



Green synthesis of CeVO₄ nanoparticles using *Azadirachta indica* leaves extract and their promising applications as an antioxidant and anticancer agent

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Abstract

This investigation reports an eco-friendly fabrication of cerium vanadate nanoparticles (CeVO₄ NPs) for the first time by an utterly green approach using *Azadirachta indica* leaves extract as a natural fuel. Textural properties of the as-prepared CeVO₄ NPs, such as structural, topological, and optical, were explored through X-ray diffraction (XRD), Fourier transforms infrared spectroscopy (FTIR), UV-visible diffuse reflectance spectra (DRS), field-emission scanning electron microscope (FESEM), energy dispersive X-ray analysis (EDX), high-resolution transmission electron microscopy (HRTEM), and zeta potential techniques. These results indicated that the as-synthesized NPs revealed a pseudo-spherical shape with a size of 43 nm. Moreover, as-prepared NPs were subjected to anticancer performance against HeLa cancer cell lines using MTT assays. In addition, the antioxidant efficacy of biosynthesized CeVO₄ NPs was scrutinized using DPPH and ABTS assays. Therefore, our study presents a facile, safe, cheap, rapid, and greener approach for producing CeVO₄ NPs and opening a new door for clinical applications.

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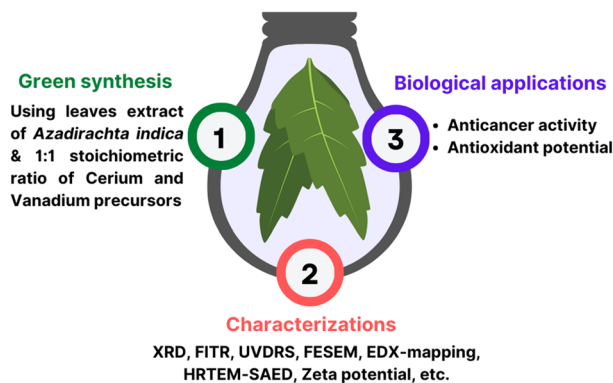
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Graphical Abstract

This investigation reports an eco-benevolent fabrication of cerium vanadate nanoparticles (CeVO_4 NPs) for the first time by an entirely green chemistry approach using *Azadirachta indica* leaves extract as a natural fuel. The physicochemical characteristics of the as-prepared CeVO_4 NPs, such as structural, topological, and optical, were explored through XRD, FTIR, UV-DRS, FESEM-EDX, HRTEM, and zeta potential techniques. Moreover, as-synthesized NPs were subjected to anticancer performance against HeLa cancer cell lines and antioxidant efficacy using DPPH and ABTS assays. Therefore, our study presents a facile, safe, affordable, swift and greener approach for producing CeVO_4 NPs and opening a new door for clinical applications.



Green Synthesis of Cerium Vanadate Nanoparticles

Keywords Green synthesis · Cerium orthovanadate nanoparticles · *Azadirachta indica* · Anticancer activity · Antioxidant efficacy

Highlights

- First-time synthesis of CeVO_4 nanoparticles using *Azadirachta indica* leaves extract through a green chemistry approach.
- Textural properties of CeVO_4 nanoparticles were revealed through XRD, FTIR, UVDRS, FESEM, EDX-mapping, HRTEM-SAED, and zeta potential techniques.
- The as-synthesized CeVO_4 nanoparticles evinced a pseudo-spherical shape with a size of 43 nm.
- Greenly produced CeVO_4 nanoparticles exhibited excellent anticancer (HeLa cell line) and antioxidant (DPPH & ABTS assays) potentials.

1 Introduction

The advent of modern nanotechnology has built splendid advancements in science and technology [1–4]. Nowadays, nanomaterial (NMs) provides a plethora of applications due to their textural properties, and they have often been a trending topic in the multidisciplinary field of sciences [5–7]. Therefore, numerous research groups connected to nanotechnology have expanded rapidly due to their diverse uses in electronics, medicines, defense, optoelectronics, energy, catalysis, sensors, and environmental remediation [8–10]. Also, NMs possess unique, controllable chemical and physical characteristics, which gives them plenty of significance in the biomedical and pharmaceutical industries [10–12]. Using newer NMs is viable for overcoming therapeutic resistance, such as malignancy and multidrug resistance [13]. Due to the escalating incidence of ailments and resulting financial

burdens, many diseases cause challenges for global health [14–16]. Novel NMs are becoming more popular for biological applications to solve this worldwide dilemma [17, 18]. Because they have a larger surface-to-volume ratio than traditional materials, nanoparticles (NPs) provide a chance to combat cancer and infections [19, 20]. Amongst all the NMs, metal oxide NPs has shown great efficiency in their anticancer activities [9, 21, 22].

Recently, rare earth orthovanadate (RVO_4) has been implemented in diverse uses such as energy storage devices, sensors, optoelectronic devices, catalysis, biomedicines, semiconductors, textiles, and ceramics because of their splendid physicochemical characteristics [23–27]. Amidst them, cerium orthovanadate (CeVO_4) is semiconductor-based vanadate and has a tetragonal (zircon) type structure with space group $I4_1/amd$ [28, 29]. In addition, CeVO_4 have snatched a plethora of interest due to its impressive optical,

electrical, and catalytic functionalities [25, 30, 31]. Therefore, CeVO_4 is extensively employed in myriad applications, including supercapacitors, solar cells, electrodes, hydrogen storage devices, sensors, and catalysts [25, 32–34]. Moreover, CeVO_4 NPs has been studied as an antimicrobial agent in our previous works [29, 35]. Hence, contemplating the merits of these CeVO_4 NPs, many researchers have reported several synthetic approaches based on diverse techniques (as mentioned in Table 1), namely hydrothermal, ultrasonic, co-precipitation, microwave radiation, sol-gel, precipitation, solvothermal, sonochemical, and electrospinning techniques [25]. Unfortunately, these methods negatively impact the environment since they require more time and energy, expensiveness, employ dangerous chemicals like solvents and stabilizing agents, and have problems with residue disposal, despite producing sufficient yields. Therefore, the research objective has recently shifted towards developing simple, one-pot, clean, facile, affordable, and environmentally acceptable synthesis protocols by using non-noxious reagents and solvents under benign circumstances to produce the required NPs [36, 37].

