

Research Trends in Green Synthesis of CeO₂ Nanoparticles: A Bibliometric Review

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Abstract

This bibliometric review examines the trends in green synthesis of CeO₂ nanoparticles (NPs) emphasizing significant contributions and emerging research applications. Through an analysis of keywords, co-authorship networks, countries, and affiliation networks, findings highlight that green synthesis of nanoparticles, applications of CeO₂ as antibacterial agent, catalyst, and photocatalysts are the most used keywords reflecting strong interests. By evaluating the citation metrics within last 20 years, it could be concluded that green synthesis of CeO₂ still have position to fill the map on the use of nanoparticles for various applications, mainly in medicine and environmental engineering. Stronger collaborations to explore linkages for creating new route as greener and sustainable method as innovation are still required.

Keywords

Green Synthesis, CeO₂ Nanoparticles (NPs), Nanoparticles

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1. INTRODUCTION

Research on nanoparticles synthesis is one of the most popular themes in term of nanotechnology in green chemistry. Using the perspective of green chemistry, green synthesis of nanoparticles is a central point. Even though the green synthesis is actually referred to the synthesis procedure involving the use of low-cost, less energy, and sustainable resources, in case of nanoparticles synthesis, majority of the published paper highlighted the use of plant extract or plant-mediated synthesis of metal oxide nanoparticles (Hussain et al., 2016). The selection of plant is usually based on the content of secondary metabolites having potential to be bio-reducers to convert metal precursor into single nanoparticles or metal oxide (Dhall and Self, 2018). In addition, selected plant which includes medicinal plant, agricultural waste, and residues represents a representative and significant sources to meet the low-cost method.

Cerium oxide (CeO₂) is one of metal oxides that have significant interest due to their various applications in biology, environment, energy, and medicine. Like many other metal oxides, CeO₂ in NP form demonstrates excellent performance in various applications due to the quantum size effect (Prieur et al., 2020). Nanoparticles can be synthesized using various methods. One of the most popular methods for CeO₂ NP

synthesis is the co-precipitation technique using cerium salts as precursors. Green synthesis methods using organic extracts have been developed to produce biocompatible CeO₂ NPs, addressing safety concerns and enhancing their potential in biomedicine (Javid et al., 2022; Gunasekaran et al., 2025). These nanoparticles exhibit promising properties for photocatalysis, antimicrobial activity, and antioxidant applications (Shlapa et al., 2022). The *Scopus* database provides some references describing the various green synthesis methods.

Previous review articles on CeO₂ nanoparticles (CeO₂ NPs) synthesis highlighted the applications and toxicological implications of the NPs (Mabood et al., 2020), and focusing on antibacterial activities (Mohajeri et al., 2025). Previous review on green synthesis CeO₂ NPs resumed the subject content of the papers, prospects for collaboration with other institutions or authors, and impacted journals for publication of any study on this topic. Meanwhile, references tracking for a specific topic is challenging for researchers to faster look at the progress, position, and the trend profile of rapid growth in the volume of research works. Bibliometric analysis methods have been widely used to figure out these researches and references big data. Based on these backgrounds, this review is trying to figure out better understanding on the current state and the trend of research in green synthesis of CeO₂ NPs.

Using *VOSviewer* and *Biblioshiny* in *RStudio*, analysis to published papers, linkage of authors/research collaborations, citation patterns, and keywords, identification of the key areas of progress, gaps in knowledge, and emerging trends are presented. The description could be used for guiding the more effective research.

