

Eco-friendly Fabrication of CeO₂ Nanoparticles with Solanum nigrum: A Study on Cytotoxicity and Photocatalysis with plant growth studies

Malarvizhi A

coolmalar83@gmail.com

Padmavani Arts and Science College for Women, Salem

Ananthi P

Padmavani Arts and Science College for Women, Salem

Karthik M

Padmavani Arts and Science College for Women, Salem

Karthikeyan P

Government Arts and Science College Idappadi

Research Article

Keywords: Photocatalyst, CeO₂ Nanoparticles, HeLa cell, Plant growth, Solanum nigrum

Posted Date: January 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8342477/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

The synthesis of cerium oxide nanoparticles (CeO_2 -NPs) has been carried out using a sol-gel method, in which *Solanum nigrum* (*S. nigrum*) extract was used as the stabilizing agent. The nanoparticles were characterized by XRD, FE-SEM, EDX, UV-Vis and XPS methods. The XRD pattern exhibits the cubic structure. The FESEM/PSA pictures have shown the agglomerated morphology of CeO_2 -NPs. The chemical bonding nature of CeO_2 nanoparticles was examined using the XPS technique, which showed that Ce, O, and Ag make up the majority of the sample. Spin-orbit doublets and a well-separated spin-orbit splitting are visible in the high-resolution Ce 3D spectra. Lattice and surface adsorbed oxygen ions are associated with the three primary binding energies. The C 1S peak indicates the presence of organic carbon. The UV-Vis spectra for the nanoparticles exhibit a prominent adsorption band at the wavenumber region of 417 nm. Moreover, the photocatalytic efficiency of CeO_2 -NPs has been examined by carrying out the degradation of RB dye under UVA light showing the degradation percentage of 78%, which are linked to contaminants found in sewage water. The MTT assay results have indicated that the cytotoxicity of CeO_2 -NPs on HeLa cell lines is not concentration-dependent. Additionally, the cytotoxicity analysis shows a significant toxicity for the higher concentration of 200 $\mu\text{g/mL}$ for the cancer cells against the nanoparticles. The study found significant differences in the effects of CeO_2 NPs on seed weights, root and shoot lengths, and both. Plants treated with a 10^{-4} M dose had longer shoots and roots, while those treated with 5a had significantly larger seeds.

1. Introduction

Cerium is an abundant rare-earth element that is frequently present in the Earth's crust in the form of uncombined metal or oxide salts. Cerium oxide nanoparticles (CeO_2 NPs) have attracted considerable interest in the field of nanotechnology because of their wide range of uses [1–3]. Cerium oxide is a semiconductor that has a large energy band gap of 3.19 eV and can absorb wavelengths between 330–370 nm. It is known for its exceptional chemical and thermal stability, high conductivity, capacity to store oxygen, absorb UV radiation, and catalytic activity. CeO_2 NPs possess exceptional characteristics that render them extremely effective photocatalysts, which are crucial for environmental and energy-related functions. Additionally, they are widely utilized in UV light absorption, glass polishing, biosensors, sunscreens, and numerous biomedical applications [4–12].

The conventional manufacturing methods for cerium oxide nanoparticles have historically depended on techniques such as hydrothermal, solvothermal, co-precipitation, sol-gel, and microwave approaches [13–20]. These techniques may produce high-quality nanoparticles, but they generally suffer from significant limitations, like the use of toxic chemical reducing agents, high-temperature, pressure requirements, high energy consumption, and environmental pollution concerns [21]. These approaches have shown effectiveness in creating nanoparticles, but they frequently require the use of strong chemicals and energy-intensive procedures, which raises environmental issues and results in the production of toxic byproducts. Recently, there has been an increasing focus on implementing green

synthesis methods to tackle these difficulties. Green synthesis approaches employ natural sources such as plant extracts, bacteria, fungi, and algae, utilizing their biochemical capabilities to generate nanoparticles in a more sustainable manner [22–32]. Plant extracts have emerged as highly promising options among the many green synthesis processes. Plant extracts contain a diverse range of phytochemicals, such as tannins, flavonoids, and terpenoids, that serve as reducing and stabilizing agents in the process of synthesizing nanoparticles. The bioactive substances have a significant impact on the nucleation, growth, and shape of the nanoparticles, resulting in the creation of precise and stable nanostructures. In addition, green synthesis techniques have the benefit of being environmentally friendly, as they remove the use of harmful chemicals and reduce energy consumption. This makes them very appealing for a wide range of industrial applications in nanotechnology [33–35]. However, several limitations remain in green synthesis investigations, such as poor control over particle agglomeration, batch-to-batch variability, and limited exploration of multifunctional properties like combined photocatalytic and biological effects.

In this study, we utilized *S. nigrum* extract as a stabilizing agent during the synthesis of CeO₂-NPs. *S. nigrum* is a prominent botanical specimen that is extensively cultivated in *S. nigrum*. *S. nigrum* is a potent medicinal plant that plays a crucial part in cancer treatment due to the therapeutic properties found in the extract derived from its leaves. *S. nigrum* has been utilized in traditional medicine and has been reported to possess cytotoxic effects on cancer cell lines [36]. Because of its abundance of phytochemicals, including flavonoids, polyphenols, alkaloids, and tannins, which function as natural reducing and capping agents during nanoparticle synthesis, *Solanum nigrum* was utilised as the stabilising agent. In addition to aiding in the reduction of cerium ions, these biomolecules also adsorb onto the surface of nanoparticles, preventing agglomeration and improving stability. The wide range of functional groups and antioxidants for the extracts promotes controlled nucleation and smaller crystallite formation, which enhances the surface reactivity and photocatalytic efficiency synthesized CeO₂ nanoparticles.

The unregulated release of chemicals into water and air in recent decades has caused considerable environmental issues, which have been worsened by the increase in energy shortages and pollution. Organic pollutants such as methylene blue, rhodamine, and reactive blue are extremely harmful to aquatic life and human health due to their non-biodegradable nature and high toxicity. Their existence in water bodies adds to worldwide water pollution, affecting the well-being of ecosystems and the purity of water. Photocatalytic degradation is a viable alternative for water treatment, with advantages over traditional methods in addressing organic dye pollution and protecting the environment and human well-being [37–40]. There has been significant interest in utilizing semiconductor materials for photocatalysis in the fields of water purification and water splitting [41, 42].

In this context, CeO₂ emerges as a promising n-type semiconductor with a band gap of approximately 3.2 eV, making it a viable material for decolorizing organic dyes found in industrial wastewaters. In this study, we employed an eco-friendly synthesis, structural characterization, utilizing *S. nigrum* plant aqueous extract to fabricate CeO₂ nanoparticles (NPs). The nanocomposite was extensively

characterized using techniques such as X-ray diffraction (XRD), Field Emission-Scanning Electron Microscopy (FE-SEM), Energy Dispersive Spectroscopy (EDS), Photoluminescence (PL), and UV-vis diffuse reflectance spectroscopy (UV-DRS). Subsequently, the synthesized CeO₂ NPs were evaluated for their efficacy in photodegrading aqueous Reactive Blue (RB) dye under light irradiation, demonstrating significantly enhanced degradation rates. Additionally, the nanocomposite's anticancer activity was assessed using HeLa cell lines, providing valuable insights into its potential biomedical applications.

2. Experimental section

2.1. Preparation of *S. nigrum* plant extract

The *S. nigrum* leaves, sourced from the *S. nigrum* plant, were thoroughly washed two to three times using distilled water to eliminate debris and additional residues. Which undergo air drying. After air-drying for 2 days, 5 g of the finely ground leaf powder were boiled in distilled water at 80 °C for 30 mins. Subsequently, the acquired extract was passed through Whatman No. 1 filter paper and stored for future investigations.

2.2. Preparation CeO₂-NPs using of *S. nigrum* plant extract

The synthesis of CeO₂ NPs using of *S. nigrum* plant extract was carried out by sol-gel approach. Ce(NO₃)₃.6H₂O was used as the cerium precursor, *S. nigrum* plant extract and DI water were employed as the stabilizing agent and solvent respectively. Subsequently, the synthesis was initiated by dissolving 3 g of cerium nitrate hexahydrate into 50 mL of DI water. The resulting mixture was then agitated at room temperature for a duration of 30 min. Thereafter, the solution was gradually introduced in small drops to a volume of m = 30mL of *S. nigrum* plant extract. The amalgamated mixture was continuously agitated at a temperature of 80°C for a duration of 16 h. Upon continual stirring, a white precipitate underwent a colour change and transformed into gel with a lemon hue. The gel was allowed to dried for a duration of 4 h at a temperature of 100°C. Ultimately, the dehydrated gel underwent calcination at temperatures of 400, 500, and 600°C for a duration of 2 h each, resulting in the formation of yellow-hued CeO₂ -NPs.