Amongst several medicinal plants, *Azadirachta indica*, an evergreen and versatile medicinal plant of the family Meliaceae, appears in tropical and semitropical countries of the globe [38]. It is applied as a traditional ayurvedic medicine to cure a plethora of diseases all over the world [39]. Since more than 4000 years ago, almost all parts of this marvelous tree have been employed as phytomedicines [40]. Diverse parts of this astounding tree were employed to cure headaches, pyrexia, respiratory disorders, ulcer, diabetes, cancer, leprosy, chicken pox, dengue, malaria, and dermal complications [41]. Therefore, this tree is prevalent for its pharmacological properties such as antifertility, hypolipidemic, antidiabetic, microbicidal, hepatoprotective, anti-inflammatory, hypoglycemic, antipyretic, nematicidal, insecticidal, antioxidant, antiulcer, cardioprotective, neuroprotective, and antileishmaniasis activities [38]. Such therapeutic uses may be observed due to the various active biomolecules (Fig. 1) of *Azadirachta indica*, namely, azadirachtin, sugiol, gedunin, mahmoodin, lupeol, nimbiol, nimbin, odoratone and (-)-epicatechin [38, 42].

To the best of our knowledge, *Azadirachta indica* leaves extract for the green production of CeVO_4 NPs has yet to be reported. Therefore, our study discloses for the first time the utterly green synthesis of CeVO_4 NPs utilizing *Azadirachta indica* leaves extract as a green fuel without needing any other chemical reagents. The textural characteristics of the greenly produced CeVO_4 NPs were explored through XRD, FTIR, UV-DRS, FESEM, EDX, HRTEM, and zeta potential analyses. Furthermore, CeVO_4 NPs were studied for their anticancer and antioxidant performance.

2 Materials and methods

2.1 Materials

Ammonium ceric nitrate $[(\text{NH}_4)_2\text{Ce}(\text{NO}_3)_6]$, 99% and ammonium metavanadate (NH_4VO_3 , 99%) were purchased from SRL Chem, India. Healthy leaves of *Azadirachta indica* were acquired from our college campus, Silvassa, UT of DD & DNH, India. Before starting the experimental work, the glassware was carefully rinsed with acetone and deionized water and then dried in a hot oven.

2.2 Preparation of leaves extract

Healthy leaves of *Azadirachta indica* were carefully rinsed with distilled water (dH_2O) to detach dust particles and snipped into small pieces using a scissor. The 250 mL beaker comprising 5 g of tiny pieces of leaves with 100 mL dH_2O was heated at 90°C for 25 min. Obtained leaves extract was filtered twice through Whatman filter paper and stored at 4°C temperature for further work.

2.3 Green synthesis of CeVO_4 NPs *Azadirachta indica* using leaves extract

The metal precursors, ammonium ceric nitrate and ammonium metavanadate were employed to synthesize CeVO_4 NPs through a green chemistry approach. The 1:1 ratio of ammonium ceric nitrate and ammonium metavanadate was mixed with 25 mL of dH_2O with constant stirring. Further, 5 mL of *Azadirachta indica* leaves extract was poured drop by drop to a solution of ammonium ceric nitrate and ammonium metavanadate at room temperature (RT); stirring the reaction mixture was continued for the next 30 min upon addition of leaves extract is over. The reaction solution was dried in a hot oven, and the resultant powder was calcined at 600°C for 3 h in a muffle furnace. The powder of CeVO_4 NPs was finally collected and stored in an airtight Eppendorf at RT for further study.

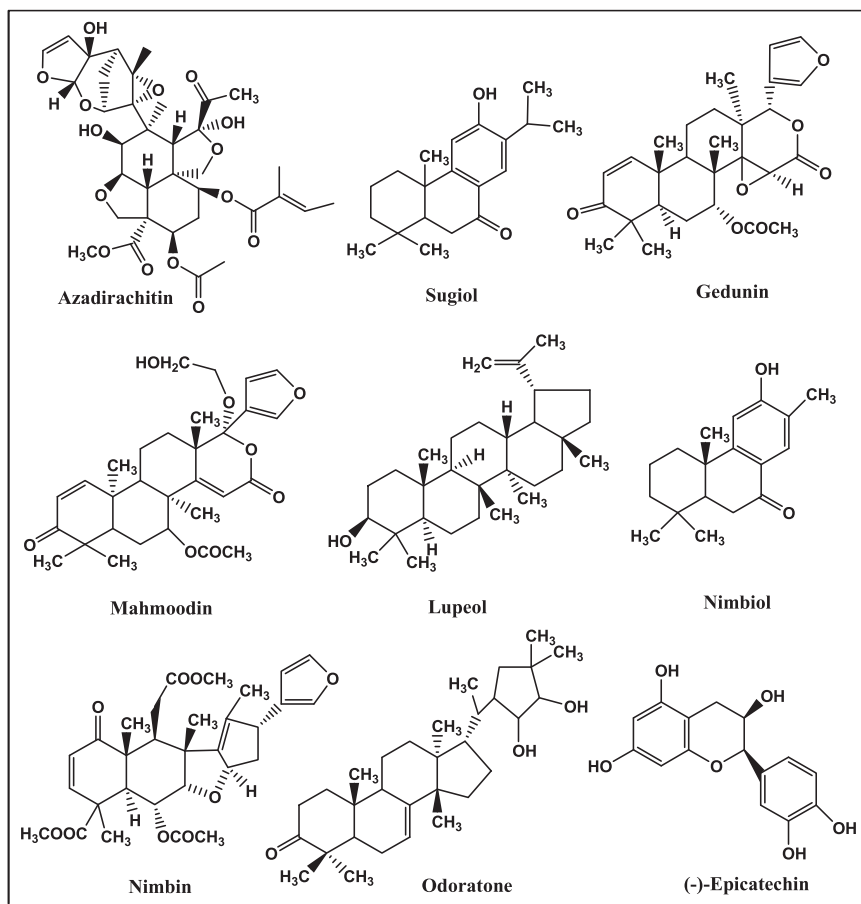
2.4 Instrumental techniques

Assorted characterization techniques were revealed to study the physicochemical features of biogenically synthesized CeVO_4 NPs. X-ray diffractometer (XRD, Bruker Advanced D8) was utilized to study the crystallographic formation of NPs. The Fourier transform infrared (FTIR) spectrometer (FTIR, Jasco-4600 Type A) model was applied to identify the functional groups of the NPs. With the aid of the UV-visible absorption spectrum, the sample's absorbance was estimated (UV-vis, Shimadzu-DRS-2600). The topologies were studied by field emission