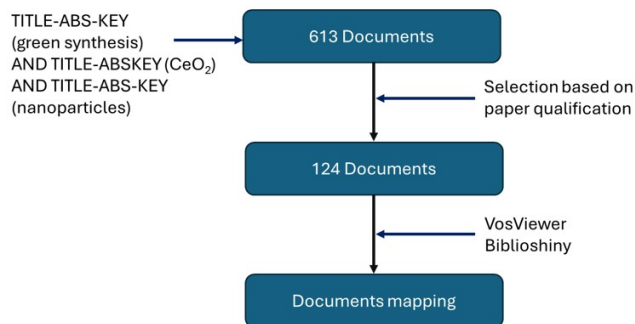


Figure 1. Flowchart of Data Collection

2. METHODOLOGY OF REVIEW

This bibliometric review was performed by a systematic approach to collect, identify, and analyze relevant papers using the *Scopus* database. Initial search for the documents was based on the search query as follows: (TITLE-ABS-KEY (green synthesis) AND TITLE-ABS-KEY (CeO₂) AND TITLE-ABS-KEY (nanoparticles)) and (TITLE-ABS-KEY (plant-mediated synthesis) AND TITLE-ABS-KEY (CeO₂) AND TITLE-ABS-KEY (nanoparticles)), with year range limited at 2019-2025. The selection of *Scopus* database was considered referred to the tight selection criteria of indexing compared to other indexing such as *Google Scholar*. However, potential drawback is the excluded scientific papers from journals that are not indexed by *Scopus*, including local or non-English journals; in fact, some papers in local or national level sometimes give novelty in term of collected data. Additionally, *Scopus* may not capture the grey literatures such as conference proceedings, government reports, and technical documents, which could provide valuable insights into practical and policy-oriented applications. Furthermore, the papers were screened objectively by looking at the content in full papers or abstracts. Descriptive analysis and visualization were performed using *VOSviewer*. Mapping on keywords, authorship, and linkage were figured out by the software. Further analysis was performed using *Biblioshiny* in *RStudio*.

3. DATA COLLECTION AND SELECTION

From the search using the *Scopus* database, 613 documents were collected. Further evaluation from the full papers and abstracts resulted in 124 papers being sorted. The selection was based on the content of the papers with consideration on the green synthesis approach and the pure synthesized material of CeO₂ NPs. The papers containing chemical synthesis were excluded.

Figure 1 provides the flowchart of procedure and Figure 2 depicts the annual publication during the last 13 years. From a total of 124 documents, about 111 papers were collected from the last 13 years. It is seen that, in general, an increased number of papers is shown. The annual publication number shows an increasing trend. This implies that the research theme is still growing and an emerging area. The document searching was performed on 7 July 2025. By using the annual growth rate of publication of about 16.17%, there will be insignificant changes for such crucial information. The selection of the documents was based on the detail of the abstract which is closer to the topic of green synthesis and chemical applications, and non-English documents were excluded.

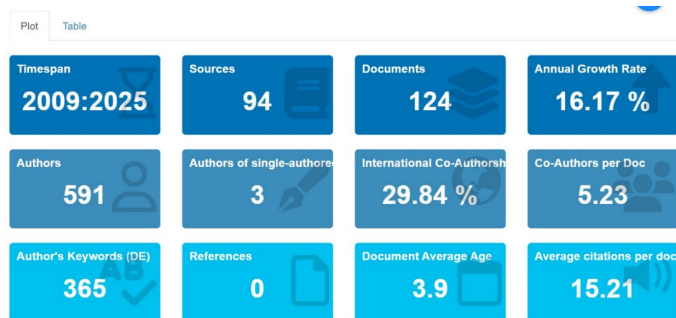


Figure 2. Annual Trend in Publications in Green Synthesis of CeO₂ NPs

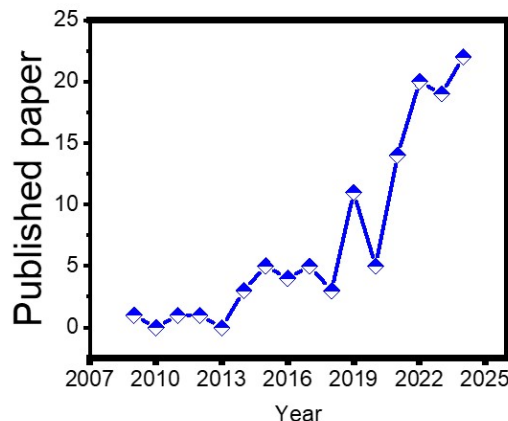


Figure 3. Main Data Information

The details of the collected documents are summarized in Figure 3. From 2009 to 2025, a total of 124 documents were published across 94 sources, with an annual growth rate of 16.17%. The publications involved 591 authors, of which 29.84% were international co-authorships. The average number of co-authors per document was 5.23. A total of 365 keywords were recorded from these documents, and the average number of citations per document was 15.21.