2.3. Characterization techniques

The X-ray diffraction (XRD) pattern of the samples that were manufactured was analyzed using a PANalytical instrument equipped with a copper K-alpha radiation source. The surface characteristics, micro/nanostructures, and elemental composition of the sample were analyzed using a FE-SEM (Quanta FEG-250 instrument), HR-TEM (JEOL-2100 + tool), and the EDS linked to the FE-SEM instrument. The absorption spectra in the UV–vis DRS range were obtained using an Analytik Jena Specord-200 model. We assessed the cytotoxic impact of CeO₂-NPs on the PC12 cancer cell line using the MTT assay.

2.4. Photocatalytic degradation test

The effectiveness of degrading reactive blue (RB) using cerium oxide nanoparticles was examined through light irradiation. To conduct the test, 50 mg of the photocatalyst was dispersed in 100ml of dye

solution and it was agitated for 30 min and kept in a dark room to achieve desired equilibrium of adsorption and desorption. It was then irradiated to light and the photocatalytic efficiency was monitored at every 30 min of time interval. The degradation efficiency was observed using UV-Vis spectroscopy. Furthermore, the stability test was performed by repeating the experiments over four cycles.

2.5 Cytotoxicity

The assessment of anticancer activity was conducted using cell lines derived from human cervical carcinoma (HeLa) cell line, obtained from the National Centre for Cell, Pune, India. Briefly, Cells were maintained in DMEM supplemented with 2 mM L-glutamine and balanced salt solution (BSS) adjusted to contain 1.5 g/L Na₂CO₃, 0.1 mM nonessential amino acids, 1 mM sodium pyruvate, 2 mM glutamine, 1.5 g/L glucose, 10 mM HEPES (4-(2-hydroxyethyl)-1-piperazine ethane sulfonic acid) and 10% fetal bovine serum (GIBCO, USA). Penicillin and streptomycin (100 IU/100µg) were adjusted to 1 mL/L. The cells were maintained at 37 °C with 5% CO₂ in a humidified CO₂ incubator. The cytotoxicity of the HeLa cell line was analysed through MTT assay. HeLa cell line with the concentrations of 1×10^5 were allowed to grow on the previously sterilized MEM and DMEM media. To this, the sample concentration of 100 and 200 µg/mL loaded in the 96 well plate and maintained in the humidified atmosphere. An inverted microscope was applied to investigate the modification in morphologies after the incubation of 48 h at 37°C. After that, to the above solution 80 µg/mL of MTT was added and then the solution was raised for 4 h and develop formazan crystals. The formazan crystals were liquified through substituting the solution with dimethyl sulphoxide (DMSO) and the cytotoxicity was measured using the optical intensity (OD) values at the wavelength of 570 nm.

3. Results and discussion

3.1. X-Ray diffraction analysis

The X-ray diffraction (XRD) technique offers a comprehensive analysis of the crystallite structure of materials, providing vital insights into their composition and phase. The X-ray diffraction (XRD) patterns shown in Fig. 1 for cerium oxide nanoparticles (CeO₂-NPs) generated from *S. nigrum* plant exhibit clear peaks that correspond to certain crystallographic planes. The major diffraction peaks appear at approximately the 2θ values at 28.6°, 33.1°, 47.5°, 56.3°, 59.1°, 69.4°, 76.7°, and 79.1° represents the peaks indexed to the (111), (200), (220), (311), (222), (400), (331), and (420) for the corresponding crystallographic planes, respectively. The indices mentioned are specific to the face-centered cubic structure commonly found in CeO₂-NPs. This is a well-established fact supported by the reference code 34–0394 from the Joint Committee on Powder Diffraction Standards (JCPDS) [43]. The detection of these peaks signifies the existence of crystalline phases in the produced CeO₂-NPs. The average crystallite size of the synthesized CeO₂ nanoparticles was calculated to be 11.4 nm employing the Debye–Scherrer formula. In addition, the presence of a small diffraction peak indicates that the material has a very pure crystalline structure, providing further confirmation of its composition and crystallinity. This thorough examination of XRD data not only offers useful understanding of the structural

characteristics of the synthesized CeO₂-NPs but also acts as a critical confirmation of their excellence and appropriateness for diverse applications like photocatalysis and anticancer activity.

3.2. FE- SEM and EDX analysis

The surface morphology of the CeO₂ nanoparticles was meticulously examined through FE-SEM and EDX analysis, as illustrated in Fig. 2(a–c). The images obtained through FE-SEM elucidate the distinctive agglomerated spherical shape of the CeO₂ nanoparticles, which were synthesized utilizing *S. nigrum* plant extract. Furthermore, the Energy Dispersive X-ray (EDX) spectrum corroborated the elemental composition of the sample, confirming the presence of atomic Ce and O with no other detectable atoms. This attests to the high purity of the synthesized CeO₂ nanoparticles. Moreover, the EDX analysis highlighted prominent peaks corresponding to Ce and O elements at an energy level of 20 keV. This clear and distinct EDX spectrum serves as compelling evidence of the successful synthesis process of CeO₂ nanoparticles. Together, these findings from FE-SEM and EDX analyses provide comprehensive insights into both the morphology and elemental composition of the synthesized CeO₂ nanoparticles, validating their quality and purity for potential applications.

3.3 UV-Vis DRS analysis

The UV-Vis DRS study was conducted to investigate the absorption and optical characteristics of the nanomaterial. Figure 3 displays the UV-Vis spectra and energy band gap of CeO₂ nanoparticles (NPs) of 300°C and 600°C. The optical absorption spectra exhibit maxima at wavelengths of 374, and 417 nm under these circumstances. The absorption peaks are most likely caused by the transfer of charge from O 2p orbitals to Ce 4f orbitals [44, 45]. The band gap energy value of the CeO₂ NPs produced using sol gel method was found by fitting the absorption of direct transition using the following equation:

$$\alpha h\nu = A(h\nu - E_g)^n \quad (1)$$

The variable α represents the coefficient of optical absorption. The energy of a photon is represented by the symbol $(h\nu)$, where h is Planck's constant and ν is the frequency of the photon. The direct band gap is denoted by the symbol E_g . The values for the indirect and direct band gaps are $n = 2$ and $n = 1/2$, respectively, and A is a constant value [46]. The band gap energy of CeO₂ at 300°C, and 600°C was determined to be 2.73 eV using the above formulaic calculation. The reduction in the band gap value can be attributed to quantum events that take place in nanoparticles at the nanoscale [47]. The band gap plot of CeO₂ NPs showed a blue shift, confirming the effective synthesis of the nanoparticles. A significant observation is that in direct semiconductors, decreasing the particle size distribution results in an elevation of the band gap energy. The reduction in nanoparticle aggregation can be ascribed to the remarkable capacity of cerium ions, obtained from *S. nigrum* plant extract, to function as stabilizing agents [48].

3.4. Photoluminescence Studies

Figure 4 illustrates the photoluminescence spectra of CeO₂ nanoparticles synthesized at temperatures of 300°C, and 600°C. The photoluminescence (PL) spectra unveil a notable emission band at 405 nm, which appears more pronounced compared to other nanoparticles synthesized under similar conditions. This enhanced PL emission intensity suggests a reduction in the recombination rate of photogenerated electron-hole (e⁻/h⁺) pairs in the nanocomposites. The decrease in PL emission intensity can be attributed to the active role of CeO₂ NPs as electron collectors on the nanoparticle surfaces [49]. This active involvement of CeO₂ nanoparticles effectively enhances the efficiency of separating photogenerated carriers, thereby reducing recombination rates. Consequently, this mechanism facilitates the utilization of visible light, offering significant advantages in bolstering the performance of photocatalytic degradation processes. In summary, the findings underscore the potential of CeO₂ nanoparticles to greatly improve the efficiency of separating photogenerated carriers, leading to a reduction in recombination rates. This enhancement in visible light utilization holds immense promise for enhancing the efficacy of photocatalytic degradation processes.

