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REVIEW ARTICLE

Bioengineered cerium oxide (CeO_2) nanoparticles and their diverse applications: a review

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Abstract

Cerium oxide nanoparticles (CeO_2 NPs) have received immense interest due to their wide application in environmental remediation, photocatalytic dye degradation, biological applications, and industrial fields. The environmental concerns and energy issues encourage the development of a green protocol to synthesize CeO_2 NPs. The greener approach proffers environment-friendly, non-toxic, economically affordable, and efficient. This review describes: (1) the plant extracts, microbes, biological product mediated synthesis of CeO_2 NPs, and the mechanism involved in manufacturing it, (2) photocatalytic dye degradation ability of CeO_2 NPs; and (3) potential biological application as an antibacterial agent, antifungal activity, antioxidant activity, antidiabetic, and anticancer property. We believe this review will provide a handy guide to the researcher interested in the biosynthesis of CeO_2 NPs and their possible applications.

Keyword Green nanotechnology · Cerium oxide nanoparticles · Plant extracts · Microbes · Biomaterials · Applications

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Abbrevations

NPs	Nanoparticles
CeO2	Cerium oxide
CDB	Czapek-Dox-Broth
XRD	X-ray diffraction analysis
JCPDS	Joint Committee on Powder Diffraction Standards
FTIR	Fourier transform infrared spectroscopy
TEM	Transmission electron microscopy
HR-TE	High-resolution transmission electron microscopy
TGA	Thermogravimetric analysis
DTA	Differential thermal analysis
UV	Ultra violet
XPS	X-ray photoelectron spectroscopy
ROS	Reactive oxygen species
DPPH	2,2-Diphenyl-1-picrylhydrazyl-hydrate
PAGE	Polyacrilamide gel electrophoresis
BHA	Butylated hydroxyanisole

Introduction

In the modern era, nanotechnology got enormous interest from the scientific community due to its synthesis, design, analysis, and applications, making human life safer and

more comfortable (Gawande et al. 2016; Dutta et al. 2021; Cuong et al. 2022). Application of the nanomaterials for water treatment (Raizada et al. 2020), environmental remediation (Khin et al. 2012), semiconductor (Dabhane et al. 2021b), gas sensor (Das et al. 2022), energy storage (Pomerantseva et al. 2019), catalysis (Pansambal et al. 2019; Bardapurkar et al. 2021; Dabhane et al. 2021a), agriculture (Peters et al. 2016), food technology (Frewer et al. 2014), pharmaceuticals (Sharma and Hussain 2020), textile industry (Makvandi et al. 2021), and biomedicine (Teradal and Jelinek 2017; Ryabchikova 2021) was well documented in the literature. Numerous physical, chemical, and biological methods have been employed for the synthesis of nanoparticles till now (Shah et al. 2015; Nikam et al. 2018). However, chemical methods use harmful chemicals and toxic reagents, influencing human health and environmental pollution (Kundu et al. 2020). To reduce this impact, the biological or green method was used to synthesize nanoparticles that proffer eclectic advantages (Nasrollahzadeh et al. 2021). Additionally, the biological or green method is simple, environmentally benign, economically affordable, and easy to scale up (Dabhane et al. 2021c; Ghotekar et al. 2021).

In the recent decade, nanoparticles synthesis of metals such as Silver, Gold, Copper, Zinc, Selenium, Aluminum, Cadmium, Titanium, Nickel, Magnesium, Iron, and Cerium employing bacteria, fungus, enzymes, proteins carbohydrates, and plant material has got the massive attraction from the scientific community (Shah et al. 2015; Hernández-Díaz et al. 2021; Mohammadzadeh et al. 2022). Cerium is the most abundant rare earth element of the lanthanide series. In a previous report, Arumugam et al. stated that CeO_2 nanoparticles (NPs) synthesized using *Gloriosa superba* L. leaf extract show spherical morphology with 5 nm size and displayed good antibacterial activity (Arumugam et al. 2015). Also, Sisubalan et al. described the synthesis of CeO_2 NPs utilizing *Rubia cordifolia* L. leaf extract and highlighted its anticancer potential on MG-63 human osteosarcoma cells (Sisubalan et al. 2017).

Moreover, CeO_2 NPs shows diverse application in optical devices (Ghanashyam Krishna et al. 1998), solar cell (Corma et al. 2004), fuel oxidation catalysis (Jung et al. 2005), antioxidant (Dutta et al. 2016), cytotoxic activity (Irshad et al. 2019), catalysis (Zamani et al. 2018), wound-healing activity (Ahmed et al. 2021), antibacterial (Arumugam et al. 2015), anticancer activity (Sisubalan et al. 2017), angiogenesis induction (Das et al. 2012), and radical scavenging activity (Korotkova et al. 2019).

The manufacturing of nanoparticles can be accomplished in one of the two ways: "top-down" or "bottom-up" (Fig. 1) (Cuong et al. 2022). In the top-down approach, bulk materials are broken down into tiny particles via size reduction utilizing various lithographic techniques, including milling, grinding, laser ablation, sputtering, and so on. On the other hand, in the bottom-up approach, nanoparticles were manufactured via chemical, physical,

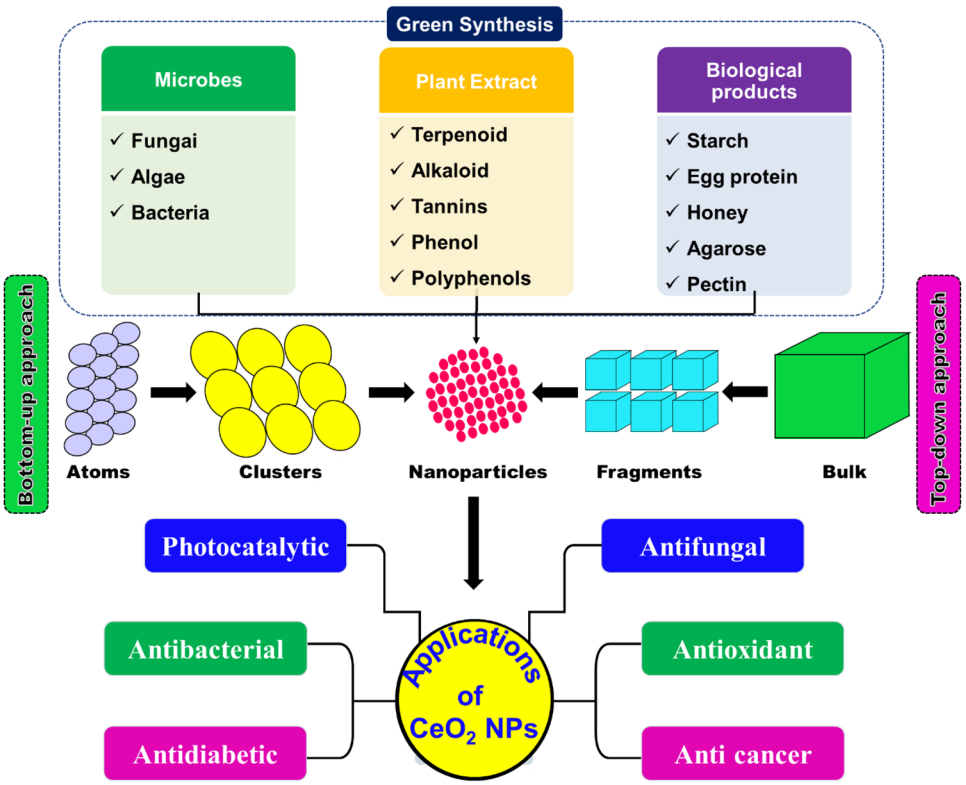


Fig. 1 Different synthetic methods for the facile synthesis of NPs

Table 1 Summary of advantages and disadvantages of diverse NPs synthetic protocols

Approach	Method	Advantages	Disadvantages
Biological	Plant extracts	Cost-effective, eco-benign, non-toxic, stable product, ambient reaction condition, and does not require perilous chemicals	Agglomeration of the individual NPs may result in a non-uniform morphology in some cases and requires low temperature (~4 °C) for extract storage
	Microbial biomass	Low thermal budget, eco-benevolent, and does not require noxious chemicals	Time-consuming, contamination susceptible from surrounding microbes, and requires well-equiped laboratory for experimental set-up
Chemical	Co-precipitation	Facile and swift preparation, requires low temperature and energy, and easy to control particle size and composition	Time-consuming, presence of trace impurities, and may not be reproducible
	Hydrothermal	Control over morphology and particle size, reduced aggregation level, ambient reaction conditions, self-purifying approach	Requires autoclave and closed reaction system for experimental set-up
	Sol–gel	Control over particle size, high purity products, operable at low temperatures	Use of organic solvents and longer reaction time
Physical	Laser ablation	High purity products	Difficult to control size distribution, agglomeration, crystal structure and requires high energy
	Metallurgical	Large-scale synthesis	Rapid agglomeration and contamination
	Solid-state	Faster synthesis and no solvent waste/excess	Contamination and neat milling may lead to unwanted product

and biological techniques (plant material, microbes, biological products, and so on). The biological methods are effectively beneficial from the environmental and economic points of view (Iravani 2011). Hence, numerous reports have been found on the synthesis of metal oxide NPs using the biological method nowadays. Likewise, there are numerous other advantages and disadvantages of diverse synthetic approaches, which have been summarized and tabulated in Table 1.

This review summarizes recent progress in the investigation and advancement of plant extract, microbes, and biological molecules mediated biosynthesis of CeO_2 NPs-based on the available scientific literature, which was searched using several keywords, i.e., plant extract, green synthesis, biosynthesis, plant extract, CeO_2 NPs, photocatalytic applications) on the Scopus database. While conducting literature reviews from 2003 to June 2022, publications published by the publishers like Elsevier, Springer, RSC, and Wiley were used. In addition, the keyword used for the literature search is "Bioengineered cerium oxide nanoparticles". Using above mentioned keyword, about 464 articles were obtained. The graphical representation of obtained literature is shown in Fig. 2. This study has also described the methods for plant extract, microbes, and biological molecule-mediated synthesis of CeO_2 NPs and possible mechanisms for synthesis. Besides this, the multifunctional application of CeO_2 NPs and biological application were explant in detail. The present review will help the researcher to understand the opportunities and challenges in the biogenic synthesis of CeO_2 NPs.

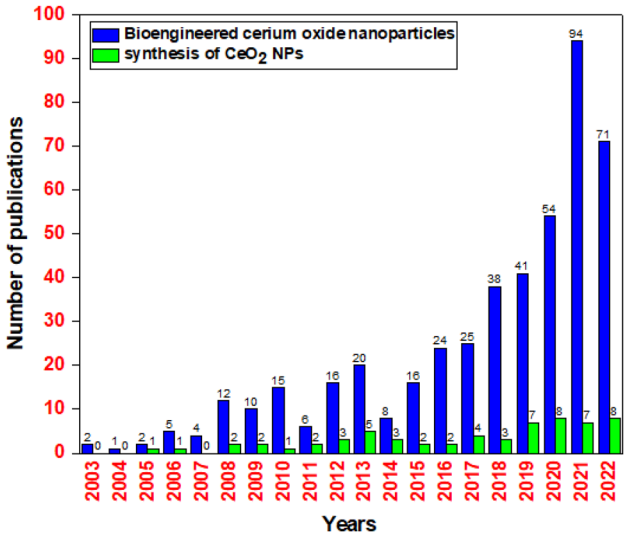


Fig. 2 The number of publications from 2003 to 2022 on CeO2 NPs, synthesis and diverse applications using keywords "Bioengineered cerium oxide nanoparticles", searched on Scopus database

Protocol for the synthesis of CeO_2 NPs

Using plant extracts

A simple method is used for the biogenic production of CeO_2 NPs using plant extracts. Initially, 10 gm of fresh plant material of the chosen plant was added into a 250 mL beaker containing 100 mL double-distilled water and heated beaker at 100 °C for 10 min. Next, filter the extract through

Table 2 Green synthesis of CeO_2 NPs using different plant source with morphology, size, band gap and applications