Table 1 A summary of synthetic approaches for the synthesis of cerium orthovanadate nanoparticles (CeVO₄ NPs)

No.	Synthesis approach	Preparation procedure	Shape	Physical properties	Ref.
1	Hydrothermal	Nitric acid was added to the equally weighted mixture of Ce(NO ₃) ₃ •6H ₂ O and NH ₄ VO ₃ . The pH of the solution was controlled by ammonia. Then, the resulting solution was autoclaved at 180 °C for 9 h. Following, it was washed and calcinated at 700 °C for 8 h.	Nanorods	Particle size: 8.08 nm	[58]
2	Sol-gel	The solution of Ce(NO ₃) ₃ •6H ₂ O, tartaric acid, and NH ₄ VO ₃ was stirred at 80 °C and heated in an electric oven at 120 °C, respectively. Finally, the powder was heated at 450–600 °C for 2 h.	–	Particle size: 20–40 nm	[59]
3	Sonochemical	1 mmol Ce(NO ₃) ₃ •6H ₂ O dissolved in 30 mL H ₂ O and heated for 10 min at 60 °C. Then, 1 mmol NH ₄ VO ₃ solution was poured, and the mixture was heated at 60 °C. The resulting solution was further treated with ultrasonic irradiation (50 W). Following, it was washed and calcinated at 500 °C for 300 min.	Nanoparticles (Spherical)	Particle size: 45–50 nm; E _g : 3.25 eV.	[60]
4	Microwave	0.005 mol Ce(NO ₃) ₃ •6H ₂ O and NH ₄ VO ₃ were dissolved in H ₂ O. The acidic and basic pH of the solution was controlled by HCl and NaOH, respectively. Then, the mixture was placed in a microwave oven (180 W) for 120 min. Finally, the precipitate was filtered, washed, and dried at 70 °C for 24 h.	Nanorods	Particle size: 30–50 nm; E _g : 3.65–3.77 eV.	[61]
5	Precipitation	An aqueous solution of Ce(NO ₃) ₃ •6H ₂ O and glucose was added to the solution of ammonium metavanadate under continuous stirring. The resulting precipitations were filtered and washed carefully; it was dried at 60 °C and then calcinated at 550 °C for 120 min.	Nanoparticles (Spherical)	Particle size: 30–35 nm; E _g : 3 eV.	[62]
6	Green synthesis	The 1:1 stoichiometric ratio of ammonium ceric nitrate and NH ₄ VO ₃ was mixed with H ₂ O with constant stirring. Then, 5 mL of <i>Azadirachta indica</i> leaves extract was mixed drop-wise into a solution under constant stirring (30 min). The resultant solution was dried in a hot oven. Finally, the material was calcined at 600 °C for 3 h.	Nanoparticles (Pseudo-spherical)	Particle size: 43 nm; E _g : 3.43 eV.	Present work

Fig. 1 Major active biomolecules of *Azadirachta indica* extract



scanning electron microscopy (FESEM, Carl Zeiss Model Supra 55) coupled with energy dispersive X-ray spectroscopy (EDX) for elemental analysis. The size, topology, and polycrystallinity of NPs were observed using a high-resolution transmission electron microscope (HRTEM, JEOL JEM 2100) combined with a selected area electron diffraction (SAED) pattern. The HORIBA zeta analyzer measured the zeta potential as as-synthesized NPs.

2.5 Anticancer activity using MTT assay

As previously reported, the anticancer effect of greenly produced CeVO_4 NPs against HeLa cancer cells was assessed through an MTT assay [43, 44]. In short, a 96-well plate comprising DMEM/RPMI raised with 10% FBS, penicillin (100 IU/mL), and streptomycin (100 g/mL) was cultured with 50,000 cells/well. The plate was incubated at 37 °C for 24 h in a CO_2 incubator with 5% CO_2 and a humid atmosphere. The consumed content was replaced with a fresh medium with different CeVO_4 NPs concentrations to check cytotoxicity effectiveness. The plate was placed back into the incubator for 24 h under the same culture environments. Following that, each well received 100 μL of the MTT solution, which was then incubated at 37 °C for 4 h.

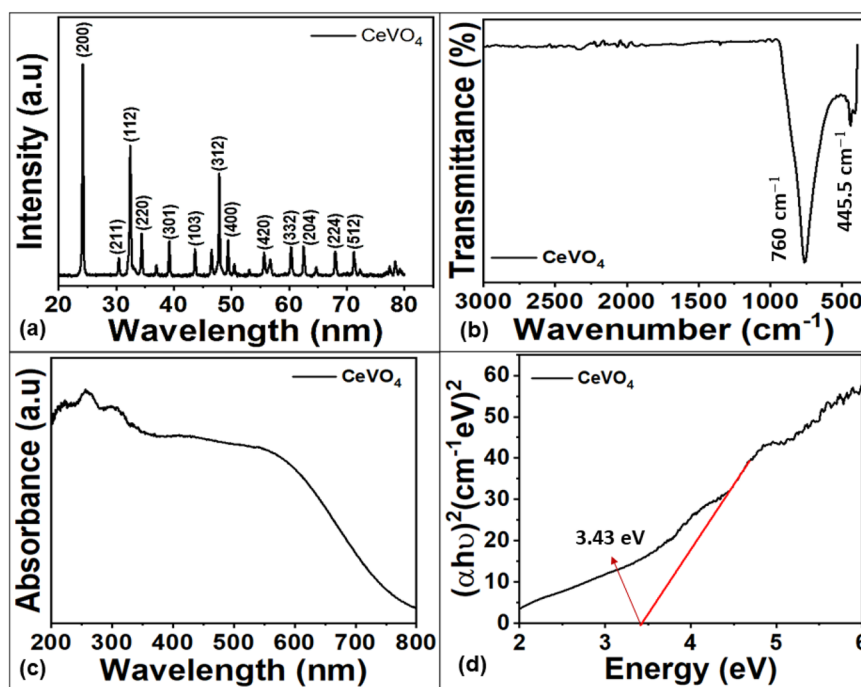
After incubation, media were gradually decanted, and each well received 100 μL of DMSO to dissolve the insoluble formazan crystals. After 15 min of constant shaking, the plate was placed in a microplate reader to determine the absorbance solution at 570 nm. Untreated (without involving CeVO_4 NPs) sets were considered control conducted concurrently under the same parameters. The accompanying equation was implemented to determine the viability percentage:

$$\% \text{ Viability} = \frac{A_{570} \text{ of treated sample}}{A_{570} \text{ of control}} \times 100$$