3.5. XPS technique

The XPS technique is used to analyze the chemical bonding nature of CeO₂ nanoparticles. With corresponding binding energies of 880–920 eV (Ce 3d) and ~ 530 eV (O 1s), the survey spectrum in Fig. 5a shows that the sample is primarily constituted of Ce, O, and Ag. The high-resolution Ce 3d spectra, which include the spin-orbit doublets Ce 3d_{5/2} (~ 882 eV) and Ce 3d_{3/2} (917 eV), are shown in Fig. 5b. The predominant Ce⁴⁺ and Ce³⁺ oxidation states of CeO₂ are appropriately attributed to these binding energies. About 18.6 eV is the well-separated spin–orbit splitting in the Ce 3d region. Furthermore, the satellite peaks (v1, v2, μ1, and μ2) are evident in Fig. 5b together with the Ce 3d_{5/2} and Ce 3d_{3/2} peaks, which are associated with the energy-gain (shake-down) process. The three main binding energies, 527.8 eV (OIII), ~ 530 eV (OII), and ~ 532.5 eV (OI), are linked to the lattice oxygen ions (Olat) and surface adsorbed oxygen ions (Oads), according to the deconvoluted O1s (Fig. 5d) spectra. Furthermore, the presence of organic carbon in the nanoparticles is indicated by the C 1S peak (Fig. 5(c)), which corresponds to the binding energies of ~ 281.5 eV (C–C), ~ 285.1 eV (C–O), and ~ 288.9 eV (C = O).

3.6 Photocatalytic Analysis

Figure 5 illustrates the photo-degradation activity of CeO₂ NPs photocatalysts utilizing CB aqueous dyes under light irradiation. The RB solution's absorption spectra were monitored periodically at intervals of 30, 60, 90, 120, and 150 min to study the rate of change in the absorption peak intensity, which indicates the degradation. The peak at 400 nm shows that 78% of the dye has been broken down after 150 min. This is because the CeO₂ -NPs synthesized from *S. nigrum* plant work so well as catalysts.

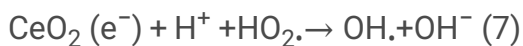
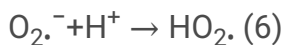
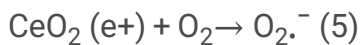
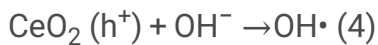
Equation 2 can be used to study the kinetics of photo-catalytic degradation.

$$-\ln C/C_0 = kt \rightarrow (2)$$

In this equation, 'k' represents the rate constant, 'C' represents the concentration at time 't', and 'C₀' represents the concentration at time 't = 0'. The relationship between the natural logarithm of the concentration ratio C/C₀ and the duration of irradiation exhibited linear patterns for CeO₂ NPs showed in Fig. 7a & b. The results indicate that the degradation of RB by CeO₂ NPs exhibits a reaction rate that approximates a first-order reaction kinetics.

3.7. Photocatalytic mechanism

The mechanism of the photocatalytic response of CeO₂-NPs synthesised from *S. nigrum* plant is described below. When CeO₂ nanoparticles (CeO₂-NPs) are exposed to sunlight, electrons in the valence band absorb energy and are excited to move to the conduction band. This transition creates vacancies, known as holes, in the valence band. As a result, electron-hole pairs are generated. These pairs are then transported to the surface of the nanoparticles. At the surface, hydroxyl radicals (OH•) are formed from water molecules present in the pores of the material. Simultaneously, the excited electrons reduce oxygen molecules to form superoxide radicals (O₂^{•-}). The interaction between these reactive species—hydroxyl radicals and superoxide radicals—plays a pivotal role in the degradation of dye molecules present in the solution. The conduction band facilitates the movement of electrons, while the valence band accommodates the holes created during the excitation process. This separation and subsequent movement of charges are crucial for the photocatalytic activity, enabling the breakdown of dye molecules. The detailed photocatalytic reaction mechanism is illustrated below.



The degradation of MO dye is mainly caused by the size, shape, and surface charge characteristics of the produced CeO₂ nanoparticles (CeO₂-NPs). Photon-induced chemical reactions take place on the catalyst's surface during photocatalytic activity [50]. Photon-generated electron-hole pairs enhance redox reactions on the catalyst's surface, resulting in the production of superoxide ions and hydroxyl free radicals [51]. The radicals produced have strong photocatalytic properties, efficiently breaking down harmful compounds present in wastewater. This suggests that the CeO₂-NPs produced by biosynthesis effectively break down the dye when exposed to sunlight. The increased photocatalytic activity of the synthesized CeO₂ nanoparticles is mainly because of their improved surface activity, and increased oxygen vacancy concentration resulting from the use of *Solanum nigrum* extract during synthesis.

Additionally, the $\text{Ce}^{4+}/\text{Ce}^{3+}$ redox pair promotes the formation of oxygen vacancies, which improves charge separation by reducing electron–hole recombination. This leads to a higher generation of reactive oxygen species ($\cdot\text{OH}$ and $\text{O}_2\cdot^-$), which are responsible for the effective degradation of dye molecules under light irradiation. Therefore, the efficiency is achieved through the combined effects of optimized nanoparticle size, surface stabilization, and enhanced charge carrier dynamics.

3.8. Anticancer activity

3.8.1. MTT Assay

CeO_2 -NPs-600°C has been chosen for MTT experiments because it has the superior optical characteristics as shown in Fig. 8. The inhibitory concentration (IC_{50}) value was evaluated using an MTT assay. Cultured cells (1×10^5) were seeded in a 96-well plate and incubated for 48 h at 37°C at 5% CO_2 incubator. After 48 h, monolayer was washed with medium and 100 μL of different test concentrations of samples were added on to the monolayer and the cells were further incubated at the same conditions. The cultured medium was removed, and 100 μL of the MTT solution was added to each well and incubated at 37°C for 4 h. After removal of the supernatant, 100 μL of DMSO was added to each of the wells and incubated for 10 min to solubilize the formazan crystals. The optical density was measured at 590 nm. The IC_{50} value is a critical parameter that represents the half-maximal inhibitory concentration, indicating the concentration at which 50% of cell growth or viability is inhibited [52]. In the context of this study, the IC_{50} value for CeO_2 NPs was determined to be 143.323. This value signifies that at a concentration of 143.323 $\mu\text{g}/\text{mL}$, CeO_2 NPs induce a 50% inhibition of cell growth in HeLa cell lines. Moreover, the comparison made between the IC_{50} value of CeO_2 NPs and that of the standard drug, cisplatin, suggests that CeO_2 NPs exhibit comparable or even higher cytotoxic efficiency against HeLa cell lines. Therefore, the finding that CeO_2 NPs demonstrate comparable cytotoxicity to cisplatin indicates their potential as a promising alternative or adjunct therapy for cancer treatment. Table 1 represents the comparative analysis of the photocatalysis and cytotoxicity of the CeO_2 NPs.

Table 1
Comparative discussion of the CeO₂ nanoparticles with the previous report

Reference	Synthesis route	Photocatalysis	Performance	Cytotoxicity
Shetty et al., 2025	Green synthesis	Dye photodegradation (reported)	High activity; stability emphasized	—
Mim et al., 2024	Green plant-mediated	Methylene Blue; UV	56.8% in 150 min	—
Kalaycioğlu et al., 2023	CeO ₂ /GO/PAM composite	MB under visible light	High, rapid MB removal; reusable	—
Dunna et al., 2023	Chemical synthesis	-	-	HeLa cell line, significant dose-dependent cytotoxicity
Abedi-Tameh et al., 2024	Green synthesis using plant extract	-	-	MCF-7 cell line shows the IC ₅₀ at 175 µg/mL

3.9. Plant growth studies

The effect of CeO₂ NPs on the growth and development of mung bean plant growth, as depicted in Fig. 9, reveals that all tested concentrations of CeO₂, ranging from 10⁻² to 10⁻⁴ M in aqueous solutions, markedly enhance the growth and development of roots, shoots, and seed systems in mung bean plants when compared to the control plant (Fig. 9).