Botanical Name	Plant Part	Morphology of nanoparticles	Size (nm)	Band gap (eV)	Applications	Refs
Abelmoschus esculentus	Fruits	Spherical	35–40	–	(1) Antioxidant, (2) Anticancer, (3) Antibacterial, (4) Wound-healing activities	Ahmed et al. (2021)
Acalypha indica	Leaf	Spherical	8–54	–	(1) Antibacterial activity	Kannan and Sundrarajan (2014a)
Aloe barbadensis miller	Leaf	Spherical	63.6	–	–	Sai Priya et al. (2014)
Aloe vera	Leaf	Spherical	2–3	–	(1) Antioxidant	Dutta et al. (2016)
Annona Muricata	Fruit	–	–	3.31	(1) Antimicrobial activity	Sebastiammal et al. (2019)
Aquilegia pubiflora	Leaf	Spherical	28	3.35	(1) Antifungal activity (2) Antibacterial activity (3) Antidiabetic activity (4) Antioxidant activity	Jan et al. (2020)
Azadirachta indica	Leaf	Spherical	10–15	–	(1) Thermal decomposition of ammonium perchlorate (2) Photodegradation	Sharma et al. (2017)
Bael	Leaf	–	50	–	–	Murugesan et al. (2020)
Calotropis procera	Flower	Spherical	21	3.29	(1) Photocatalytic activity (2) Antibacterial activity	Muthuvel et al. (2020)
Carrageenan	Hydrogel	Spherical	34	2.69	(1) Cytotoxic activity	Nourmohammadi et al. (2018a)
Centella asiatica	–	Spherical	8	–	(1) Antioxidant potential (2) Efficacy against cardio myoblast hypertrophy	Sankar et al. (2015)
Ceratonia siliqua	Leaf	Spherical	22	–	(1) Antioxidant cytotoxic activity	Javadi et al. (2019)
China rose	Petal	Nano sheet	7	–	–	Qian et al. (2011)
Cydonia oblonga miller	Seed	Shapeless	11,9,8		(1) Cytotoxicity effects (2) Photocatalytic degradation	Elahi et al. (2020)
Datura metel L	Leaf	Spherical	5–15	–	(1) Degradation activity of DPPH radical	Yulizar et al. (2020)
Elaeagnus angustifolia	Leaf	Spherical	35–70	–	(1) Antioxidant	Singh et al. (2019)
Euphorbia amygdaloides	Plants	Spherical	8.6–10.5	3.70	(1) Antioxidant (2) Antibacterial	Nadaroglu et al. (2017)
E. globulus	Leaves	Spherical	20.72	2.91	(1) Photocatalytic (2) Cytotoxic activity	Balaji et al. (2020)
Euphorbia tirucalli	Stem	Flaky	15–25	–	(1) Photo luminescence emission	Malleshappa et al. (2014)
Gloriosa superba L	Leaf	Spherical	5	3.78	(1) Antibacterial	Arumugam et al. (2015)
Hibiscus Sabdariffa	Flower	Crystalline	3.9	–	–	Thovhogi et al. (2015)
Hyphaene thebaica	Fruit	Spherical or quasi spherical	14.86	–	(1) Antimicrobial activities (2) Cytotoxicity assessment (3) Antioxidant assays (4) Antiviral activity	Mohamed et al. (2020)

Table 2 (continued)

Botanical Name	Plant Part	Morphology of nanoparticles	Size (nm)	Band gap (eV)	Applications	Refs
Jatropha curcus	–	–	3–5	> 3.19	(1) Photocatalytic degradation of indoor air pollutant	Magudieshwaran et al. (2019)
Lemon grass	Grass	–	10–40	–	–	Maensiri et al. (2014)
Leucas aspera	Leaf	Microsphere	4–13	2.98–3.4	(1) Antibacterial activity (2) Photocatalytic activity	Malleshappa et al. (2015)
Moringa oleifera	*Peel*	Spherical	40	–	(1) Photocatalytic degradation of the dye (2) Antibacterial	Surendra and Roopan (2016)
Morus nigra	Fruit	Irregular	8.5	3.52	(1) Antidiabetic activity	Rajan et al. (2019)
Nelumbo nucifera	Flower	Spherical	5.84	2.335	(1) Anticancer activity	Pon et al. (2020)
Olea europaea	Leaf	Spherical	24	–	(1) Antibacterial potential (2) Antifungal assay	Maqbool et al. (2016)
Orange Peel	Peel	Spherical	20–25	–	(1) Cytotoxicity, (2) Antioxidant (3) Photocatalytic activity	Irshad et al. (2019)
Origanum majorana	Leaf	Spherical	20	–	(1) Antioxidant activity (2) Cytotoxicity assay	Aseyd Nezhad et al. (2020a)
Origanum majorana	Leaf	Spherical	10–70	–	Antioxidant activity cytotoxicity against breast cancer	Aseyd Nezhad et al. (2020b)
Petroselinum crispum	–	Spherical and irregular	–	–	Anti-radical scavenging activity (oxidative damage protection of agricultural plants)	Korotkova et al. (2019)
Pisonia alba	Leaf	Spherical	< 10	< 2.97	(1) Antioxidant activity (2) Antifungal activity	Sharmila et al. (2019)
Prosopis farcta	Leaves	Spherical	30	–	–	Miri and Sarani (2018)
Prosopis juliflora	leaf	Spherical	15	3.62	(1) Antibacterial activity	Arunachalam et al. (2017)
Rubia cordifolia L	leaf	Spherical	26	–	(1) Anti-carcinomal activity	Sisubalan et al. (2017)
Salvadora persica	Bark	Spherical	10–15	4.1	(1) Cytotoxicity survey against colon cancer cell line	Miri et al. (2020)
Salvia macrosiphon Boiss	Seeds	–	–	2.5–3.5	(1) Photocatalytic degradation	Elahi et al. (2019)
Simarouba glauca	Leaf	Isotropic spherical	9.9	3.81	(1) Optical properties (2) Bactericidal activity (3) Prominent wound-healing activity	Rajan et al. (2020)
Stevia rebaudiana	Leaves	Spherical	8–10	–	(1) Protective effect against harmful ultraviolet rays	Khatami et al. (2019)
Walnut	Shell	Spherical	9–12	–	Catalyst for (1) Oxidation reaction (2) Three component reaction	Zamani et al. (2018)
Watermelon	Fruit	Irregular	36	5.57	(1) Photocatalytic degradation antibacterial	Reddy Yadav et al. (2016)

Whatman No. 1 filter paper. Afterward, the aqueous solution of selected cerium salt was prepared using double-distilled water. The prepared cerium salt solution is mixed with aqueous plant extract and stirred the mixture at 80 °C for 4–8 h. After a certain period, a yellowish precipitate of CeO_2 NPs was formed. Next, the synthesized CeO_2 NPs were separated using centrifugation, washed with double-distilled water, and the precipitate was calcined at 500 °C for 2 h. Thus, yellow-colored CeO_2 NPs were carefully collected and packed for characterization purposes. Table 2 offers numerous examples of plant extract-mediated synthesized CeO_2 NPs.

Using microbial biomass

A selected fungus was inoculated in Czapek-Dox-Broth (CDB) medium, and the flask was incubated at 37–50 °C, at 120 rpm for 72–120 h. The fungi grown on CDB medium were filtered using Whatman No. 1 filter paper amd were stored at 4 °C for further use. Afterward, the selected cerium salt was added to 100 mL fungal filtrate under vigorous stirring. The stirring was continued for 4–6 h at 27–80 °C. A color change indicates completion of the reaction, and a precipitate was formed. The formed precipitate was collected, washed with double-distilled water several times, and the precipitate was calcined at 300–400 °C for 2 h to obtain CeO_2 NPs.

Using biological products

Cerium nitrate was dissolved in 50 mL double-distilled water to prepare cerium salt solution and stirred for 5 min. In the meantime, the selected biological product was dissolved in 50 mL double-distilled water and he cerium salt solution was added. The mixture was heated to 60–70 °C with stirring for 3–8 h. Next, the dark color solution was centrifuged, the precipitate was washed with double-distilled water to remove impurities, and the precipitate was calcined at 300–400 °C for 2 h to obtain CeO_2 NPs. Table 3 presents several examples of using different biological products and fungi source-assisted synthesized CeO_2 NPs.

Green synthesis of CeO_2 nanoparticles

From biological products

Biological products used to synthesize nanoparticles can tailor the properties such as morphology, polymorphism, and size of nanoparticles (Kargar et al. 2015b). Moreover, the bio-products are easily available, economical, biodegradable, non-toxic, and simple to use. Darroudi et al. reported the starch-mediated synthesis of CeO_2 NPs using cerium nitrate hexahydrate as a precursor (Darroudi et al.

Table 3 Green synthesis of CeO_2 NPs using different biological product and fungi source with morphology, size, band gap, pH and applications

Biological product/ Microbe Name/	Morphology of nanoparticles	Size (nm)	Band gap (eV)	pH	Applications	Refs
Agarose	–	10	–	–	(1) Cytotoxicity studies onL929cells (2) Evaluation of neurotoxicity effect	Kargar et al. (2015a)
Aspergillus niger	Cubic and spherical	14.95	–	–	(1) Antibacterial activity (2) Larvicidal activity	Gopinath et al. (2015)
Dextran	Spherical	5	–	6–9	(1) Antioxidant activity (2) Anticancer activity	Alpaslan et al. (2015)
Egg protein	Spherical	8–18	–	–	(1) Evaluation of cytotoxicity effect	Kargar et al. (2015b)
Fusarium solani	Spherical	11	–	6.8	(1) Antibacterial activity (2) Antibiofilm activity	Venkatesh et al. (2016)
Honey	Spherical	23	3.5	–	(1) Evaluation of neurotoxicity effect	Darroudi et al. (2014a)
Humicola sp.	Spherical	16	3.28	9	–	Khan and Ahmad (2013)
Pectin	Spherical	23.71	3.59	10	(1) Antioxidant activity (2) Antibacterial activity (3) Cytotoxicity assessment	Patil et al. (2016)
Polyethylene glycol	Faceted	2	–	–	(1) Study of interfacial properties	Qi et al. (2012)
Starch	–	6	3.6	10	(1) Optical properties study	Darroudi et al. (2014b)
Tannic acid	–	10	3.05	7.8 ± 0.2	(1) Antibacterial activity	Kumar et al. (2018)

2014b). How the starch molecules are responsible for synthesizing CeO_2 NPs, the detailed mechanism is shown in Fig. 2. Patil et al. highlighted the use of pectin for the synthesis of CeO_2 NPs, which act as a reducing agent. First, the pectin on hydrolysis yields d-galacturonic acid, the functional group present in d-galacturonic acids such as carboxyl, hydroxyl, and keto carry out the formation of CeO_2 NPs (Patil et al. 2016). Similarly, the synthesis of CeO_2 NPs has been reported by other researchers and was tabulated in Table 3.

From microbial biomass

The metabolites found in the extracellular membrane of fungal cells, such as enzymes, proteins, and heterocyclic derivatives, can be used to make reducing and capping agents along with decent biocatalytic performance (Gopinath et al. 2015). Riddin et al. reported that using certain fungal species secreted proteins and enzymes could efficiently synthesize metal nanoparticles extracellularly, stabilizing the particles and allowing for a higher yield than intracellular production (Riddin et al. 2006). Moreover, fungi are easily available, easy to scale up on mass level, economical, and highly tolerant of heavy metals (Gade et al. 2010). *Fusarium solani* mediated synthesis of CeO_2 NPs was carried out at pH 6.8, and within 5 h shows spherical morphology of synthesized CeO_2 NPs was described by Venkatesh et al. (Venkatesh et al. 2016). *Aspergillus niger*-mediated synthesis of CeO_2 NPs was achieved at 80 °C in 6 h with cubic and spherical morphology (Gopinath et al. 2015). The fungi-mediated synthesis is superior in economic and environmental viewpoints; hence, more attestation is needed. Figure 3 depicts the different green approaches for synthesizing CeO_2 NPs.

From plants extract

Plants are the most common, readily available, and cost-effective source for the synthesis of nanoparticles. Plant-facilitated nanoparticle synthesis has several advantages over the fungi, bacteria, and algae reported by Tran et al. (Tran et al. 2022). *Abelmoschus esculentus* fruits-mediated synthesis of CeO_2 NPs shows spherical morphology having 35–40 nm size with antioxidant, anticancer, antibacterial, and wound-healing activities (Ahmed et al. 2021). Leaf extract of *Ceratonia siliqua* utilized in the bio-fabrication of CeO_2 NPs displays good antioxidant and cytotoxic activity. The synthesized particles were spherical with a size of 22 nm (Javadi et al. 2019). Irshad et al. synthesized CeO_2 NPs applying *Orange Peel* and studied cytotoxicity, antioxidant, and photocatalytic activity (Irshad et al. 2019). Flower extract of *Calotropis procera* used to manufacture CeO_2 NPs exhibited spherical morphology with 21 nm size besides, has a band gap of 3.29 eV, and studied their photocatalytic and antibacterial activity (Muthuvel et al. 2020). Similarly, there are several reports listed in Table 2.