2.6 Antioxidant efficacy

To investigate the antioxidant performance of greenly produced CeVO_4 NPs, the DPPH and ABTS assay was employed to evaluate the free radical scavenging capacity. The whole protocol for the antioxidant study of both assays was described in our earlier study [43, 45]. The experiment applied diverse concentrations (10–50 $\mu\text{g}/\text{mL}$) of CeVO_4 NPs, and ascorbic acid was kept as a positive control. The scavenging efficiency of DPPH and ABTS assays was ascertained using the equation below as

Fig. 2 **a** XRD spectrum of *Azadirachta indica*-mediated CeVO₄ NPs, **b** FTIR spectrum of *Azadirachta indica*-mediated biosynthesized CeVO₄ NPs, **c** UV-Vis spectrum of *Azadirachta indica*-mediated biosynthesized CeVO₄ NPs, and **d** The corresponding Tauc plot for band gap determination



follows:

$$\text{Scavenging capacity (\%)} = \frac{\text{OD}(\text{blank}) - \text{OD}(\text{sample})}{\text{OD}(\text{blank})} \times 100$$

3 Results and discussion

3.1 XRD analysis

The phase formation, purity, and crystallinity of the as-fabricated *Azadirachta indica*-assisted CeVO₄ NPs were characterized using the XRD technique. The result of the XRD profile is displayed in Fig. 2a. X-ray diffraction signals matched perfectly with the tetragonal (zircon) type CeVO₄ structure in accordance with ICDD card no. 12-0757 [29]. The prominent diffraction peaks were obtained at 2θ values of 24.25°, 30.43°, 32.44°, 34.46°, 39.13°, 43.66°, 47.95°, 40.47°, 55.77°, 60.44°, 62.57°, 67.88°, and 71.15° corresponding to the (200), (211), (112), (220), (301), (103), (312), (400), (420), (332), (204), (224), and (512), diffraction planes, respectively. Peaks corresponding to impurities or other phases were not discerned, implying the purity of the as-synthesized CeVO₄ NPs. The characteristic sharp peaks ascertained the high crystallinity of the sample. Further, the median size of the CeVO₄ NPs was ascertained using Scherer's equation [46] and was observed to be 43 nm.

3.2 FTIR study

The FTIR spectrum of the as-synthesized CeVO₄ NPs was achieved in the scanning range of 400 to 4000 cm⁻¹.

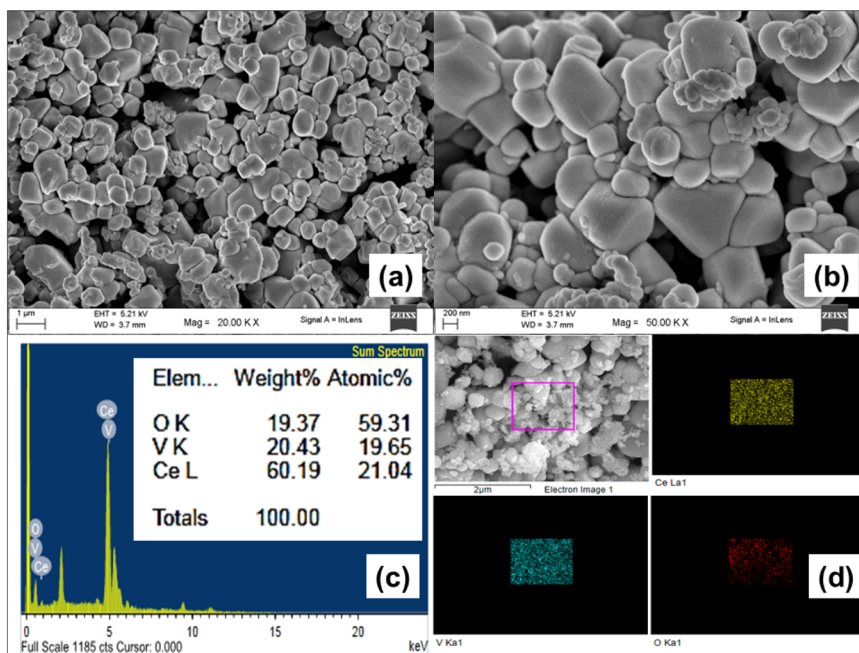
Moreover, the result has been presented in Fig. 2b. The FTIR data of these CeVO₄ NPs indicated the presence of two strong bands at 760 and 445.5 cm⁻¹, which may be associated with the stretching vibrations of V-O and VO₄, respectively [47]. Other shallow bands were also detected, but their transmittance intensities were not promising.

3.3 UV-Vis analysis

The optical absorption of the as-fabricated CeVO₄ NPs was assessed using the UV-Vis technique, wherein the absorbance was acquired in the scanning range of 200 to 800 nm. The as-obtained UV-Vis absorption plot has been illustrated in Fig. 2c.

It may be noticed from the given absorbance plot that a strong absorption band was obtained at 258 nm with a shoulder band at 296 nm. These prominent bands may be connected to the UV-absorption characteristic of VO₄³⁻ [47]. The appearance of these bands may further be ascribed to the charge migration from the oxygen ligands to the inner vanadium atoms inside the VO₄³⁻ clusters of CeVO₄ [48, 49]. Additionally, an expansive absorption peak ranging from 340 to 800 nm implies the UV-visible radiation absorption ability of the as-prepared CeVO₄ NPs. The inset of Fig. 2d represents the Tauc plot used to ascertain the effective band gap energy of the as-synthesized CeVO₄ NPs. From this plot of $(\alpha h\nu)^2$ versus $h\nu$, the band gap energy was calculated by extrapolating the linear part of the curve to the energy axis and was found to be 3.43 eV.

Fig. 3 FESEM images of CeVO₄ NPs at magnifications of **a** 1 μ m, and **b** 200 nm, **c** EDX spectrum, and **d** EDX mapping of CeVO₄ NPs



3.4 FESEM and EDX study

The morphological natures of the as-synthesized CeVO₄ NPs were scrutinized via a FESEM study. Figure 3a and b show the FESEM micrographs of CeVO₄ NPs at magnifications of 1 μ m and 200 nm, respectively. These FESEM images clearly depict that the particles do not have a specific morphology but are largely irregular in shape. Nevertheless, the particles are monodisperse with similar particle sizes. Monodispersity in particle size has confirmed the functionality of *Azadirachta indica* as a promising reducing and capping constituent for producing uniformity in particle size.