The CeO₂ NPs exhibited variable effects on root and shoot lengths as well as seed weights, demonstrating significant differences across treatments. The maximum shoot length of 27.0 cm was observed in plants treated with a 10⁻⁴ M concentration, whereas the shortest shoot length of 21.0 cm was recorded in the control plants. Similarly, the longest root length, measuring 15.0 cm, was noted in plants treated with the 10⁻² M concentration, while the shortest root length of 10.0 cm occurred in plants treated with control plants. Seed weights were notably higher in the CeO₂-treated plants, with the heaviest seeds (0.7012 g) found in plants treated with the 10⁻⁴ M concentration, compared to the lowest seed weight of 0.2351 g in the control plants. The plant growth analysis further demonstrated that the CeO₂ nanoparticles endorsed seed germination, root elongation, and biomass accumulation at low concentrations, however, growth inhibition was observed at higher nanoparticle doses, suggesting that excessive reactive oxygen species generation can induce oxidative stress and physiological imbalance.

Table 2
Effects on root and shoot lengths and seed weights with respect to the CeO₂ NPs

S. no	Parameters	Control	Molar concentration (CeO ₂ NPs)	
			10 ⁻²	10 ⁻⁴
1	Shoot length (cm)	20.10 ± 0.97	22.17 ± 0.88	26.22 ± 1.08
2	Root length (cm)	09.90 ± 1.02	14.06 ± 0.97	12.25 ± 1.09
3	Seed weight (g)	0.224 ± 0.009	0.513 ± 0.008	0.691 ± 0.009

4. Conclusion

In this work, a green sol–gel method was successfully used to create CeO₂ nanoparticles from *S. nigrum* leaf extract, providing an eco-friendly substitute for chemically assisted synthesis. The formation of phase-pure, crystalline CeO₂ with bio-functional surface groups derived from the plant extract was validated by the structural and surface analyses. Under light irradiation, the produced nanoparticles showed strong photocatalytic activity towards Reactive Blue dye, which is explained by enhanced surface-active sites, oxygen vacancy formation, and charge separation. A moderate inhibitory effect on HeLa cancer cells was found in the cytotoxicity evaluation, suggesting that CeO₂ nanoparticles could be used as an additional anticancer agent while still having acceptable biocompatibility at lower concentrations. Additionally, the plant growth assay demonstrated that CeO₂ nanoparticles have a dose-dependent effect, preventing growth at higher amounts while promoting germination of seeds and seedling growth at lower concentrations. Overall, the findings indicate that, through careful oversight of concentration and exposure levels, green-synthesized CeO₂ nanoparticles have promising multifunctional applications in agriculture, biomedical fields, and environmental remediation. Optimisation of nanoparticle dosage, assessing long-term biological interactions, and investigating useful application systems should be the primary objectives of future research.

Declarations

Funding : Not Abblicable

Conflict of Interest : Not Abblicable

Ethical approval : Not Abblicable

Informed Consent : Not Abblicable

Author Contribution

Dr. A. Malarvizhi: Conceptualization, Methodology, Investigation Supervision; Writing-Original Draft and Formal analysis. Dr. P. Ananthi: Validation, Resources, Formal analysis, Methodology. Dr. M. Karthik: Resources, Formal analysis, and Editing. Dr. P. Karthikeyan: Validation, Visualization, Reviewing and editing.

References

1. C. M. Strieder, D L P Macuvele, C. Soares, et. al., J Mater Res Tech, 30, 2024, 6376-6388.
2. T. Surendra, S.M. Roopan, Journal of Photochemistry and Photobiology B: Biology, 161 (2016) 122-128.
3. M. Keerthana, T. Pushpa Malini, R. Sangavi, J. P. Arockia Selvi, M. Arthanareeswari, *ChemistrySelect* 2022, 7, e202103610.
4. L. Wasef, AMK. Nassar, YS. El-Sayed, D. Samak, A. Noreldin, Elshony N, Sci Rep, (2021) 11:1-15.
5. L. Lu, G. Dai, L. Yan, L. Wang, L. Wang, Z. Wang, Optical Material (Amst), (2020) 101:109724.
6. J. Calvache-Munoz, FA. Prado, Rodri guez-Paez JE. Colloids Surfaces A Physicochem Engineering Asp, (2017) 529:146-59. <https://doi.org/10.1016/j.colsurfa.2017.05.059>.
7. M. Kurian. Journal of Environmental Chemical Engineering, (2020) 104439.
8. C. Maria Magdalane, K. Kaviyarasu, J. Judith Vijaya, B. Siddhardha, B. Jeyaraj. Journal of Photochemistry Photobiology B Biology, (2017) 173:23-34. <https://doi.org/10.1016/j.jphotobiol.2017.05.024>.
9. J. Malleshappa, H. Nagabhushana, SC. Prashantha, SC. Sharma, N. Dhananjaya, C. Shivakumara Joirnal of Alloys Compound, (2014) 612:425-34. <https://doi.org/10.1016/j.jallcom.2014.05.101>.
10. S. Kumar, S. Tripathy, OK. Singh, SG. Singh. Bioelectrochemistry, (2021), 138:107725. <https://doi.org/10.1016/j.bioelechem.2020.107725>.
11. A.M. Amanulla, C.M. Magdalane, S. Saranya, R. Sundaram, K. Kaviyarasu. Surface Interface, (2021) 22:100835. <https://doi.org/10.1016/j.surfin.2020.100835>.
12. F. Caputo, M. Mameli, A. Sienkiewicz, S. Licoccia, F. Stellacci, L. Ghibelli, Sci Rep (2017) 7:1-13. <https://doi.org/10.1038/s41598-017-04098-6>
13. Z. Sabouri, A. Akbari, HA. Hosseini, Journal of Molecular Structure (2018) 1173:931–936.
14. Nadeem, M., Khan, R., Afridi, K., Nadhman, A., Ullah, S., Faisal, S., ... Abbasi, B. H. (2020). International Journal of Nanomedicine, 15, 5951–5961.
15. E. Bin Osman, T. Moriga, K-I. Murai, Indian Crops Production (2018) 113:210–216.
16. F. Zhang, S.W. Chan, J.E. Spanier, E. Apak, Q. Jin, R.D. Robinson, I.P. Herman, Appl. Phys. Lett. 80 (2002) 127–129.
17. Ramanathan, G., Rathan, S.V. & Murali, K.R. *SN Appl. Sci.* 1, 116 (2019).
18. H. Wang, J.J. Zhu, J.M. Zhu, X.H. Liao, S. Xu, T. Ding, H.Y. Chen, Phys. Chem. Chem. Phys. 4 (2002) 3794–3799.

19. W H Zhu, J J Zhu, J M Liao, et al, *Phys. Chem. Chem. Phys.*, 2002, 4, 15, 3794-3799.
20. S.Y. Yao, Z.H. Xie, *J. Mater. Process. Technol.* 186 (2007) 54–59.
21. C Chesneau, S Belbekhouche, *Powder Technology*, 464, 2025, 121167.
22. C. Hu, Z. Zhang, H. Liu, P. Gao, Z.L. Wang, *Nanotechnology* 17 (2006) 5983–5987.
23. Y. Huang, Y. Cai, D. Qiao, H. Liu, *Particuology* 9 (2011) 170–173.
24. A. Krishnan, T.S. Sreeremya, E. Murray, S. Ghosh, *J. Colloid Interface Sci.* 389 (2013) 16–22.
25. S. Maensiri, C. Masingboon, P. Laokul, W. Jareonboon, V. Promarak, P.L. Anderson, S. Seraphin, *Cryst. Growth Des.* 7 (2007) 950–955.
26. S. Maensiri, S. Labuayai, P. Laokul, J. Klinkaewnarong, E. Swatsitang, *Jpn. J. Appl. Phys.* 53 (2014) 06JG14.
27. S. Phoka, P. Laokul, E. Swatsitang, S. Maensiri, *Mater. Chem. Phys.* 115 (2009) 424–428.
28. S. Sathyamurthy, K.J. Leonard, R.T. Dabestani, M.P. Paranthaman, *Nanotechnology* 16 (2005) 1960–1964.
29. R. Suresh, V. Ponnuswamy, R. Mariappan, *Appl. Surf. Sci.* 273 (2013) 457–464.
30. Y. Tao, F.H. Gong, H. Wang, H.P. Wu, G.L. Tao, *Mater. Chem. Phys.* 112 (2008) 973–976.
31. S. George, S. Pokhrel, T. Xia, B. Gilbert, Z. Ji, M. Schowalter, A. Rosenauer, R. Damoiseaux, K.A. Bardley, L. Madler, A.E. Nel, *ACS Nano* 4 (2010) 15–29
32. M. Darroudi, S.J. Hoseini, R.K. Oskuee, H.A. Hosseini, L. Gholami, S. Gerayli, *Ceram. Int.* 40 (2014) 7425–7430.
33. S.A. Khana, A. Ahamad, *Mater. Res. Bull.* 48 (2013) 4134–4138
34. Gomez-Garay A, Pintos B, Manzanera JA, et al. *Biol Trace Elem Res.* 2014;161(1):143–150
35. A. Nawaz, A. Jamal, A. Arif, Z. Parveen, *Saudi Journal of Biological Sciences*, 28, 2021, 4786-4792, <https://doi.org/10.1016/j.sjbs.2021.05.004>
36. M. Patel, R. Kumar, K. Kishor, T. Mlsna, C.U. Pittman, D. Mohan, *Chem. Rev.* 119 (2019) 3510–3673, <https://doi.org/10.1021/acs.chemrev.8b00299>
37. S. Singla, S. Sharma, S. Basu, N.P. Shetti, K.R. Reddy, *FlatChem* 24 (2020) 100200, <https://doi.org/10.1016/j.flatc.2020.100200>
38. T. Rasheed, M. Bilal, F. Nabeel, M. Adeel, H.M.N. Iqbal, *Environ. Int.* 122 (2019) 52–66, <https://doi.org/10.1016/j.envint.2018.11.038>
39. K.K. Kesari, R. Soni, Q.M.S. Jamal, P. Tripathi, J.A. Lal, N.K. Jha, M.H. Siddiqui, P. Kumar, V. Tripathi, J. Ruokolainen, *Water Air. Soil Pollut.* 232 (2021) 208, <https://doi.org/10.1007/s11270-021-05154-8>
40. S. Chen, D. Huang, P. Xu, W. Xue, L. Lei, M. Cheng, R. Wang, X. Liu, R. Deng, *J. Mater. Chem.A.* 8 (2020) 2286–2322, <https://doi.org/10.1039/c9ta12799b>
41. X. Zhang, P. Yang, S.P. Jiang, *Carbon* 175 (2021) 176–186, <https://doi.org/10.1016/j.carbon.2021.01.010>
42. J. Wang, Z. Li, S. Zhang, et al., *Sensor Actuators B Chemistry* (2018) 255:862– 870.