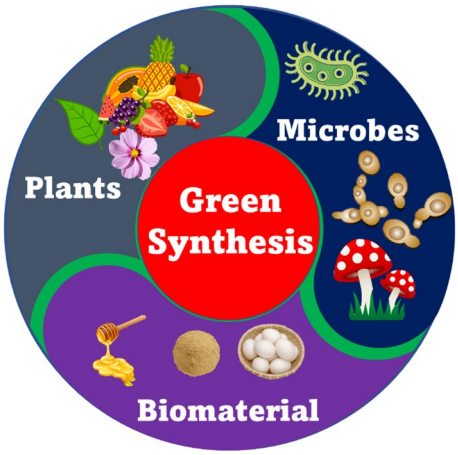


Fig. 3 Diverse green approaches for the synthesis of CeO_2 NPs using biological entities

Characterization techniques

X-ray diffraction analysis (XRD)

In materials science, a technique for identifying a material's crystallographic structure is XRD. Miri and Sarani explain the *Prosopis farcta* leaf extract abetted synthesis of CeO_2 NPs (Miri and Sarani 2018). The authors studied the effect of calcination temperature on the synthesis of CeO_2 NPs (Fig. 4). The XRD pattern is in good agreement with JCPDS card number 00–043-1002, and the structure is fluorite cubic. The miller indices for the pattern are (111), (200), (220), (311), (222), (400), (331), and (420). Similarly, Singh et al. reported the fluorite cubic structure of CeO_2 NPs synthesized utilizing *Elaeagnus angustifolia* leaves. The (2θ) angles 69.02°, 56.47°, 47.21°, 33.11°, and 28.51° are observed in the XRD peaks of CeO_2 NPs (Singh et al. 2019).

Fourier transforms infrared spectroscopy (FTIR)

The technique used to recognize organic, polymeric, and inorganic materials is called FTIR. Dutta et al. described *Aloe vera* extract-facilitated synthesis of CeO_2 NPs. They have explained how *Aloe vera* extract carries out the synthesis of CeO_2 NPs (Fig. 5). The FTIR spectrum *Aloe vera* extract shows the band at 3410.23, 2926.03, 1610.88,

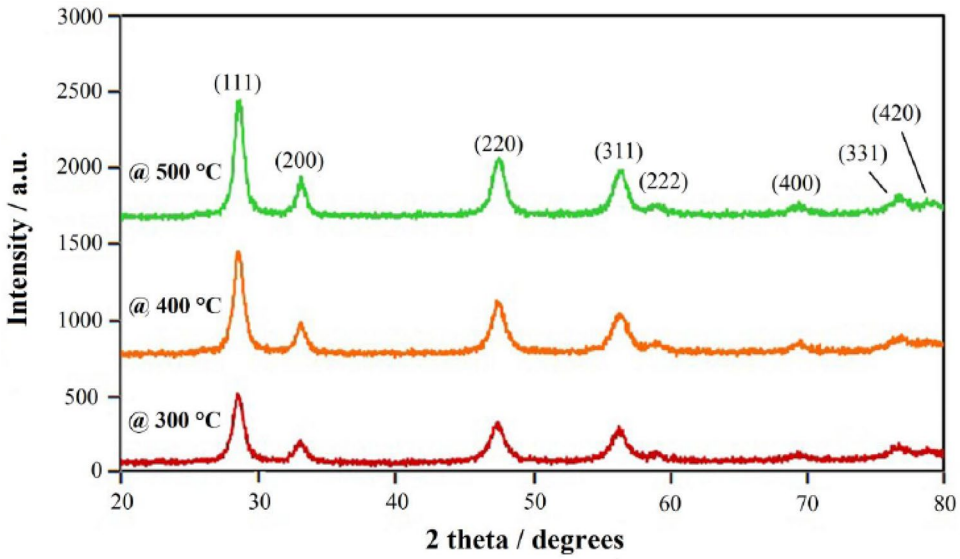


Fig. 4 XRD pattern of synthesized CeO_2 NPs at three different calcination temperature including 300, 400, 500 °C. License No. 5246481286341 Adopted from Miri and Sarani (2018) with permission from Elsevier

1493.83, 1244.27, 1060.69, 876.93, 772.72 and 621.90 cm^{-1} due to –OH gr, C–H bond, C=O stretching (symmetric and asymmetric), C–O, C–O–C, and C-H group respectively (Dutta et al. 2016). In CeO_2 NPs, spectra show decreasing wavenumbers in a few peaks, which appear at 67.86, 747.98, 848.60, 1075.62, and 3384.14 cm^{-1}, implying the participation of the C–H, C–N, and –OH group. Besides, the peaks at 1244.27, 1493.83, and 1610.88 cm^{-1} disappeared due to Ce ions interaction with the carbonyl group, and the new peak at 1390.94, 1560.86 cm^{-1} –C–H and C–C stretching, respectively (Dutta et al. 2016). The spectra of a mixture of *Aloe vera* extract and $Ce(NO_3)_3$ differed slightly from CeO_2 NPs, implying that *Aloe vera* extract's distinct components were not solely involved with CeO_2 NPs instead, they attached and stabilized the surface of CeO_2 NPs (Dutta et al. 2016).

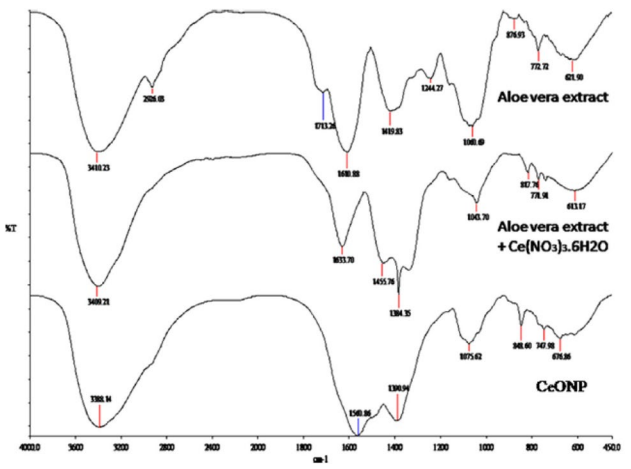


Fig. 5 FTIR spectrum of CeO_2 NPs, mixture of cerium nitrate and Aloe vera extract and Aloe vera extract. License No. 5246481489136 Adopted from Dutta et al. (2016) with permission from Elsevier

Transmission electron microscopy (TEM)

To evaluate the particle size, the TEM technique is used commonly. For example, Balaji et al. reported that *E. globulus* leaves extract assisted the synthesis of CeO_2 NPs (Balaji et al. 2020). HRTEM micrograph showing particle size is in the range of 15–20 nm (Fig. 6).

Aseyd Nezhad et al. synthesized spherical CeO_2 NPs using *O. majorana* leaf extract the size of the synthesized CeO_2 NPs 20 nm (Aseyd Nezhad et al. 2020b). The *Ceratonia siliqua* leaf extract-mediated Javadi and co-worker reported CeO_2 NPs synthesis NPs to possess spherical morphology with a size of 22 nm (Javadi et al. 2019). Similarly, more reports were summarized in Tables 2 and 3.

Thermogravimetric analysis and differential thermal analysis (TGA–DTA)

Darroudi et al. (Darroudi et al. 2014a) reported the honey-mediated synthesis of CeO_2 NPs described in the TGA analysis. An initial temperature of 20 °C was used for the heating procedure, with a 10 °C/min rise to 800 °C. Adsorbed water and crystal water are the primary causes of the 37.4% mass loss between 20 °C and 160 °C (see Fig. 7. Ed1 and Ed2) because of the slow dehydration of cerium hydroxide occurs in this temperature range. According to Ed3 and Ed4 (see Fig. 7), the breakdown of chemically bonded groups is responsible for the second stage, which occurs around 160–355 1C (48.5%). As cerium components continue to oxidize, a further 8.2% (see Fig. 7 Ed5) of mass is lost between 355 and 400 °C. The sample has lost 94.1% of its original bulk. The TGA curve shows no weight loss between 400 and 800 °C,

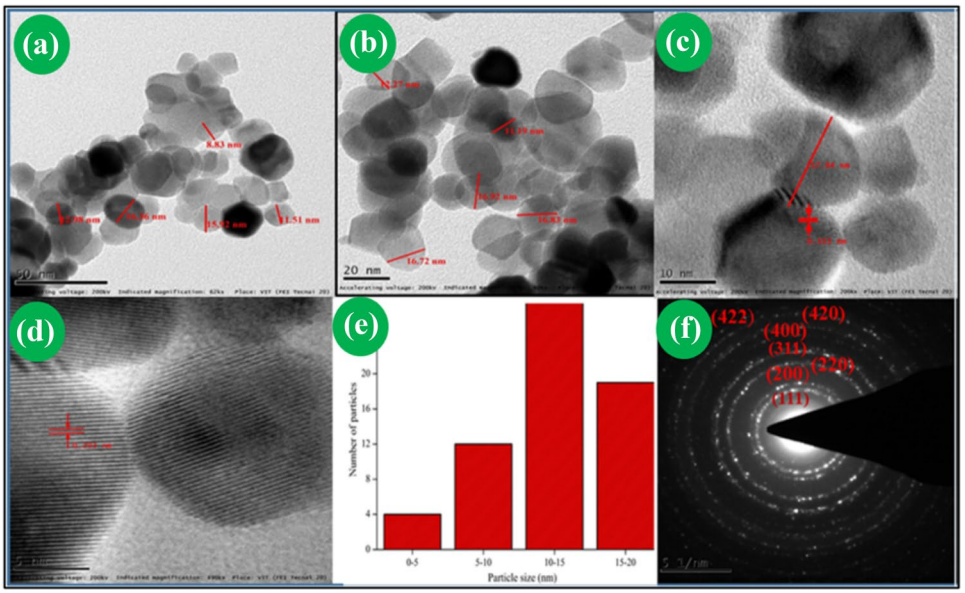


Fig. 6 TEM images of CeO_2 NPs at different magnifications: **a** 50 nm, **b** 20 nm, **c** 10 nm, **d** 5 nm; **e** Particle size histogram, **f** SAED pattern with hkl values. Open access; Reproduced from Balaji et al. (2020) with permission from MDPI

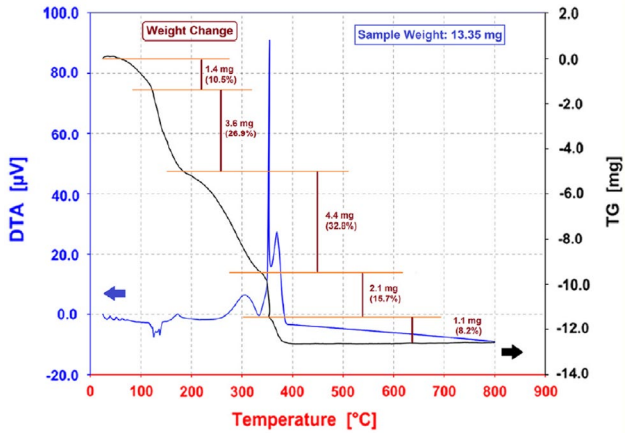


Fig. 7 TGA-DTA spectrum of honey-mediated synthesis of CeO_2 NPs. License No. 5320870350678 Adopted from Darroudi et al. (2014a) with permission from Elsevier

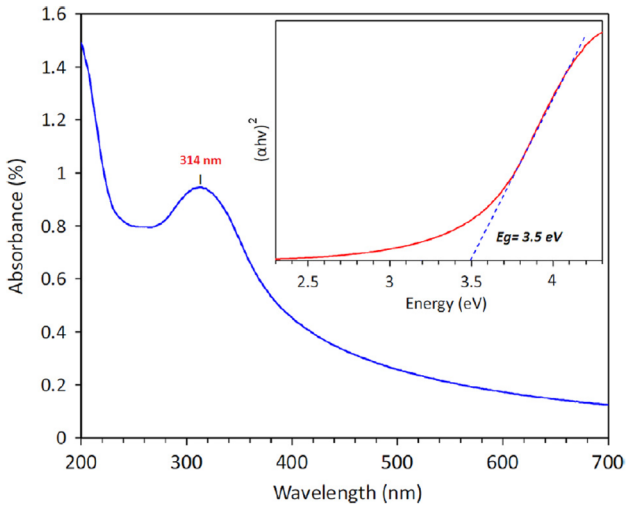


Fig. 8 UV–vis spectrum and bandgap estimation(inset) spectrum of honey-mediated synthesis of CeO_2 NPs. License No. 532087035 0678 Adopted from Darroudi et al. (2014a) with permission from Elsevier

confirming the synthesis of CeO_2 NPs as a stable product (Darroudi et al. 2014a).

UV–Vis spectrum of CeO_2 NPs

Darroudi et al. (Darroudi et al. 2014a) presented the typical UV–vis spectrum of honey-mediated synthesized CeO_2 NPs. The spectrum shows CeO_2 NPs have an inherent bandgap absorption peak at 314 nm, which may be ascribed to electron transitions from the valence band to the conduction band. The band at 300 nm is produced by the absorption of the charge transfer transition from O_{2p} to Ce_{4f} in CeO_2 NPs (Orel and Orel 1994). CeO_2 NPs have a bandgap of 3.5 eV, as seen in the inset of Fig. 8 (Darroudi et al. 2014a).

