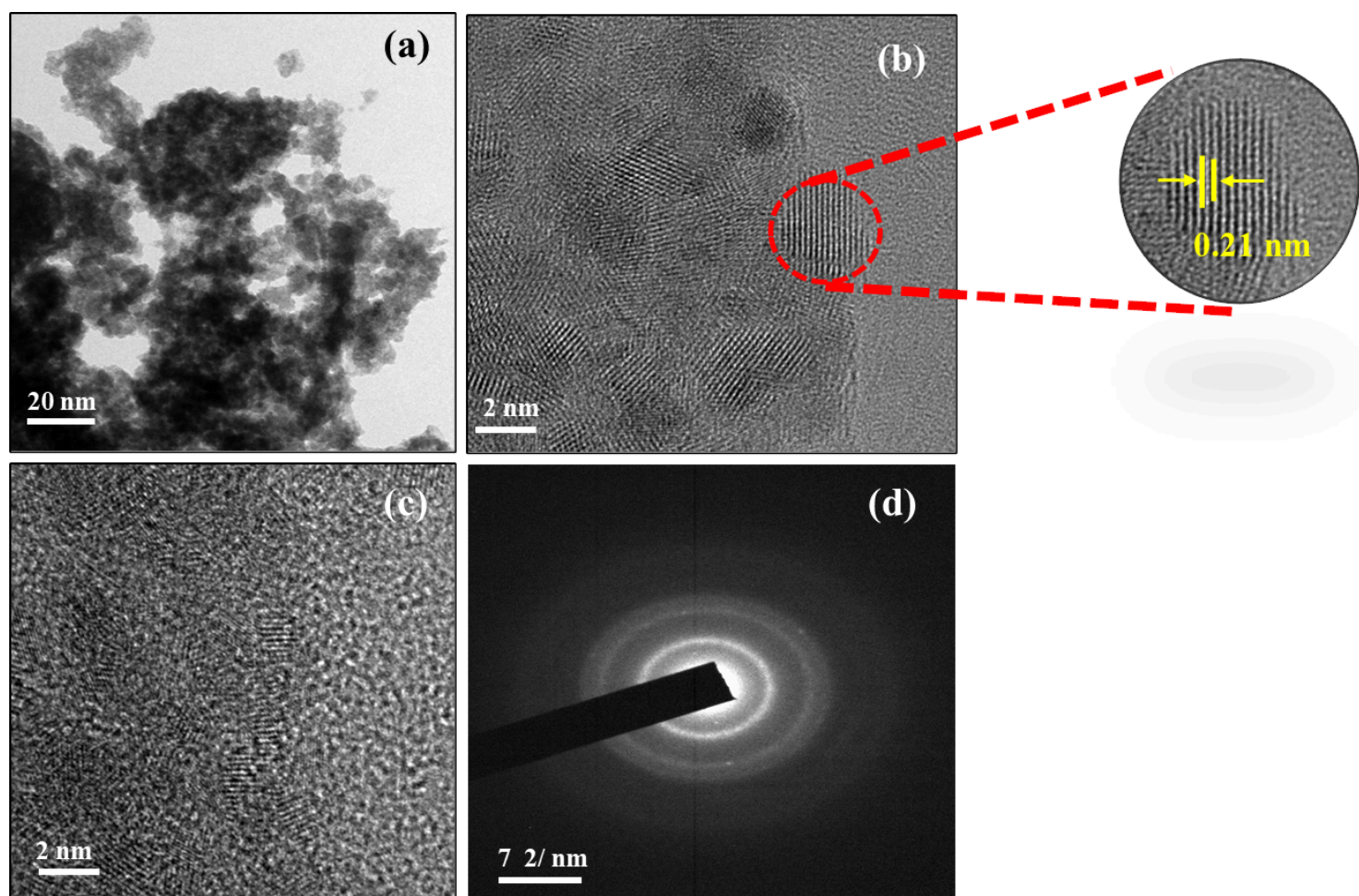


Figure 3

(a-c) HR-TEM image at various magnification (d) SAED patterns

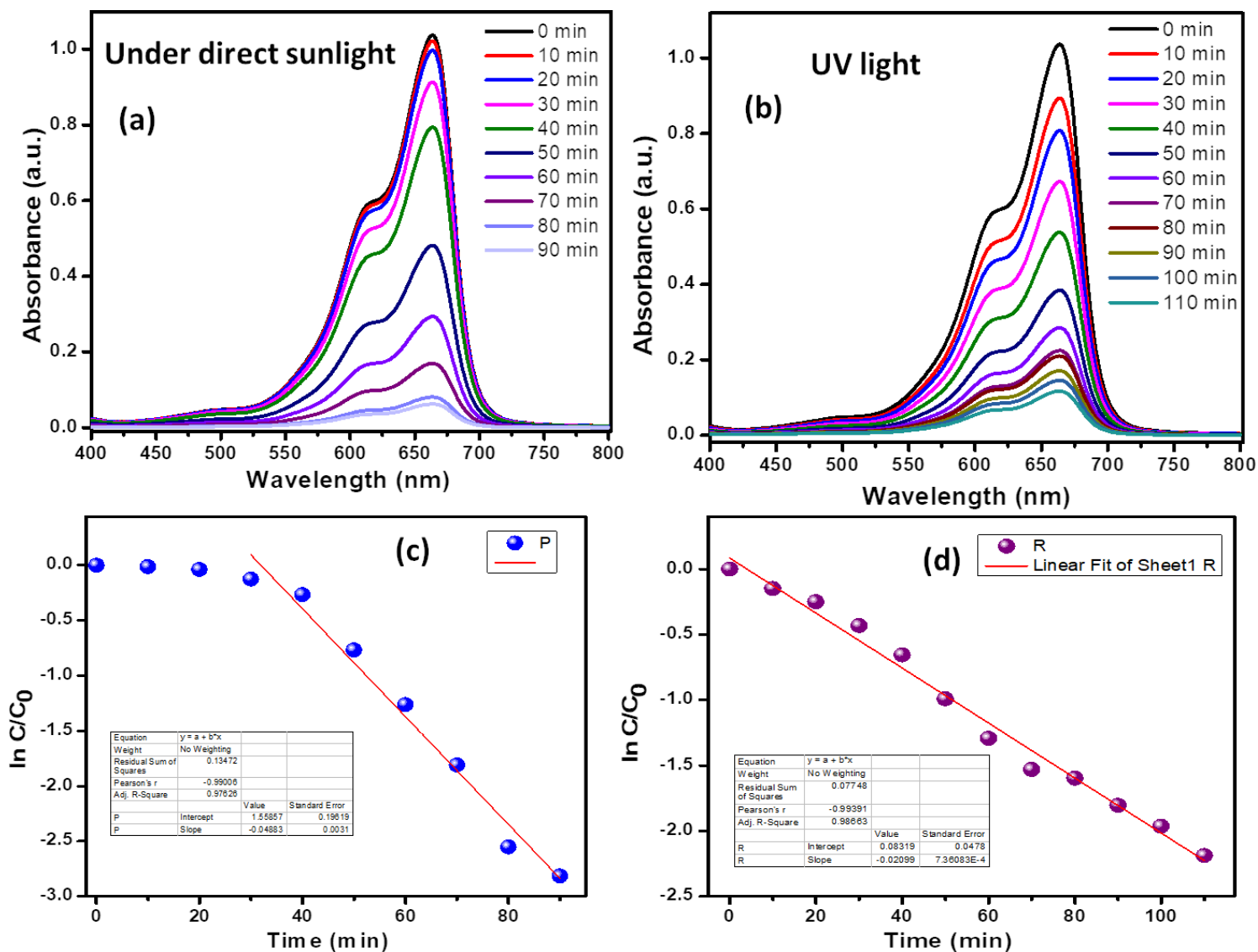


Figure 4

The effect of light irradiation under different conditions on MB dye degradation. (a, b) UV-Vis spectra of MB at different time intervals under direct sunlight and UV chamber irradiation. (c, d) MB degradation kinetics plotted under sunlight and UV chamber conditions.