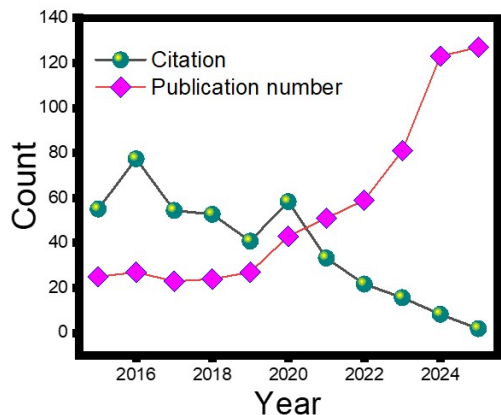


Figure 4. Progress of Publications on Green Synthesis of CeO₂ NPs

4. DATA ANALYSIS

From the documents collected, the number of publications during the last 10 years and the citation average each year are presented in Figure 4. It is seen an increased number of publications appearing from year to year during 2015-2025, but the citation average is decreased throughout the year. This trend is common in some other topics of publications.

Figure 5 depicts three-field plots of the most selected keywords, author's institution and country. The popularity of the keywords is as follows: catalytic activity, CeO₂, catalysis, synthesis, metal nanoparticles, synthesis (chemical), X-ray diffraction, transmission electron microscopy, Fourier-transform infrared, particle size, and cerium oxide nanoparticles, biosynthesis, photocatalytic activity, cytotoxicity, antioxidant, antibacterial activity. Meanwhile, the top author's affiliations are: Islamic Azad University, Mashhad University of Medical Science, College Science, Chona, Tumkur University, Beijing University, College of Chemistry and Chemical Engineering.

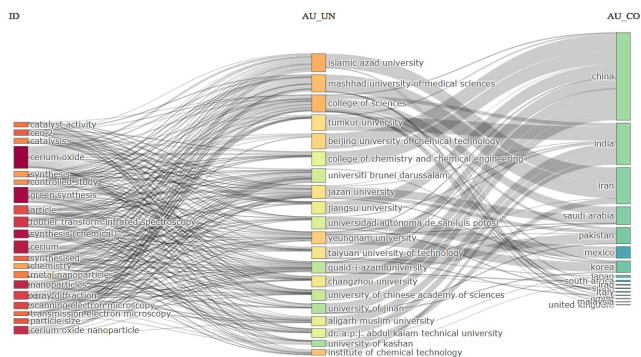


Figure 5. Three-Field Plots of Collected Documents [Analysis Parameter: Left-field: Keywords, Middle-field: Affiliations, Right-field: Countries, Number Items: 20]

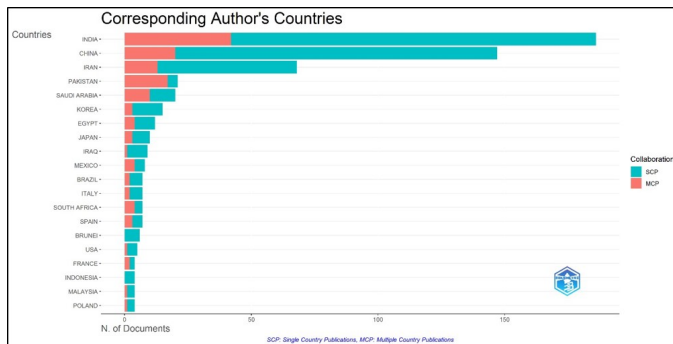


Figure 6. Corresponding Authors Countries of The Collected Documents [Parameter: 20]

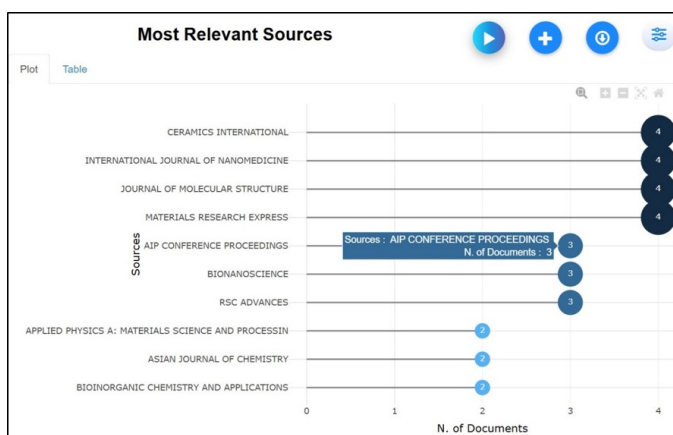


Figure 7. The Most Relevant Source of Selected Documents [Parameter: 10]

The top five authors' countries are China, India, Iran, Saudi Arabia, and Pakistan. The most relevant sources are presented in Figure 6, and the popular sources are provided in Figure 7. Beyond China, the affiliated countries are mostly Asian nations classified as low socioeconomic countries. The high number of publications may be associated with the abundant plant diversity, which contributes to the novelty of research in green synthesis.