X-ray photoelectron spectroscopy (XPS)

Iqbal et al. (Iqbal et al. 2021) Reported the XPS spectra of plant extract-mediated synthesis of CeO_2 NPs (See Fig. 9 (a–d)). Fig (a) shows the survey scan that demonstrates the absence of any pollutants other than carbon species produced from a plant extract or organic contaminants absorbed by the sample during handling. Figure 9(b) Ce (3d) spectra contain eight peaks with binding energy ranges between 880

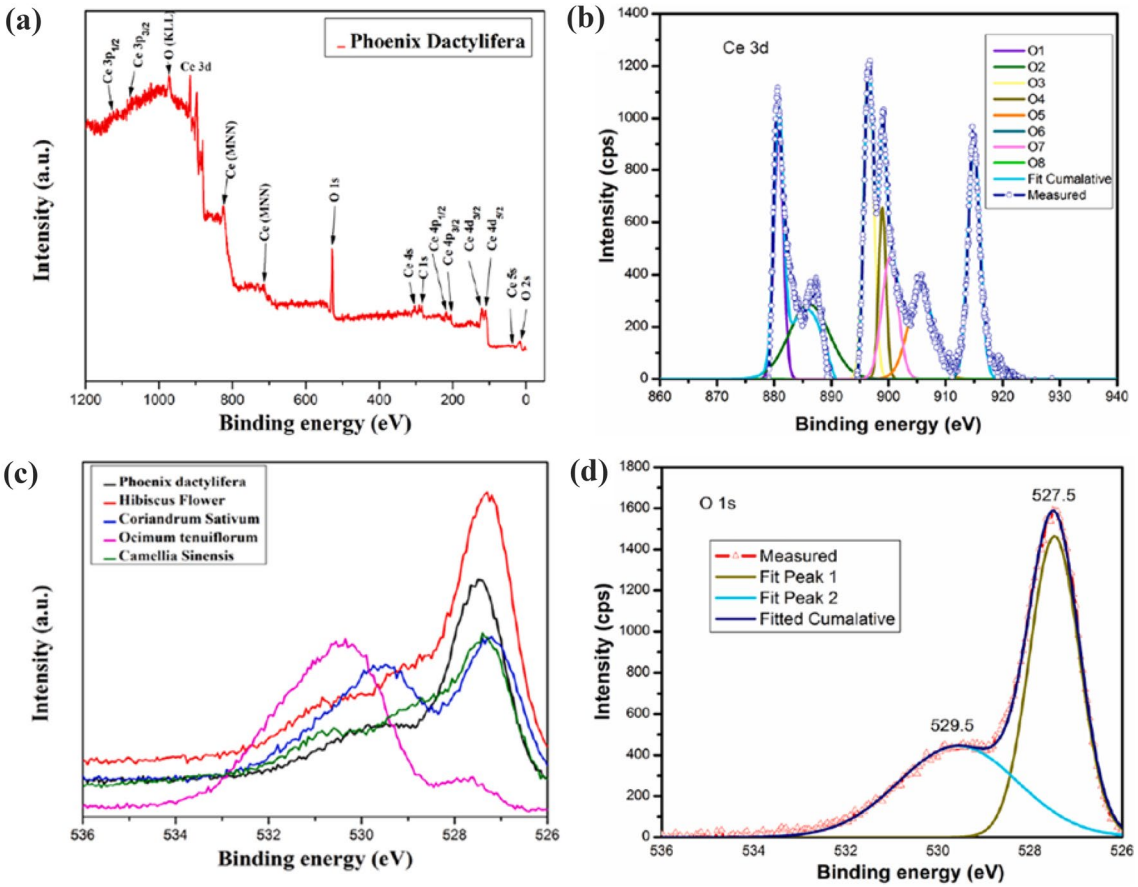


Fig. 9 XPS spectrum **a** Survey spectrum **b** Fitted XPS spectrum of Ce(3d) **c** XPS spectra of O (1 s) and **d** Fitted XPS spectrum of O (1 s) for CeO_2 NPs. License No. 5322460343240 Adopted from Iqbal et al. (2021) with permission from Elsevier

and 925 eV, which matches the literature data well. The XPS peaks between 891.12 and 900.09 and 900.09 to 925.47 are linked to Ce ($3d_{5/2}$) and Ce ($3d_{3/2}$), respectively, according to previous reports (Zhang et al. 2012; Krawczyk et al. 2015; Dutta et al. 2016). There are two distinct peaks in the binding energy of CeO_2 NPs at 527.5 and 529.5 energy levels, shown in Fig. 9(c) and (d) are attributed to O_2^- ion and O–H or COO^- from plant extract used for the synthesis of CeO_2 NPs, respectively (Iqbal et al. 2021).

Factors considered for the synthesis of CeO_2 NPs

Various factors are responsible for altering the properties of synthesized nanoparticles, such as size, shape, surface area, etc. (Khan et al. 2019). Altering the synthesis condition, specifically metal ion concentration, pH, reaction temperature, reaction time, calcination temperature, etc. As a result, obtaining magnificent CeO_2 NPs within a short reaction time, at moderate reaction conditions, which possesses manifold applications, is possible. Table 4 offers several examples of various factors used in synthesizing CeO_2 NPs.

A proposed mechanism for plant extract-mediated synthesis of CeO_2 NPs

Plant material contains phenolics, flavonoids, carotenoids, anthocyanins, hydroxytyrosol, tocopherols, etc. (Altemimi et al. 2017). These compounds were utilized to convert/reduce cerium salt into CeO_2 NPs. Qaisar Maqbool et al. elaborated that these compounds reduced cerium salt into CeO_2 NPs (Maqbool et al. 2016).

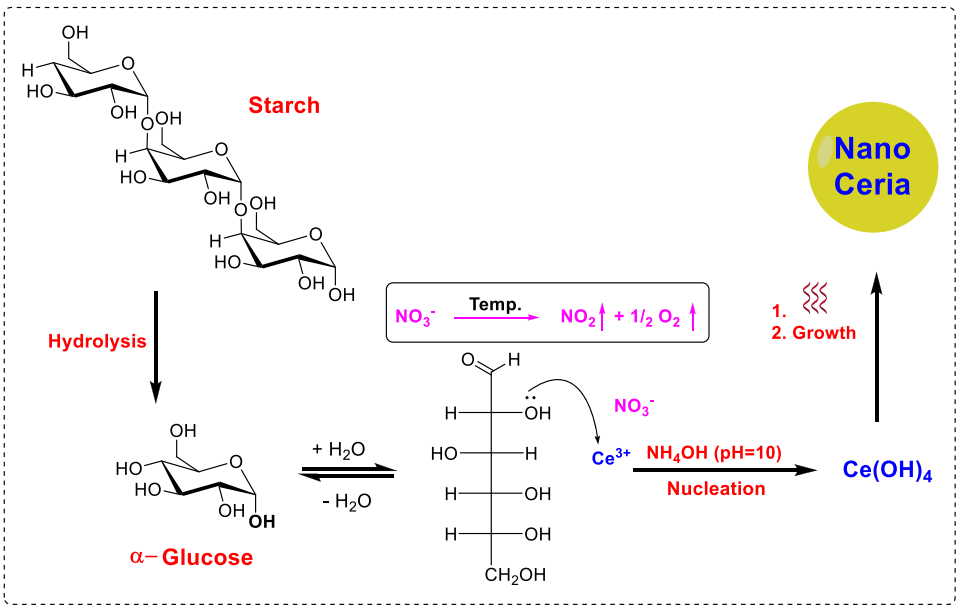
Darroudi et al. reported that in the starch-mediated synthesis of CeO_2 NPs, the starch was hydrolyzed to α-glucose, and the hydroxyl group of α-glucose attacks the metal cation. Then, the nitrate associated with the metal precursor gets decomposed on heating to nitrogen dioxide and oxygen. Besides this form $Ce(OH)_3$, which oxidized to $Ce(OH)_4$ by adjusting the pH, the formation of $Ce(OH)_4$ was identified by a change in solution from colorless to light yellow. The sol–gel process and

Table 4 Factors considered for CeO_2 NPs' formation include metal concentration, pH, reaction time, reaction, and calcination temperature

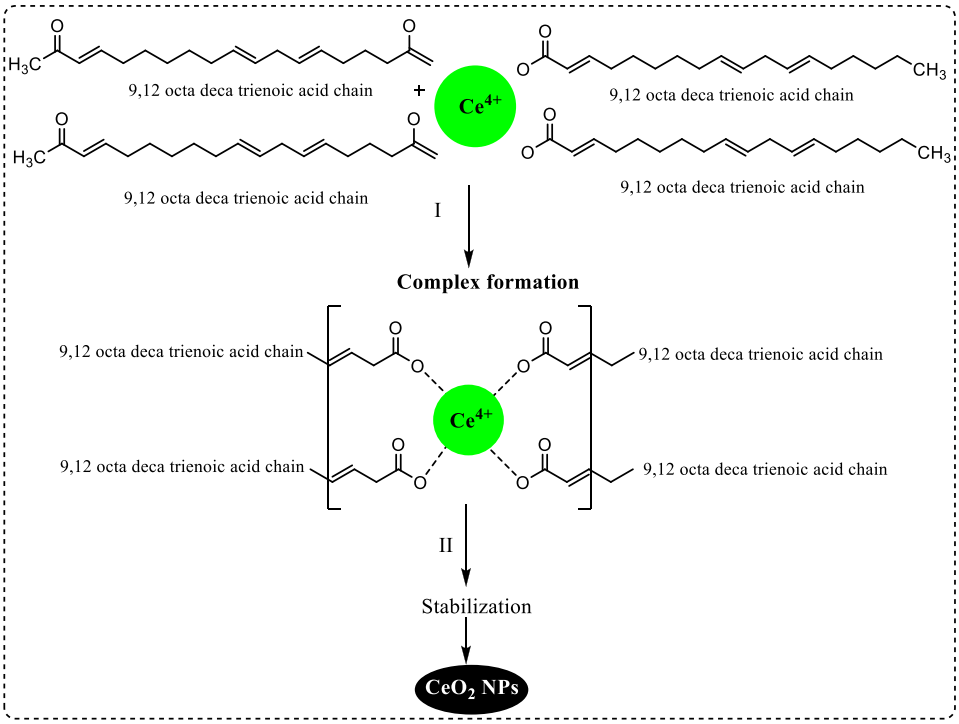
Sources used	Parameters-dependent green synthesis of CeO_2 NPs					Refs
	Concentration of Ce salt or weight	pH	Temperature		Reaction time (Hr.)	
			reaction (°C)	Calcination (°C)		
Plant material						
Abelmoschus esculentus	0.5 M	–	–	600	–	Ahmed et al. (2021)
Acalypha indica	0.1 M	–	80	400	2	Kannan and Sundrarajan (2014a)
Aloe barbadensis miller	0.1 M	–	80		–	Sai Priya et al. (2014)
Aloe vera	10 mM	–	RT	–	48	Dutta et al. (2016)
Aquilegia pubiflora	3 gm	–	60	500	2	Jan et al. (2020)
Azadirachta indica	0.1 M	–	Reflux	400	–	Sharma et al. (2017)
Bael	25 mg	–	RT		4	Murugesan et al. (2020)
Calotropis procera	3.72 gm	–	85	400	3	Muthuvel et al. (2020)
Carrageenan	25.2 gm	–	60	400	8	Nourmohammadi et al. (2018a)
Centella asiatica	4.5 mM	–	–	–	20 min	Sankar et al. (2015)
Ceratonia siliqua	–	–	80	400	4–6	Javadi et al. (2019)
China rose	2.5 gm	–	RT	550	24	Qian et al. (2011)
Cydonia oblonga miller	5.0 gm	–	80	400 500 600	6	Elahi et al. (2020)
Datura metel L	10 mM	–	80	500	4	Yulizar et al. (2020)
Elaeagnus angustifolia	3.7 gm	–	RT	250	6	Singh et al. (2019)
Euphorbia amygdaloides	10 mM	–	–	–	4	Nadaroglu et al. (2017)
E. globulus	0.1 N	8.2	RT	400	24	Balaji et al. (2020)
Gloriosa superba L	*3.72* gm	–	80	400	4–6	Arumugam et al. (2015)
Hibiscus Sabdariffa	2.0 gm	–	–	500	2	Thovhogi et al. (2015)
Hyphaene thebaica	6.0 gm	–	60	500	2	Mohamed et al. (2020)
Jatropha curcus	–	–	150	500	12	Magudieshwaran et al. (2019)
Lemon grass	9.45 mmol	5.15	80	400 500 600	12	(Maensiri et al. 2014)
Moringa oleifera	1 mmol	–	300 W	400	120Sec	Surendra and Roopan (2016)
Morus nigra	–	–	65	500	2	Rajan et al. (2019)
Nelumbo nucifera	0.1 M	–	80	400	2	Pon et al. (2020)
Olea europaea	8.68 gm	–	50	500	2	Maqbool et al. (2016)
Orange Peel	–	–	80	–	1.5	Irshad et al. (2019)
Origanum majorana	8.68gm	–	100	450	48	Aseyd Nezhad et al. (2020a)
Petroselinum crispum	0.862gm	–	80–90	500	6	Korotkova et al. (2019)
Pisonia alba	1 mM	–	RT	–	96	Sharmila et al. (2019)
Prosopis farcta	4.34gm	–	80	300 400 500	5	Miri and Sarani (2018)
Prosopis juliflora	0.1 M	–	2450 W	800	10 min	Arunachalam et al. (2017)
Rubia cordifolia L	1 mM	–	120	500	4–6	Sisubalan et al. (2017)
Salvadora persica	0.1 M	–	70	400	5	Miri et al. (2020)
Salvia macrosiphon Boiss	5.0 gm	–	80	400	6	Elahi et al. (2019)
Simarouba glauca	0.003 M	–	65	500	2	Rajan et al. (2020)
walnut	6.9 mmol	–	RT	500	5	Zamani et al. (2018)
watermelon	–	–	–	500	–	Reddy Yadav et al. (2016)