Figure 3c reveals the EDX results of CeVO₄ NPs with the in-set representing the elemental composition. From this spectrum as well as the table for elemental composition, it is clear that the as-synthesized CeVO₄ NPs are composed of Ce, V, and O with no other impurity elements. Figure 3d represents the EDX mapping of the elements, confirming that all the elements are present in conjugation. Furthermore, from the EDX data, a CeVO₃ stoichiometry has been formed instead of a CeVO₄ stoichiometry. Akhavan et al. [50] have reported that plant phytochemicals such as polyphenols serve a crucial function in the antioxidant property of NPs. Hence, the oxygen deficiency observed in this case may be attributed to the antioxidant activity of the *Azadirachta indica* phytochemicals used for the biosynthesis of CeVO₄ NPs in this study.

3.5 HRTEM analysis

To analyze the microstructure of the as-synthesized sample, the HRTEM technique was employed. The data of the

HRTEM investigation are displayed in Fig. 4. The TEM images of CeVO₄ given in Fig. 4a and b clearly indicate that the particles so-formed are not exactly spherical in shape but very close to sphere morphology; hence, the particles resemble pseudo-spheres. The monodispersity of the particles may also be observed with little agglomeration sites. The average particle size was calculated and was observed to be 28.15 nm. Figure 4c represents the HRTEM picture of the as-synthesized CeVO₄ NPs. This information was used to analyze the value of lattice (d) spacing by measuring the distance between the lattice fringes. The value of d-spacing was found to be 0.38 nm (or 3.8 Å), corresponding to the (200) plane of CeVO₄ NPs. From the SAED pattern presented in Fig. 4d, the polycrystalline appearance of the CeVO₄ NPs was detected.

3.6 Zeta potential

The exact surface charge and stability of the as-synthesized CeVO₄ NPs were determined through zeta potential measurement (Fig. 5) and were found to be -20.4 mV. This implies that the surface of CeVO₄ NPs is negatively charged. Moreover, the zeta potential distribution has just one peak, which reveals that CeVO₄ NPs are highly uniform.

3.7 Anticancer performance of CeVO₄ NPs

The anticancer potential of synthesized CeVO₄ NPs using a leaves extract of *Azadirachta indica* was studied against the HeLa cell line. The HeLa cell line exposed to CeVO₄ NPs showed significant viability and proliferation inhibition of

Fig. 4 TEM pictures of CeVO_4 NPs at magnifications of **a** 100 nm, and **b** 50 nm, **c** HRTEM image at a magnification of 10 nm, and **d** SAED image

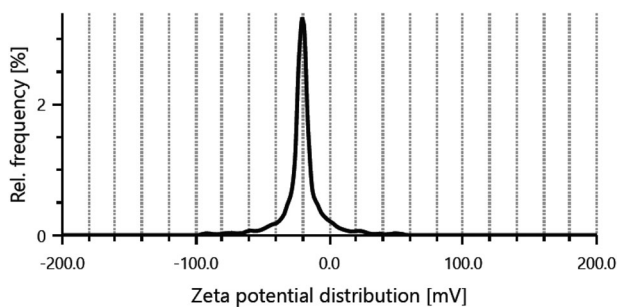
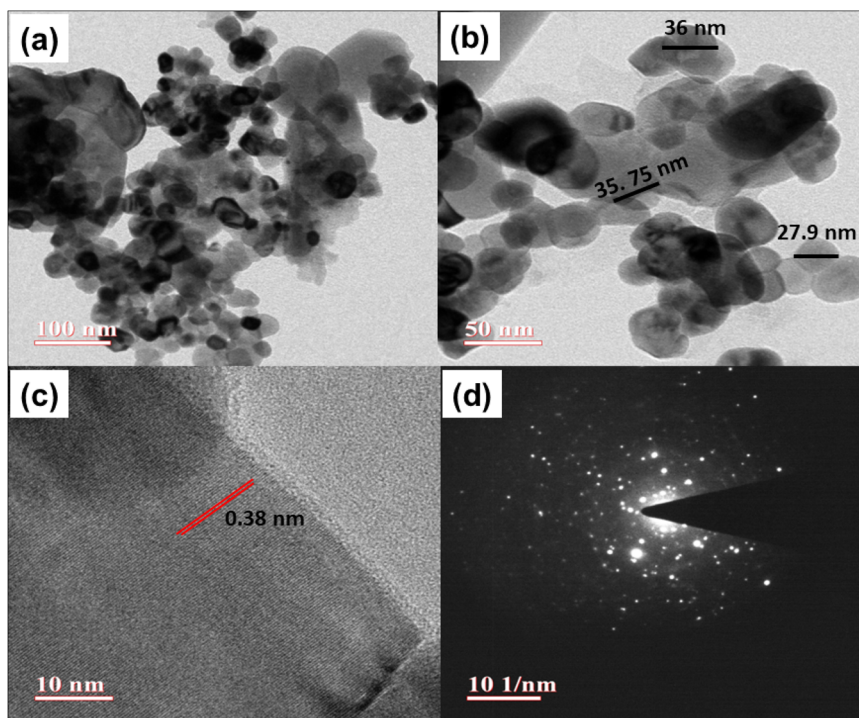


Fig. 5 Zeta potential distribution of *Azadirachta indica*-mediated bio-fabricated CeVO_4 NPs

the cell line. Results indicated that the viability of cells reduced at increasing NPs concentration (Fig. 6). Using confocal microscopy, morphological changes that demonstrated cell shrinkage at various doses of CeVO_4 NPs compared to the positive control were observed. The cytotoxicity assay observations are displayed in Fig. 7. In the present study, the results reveal that the influence of the treatments is dose-reliant because the cells were 36.56% inhibited at a concentration of 500 $\mu\text{g}/\text{mL}$ of CeVO_4 NPs due to the selective binding to cancer cell surfaces [51]. However, Doxorubicin inhibited 66.49% of cells at the same concentration. Moreover, as-synthesized CeVO_4 NPs exhibited an IC_{50} value at 89.15 $\mu\text{g}/\text{mL}$, signifying a considerable cytotoxic activity against HeLa cell lines, while Doxorubicin exhibited an IC_{50} at 53.55 $\mu\text{g}/\text{mL}$. According to the literature, some of the greenly synthesized BiVO_4