Based on number of documents, India affiliated authors contributed the most documents followed by China, Iran, Pakistan, and Korea. The plot identifies the variability of the source of plant extracts for reduction of Ce precursors in those countries rather than some countries such as European countries. The multiple country publications from India, China and Iran affiliation countries reflect the collaborative research supporting the output of research.

Figure 7 shows that the green synthesis of CeO₂ research is widely published in various international journals focusing on materials and nanotechnology. Based on the graph, the *Ceramics International*, *International Journal of Nanomedicine*, *Journal of Molecular Structure*, and *Materials Research Express* are the main sources and media in disseminating green synthesis of

Table 1. Most Cited Papers in Green Synthesis of CeO₂ NPs

Authors	Paper Title	Year	Journal	Citations
Charbgoon F.; Ahmad M.B.; Darroudi M.	Cerium oxide nanoparticles: Green synthesis and biological applications	2017	<i>International Journal of Nanomedicine</i>	253
Nadeem M.; Khan R.; Afridi K.; Nadhman A.; Ullah S.; Faisal S.; Mabood Z.U.; Hano C.; Abbasi B.H.	Green synthesis of cerium oxide nanoparticles (CeO ₂ NPs) and their antimicrobial applications: A review	2020	<i>International Journal of Nanomedicine</i>	210
Kannan S.K.; Sundrarajan M.	A green approach for the synthesis of a cerium oxide nanoparticle: Characterization and antibacterial activity	2014	<i>International Journal of Nanoscience</i>	183
Pansambal S.; Oza R.; Borgave S.; Chauhan A.; Bardapurkar P.; Vyas S.; Ghotekar S.	Bioengineered cerium oxide (CeO ₂) nanoparticles and their diverse applications: A review	2023	<i>Applied Nanoscience (Switzerland)</i>	103
Ahmed H.E.; Iqbal Y.; Aziz M.H.; Atif M.; Batool Z.; Hanif A.; Yaqub N.; Farooq W.A.; Ahmad S.; Fatehmulla A.; Ahmad H. Magudieswaran R.; Ishii J.; Raja K.C.N.; Terashima C.; Venkatachalam R.; Fujishima A.; Pitchaimuthu S.	Green synthesis of CeO ₂ nanoparticles from the <i>Abelmoschus esculentus</i> extract: Evaluation of antioxidant, anticancer, antibacterial, and wound-healing activities	2021	<i>Molecules</i>	94
Miri A.; Beiki H.; Najafidoust A.; Khatami M.; Sarani M.	Green and chemical synthesized CeO ₂ nanoparticles for photocatalytic indoor air pollutant degradation	2019	<i>Materials Letters</i>	87
Foroutan Z.; Afshari A.R.; Sabouri Z.; Mostafapour A.; Far B.F.; Jalili-Nik M.; Darroudi M.	Cerium oxide nanoparticles: Green synthesis using banana peel, cytotoxic effect, UV protection and their photocatalytic activity	2021	<i>Bioprocess and Biosystems Engineering</i>	59
	Plant-based synthesis of cerium oxide nanoparticles as a drug delivery system in improving the anticancer effects of free temozolomide in glioblastoma (U87) cells	2022	<i>Ceramics International</i>	51
Iqbal A.; Ahmed A.S.; Ahmad N.; Shafi A.; Ahamad T.; Khan M.Z.; Srivastava S.	Biogenic synthesis of CeO ₂ nanoparticles and its potential application as an efficient photocatalyst for the degradation of toxic amido black dye	2021	<i>Environmental Nanotechnology, Monitoring and Management</i>	45
Parvathy S.; Manjula G.; Balachandar R.; Subbaiya R.	Green synthesis and characterization of cerium oxide nanoparticles from <i>Artabotrys hexapetalus</i> leaf extract and its antibacterial and anticancer properties	2022	<i>Materials Letters</i>	41
Irshad M.S.; Aziz M.H.; Fatima M.; Rehman S.U.; Idrees M.; Rana S.; Shaheen F.; Ahmed A.; Javed M.Q.; Huang Q.	Green synthesis, cytotoxicity, antioxidant and photocatalytic activity of CeO ₂ nanoparticles mediated via orange peel extract (OPE)	2019	<i>Materials Research Express</i>	40
Zinatloo-Ajabshir S.; Mehrabadi Z.; Khojasteh H.; Sharifianjazi F.	Innovative fabrication of highly efficient CeO ₂ ceramic nanomaterials for enhanced photocatalytic degradation of toxic contaminants under sunlight	2024	<i>Ceramics International</i>	36