Table 4 (continued)

Sources used	Parameters-dependent green synthesis of CeO_2 NPs					Refs
	Concentration of Ce salt or weight	pH	Temperature		Reaction time (Hr.)	
			reaction (°C)	Calcination (°C)		
Biological product						
Agarose	12.6 gm	–	60	200 400 600 800	8	Kargar et al. (2015a)
Dextran	1 M	6–9	25	–	24	Alpaslan et al. (2015)
Egg protein	12.6 gm	–	60	200 400 600 800	8	Kargar et al. (2015b)
Honey	12.6 gm	–	60	200 400 600 800	6	Darroudi et al. (2014a)
Pectin	0.5 M	10	60	400	1	Patil et al. (2016)
Polyethylene glycol	–	–	70	–	–	Qi et al.(2012)
Starch	0.5 M	10	RT	120 200 400 600	1	Darroudi et al. (2014b)
Tannic acid	1.9 gm	7.8 ± 0.2	Reflux	400	3	Kumar et al. (2018)
Fungus						
Aspergillus niger	3.72 gm	–	80	350 400	4–6	Gopinath et al. (2015)
Fusarium solani	5.589 gm	6.8	RT	400	5	Venkatesh et al. (2016)
Humicola sp.	0.01 M	9	50	–	–	Khan and Ahmad (2013)



Scheme 1. Plausible mechanism for the synthesis of CeO_2 NPs. License No. 5245400066113: Reproduce from Darroudi et al. (2014b) with permission from Elsevier



Scheme 2. Proposed mechanism of green synthesis of CeO_2 NPs using *E. globulus* leaf aqueous extract. Open access; Reproduced from Balaji et al. (2020) with permission from MDPI

calcination converts $Ce(OH)_4$ to CeO_2 (Darroudi et al. 2014b). The detailed mechanism is shown in Scheme 1.

Similarly, Patil et al. highlighted the use of pectin for the synthesis of CeO_2 NPs. Oxidizing destruction, depolymerization, and alkaline hydrolysis occur in an alkaline medium and convert pectin into galacturonic acid. The oxygen in the acid attacks the Cerium metal, and the nitrate associated with the metal gets decomposed into nitrogen dioxide and oxygen. The addition of ammonia converted Ce^{3+} into $Ce(OH)_3$ and further oxidized to $Ce(OH)_4$. Then, the calcination converted $Ce(OH)_4$ into CeO_2 NPs (Patil et al. 2016).

E. *globulus* leaves extract-facilitated synthesis of CeO_2 NPs was reported by Balaji et al. The leaves extract encompasses 9, 12 octadeca trienoic acid chains the hydroxyl group present in the acid react with the cerium metal to form a complex structure. In a later step, CeO_2 NPs were obtained on calcination (Balaji et al. 2020). Scheme 2 depicts the mechanism in further depth.

Multifunctional applications of the CeO_2 NPs

This paper focuses on recent advances in the biosynthesis of CeO_2 NPs as building blocks for applications in various disciplines. These fields include environmental sensing, environmental remediation (adsorption, catalysis, and photocatalysis), antibacterial, antioxidant, and anticancer activities, organic synthesis, and emerging applications (nanofluid and energy storage) addressed as below. In addition, it is anticipated that CeO_2 NPs possess potential applications in diverse areas, especially medicinal applications such as cosmetics, sun-screen protectors, and as antiseptics in ointments (Darroudi et al. 2014a).

Photocatalytical applications

Photocatalysis is considered an environmentally accepted method for strengthening the green economy. This technique is one of the most useful, cost-efficient, and non-toxic strategies for successfully degrading a wide spectrum of environmental pollutants at ambient temperature and pressure. On scrutiny, the literature uncovers that in the photocatalytic degradation of organic dyes, hydroxyl radicals ($^{\bullet}OH$), superoxide radicals ($O_2^{\bullet-}$), and holes (h^+) are the main active species (Elahi et al. 2019). Recently, some researchers concentrating on the green synthesis of CeO_2 NPs for photocatalytic environmental remediation have received substantial consideration in this perspective. Different types of toxic chemical and environmental pollutant, such as Rhodamine B (Sharma et al. 2017) (Malleshappa et al. 2015), Methylene blue (Reddy Yadav et al. 2016), Methyl orange (Muthuvel et al. 2020), 4-nitrophenol, Acetaldehyde (Magudieshwaran et al. 2019), Crystal Violet (Surendra and Roopan 2016) has been degraded using biologically synthesized CeO_2 NPs.

Surendra and Roopan (Surendra and Roopan 2016) reported the photocatalytic ability of CeO_2 NPs toward Crystal Violet dye degradation. The degradation was done using Heber multi-lamp photoreactor with a UV lamp at 365 nm. It

is observed that the 97.5% dye was degraded within 1 h following first-order kinetics, indicating the rate of degradation of crystal violet dye at 0.88 per min (Surendra and Roopan 2016). Elahi et al. (Elahi et al. 2019) illustrated the degradation of Rhodamine B dye by applying CeO_2 NPs synthesized using different amounts of *Salvia Macrosiphon Boiss* seeds extract, suggesting that the degradation follows pseudo-first-order kinetics. The results revealed that the CNPs-30 shows superior degradation ability than the CNPs-10 and CNPs-20, i.e., 100% degradation in 12 h. Moreover, the enhanced degradation ability of CNPs-30 over the others is the smaller particle size that provides a large surface area for the RhB dye for faster degradation (Elahi et al. 2019).

Azadirachta indica leaf extract-mediated synthesis of CeO_2 NPs was reported by Sharma and co-workers (Sharma et al. 2017), in which they described the efficiency of CeO_2 NPs towards RhB dye degradation. The results suggest that 96% of the RhB dye was degraded within 2-h duration using a Xenon arc lamp of 300 W (Sharma et al. 2017). Malleshappa et al. (Malleshappa et al. 2015) stated the synthesis of CeO_2 NPs utilizing leaves of *Leucas aspera.* They studied their photocatalytic ability for the RhB dye degradation using UV light and sunlight. The CeO_2 NPs with varying amounts (i.e., 5, 10, 15, and 20 mL) of *Leucas aspera* leaf extract were designated as S1, S2, S3, and S4. The XRD results show that as the amount of leaf extract increases from 5, 10, 15, to 20 mL, the CeO_2 NPs decrease and were found to be 11, 8, 5 to 5 nm for S1, S2, S3, and S4, respectively. However, the photocatalytic activity shows 73% efficiency (90 min) in UV light; whereas, in sunlight, the efficiency was further increased as was reached up to 80% (90 mint.) for the S4 sample. The highest efficiency of the S4 was attributed to the small crystalline size, which has a high surface defect and increases the concentration of both electron and hole traps. The catalyst also shows recyclability up to the 4th cycle without significant decrees in the catalytic efficiency (Malleshappa et al. 2015).

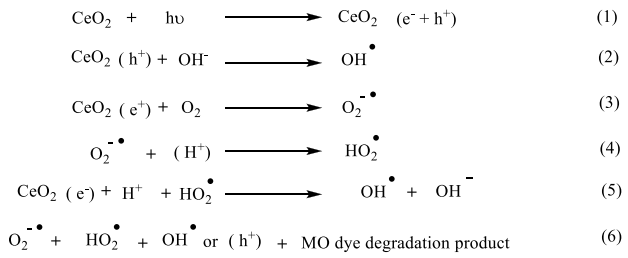


Fig. 11 Mechanism of MO dye degradation using CeO_2 NPs

Reddy Yadav et al. (Reddy Yadav et al. 2016) studied the photocatalytic ability of CeO_2 NPs synthesized from watermelon juice toward methylene blue (MB) dye degradation in UV and sunlight. The findings show that 98% of the MB dye was degraded in 3 h in UV light, whereas 93% in sunlight under the same conditions. The higher degradation rate in the UV light was observed because of the high intensity of light, which facilitates the easy penetration of light that results in a larger number of radicals and hence increases the degradation rate. Reddy Yadav et al. (Reddy Yadav et al. 2016) described the mechanism of dye degradation using CeO_2 NPs synthesized from watermelon juice, as shown in Fig. 10. Green synthesis of CeO_2 NPs was achieved using *Calotropis procera* flower extract by Muthuvel et al. and highlighted the photocatalytic degradation for methyl orange (MO) dye under sunlight irradiation (Muthuvel et al. 2020). The results show that 98% of the MO dye was degraded within 50 min of time interval under sunlight irradiation. Muthuvel et al. described the detailed mechanism (Fig. 11) of MO dye degradation was reproduced with License No.

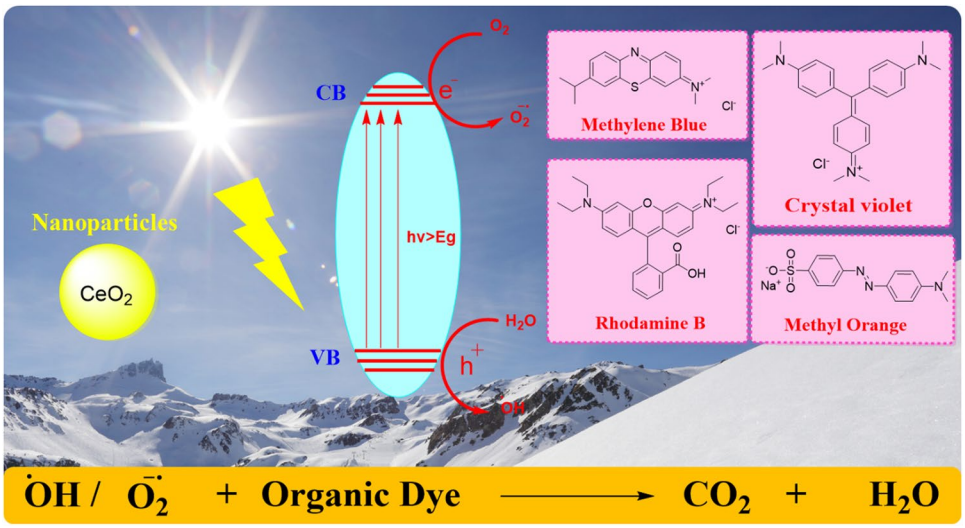


Fig. 10 Schematic mechanism of dye degradation using CeO_2 NPs

Table 5 Green-synthesized CeO_2 NPs for several dyes degradation

Dye/pollutant	Source	Efficiency	Refs
Acetaldehyde	Xenon lamp	99.6% degradation	Magudieshwaran et al. (2019)
Crystal violet	UV light UV lamp at 365 nm	5 PPM 1000 mL 10 mg catalyst 60 min 97.50% degradation	(Surendra and Roopan 2016)
Rhodamine B	Fluorescence UV-A light source 11 W	8 PPM 50 mL 200 mg catalyst 12 h. 100% degradation	Elahi et al. (2019)
Rhodamine B	Xenon arc lamp 300 W	10 PPM 100 mL 100 mg catalyst 120 min 96% degradation	Sharma et al. (2017)
Rhodamine B	125 W mercury vapor lamp	20 PPM 250 mL 60 mg catalyst 90 min 73% degradation	Malleshappa et al. (2015)
	Sunlight	20 PPM 250 mL 60 mg catalyst 90 min 80% degradation 4th cycle	Malleshappa et al. (2015)
Methylene blue	UV light	10 PPM 100 mL 100 mg catalyst 180 min 98% degradation	Reddy Yadav et al. (2016)
	Sunlight	10 PPM 100 mL 100 mg catalyst 180 min 93% degradation	Reddy Yadav et al. (2016)
Methyl orange	Sunlight	(1×10^{-5} M) 100 mL 1 mg catalyst 50 min 98.64% degradation	Muthuvel et al. (2020)
Sunset yellow (SY)	Mercury lamp of 8 W UV light	10 PPM 100 mL 35 mg catalyst 90 min 97.3% degradation	Balaji et al. (2020)

5282230449234 Adopted from (Muthuvel et al. 2020) with permission from Elsevier.

Balaji et al. (Balaji et al. 2020) prepared CeO_2 NPs using *E. globulus* leaf extract. They studied their photocatalytic activity for the sunset yellow (SY) dye degradation using Heber multi-lamp photo reactor HML MP 88 with an 8 W mercury lamp as a UV source. The results discovered that 97.3% of dye was degraded in 90 min under UV irradiation. In addition, the CeO_2 NPs show threefold recyclability without significantly decreasing catalytic efficiency (Balaji et al. 2020).