43. H. Kargar, H. Ghazavi, M. Darroudi. *Ceramic International* (2015) 41(3, Part A):4123–4128
44. F. Caputo, M. Mameli, A. Sienkiewicz, S. Licoccia, F. Stellacci, L. Ghibelli, et al *Sci Rep* (2017) 7:1e13. <https://doi.org/10.1038/s41598-017-04098-6>.
45. AR. Unnithan, A. Ramachandra Kurup Sasikala, Y. Sathishkumar, YS. Lee, CH. Park, CS. Kim. *Ceramic International* (2014) 40:12003-12. <https://doi.org/10.1016/j.ceramint.2014.04.038>.
46. A. Rahdar, H. Beyzaei, F. Askari, GZ. Kyzas. *Applied Physics Material Science Process* (2020) 126:1-9. <https://doi.org/10.1007/s00339-020-03507-4>
47. B. Elahi, M. Mirzaee, M. Darroudi, et al. *Journal of Alloys Compound* (2020) 816:152553
48. Sarah Almofty , Vijaya Ravinayagam, Norah Alghamdi, Wejdan Alghamdi, Zainab Albazroun, Layan Almulla, Sultan Akhtar, Ali Awad Almofleh, Gazali Tanimu, H. Dafalla, B. Rabindran Jermy, *Open Nano*, (2023) 100169.
49. A. Muthuvel, M. Jothibas, C. Manoharan, S. J. Jayakumar, *Research Chemical Intermediate Mar.* (2020). Doi:10.1007/s11164-020-04115-
50. V. Ramasamy, V. Mohana, G. Suresh, *Indian Physics*, 92 (2018) 1601–1612.
51. L. Tolosa, M.T. Donato, Gomez-Lechon, M.J. (2015). General Cytotoxicity Assessment by Means of the MTT Assay. In: Vinken, M., Rogiers, V. (eds) *Protocols in In Vitro Hepatocyte Research. Methods in Molecular Biology*, vol 1250. Humana Press, New York, NY. <https://doi.org/10.1007/978-1-4939-2074-7-26>.