Zinatloo-Ajabshir S.; Mehrabadi Z.; Khojasteh H.; Sharifianjazi F.	Innovative fabrication of highly efficient CeO ₂ ceramic nanomaterials for enhanced photocatalytic degradation of toxic contaminants under sunlight	2024	<i>Ceramics International</i>	36
Rahdar A.; Beyzaei H.; Askari F.; Kyzas G.Z.	Gum-based cerium oxide nanoparticles for antimicrobial assay	2020	<i>Applied Physics A: Materials Science and Processing</i>	33
Zinatloo-Ajabshir S.; Ahmadi-Zeidabadi M.; Amiri M.; Sharifianjazi F. Alotaibi M.O.; Alotaibi N.M.; Ghoneim A.M.; Ain N.U.; Irshad M.A.; Nawaz R.; Abbas T.; Abbas A.; Rizwan M.; Ali S.	Innovative sono-synthesis of cerium dioxide nanomaterials using <i>Mentha</i> extract with efficient activity for cancer therapy application	2024	<i>Results in Engineering</i>	32
	Effect of green synthesized cerium oxide nanoparticles on fungal disease of wheat plants: A field study	2023	<i>Chemosphere</i>	30

Table 2. Varied CeO₂ Nanoparticle Sizes Obtained from Different Plant Extracts used for Green Synthesis

Plant Extract	Particle Size (nm)	Reference
<i>Gloriosa superba</i>	5	(Arumugam et al., 2015)
<i>Hibiscus sabdariffa</i>	3.9	(Thovhogi et al., 2015)
<i>Vigna radiata</i>	2.94	(Ahmad, 2023)
<i>Linum usitatissimum</i> seed	20	(Foroutan et al., 2024)
<i>Oroxylum indicum</i>	23.58	(Mim et al., 2024)
<i>Centella asiatica</i>	10	(Mamatha et al., 2024)
<i>Prosopis juliflora</i>	3.7	(Arunachalam et al., 2017)
<i>Azadirachta indica</i>	2	(Arunachalam et al., 2017)
<i>Pimpinella anisum</i>	100	(Alarfaj et al., 2024)
<i>Acacia concinna</i> fruit	22.7	(Muduli and Sahoo, 2022)
<i>Petroselinum crispum</i>	12.6	(Korotkova et al., 2019)
<i>Lemon grass</i>	10–40	(Maensiri et al., 2009)
<i>Azadirachta indica</i>	10–15	(Sharma et al., 2017)
<i>Acalypha indica</i>	35–45	(Magdalane et al., 2020)
<i>Melissa officinalis</i>	< 10	
<i>Pometia pinnata</i>	6–9	(Naidi et al., 2022)
<i>Citrus limon</i>	10–15	(Kumar et al., 2022)
<i>Linum usitatissimum</i> seed	20	(Foroutan et al., 2024)

use of plant extracts aligns with the green chemistry principles of using less hazardous chemicals and renewable resources as replacements for conventional chemical reducers such as sodium borohydride.

General methods for CeO₂ NPs synthesis include precipitation, mechanochemical, combustion, and sol-gel approaches (Lim et al., 2004; Farahmandjou et al., 2016; Ravishankar and Ramakrishna, 2015; Nosrati et al., 2023). The precipitation method can be performed using cerium(III) nitrate hexahydrate as a precursor and water (H₂O) as a solvent at varied pH values, or by mixing cerium precursors with ammonia solution (Liu et al., 2014; Shlapa et al., 2022). As the precipitate forms under alkaline conditions, the pH of the solution

determines the particle size and characteristics, including the morphology of the nanoparticles (Yan et al., 2007; Liu et al., 2014; Alpaslan et al., 2017).