We have summarized the photocatalytic application of green-synthesized CeO_2 NPs by scrutiny the literature (Table 5).

Biological applications

Studies on the biomedical properties of green-synthesized CeO_2 NPs have opened a new medical biology and pharmacology era. Recent reports have highlighted the negative effects of CeO_2 on various microbes, larvae, and oxidative stress with potential photocatalytic activity. Some of the crucial biological activities of CeO_2 NPs are summarized below.

Antibacterial agent

Bacteria are one of the microorganisms present everywhere, and they can have positive and negative effects on the surrounding life. The bacterial diseases encompass an array ranging from mild illnesses like the common cold to deadly pneumonia and tuberculosis. In such cases, antibacterial therapy comes handy besides giving symptomatic relief from the disease. The process of controlling and reducing bacterial counts in the body by tapping every step of life like sustenance, metabolism, respiration, and reproduction of bacteria is known as antibacterial activity. However, conventional antibacterial drugs usually possess short-term activity with potential environmentally toxic effects. On the other hand, antibacterial nanoparticles are thought to be minimally toxic with prolonged effects on drug-resistant bacterial strains.

Cerium dioxide, a rare earth metal oxide, is of biological interest due to its electronic, optical properties, unique surface chemistry, and biocompatible nature with high stability. These properties are due to the stable tetravalent valence state of the metal. It is a cubic fluorite-type metal oxide (Farias et al. 2018). In the quest for the green synthesis of CeO_2 NPs, researchers have used various biological materials like plants (whole or parts of it), microbes, bio-products, etc. Several plants have been used for the biogenesis of CeO_2 NPs. The leaf extracts of *Acalypha indica* (Kannan and Sundrarajan 2014b), *Olei europaea* (Maqbool et al. 2016), *Gloriosa superba* (Gopinath et al. 2015), *Sida acuta* (Senthilkumar et al. 2017), *Prosofis julifora* (Arunachalam et al. 2017), *Moringa oleifera L* (Eka Putri et al. 2021), flower extracts of *Hibiscus sabdarifa* (Thovhogi et al. 2015) and *Calotropis procera* (Muthuvel et al. 2020), Aloe vera (Sai Priya et al. 2014), etc. Further investigations on the biological activities of these bio-generated CeO_2 NPs of varied sizes and

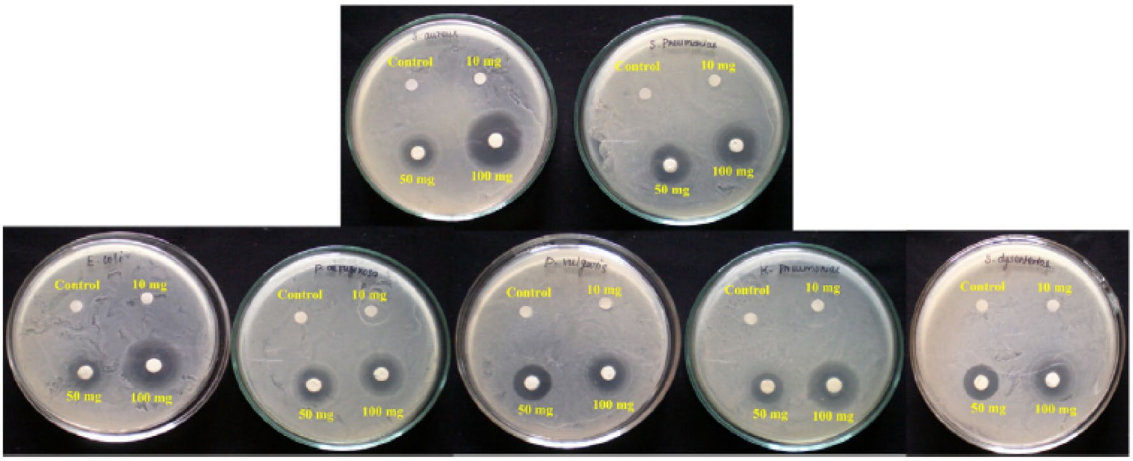


Fig. 12 Size of the zone of inhibition formed around each disc, loaded with test samples, indicating the antibacterial activity CeO_2 NPs using G. superba leaf extract License No. 5254790351005 Adopted from Arumugam et al. (2015) with permission from Elsevier

shapes revealed their prominent antibacterial activities. The CeO_2 NPs were found to possess anti-activities against many Gram-positive and Gram-negative bacteria, including a few multidrug-resistant pathogenic species. Gram-positive bacteria were detected to be more susceptible to the adverse effects of CeO_2 NPs (Fig. 12) (Kannan and Sundrarajan 2014c; Maqbool et al. 2016; Arunachalam et al. 2017; Kumar et al. 2018).

A study on antibacterial activity of CeO_2 NPs, synthesized by the green approach, on *E. coli* (Gram negative) and *Staphylococcus aureus* (Gram positive) demonstrated *Staphylococcus aureus* to be more sensitive to CeO_2 NPs treatment. The antibacterial activity of these NPs was observed to be dose dependent, i.e., higher antibacterial activity at higher concentrations of the nanoparticles was reported (Surendra and Roopan 2016). Another group of researchers synthesized CeO_2 NPs using *Calotropis procera* flower extract that showed significant antibacterial activity against Gram-negative bacteria—*Escherichia coli* and *Pseudomonas aeruginosa* (Muthuvel et al. 2020). CeO_2 NPs synthesized using *Pedalium murex* L extract (Pandiyan et al. 2019), *Moringa oleifera L* (Surendra and Roopan 2016), *Gloriosa Superba* (Arumugam et al. 2015), and *Oleo europaea* (Maqbool et al. 2016) demonstrated potential antimicrobial activities (Fig. 13). The biogenic synthesis of CeO_2 NPs using *Moringa oleifera* L exhibited good antibacterial activity against *Staphylococcus aureus* (Gram-positive), *Pseudomonas aeruginosa*

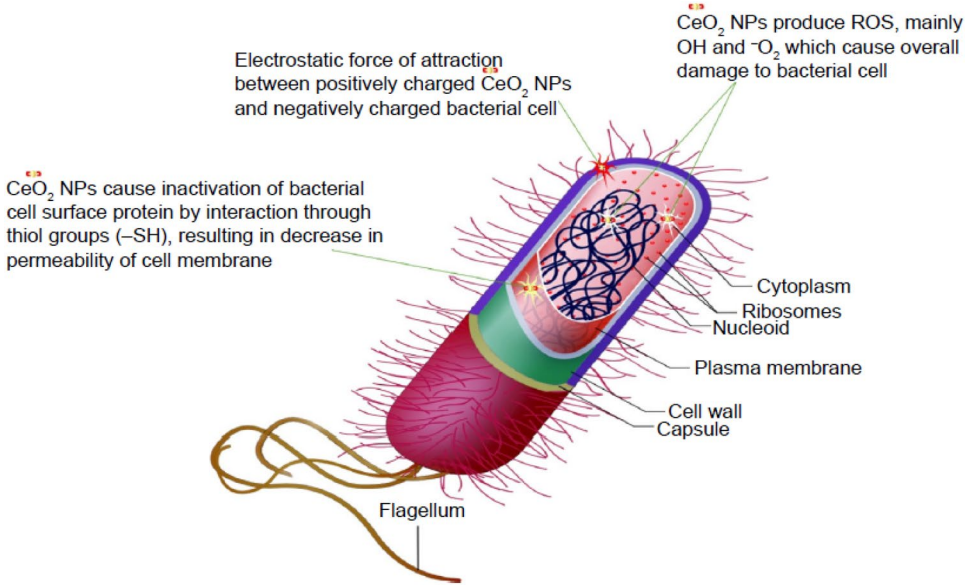


Fig. 13 Schematic illustration of CeO_2 NPs antibacterial activity. Open access Reproduced from Maqbool et al. (2016) with permission from Dove Press

(Gram-negative), and *E. coli* (Gram-negative) bacteria. Again, Gram-positive bacteria are more susceptible to CeO_2 NPs than their Gram-negative counterparts (Eka Putri et al. 2021). Green-synthesized CeO_2 NPs using *Oleo europaea* reported antibacterial activity against Gram-positive and Gram-negative bacterial strains (Maqbool et al. 2016). In a recent study by Altaf and his group (2021), the CeO_2 NPs (22.03 nm) synthesized using an aqueous extract of *Acorus calamus* showed more than 75% antibiofilm activity against Gram-positive and Gram-negative bacteria, both in a dose-dependent manner. This study again highlighted the higher susceptibility of Gram-positive bacteria to the CeO_2 NPs. (Altaf et al. 2021). The antibacterial effects of the CeO_2 NPs generated using *Abelmoschus esculentus* extracts were tested using standard agar diffusion experiments. The results obtained in the study were following earlier studies exhibiting a more profound antibacterial effect on *S. aureus* (Gram-positive) bacteria as compared to *K. pneumonia* (Gram-negative) bacteria, with a higher zone of inhibition at increasing concentrations of NPs in both cases (Ahmed et al. 2021).

In this way, different studies carried out in various laboratories unanimously exhibited significant antibacterial activity of green-synthesized CeO_2 NPs against Gram-positive and Gram-negative bacteria, with the greatest susceptibility of Gram-positive bacteria to these NPs. Till now, the antibacterial activity of CeO_2 NPs has been explained through many mechanisms. One of the proposed mechanisms is via Peptidoglycans, a linear polysaccharide chain with short peptides, forming a thick layer of Gram-positive bacteria. On the other hand, Gram-negative bacteria have a thin layer of peptidoglycans and lipopolysaccharides. Moreover, the peptidoglycan layer has teichoic acid, which interacts well with the CeO_2 NPs, thus inducing more toxicity of the NPs in the Gram-positive bacteria (Farias et al. 2018).

The other proposed mechanism for the antibacterial activity of CeO_2 NPs is attributed to the strong electrostatic properties and unique morphologies of the CeO_2 NPs. Due to these, the CeO_2 NPs interact with the thiol groups of the bacterial cell membrane proteins. The interaction with the thiol groups denatures the cell membrane proteins and turns them impermeable to outside material resulting in the death of the bacteria (Nadeem et al. 2020a).

Another, widely accepted mechanism suggests that the reactive oxygen species (ROS) in the bacterial cells are elevated due to the electrostatic attractions of the CeO_2 NPs. As a result, the bacterial cells cannot cope with the high levels of ROS and oxidative stress, thus showing a decline in growth (Nadeem et al. 2020a). In this way, the biogenic CeO_2 NPs have been proved to be one of the best baits for antibacterial therapy in various studies and with medical implications in bacterial diseases.

Nadeem et al. reported the antibacterial activity of CeO_2 NPs. The precise process by which bacteria are killed is still a mystery. Despite this, it is believed that CeO_2 NPs destroy microorganisms by causing cells to produce a large amount of reactive oxygen species (ROS) (Nadeem et al. 2020b). Fig. 14 represents the antibacterial activity of CeO_2 nanoparticles.