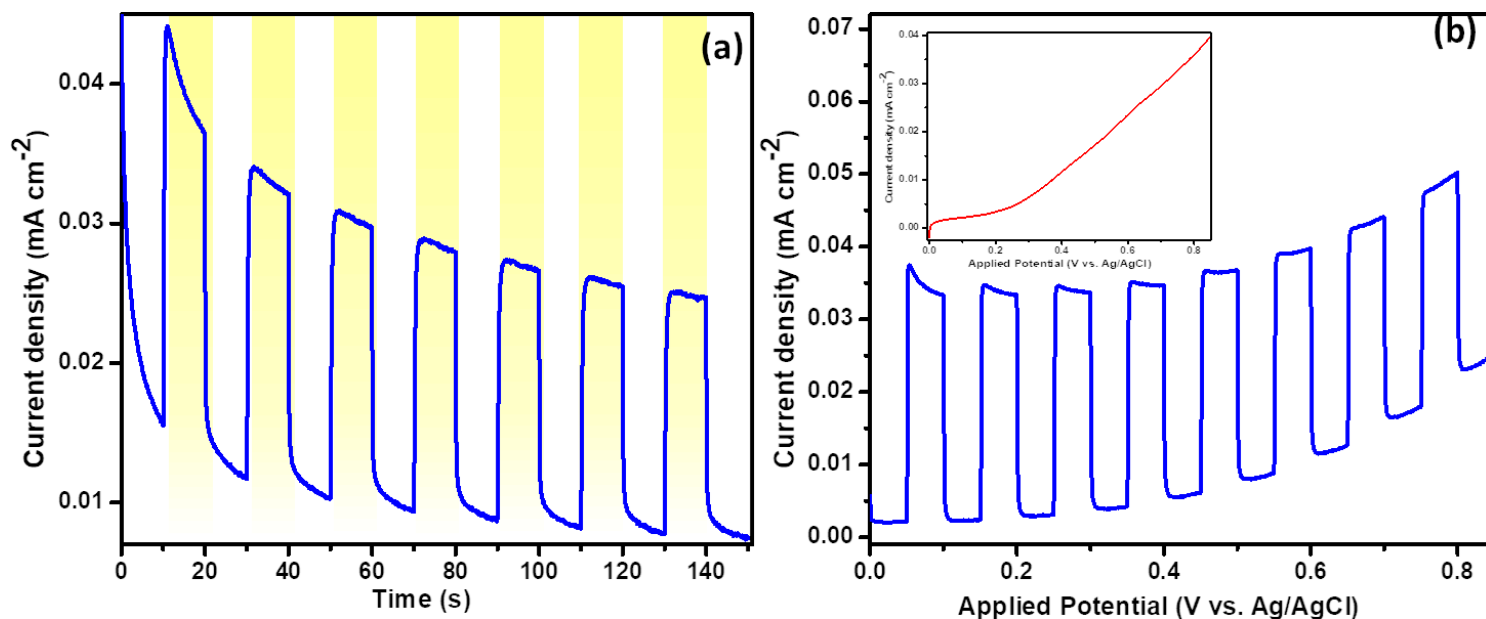


Figure 5

(a) Transient plot of a working electrode at constant potential, time (seconds) vs photocurrent density. (b) CLV and LSV plots of green synthesized CdS NPs with forward-applied voltage vs photocurrent density.