The combustion method has been applied to synthesize CeO₂ using (NH₄)₂Ce(NO₃)₆ and EDTA disodium salt as oxidizer and fuel. In another approach, the combustion method involves mixing cerium precursors with polymer followed by firing at 800 °C (Secerov et al., 2008; Bakkiyaraj et al., 2016; Wang et al., 2022; Hosseiny et al., 2024). Mixing cerium hydroxide and urea as precursors forms a stable water-dispersed sol. The sol-gel system is produced by peptization using HCl, where H₃O⁺ acts as a charge stabilizer to prevent agglomeration of cerium hydroxide nanoparticles. The sol remains stable at

Table 3. Photocatalytic Activities of Some Plant-mediated CeO₂ NPs

Plant Extract Used for Synthesis	Band Gap Energy (eV)	Photocatalysis Reaction	Efficiency	Reference
<i>Psidium guajava</i> leaf	3.62	Methylene blue (MB) photocatalytic degradation	Degradation efficiency (DE) of 80% at 80 min	(Ahamed, 2022)
<i>Aloe vera</i> leaf	2.92–3.00	Malachite green (MG) photocatalytic degradation	DE of 97.5% at 180 min	(El-salamony and Aboutaleb, 2022)
<i>Mangifera indica</i>	3.3	Photocatalytic transformation of 4-nitrophenol to 4-nitrophenolate	Photocatalytic conversion of 17–19%	(Najihah et al., 2024)
<i>Manilkara zapota</i>	3.25–3.45	Photocatalytic degradation of crystal violet (CV) and tetracycline (TC)	DE for CV: 97.33%, TC: 93.4%	(Ayodhya et al., 2022)
Tea waste	No information	Photocatalytic degradation of Congo red (CR)	DE for CR: 95%	(Liu et al., 2021)
<i>Portulaca ortelacea</i>	No information	Photocatalytic degradation of methyl orange (MO)	DE for MO: 97%	(Hkiri et al., 2024)
<i>Crataegus</i> sp.	No information	Photocatalytic degradation of acid orange 7 (AO7)	DE of 98%	(Mutashar et al., 2025)
<i>Stevia rebaudiana</i> leaf	No information	Photocatalytic degradation of TC	DE of 80.06%	(Malakootian et al., 2024)
Turmeric	2.80–3.21	MB photocatalytic degradation	DE of 93% at 60 min	(Kalaycıoğlu et al., 2022)
<i>Saccostrea cucullata</i>	No information	MB photocatalytic degradation	DE of 99% at 70 min	(Safat et al., 2021)
<i>Tectona grandis</i>	No information	Rhodamine B (RhB) photocatalytic degradation	DE of 90% at 60 min	(Shetty et al., 2025)

pH ranging from 1.8 to 2 (Secerov et al., 2008). Calcination temperature is an important parameter influencing crystallite size, specific surface area, and pore diameter of CeO₂ NPs (Ramos-Huerta et al., 2025).

The green synthesis approach refers to the role of secondary metabolites in reducing Ce²⁺ precursors through simple mixing or intensified procedures such as microwave-assisted or ultrasound (US) irradiation methods. Phytoconstituents present in plant parts such as polyphenols, flavonoids, and flavanones act not only as reducing agents but also influence the morphology of nanoparticles, serving as stabilizing, capping, and reducing agents (Fatimah et al., 2020; Citradewi et al., 2021). Compared to sol-gel or combustion methods, the use of plant extracts reduces the need for solvents, surfactants, bases, and other templating agents.

For example, in the synthesis using *Ocimum tenuiflorum*, eugenol, quercetin, linolenic acid, palmitic acid, and guanosine are the main compounds responsible as reducing agents. Meanwhile, when using *Hibiscus sabdariffa* flower extracts, the major constituents include pyrogallol, glycerol, pyranone, linolenic acid, and palmitic acid. The nanoparticles are formed via complexation of cerium ions with hydroxyl or phenolic sites of the

secondary metabolites, as represented in Figure 12.