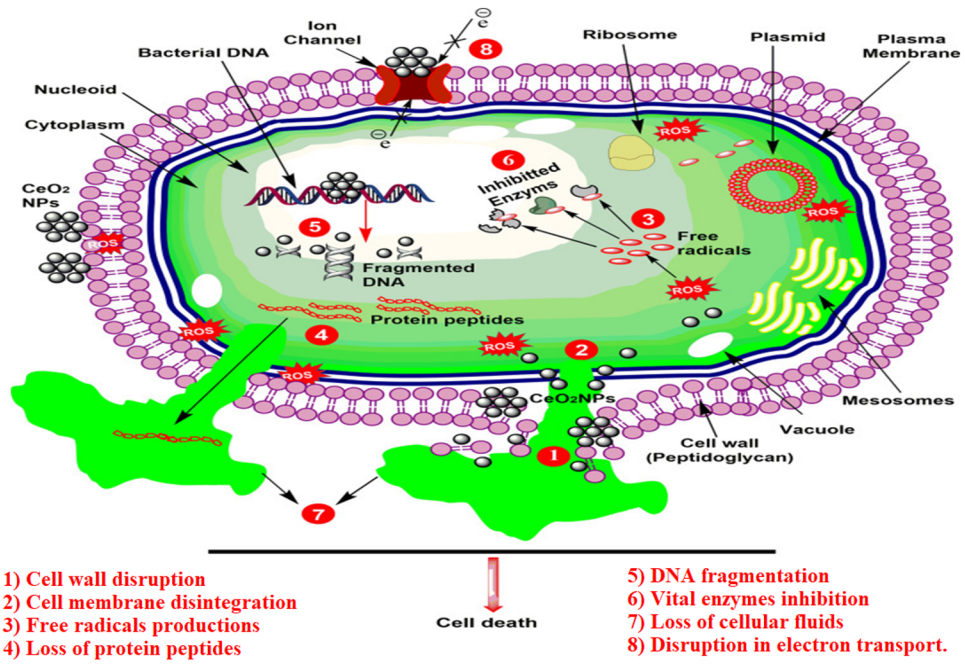


Fig. 14 **a** MTT cell viability assay of synthesized CeO2 NPs on HT-29 cancer cell line were measured at 24 h. Morphology of cells **b** Before treatment and **c** After treatment with 800 µg/mL of synthesized CeO2 NPs. License number 5246190583995; Reproduced from Miri et al. (2020) with permission from John Wiley and Sons

Antifungal activity

Fungal infection has become a public health issue. Amongst many infectious fungal species, *Candida albicans* is the most prevalent or dominant species worldwide, mainly in hospitalized and immune-compromised patients (Bassetti and Righi 2015). The most widely used antifungal agents come under flucytosine, polyenes, echinocandins, or azoles class of drugs (Mukherjee et al. 2005). Similar to many pathogenic bacteria, many infectious fungal species have developed multidrug resistance. Therefore, besides the antibacterial potential, researchers have also investigated the antifungal activities of the green-synthesized CeO_2 NPs as one of the potential antifungal medications in the future.

Recent studies have put forth CeO_2 NPs to be a better antimicrobial agent in the case of multidrug-resistant microbes as it is heat resistant with very low cytotoxic effects, as proposed by Puri and his group (Putri et al. 2019). A study on investigations of antifungal potential of biogenic CeO_2 NPs synthesized using *Moringa oleifera* leaf extract was tested on *Candida albicans* and *Aspergillus fumigatus.* These fungi were cultured for 24 h at 37 °C on Sabouraud Dextrose Agar (SDA) plates, and the CeO_2 NP solution was applied at certain sites to observe the zone of clearance, if any. Surprisingly, the antifungal potential of these CeO_2 NPs was found to be very strong as compared to its bactericidal activity. The NPs could effectively inhibit the growth of both the fungi, and the zone of clearance was calculated to be 20 mm for *Candida albicans* and 26 mm for *Aspergillus fumigatus.* A drug/test substance inducing a zone of inhibition of more than 20 mm is classified as a very strong antimicrobial agent (Sebastiammal et al. 2019). In another study, Maqbool and his group (2016) tested the antifungal activity of biogenic CeO_2 NPs on Mucor species, *Aspergillus flavus, Aspergillus niger and Fusarium solani* by disk diffusion method. This study reported the highest zone of clearance for Mucor species (22 mm), followed by *Aspergillus flavus*, and *Aspergillus niger* (19 mm for both), and the least zone of clearance for *Fusarium solani* (10 mm). In this way, CeO_2 NPs exhibited a great ability to act as antifungal agents (Maqbool et al. 2016).

The antifungal potential of green-synthesized CeO_2 NPs needs to be further addressed against various pathogenic fungi to analyze its potential in the biomedical field, especially against the multidrug-resistant fungal species. Currently, the mechanism by which CeO_2 NPs elicit antifungal activity is not well understood. However, some of the reports point to the formation of excess ROS, electromagnetic interactions (Xia et al. 2008), and cell membrane protein denaturation (Howlett and Avery 1997) as the route cause of the antimicrobial activity of CeO_2 NPs (Estes et al. 2021). Therefore, more rigorous studies on antifungal activities of bio-mediated CeO_2 NPs are essential to explore the canopy of fungal species sensitive to the CeO_2 NPs.

As mentioned earlier, bacteria and fungi are the most diverse organisms on this earth. Some of the species of these groups can have beneficial and adverse impacts on life. However, these organisms adapt quickly to the changing environment and, thus, develop resistance to antibiotics/antifungal medicines in a short time. Thus, developing novel efficient therapies to treat these pathogenic organisms is essential. Green-synthesized nanoparticles of many metals have been shown to possess antibacterial and antifungal potential against a wide variety of species. Compared to these metals, cerium has a unique advantage of biocompatible nature with small size and specific morphological features, which imparts it more efficient in killing a vast range of pathogenic microorganisms (Nadeem et al. 2020a).

Antioxidant activity

The process of limiting or inhibiting the oxidation of biomolecules, especially lipids and proteins, and restraining oxidative chain reactions is known as antioxidant activity. Endogenous antioxidant activity checks the production of reactive oxygen and/or nitrogen species (ROS/RNS), which are highly unstable and responsible for the oxidation of lipids, proteins, DNA, etc. Thus, to avoid physiological problems, the body must tackle and maintain the balance between producing and utilizating ROS/RNS through endogenous antioxidant enzymes. Nevertheless, on the other hand, higher production of reactive oxygen species results in oxidative stress in an organism that forms the base for several pathological conditions like cellular death, cancer, diabetes, etc. (Perona et al. 2021).

Antioxidants minimize oxidative stress by reacting with free radicals and inhibiting the downstream chain of reactions and producing harmful byproducts. However, natural and synthetic antioxidants exhibit poor absorption with limited cell permeability and biodegradation till it reaches the activity site. In this scenario, the antioxidants coupled with metals in metal oxide nanoparticles serve as an alternative to natural and synthetic antioxidant supplements (Khalil et al. 2019). To date, nanoparticles of various metals like silver (Ansar et al. 2020), zinc (Daoud et al. 2021 123AD), etc., are known to possess antioxidant potential. In the crystalline structure, cerium oxide exhibits a deficiency of oxygen atoms and is available in Ce^{3+} and Ce^{4+} oxidation states. Due to its unique structural property, it mimics endogenous antioxidant enzymes like phosphatase, oxidase, catalase, superoxide dismutase, and peroxidase in their activity and, thus, shows high antioxidant potential (Turin-Moleavin et al.).

Custom-synthesized CeO_2 NPs by the wet synthetic process have been shown to possess antioxidant and

neuroprotective activities. However, the chemically synthesized NPs may have toxic effects at higher concentrations. CeO_2 NPs induced antioxidant activity and declined the damage caused due to oxidation and lipid peroxidation in the rat brain (Najafi et al. 2017; Estevez et al. 2019) CeO_2 NPs have also exhibited radioprotective capability due to there free radical scavenging activity (Popov et al. 2016). In this way, the neuroprotective and radioprotective activities of CeO_2 NPs are attributed to their antioxidant potential. A fructose polysaccharide-Levan is a bio-product produced by many plants, bacteria, and other animals. Levan has been extensively explored for its antioxidant and antibacterial potential (Hertadi et al. 2021). The CeO_2 NPs, coated with Levan polysaccharide, significantly inhibited the oxidation of biomolecules in NIH 3T3 cells treated with hydrogen peroxide. The study also reported enhanced water solubility and stability of Levan coated CeO_2 NPs. Further, CeO_2 NPs were shown to interfere with hydrogen peroxide activity, reduce the production of ROS/RNS and increase the life expectancy of human epithelial cells (Rubio et al. 2015).

In another study, CeO_2 NPs stabilized with *Aloe vera* leaf extracts were shown to neutralize the adverse effects of hydrogen peroxide and protect mouse brain cells from an overproduction of ROS, cell death, and loss of connectivity between neural cells (Dutta et al. 2016). Biogenically, CeO_2 NPs synthesized using *Origanum majorana* L. leaf extract. Synthesized CeO_2 NPs increased catalase and superoxide dismutase expression levels and exhibited higher antioxidant activity in human umbilical vein endothelial cells (Aseyd Nezhad et al. 2020b). CeO_2 NPs generated using *Ceratonia siliqua* extracts exhibited antioxidant activities in a dose-dependent manner with high antioxidant potential at high concentrations. Surprisingly, these CeO_2 NPs demonstrated better antioxidant potential than the industrial antioxidant—BHA (Javadi et al. 2019). Cerium oxide NPs generated with *Aloe barbadensis,* a medicinally important plant, resulted in the generation of spherical nanoparticles of approximately 63.6 nm with high antioxidant potential (Sai Priya et al. 2014). Earlier studies suggest that biosynthesized CeO_2 NPs could eradicate free radicals more efficiently, resulting in better cellular functions.

Vitamin C (ascorbic acid) is a conventional natural antioxidant used by humankind for years for its highest antioxidant potential. However, a recent study wherein the antioxidant potential of ascorbic acid was compared with CeO_2 NPs, generated using *Abelmoschus esculentus* extract, exhibited higher antioxidant activity in CeO_2 NPs compared to ascorbic acid in a standard DPPH assay. In this way, green-synthesized CeO_2 NPs are proposed to be a better candidate for antioxidant therapy in contrast to conventional natural antioxidants (Ahmed et al. 2021) and commercial synthetic antioxidants (Aseyd Nezhad et al. 2020b). Hence, the green-synthesized CeO_2 NPs exhibit effective scavenging the free radicals and possessed remarkable antioxidant potential with significant biomedical applications.

Antidiabetic activity

Diabetes is a chronic health condition where the pancreas cannot produce sufficient amounts of insulin, or the body cannot use the insulin produced by the pancreas effectively. As a result, patients with unattended diabetes usually experience hyperglycemia and oxidative stress induced by high sugar levels. Oxidative stress is the cause of pathogenesis and complications of diabetes. The free radicals formed under hyperglycemic conditions lead to glucose oxidation, increased lipid peroxidation and oxidation of biomolecules resulting in their degradation (Maritim et al. 2003).

Since being green-synthesized, CeO_2 NPs have displayed a significant antioxidant potential, even better than the conventional natural and synthetic antioxidants. The studies on the probable use of these NPs for combating the complications of diabetes are in progress. A group of researchers looked at the effect of biogenic CeO_2 NPs on the L6 (rat myoblast) cells which exhibit insulin-driven movement of glucose across the cell membrane, i.e., show glucose uptake by cells in response to insulin (Shamprasad et al. 2019). In diabetic conditions, cells usually fail or show a very low capacity to respond to insulin signals and uptake glucose from circulating blood (Cerf 2013). Thus, the L6 cell line is thought to be one of the best models to investigate the antidiabetic activity of various agents, as detected by glucose uptake by the cells in response to these agents. The CeO_2 NPs synthesized using the fruit extract of *Morus nigra*, when used to treat the L6 cell line, showed significantly higher uptake of glucose (more than 65% at 100 ug/mL concentration of NPs), suggesting the excellent antidiabetic potential of the NPs. The L6 cells could show higher glucose uptake in response to higher doses of CeO_2 NPs. The efficient antidiabetic activity of the CeO_2 NPs may be because of the very small dimensions of the NPs facilitating their easy penetration into the cells (Rajan et al. 2019).

In an experiment, the diabetic rats (streptozotocin induced) were treated with either CeO_2 NPs and sodium selenite, alone or in combination, which resulted in higher expression levels of antioxidant enzymes and reduced cholesterol levels triglycerides oxidative stress that is elevated under diabetic conditions in treated rats. Again, this study again clearly hints at the probable antidiabetic activity of the CeO_2 NPs (Pourkhalili et al. 2011). In another set of experiments, a combination of CeO_2 NPs and sodium selenium led to lower levels of ROS and higher levels of secreted insulin. These studies hint at the potential use of CeO_2 NPs to treat physiological disorders like diabetes (Singh et al. 2020). In a recent study, CeO_2 NPs synthesized using the *Stachys japonica* Miq plant extract and posed no toxicity

to NIH3T3 (immortalized mouse embryonic fibroblast cell line) and HepG2 (human hepatoma) cells. Simultaneously these biogenic CeO_2 NPs reverted the insulin resistance of HepG2 cells and, thus, elevated the glucose uptake by these cells hinting at the antidiabetic activity of the NPs (Saravanakumar et al. 2021).

Because of these studies, it would be interesting to prepare and explore the antidiabetic potential of CeO_2 NPs, synthesized using either *Rhus hirta*, *Picea glauca, Juniperus communis*, or *Solidago Canadensis*, plants with high antioxidant capacity (LM McCune 2013).