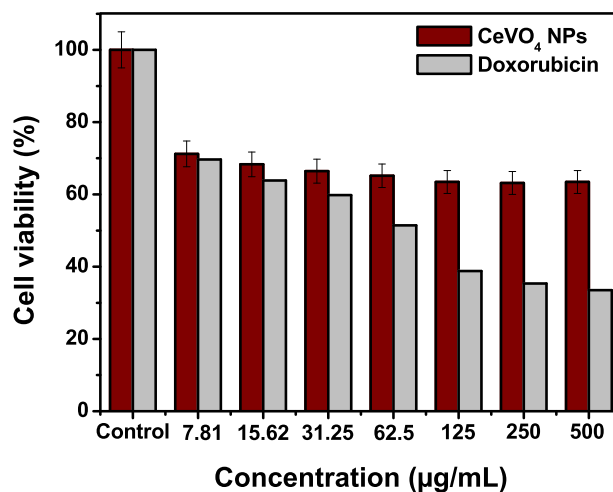


Fig. 6 Anticancer potential of CeVO_4 NPs against HeLa cell line

NPs [52] have been explored for anticancer efficacy in a dose-dependent manner, but CeVO_4 NPs have not been reported yet for anticancer activity. Therefore, the present work has highlighted the cytotoxic efficacy of CeVO_4 NPs against HeLa cancer cell lines.

3.8 Antioxidant efficacies

DPPH and ABTS free radical scavenging assays were applied to ascertain the CeVO_4 NPs antioxidant performance. The ability to scavenge free radicals is observed to be excellent.

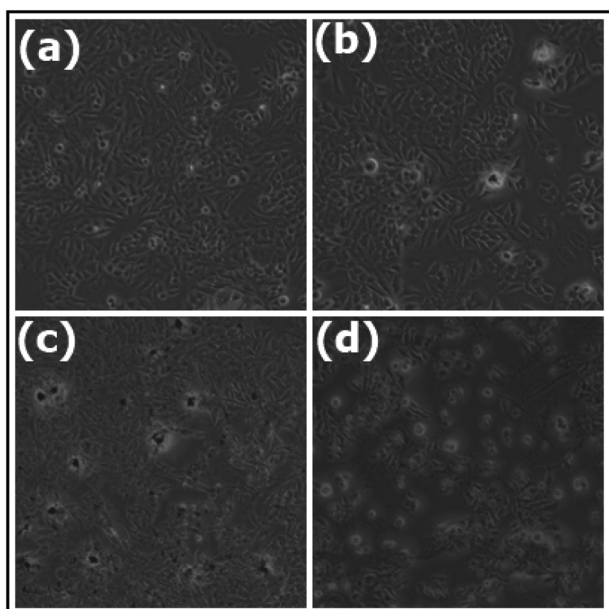


Fig. 7 Morphological changes in HeLa cell line after treatment of **a** control, **b** 7.81 µg/mL of NPs, **c** 500 µg/mL of NPs, and **d** 500 µg/mL of doxorubicin

The percent scavenging of CeVO₄ NPs was determined to be 71.03 and 85.65% at the maximum tested concentration of 50 µg/mL for DPPH and ABTS assay. It exponentially decreased when the concentration was lowered below 50 µg/mL. Based on the findings, the IC₅₀ values for CeVO₄ NPs capacities to scavenge DPPH and ABTS are 119 and 264.1 µg/mL, respectively. However, positive control (ascorbic acid) displayed IC₅₀ at 93.42 and 122.6 µg/mL at the same concentration. Overall, it can be noticed that the antioxidant potential is dose-dependent and considerable. Figure 8 (a-DPPH, b- ABTS) shows the results of the antioxidant study. However, according to the literature, several orthovanadate and cerium-based NPs have been studied extensively for their antioxidant ability [53–56]. Thus, these antioxidant NPs could be used for cutting-edge ischemia-reperfusion injury diagnoses and treatments [57].

4 Conclusion

In summary, the present study has explored the simple, rapid, economically viable, and environmentally benign approach for synthesizing CeVO₄ NPs using leaves extract of *Azadirachta indica* as a natural fuel. The textural properties of the as-fabricated CeVO₄ NPs were studied extensively through a diverse characterization tool. The XRD data revealed the tetragonal (zircon) type structure of the NPs. The HRTEM analysis displayed the pseudo-spherical shape of the NPs. Moreover, as-synthesized NPs considerably inhibited the proliferation of the HeLa cell line using MTT assay. Additionally, the noteworthy antioxidant potential of CeVO₄

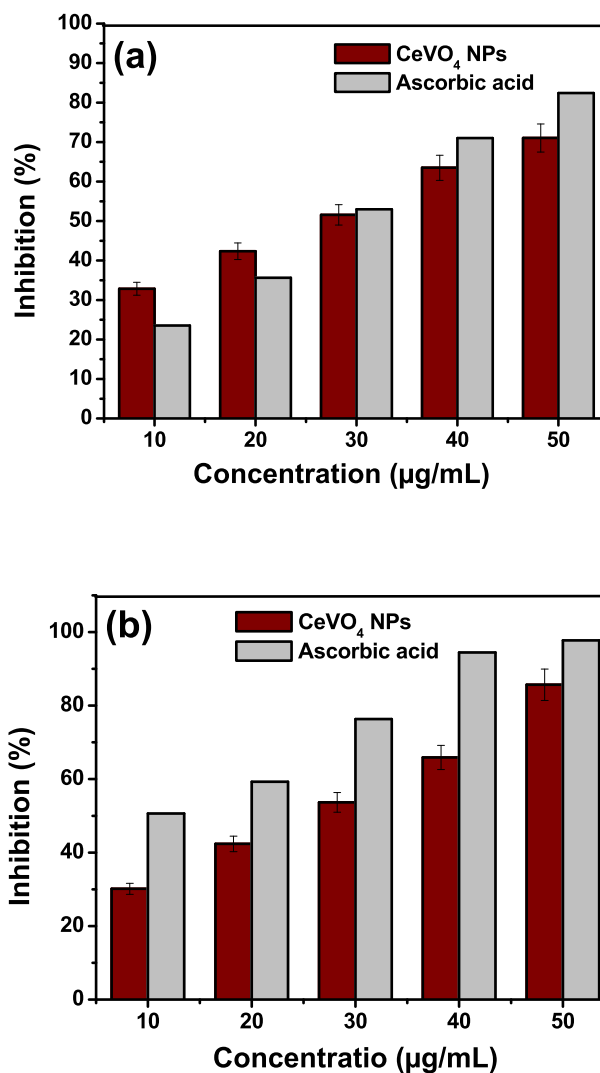


Fig. 8 Antioxidant potential of CeVO₄ NPs employing **a** DPPH and **b** ABTS assays

NPs was noticed. Both anticancer and antioxidant studies displayed concentration-dependent performance. Hence, the greenly produced CeVO₄ NPs could be potential candidates for biomedical applications in the future.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

Research involving humans and animals statement No humans/animals were used for the experiments in this study.