Figures

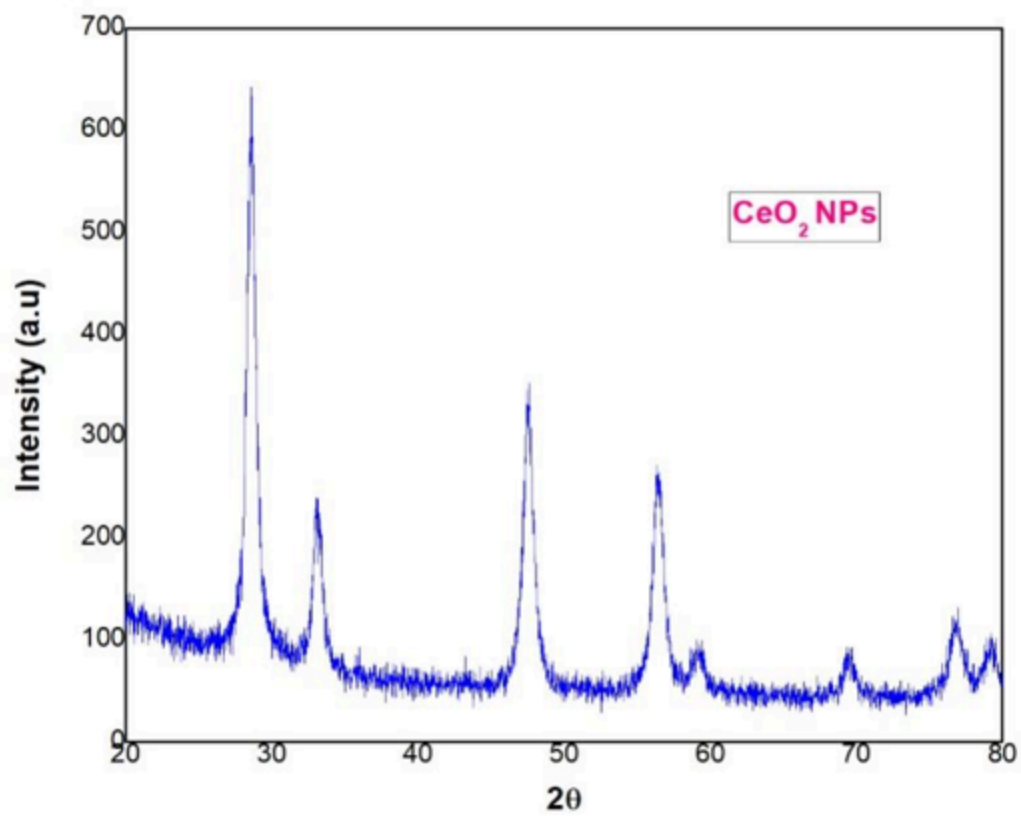


Figure 1

XRD of biogenic CeO₂ nanoparticles

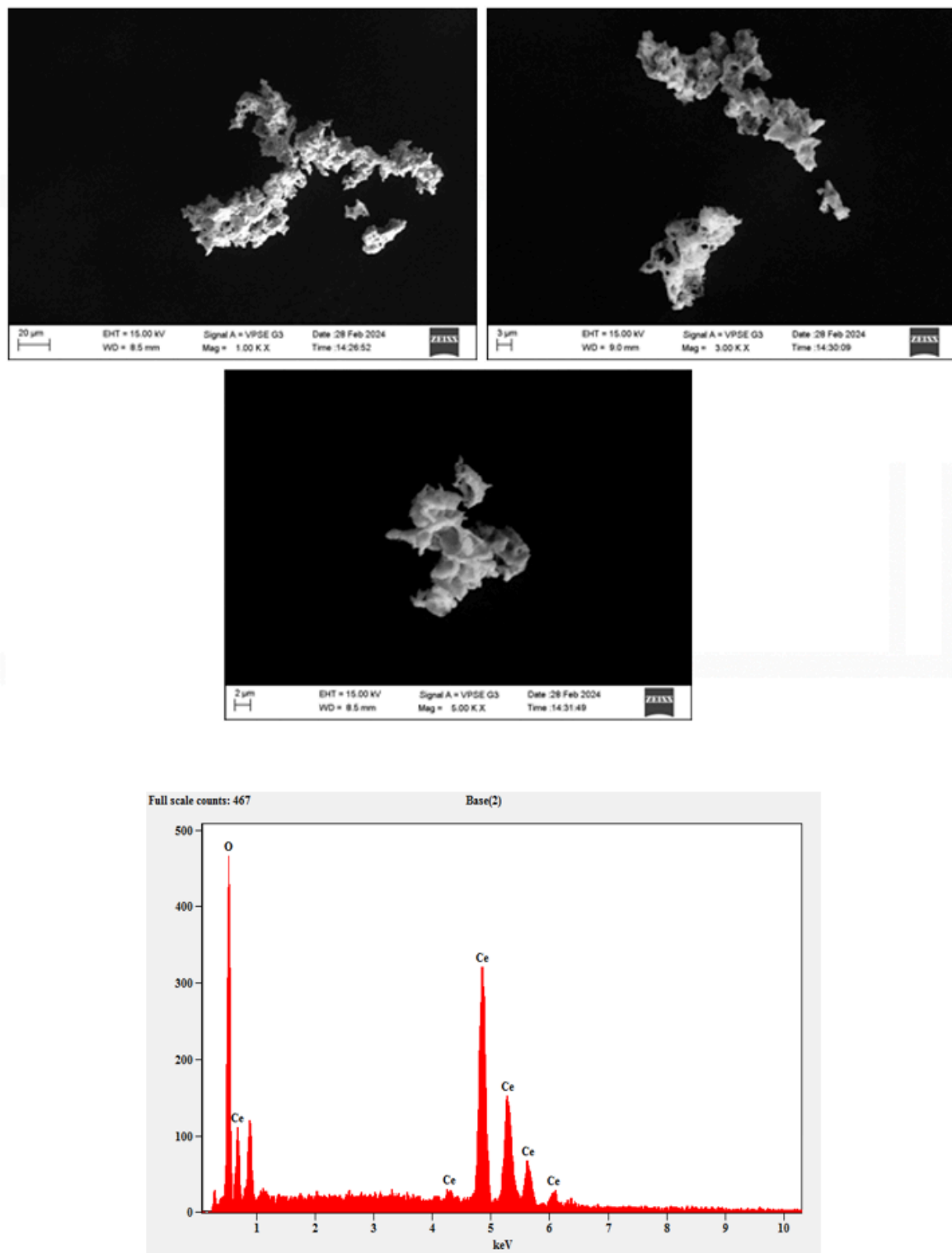


Figure 2

SEM images and the EDX spectrum of CeO_2 NPs prepared through *S. nigrum* plant extract

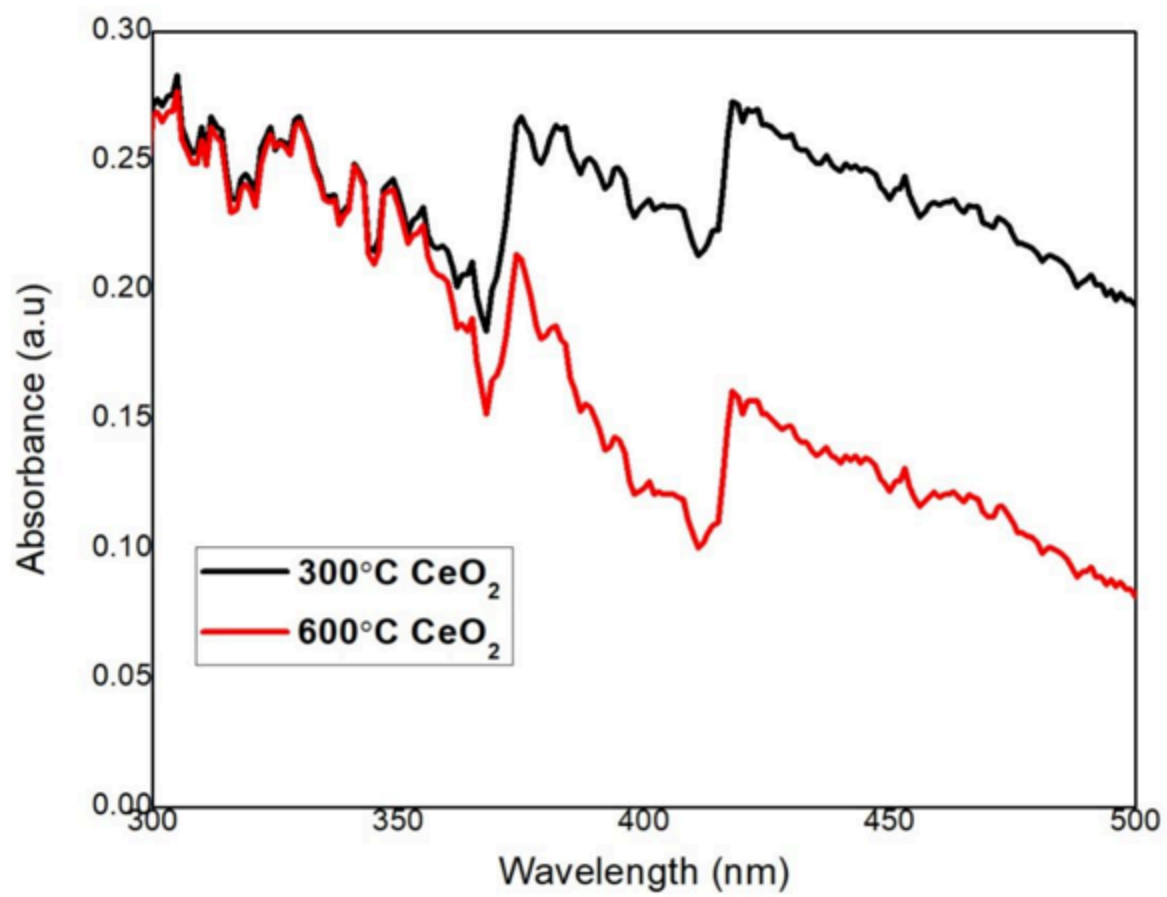


Figure 3

UV-Vis DRS spectra of CeO_2

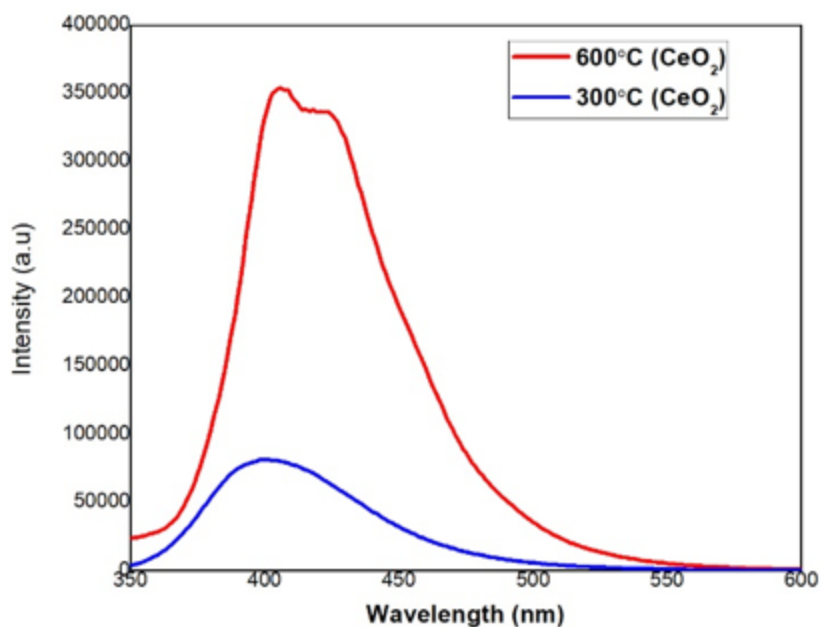


Figure 4

Photoluminescence spectra of CeO₂ nanoparticles synthesized at temperatures of 300 °C, and 600 °C