Anticancer activity

ROS has been implicated in normal cell–cell signaling and related cellular processes. Organisms have an antioxidant defense mechanism to check the ROS levels. Either way, higher or lower, uncontrolled modulation in the ROS amounts can impair cellular functioning and cause diseased conditions. Cancer is one such critical illness that is related to cellular ROS levels. Cancer is characterized as the uncontrolled growth of abnormal cells that can infiltrate, spread to other parts of the body and destroy surrounding normal tissues. It is one of the leading clinical causes of death worldwide. ROS is thought to possess pro-tumorigenic activity that promotes cell survival and proliferation. The metabolic rate is elevated in tumor cells, producing higher ROS amounts. Moderately elevated levels of ROS cause oxidative stress, gene mutations, and DNA instability in cells leading to cancer progression. On the other hand, very high levels of ROS can be toxic to the cancer cells as they trigger programmed cell death (apoptosis). Cancer cells usually have their mechanism to maintain ROS levels to avoid apoptotic death. Because of these conditions, researchers find ROS a potential and crucial target for cancer therapies as it can be used as both pro- and anti-tumorigenic agents (Perillo et al. 2020; Arfin et al. 2021).

Conventional cancer treatments include the use of alkylating agents, biological agents, and antimetabolites, which have serious side effects like drug resistance, loss of hair, and obliteration of normal cells, as these drugs cannot differentiate between cancerous and normal cells. Nanoparticles of various metal oxides like zinc, copper, iron, cobalt, etc., drew scientists' attention as the NPs were found to differentiate between cancer cells and normal cells and induce cytotoxic effects selectively in cancer cells (Anjum et al. 2021). Metal oxide NPs (zinc oxide) have been shown to induce ROS formation, destroy mitochondrial membrane potential and activate apoptotic pathways via caspase cascade in cancerous cells (Anjum et al. 2021). Thus, the antitumor mechanism of metal oxide NPs is thought to be mainly through the generation of excess ROS and apoptosis, among other possibilities. Compared to synthesizing metal oxide NPs chemically, green-synthesized NPs have proved to be better in medical therapies, mainly due to their non-toxic nature (Marouzi et al. 2021).

The CeO_2 NPs, synthesized with leaf extract of *E. globulus*, resulted in the formation of NPs of about 13.7 nm. Human adenocarcinomic alveolar epithelial cells (A549) were more susceptible than another cancer cell line (HCT 116) developed from human colorectal carcinoma. The study further revealed that the toxic effects of these NPs were mediated through ROS generation (Balaji et al. 2020). In another study, CeO_2 NPs (26 nm), synthesized using the *Rubia cordifolia* leaf fusions, exhibited remarkable anticancer activity against the MG-63 cell line (human osteosarcoma cells). However, the treated cells lost the membrane integrity and suffered oxidative stress-mediated apoptosis (Sisubalan et al. 2017).

Orange peel extract was used to synthesize CeO_2 NPs of about 23 nm by Irshad and group (2019). These biogenic CeO_2 NPs exhibited significant ROS and cytotoxic activities in human cervical cancer cells (HeLa) (Irshad et al. 2019). Ahmed and his group prepared CeO_2 NPs using *Abelmoschus esculentus* extract and tested its cytotoxicity on HeLa cells. The results obtained in this study followed the earlier studies on CeO_2 NPs generated with orange peel by Irshad et al. (2019). HeLa cells exhibited mortality in a dose-dependent manner in response to the CeO_2 NPs generated with *Abelmoschus esculentus* extract (Ahmed et al. 2021). Remarkable growth inhibition of breast cancer cells is reported in CeO_2 NPs prepared with *Ceratonia siliqua* extracts (Javadi et al. 2019). In an another study, the cytotoxic effects of green-synthesized CeO_2 NPs (10–70 nm) using *Origanum majorana* L. leaf extract on MDA-MB-231 (human breast cancer cells) showed higher adverse effects as compared to the HUVEC cells (human vein endothelial); normal cell line that was used as the control (Aseyd Nezhad et al. 2020b). CeO_2 NPs, synthesized using the *Prosopis farcta* extract, exhibited cytotoxic effects on HT-29 (human colorectal adenocarcinoma) cells (Miri and Sarani 2018). Miri et al. reported that the cytotoxic activity of *Salvadora persica* extract-mediated synthesis of CeO_2 NPs was determined through 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide assay against a colon (HT-29) cancer cell line (Fig. 15) (Miri et al. 2020). The number of WEHI 164 (mouse fibrosarcoma) cells was significantly lowered, in a dose-dependent fashion, when treated with CeO_2 NPs generated using carrageenan (Nourmohammadi et al. 2018b).

In this way, research on the anticancer activity of green-synthesized CeO_2 NPs, carried out in various laboratories across the world, hints at the cytotoxic activity of these NPs specifically against cancerous cells and does not affect normal cells. Therefore, as indicated in earlier studies, the strong anticancer potential of these biogenic NPs should be explored further in detail to approve the NPs as a safer or

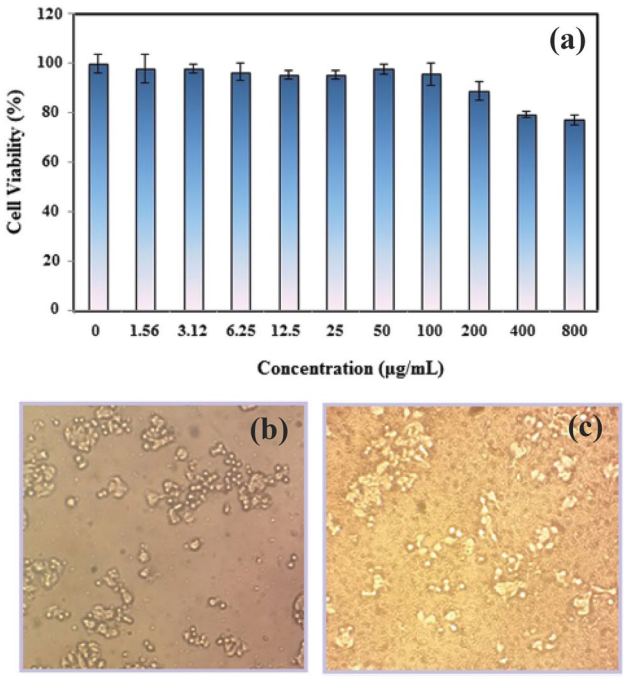


Fig. 15 Schematic representation of antibacterial activity of CeO_2 nanoparticles. Open access Reproduced from Nadeem et al. (2020b) with permission from Dove Press

better chemotherapeutic agent with minimum toxicity on normal cells.

Commercialization of CeO_2 nanoparticles with polymers

To improve the properties of both ceria and polymers, the fabrication of CeO_2-based polymer composites appears to be a beneficial tool for Biomedical Applications (Shcherbakov et al. 2021). CeO_2 NPs therapeutic antioxidant potential has been recently verified by advances in nanomedicine(Davoodbasha et al. 2019). Davoodbasha et al. synthesized the cellulose-coated CeO_2 NPs and studied DPPH, superior hydroxyl, superoxide, and hydrogen peroxide radicals scavenging activity in a pH-depended manner (Davoodbasha et al. 2019). Besides, Davoodbasha et al. also stated that cellulose-coated CeO_2 NPs, as a possible antioxidant material, might be used in targeted treatment to reduce ROS and oxidative stress in the cells. Furthermore, according to Cheng et al. impressively high electrical characteristics, the CeO_2@G modified separator has the potential to be used in the development of high-performance Li–S batteries (Cheng et al. 2021).

The wound-healing activity of biocompatible poly (acrylamide) hydrogel (PAGE)-based dressing material encompassing CeO_2 NPs and curcumin was tested by Bhattacharya et al. (Bhattacharya et al. 2019). Moreover, the combination of curcumin and CeO_2 NPs improved cell proliferation, higher collagen content, accelerated wound maturity, re-epithelialization, and granulation tissue formation (Bhattacharya et al. 2019). According to Huang et al., adding two weight percent CeO_2 NPs to poly(ether–ester) gave it the best mechanical and low-temperature elastic recovery properties (Huang et al. 2014). Electrospun polycaprolactone-based tissue engineering scaffolds loaded with CeO_2 NPs have been developed and tested as an innovative approach for tissue engineering(Augustine et al. 2018). CeO_2 NPs are an essential component of scaffolds used in situ tissue engineering for enhancing angiogenesis, cell adhesion, and cell proliferation(Augustine et al. 2018).

CeO_2 NPs can be delivered via biodegradable PLGA (lactide: glycolide), which provides a long-term release of the CeO_2 NPs, as reported by Singh et al. (Singh et al. 2012). Furthermore, the synthesized PLGA (lactide: glycolide) encapsulated CeO_2 NPs were studied for tissue engineering, such as bone remodeling, regeneration, and protection from neurological illnesses (Singh et al. 2012).

Challenges and opportunities

The green chemistry of CeO_2 NPs synthesis has been studied, and some important difficulties and opportunities have been found. Almost 90% of the waste from nanoparticle syntheses is generated by precipitation, and separations raise solvent waste even more. The elimination of size sorting and other post-processing of the product, as well as developing syntheses that reduce solvent consumption, maybe through wholly new methodologies, is crucial to decreasing waste.

Because green and non-toxic reducing agents are too weak to create high-quality CeO_2 NPs, which require faster kinetics, the toxicity of reducing agents was highlighted as a critical concern. To manufacture high-quality CeO_2 NPs without harmful ingredients, either stronger green reducing agents must be developed, or more effective reaction conditions for weaker reducing agents must be discovered; this remains an open and critical challenge.

Furthermore, achieving high-yield synthesis of CeO_2 NPs with little or no solvent employing benign reducing and capping agents is also a challenging but worthwhile goal. To work toward this aim and secure a greener future for CeO_2 NPs in research, industry, and the marketplace, it is evident that larger debates on sustainability lead to a greater appreciation among nanoparticle chemists of the benefits of green synthetic techniques are required.

Conclusion and future prospects

In conclusion, we lucidly emphasized and considered the current advancement in the fabrication and application of biosynthesized CeO_2 NPs as an effective nanomaterial for numerous applications. In recent years green or biosynthesis of CeO_2 NPs has fascinated the research community and is at an exponential pace. Biosynthesis implicated plant extract, nutrients, bacteria, fungai, biological products, etc., mediated the synthesis of CeO_2 NPs, which is environment-friendly, non-toxic, economically affordable, and effective. Furthermore, green or biosynthesis protocols have various advantages in the eco-friendly synthesis of CeO_2 NPs. Some of the crucial points are listed below.

- Prevention—The green or biosynthesis of CeO_2 NPs prevents waste generation.
- Less hazardous chemical—The non-toxic and eco-friendly chemicals were used in the green or biosynthesis of CeO_2 NPs.
- Designing safer chemicals—Plant extract, nutrients, bacteria, fungi, and biological product encompasses biomolecules that act as reducing and/or stabilizing agents in the manufacture of CeO_2 NPs. Hence, there is no need to employ harmful compounds like sodium borohydride, hydrazine hydrate, or ethylene glycol, which raises toxicity risk.
- Solvents—The green or biosynthesis approaches involve water as a solvent in preparing CeO_2 NPs, which is inexpensive, environmentally benign, non-flammable, non-toxic, and pollution-free.
- Energy Efficiency—The ambient temperature, pressure, and energy is required for the green or biosynthesis of CeO_2 NPs. which reduces production expense. As a result of the lower production costs, the process becomes more cost-effective.
- Renewable raw material—The green or biosynthesis of CeO_2 NPs utilizes renewable materials such as plant extract, nutrients, bacteria, fungi, and biological products that are abundant and readily available in nature.
- Degradation—In the green or biosynthesis of CeO_2 NPs, biodegradable material is used. So, there is no issue of environmental hazard, and the method is eco-friendly.

To make versatile CeO_2 NPs, a variety of plants have been used. However, this technique impedes practical uses of biosynthesis-assisted CeO_2 NPs that need enhancement. Various reaction parameters such as precursor concentration, reaction temperature, reaction time, pH, and calcination temperature, can play a vital role in regulating the size, shape, and morphology of CeO_2 NPs. To achieve desired CeO_2 NPs, the parameters should be optimized. In addition, researchers need to explore the fungi-mediated CeO_2 NPs as very few reports present on the fungi-mediated synthesis of CeO_2 NPs. Moreover, the underlying mechanism by which microorganisms and medicinal plant extracts are examined for the biosynthesis of CeO_2 NPs is still unknown. Also, the stoichiometric ratios of microorganisms, plant extracts, and metal precursors are needed to describe the fabrication and morphological control.

Furthermore, the researcher has not explored the application of CeO_2 NPs as a catalyst in organic transformations. After all, discovering unique features for plants, microbes, and biological product extract-assisted CeO_2 NPs is essential. Plant extract, microbes, and biological product directed CeO_2 NPs will undoubtedly gain significance and use in catalysis, biomedicine, bio-sensing, energy, agriculture, and the environment in the subsequent years and will become more powerful and reliable.

Declarations

Conflict of interest The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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