References

1. Pushparaj K et al. (2022) Nano-from nature to nurture: A comprehensive review on facets, trends, perspectives and sustainability of nanotechnology in the food sector. *Energy* 240:122732

2. Lu J et al. (2016) The role of nanotechnology in the development of battery materials for electric vehicles. *Nat Nanotechnol* 11(12):1031–1038
3. Lowry GV, Avellan A, Gilbertson LM (2019) Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nat Nanotechnol* 14(6):517–522
4. Ghotekar S (2019) A review on plant extract mediated biogenic synthesis of CdO nanoparticles and their recent applications. *Asian J Green Chem* 3(2):187–200
5. Barhoum A et al. (2022) Review on natural, incidental, bioinspired, and engineered nanomaterials: history, definitions, classifications, synthesis, properties, market, toxicities, risks, and regulations. *Nanomaterials* 12(2):177
6. Lim E-K et al. (2015) Nanomaterials for theranostics: recent advances and future challenges. *Chem Rev* 115(1):327–394
7. Korde P et al. (2020) Plant extract assisted eco-benevolent synthesis of selenium nanoparticles—a review on plant parts involved, characterization and their recent applications. *J Chem Rev* 2(3):157–168
8. Gawande MB et al. (2016) Cu and Cu-based nanoparticles: synthesis and applications in catalysis. *Chem Rev* 116(6):3722–3811
9. Cuong HN et al. (2022) New frontiers in the plant extract mediated biosynthesis of copper oxide (CuO) nanoparticles and their potential applications: A review. *Environ Res* 203:111858
10. Ndaba B et al. (2022) Biosynthesized metallic nanoparticles as fertilizers: An emerging precision agriculture strategy. *J Integr Agric* 21(5):1225–1242
11. Halwani AA (2022) Development of pharmaceutical nanomedicines: From the bench to the market. *Pharmaceutics* 14(1):106
12. Lu Y et al. (2022) Multidisciplinary strategies to enhance therapeutic effects of flavonoids from *Epimedium Folium*: Integration of herbal medicine, enzyme engineering, and nanotechnology. *J Pharm Anal* 13(3):39–254
13. Li Y et al. (2022) Treating multi-drug-resistant bacterial infections by functionalized Nano-Bismuth sulfide through the synergy of immunotherapy and bacteria-sensitive phototherapy. *ACS Nano* 16(9):14860–14873
14. Lai M et al. (2022) Characteristics and management of skin cancers in very elderly patients: A real-world challenge for clinicians. *Exp Dermatol* 31(10):1554–1562
15. Durairaj K et al. (2023) Biocompatibility of Veratric acid–encapsulated Chitosan/Methylcellulose Hydrogel: Biological characterization, osteogenic efficiency with in silico molecular modeling. *Appl Biochem Biotechnol* 1–18
16. Thanuja B et al. (2022) Anticancer and cytotoxicity activity of native and modified black rice flour on colon cancer cell lines. *Evid-based Complement Altern Med* 2022:1–9
17. Salvador-Morales C, Grodzinski P (2022) Nanotechnology tools enabling biological discovery. *ACS Nano* 16(4):5062–5084
18. Waheed S et al. (2022) Engineering nano-drug biointerface to overcome biological barriers toward precision drug delivery. *J Nanobiotechnology* 20(1):1–25
19. Li B et al. (2022) Nano-drug co-delivery system of natural active ingredients and chemotherapy drugs for cancer treatment: A review. *Drug Deliv* 29(1):2130–2161
20. Arshad R et al. (2022) Nano-based theranostic platforms for breast cancer: A review of latest advancements. *Bioengineering* 9(7):320
21. Pansambal S et al. (2022) Bioengineered cerium oxide (CeO₂) nanoparticles and their diverse applications: a review. *Appl Nanosci* 1–26
22. Alavi M et al. (2022) The efficiency of metal, metal oxide, and metalloid nanoparticles against cancer cells and bacterial pathogens: different mechanisms of action. *Cell Mol Biomed Rep* 2(1):10–21
23. Chen H et al. (2021) Vanadate-based electrodes for rechargeable batteries. *Mater Chem Front* 5(4):1585–1609
24. Eghbali-Arani M et al. (2018) Green synthesis and characterization of SmVO₄ nanoparticles in the presence of carbohydrates as capping agents with investigation of visible-light photocatalytic properties. *J Electron Mater* 47(7):3757–3769
25. Ghotekar S et al. (2022) Recent advances in synthesis of CeVO₄ nanoparticles and their potential scaffold for photocatalytic applications. *Top Catal* 66:1–15
26. Ghotekar S et al. (2020) A review on eco-friendly synthesis of BiVO₄ nanoparticle and its eclectic applications. *Adv J Sci Eng* 1(4):106–112
27. Van Thuan D et al. (2022) Development of Indium vanadate and Silver deposited on graphitic carbon nitride ternary heterojunction for advanced photocatalytic degradation of residual antibiotics in aqueous environment. *Opt Mater* 123:111885
28. Morimoto T et al. (2022) Novel near-infrared reflective black inorganic pigment based on cerium vanadate. *RSC Adv* 12(26):16570–16575
29. Ghotekar S et al. (2018) Synthesis of CeVO₄ nanoparticles using sol-gel auto combustion method and their antifungal activity. *Nanochem Res* 3(2):189–196
30. Kokulnathan T, Sakthi Priya T, Wang T-J (2019) Surface engineering three-dimensional flowerlike cerium vanadate nanostructures used as electrocatalysts: real time monitoring of cloquinol in biological samples. *ACS Sustain Chem Eng* 7(19):16121–16130
31. Ameri V, Eghbali-Arani M, Pourmasoud S (2017) New route for preparation of cerium vanadate nanoparticles with different morphology and investigation of optical and photocatalytic properties. *J Mater Sci: Mater Electron* 28(24):18835–18841
32. Zonarsaghar A, Mousavi-Kamazani M, Zinatloo-Ajabshir S (2022) Sonochemical synthesis of CeVO₄ nanoparticles for electrochemical hydrogen storage. *Int J Hydrog Energy* 47(8):5403–5417
33. Ponnaiah SK, Prakash P (2021) A new high-performance supercapacitor electrode of strategically integrated cerium vanadium oxide and polypyrrole nanocomposite. *Int J Hydrog Energy* 46(37):19323–19337
34. Hou J et al. (2016) The role of oxygen adsorption and gas sensing mechanism for cerium vanadate (CeVO₄) nanorods. *RSC Adv* 6(18):14552–14558
35. Kamble DR et al. (2018) Efficient synthesis of CeVO₄ nanoparticles using combustion route and their antibacterial activity. *J Nanostruct* 8(2):144–151
36. Rizki IN, Klaypradit W (2023) Utilization of marine organisms for the green synthesis of silver and gold nanoparticles and their applications: A review. *Sustain Chem Pharm* 31:100888
37. Kashid Y et al. (2022) Bio-inspired sustainable synthesis of silver chloride nanoparticles and their prominent applications. *J Indian Chem Soc* 99(5):100335
38. Saleem S et al. (2018) A comprehensive review of phytochemical profile, bioactives for pharmaceuticals, and pharmacological attributes of *Azadirachta indica*. *Phytother Res* 32(7):1241–1272
39. Ahmad S et al. (2019) Biological detail and therapeutic effect of *Azadirachta indica* (neem tree) products—a review. *Evid Based Med Healthc* 6(22):1607–1612
40. Maithani A et al. (2011) *Azadirachta indica* (neem) leaf: A review. *J Pharm Res* 4(6):1824–1827
41. Kumar VS, Navaratnam V (2013) Neem (*Azadirachta indica*): prehistory to contemporary medicinal uses to humankind. *Asian Pac J Tropical Biomed* 3(7):505–514
42. Zeenat F et al. (2018) Therapeutic, phytochemistry and pharmacology of *Azadirachta indica*: A review. *Int J Unani Integr Med* 2(1):20–28