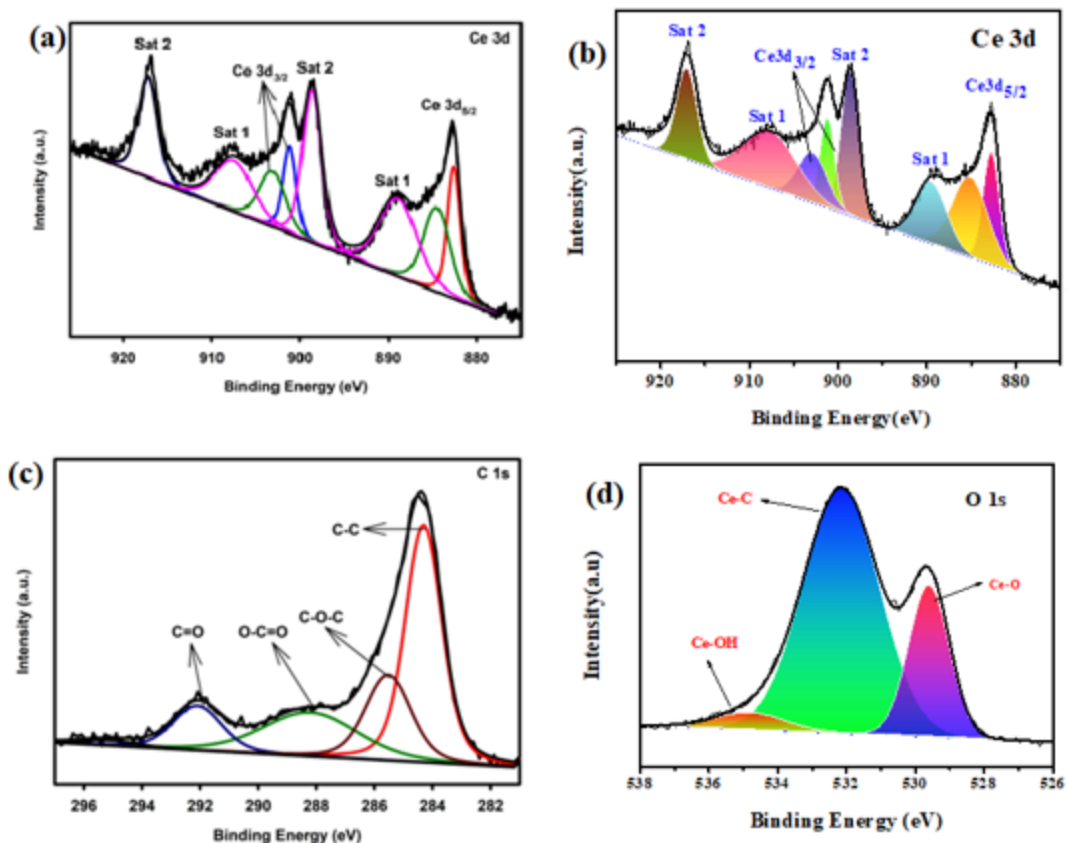


Figure 5

XPS survey full survey a) high-resolution spectra of CeO₂ nanoparticles, b) Ce 3d, c) C 1s and d) O 1s

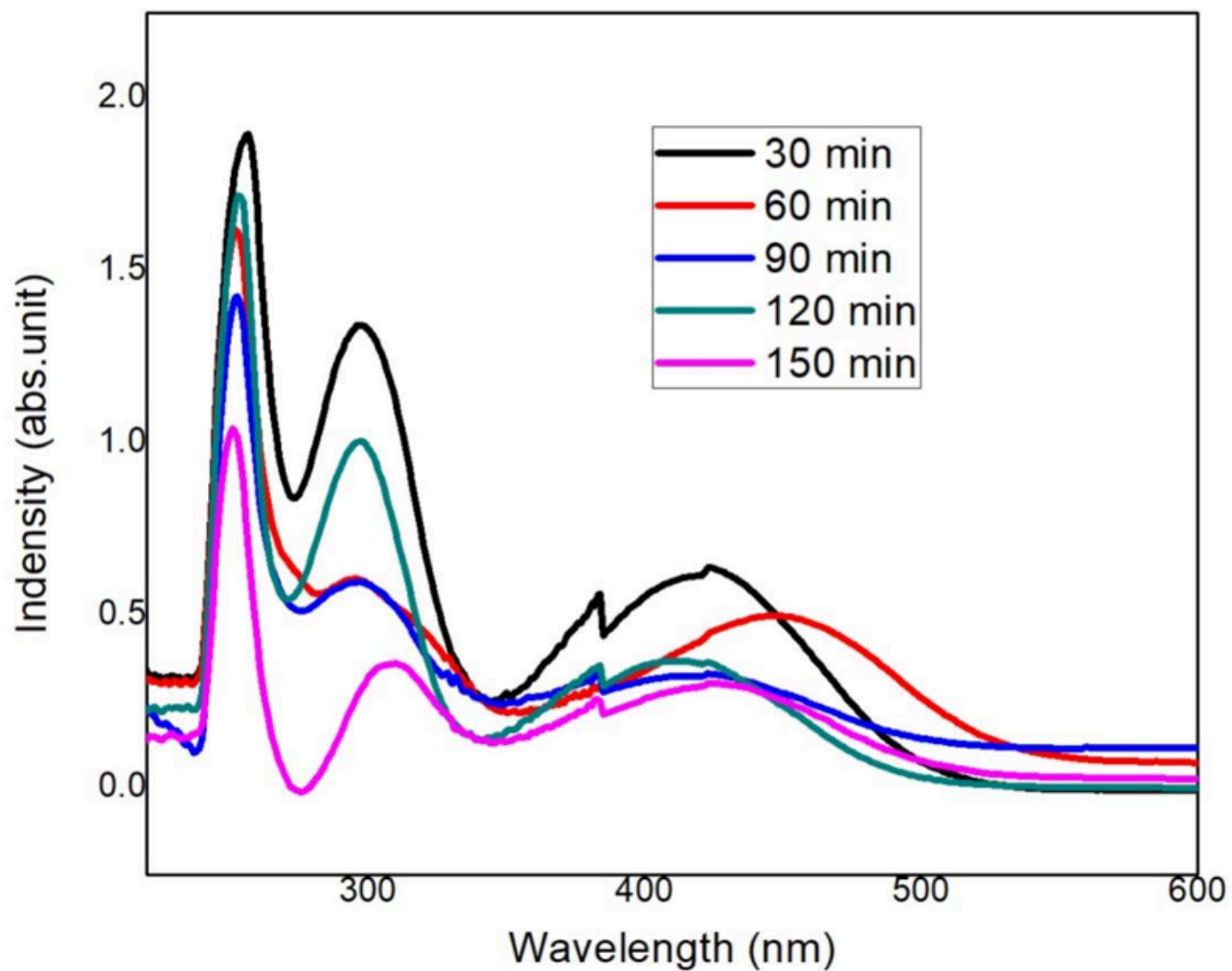
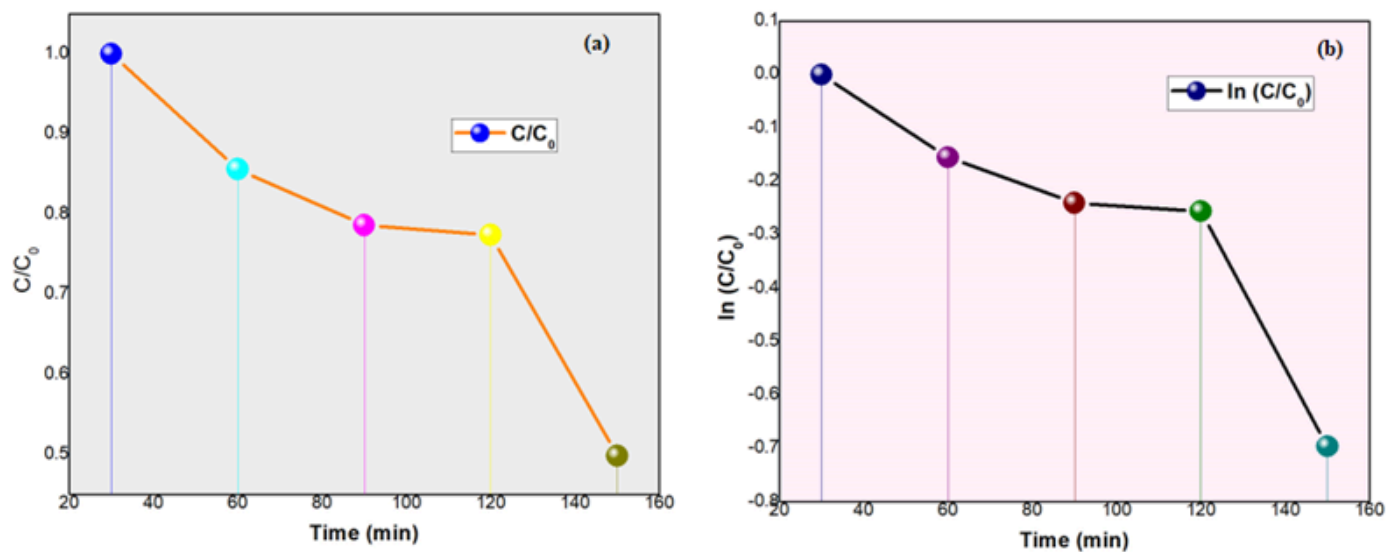