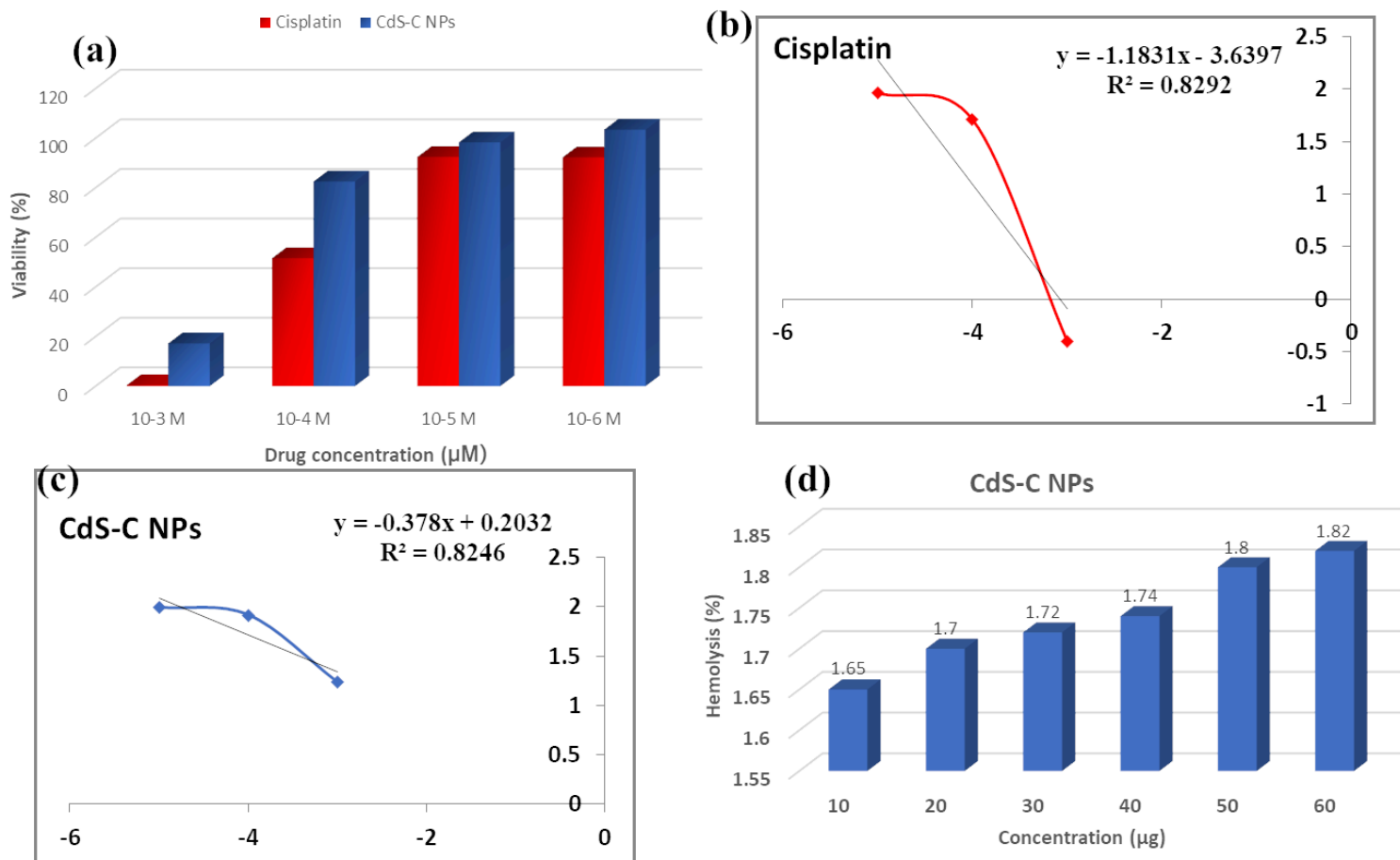


Figure 6

The anticancer experiment was carried out on human MCF-7 breast cancer cell line (a) IC_{50} concentration in μM of CdS NPs compared to the standard drugs cisplatin. (b) The slope of the cisplatin dose-response curve with the regression factor applied. (c) The slope of the dose-response curve for CdS NPs is determined by the regression factor. (d) The hemolytic biocompatibility of CdS NPs.

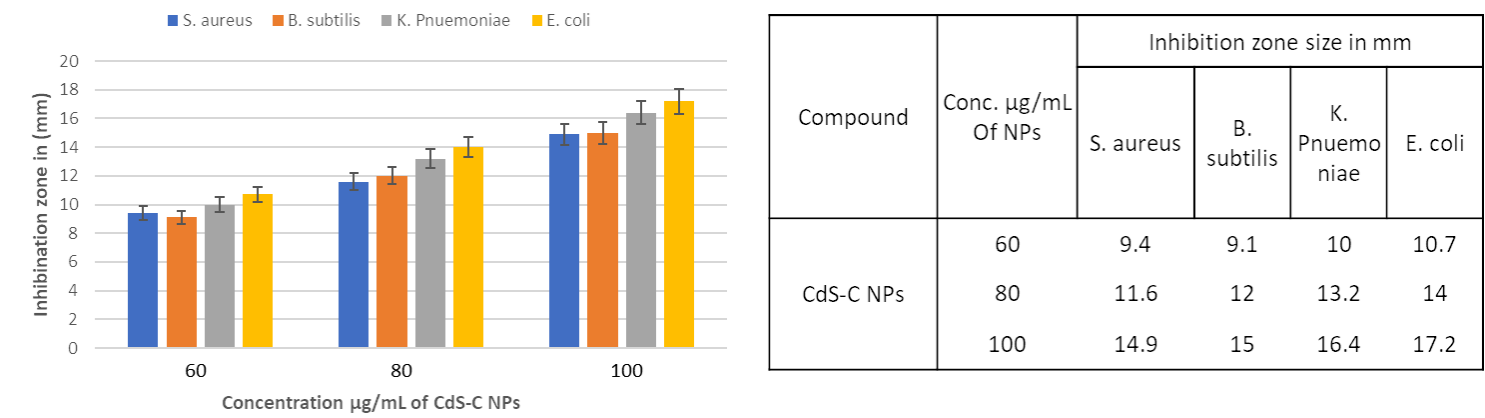


Figure 7

Antimicrobial activity of CdS NPs

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