43. Barwant M et al. (2022) Eco-friendly synthesis and characterizations of Ag/AgO/Ag₂O nanoparticles using leaf extracts of *Solanum elaeagnifolium* for antioxidant, anticancer, and DNA cleavage activities. *Chem Pap* 1–13
44. Shahzamani K et al. (2022) Bioactivity assessments of phyco-assisted synthesized selenium nanoparticles by aqueous extract of green seaweed, *Ulva fasciata*. *Emergent Mater* 5(6):1689–1698
45. Marzban A et al. (2022) Biogenesis of copper nanoparticles assisted with seaweed polysaccharide with antibacterial and anti-biofilm properties against methicillin-resistant *Staphylococcus aureus*. *J Drug Deliv Sci Technol* 74:103499
46. Holzwarth U, Gibson N (2011) The Scherrer equation versus the 'Debye-Scherrer equation'. *Nat Nanotechnol* 6(9):534–534
47. Ekthammathat N et al. (2013) Synthesis and characterization of CeVO₄ by microwave radiation method and its photocatalytic activity. *J Nanomater*. 2013:1–7
48. Liu J, Li Y (2007) General synthesis of colloidal rare earth orthovanadate nanocrystals. *J Mater Chem* 17(18):1797–1803
49. Nguyen T-D, Dinh C-T, Do T-O (2009) Monodisperse samarium and cerium orthovanadate nanocrystals and metal oxidation states on the nanocrystal surface. *Langmuir* 25(18):11142–11148
50. Akhavan O et al. (2012) Increasing the antioxidant activity of green tea polyphenols in the presence of iron for the reduction of graphene oxide. *Carbon* 50(8):3015–3025
51. Abdolhad M et al. (2013) Polyphenols attached graphene nanosheets for high-efficiency NIR mediated photodestruction of cancer cells. *Mater Sci Eng: C* 33(3):1498–1505
52. Mohamed HEA et al. (2019) Phytosynthesis of BiVO₄ nanorods using *Hyphaene thebaica* for diverse biomedical applications. *AMB Express* 9(1):1–14
53. Nikitchenko YV et al. (2021) Anti-aging effects of antioxidant rare-earth orthovanadate nanoparticles in Wistar rats. *Biol Trace Elem Res* 199(11):4183–4192
54. Maksimchuk P et al. (2021) High antioxidant activity of gadolinium–yttrium orthovanadate nanoparticles in cell-free and biological milieu. *Nanotechnology* 33(5):055701
55. Soundarya T et al. (2022) Green synthesis of LiZnVO₄ nanoparticles and its multiple applications towards electrochemical sensor, supercapacitor, humidity sensing, photoluminescence and antioxidant activities. *J Mater Sci: Mater Electron* 33(14):10902–10918
56. Lee SS et al. (2013) Antioxidant properties of cerium oxide nanocrystals as a function of nanocrystal diameter and surface coating. *ACS Nano* 7(11):9693–9703
57. Amani H et al. (2017) Antioxidant nanomaterials in advanced diagnoses and treatments of ischemia reperfusion injuries. *J Mater Chem B* 5(48):9452–9476
58. Akilarasan M et al. (2020) Using cerium (III) orthovanadate as an efficient catalyst for the electrochemical sensing of anti-prostate cancer drug (flutamide) in biological fluids. *Microchem J* 159:105509
59. Phuruangrat A, Thongtem S, Thongtem T (2021) Synthesis, characterization, and UV light-driven photocatalytic properties of CeVO₄ nanoparticles synthesized by sol-gel method. *J Aust Ceram Soc* 57:597–604
60. Mosleh M, Mahinpour A (2016) Sonochemical synthesis and characterization of cerium vanadate nanoparticles and investigation of its photocatalyst application. *J Mater Sci: Mater Electron* 27:8930–8934
61. Ekthammathat N et al. (2013) Synthesis and characterization of CeVO₄ by microwave radiation method and its photocatalytic activity. *J Nanomater* 2013:5–5
62. Rahimi-Nasrabadi M, Ahmadi F, Fosooni A (2017) Influence of capping agents additives on morphology of CeVO₄ nanoparticles and study of their photocatalytic properties. *J Mater Sci: Mater Electron* 28:537–542

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