Figure 6

Photo-degradation activity of CeO₂ NPs photocatalysts utilizing RB aqueous dyes under light irradiation



Time	C	C/C ₀	ln(C/C ₀)
30	0.5672±0.012	1	0
60	0.4857±0.007	0.85631	-0.15512
90	0.4460±0.012	0.78632	-0.24039
120	0.4391±0.010	0.77415	-0.25598
150	0.2827±0.008	0.49841	-0.69633

Figure 7

a & b concentration ratio C/C_0 and the duration of irradiation for CeO_2 NPs

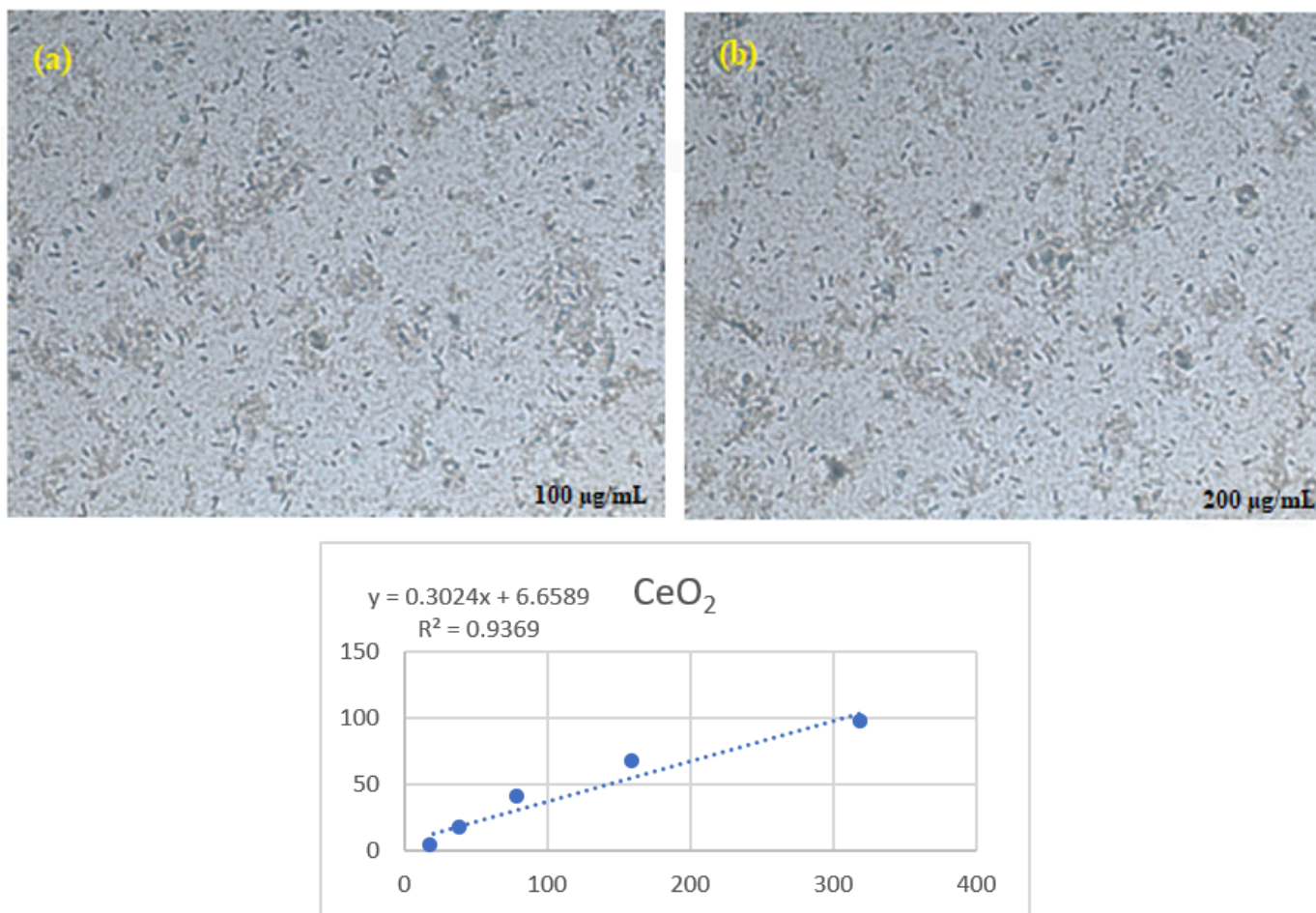


Figure 8

cytotoxicity image for blank and CeO₂ nanoparticles a) 100 µg/mL and b) 200 µg/mL for HeLa cells

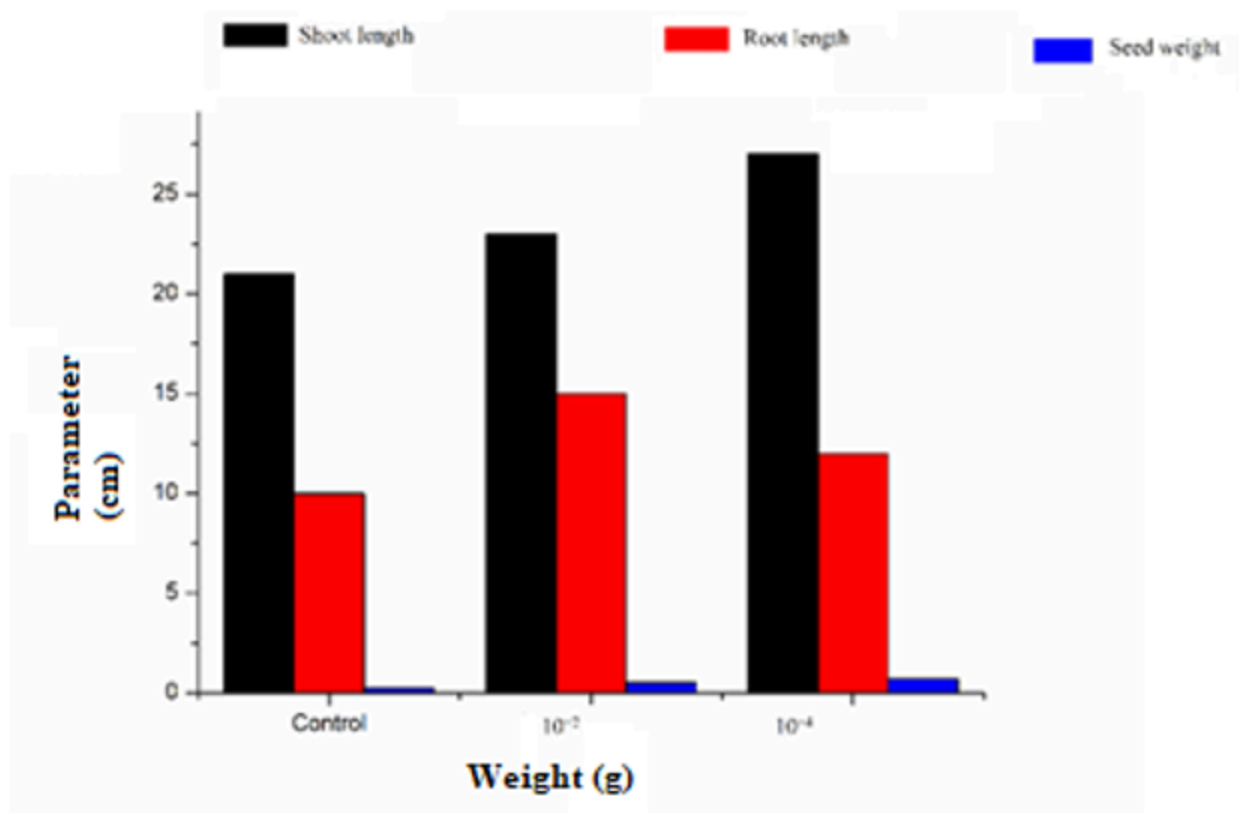


Figure 9

Plant growth studies of CeO₂ nanoparticle