The use of *Quercus infectoria* as a bioreductor for CeO₂ NPs produced nanoparticles with sizes ranging from 26.8 to 50.28 nm, showing potential applications as antioxidant and antibacterial agents (Fahimeh et al., 2024). Other plant extracts utilized for the synthesis in the listed papers include *Abelmoschus esculentus*, *Jatropha curcas*, banana peel, *Caccinia macranthera*, *Phoenix dactylifera* fruit, *Artabotrys hexapetalus*, orange peel, and *Chenopodium quinoa* L., in addition to glucose and xanthan gum as green bioreductors (Ahmed et al., 2021; Iqbal et al., 2021; Miri et al., 2021; Parvathy et al., 2022). Various applications of CeO₂ NPs have been reported, including their use as antibacterial agents, photocatalysts, antifungal agents, and cancer therapeutics (Irshad et al., 2019; Magudieswaran et al., 2019; Zinatloo-Ajabshir et al., 2024).

Different components in the plant extracts determine the particle size distribution of the nanoparticles. Using *Stevia rebaudiana* and *Syzygium aromaticum* extracts, the particle sizes of CeO₂ NPs were found to be 20–30 nm and 65.6 nm, respectively (Malakootian et al., 2024; Alarfaj et al., 2024). *Olea* leaf-mediated CeO₂ NPs demonstrated distinct morphologies depending on the employed hydrothermal and microwave ir-

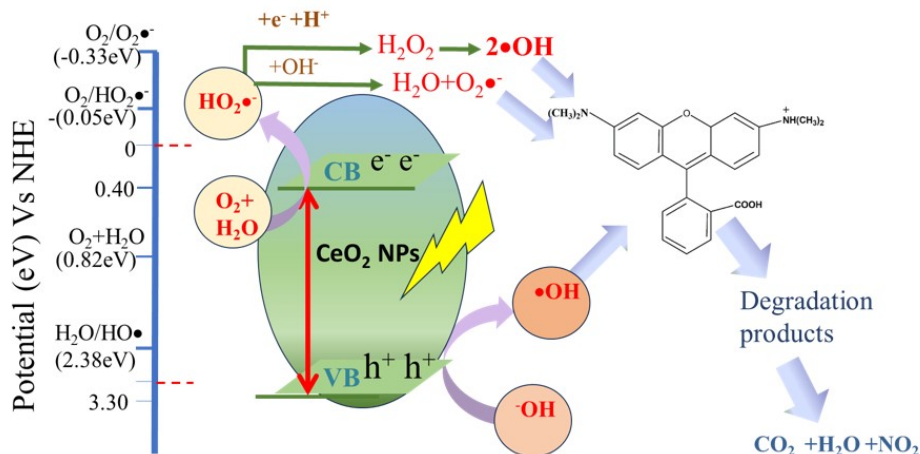


Figure 13. Photocatalytic Mechanism on CeO_2 NPs (Prieur et al., 2020; Doustkhah et al., 2023)

radiation methods (Gharbia et al., 2022). Table 2 summarizes the use of various plant extracts in CeO_2 NPs synthesis, highlighting the resulting nanoparticle sizes.

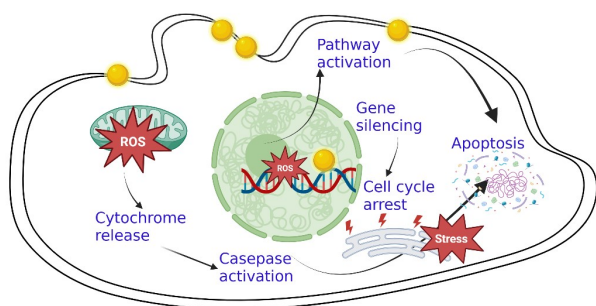


Figure 14. Anticancer Mechanism of CeO_2 NPs

6. APPLICATIONS OF GREEN SYNTHESIZED- CeO_2 NPs

The potency of CeO_2 NPs is regarded as its band gap energy within the range of 2.6 eV-3.2 eV that is responsible for capturing photons within the visible range, and it has been confirmed by some research exploring the efficacy of degradation efficiencies toward dyes and organic pollutants (You et al., 2019; Murugadoss et al., 2023). As light impinges on CeO_2 NPs, there will be an electron excitation from the valence band (VB) into the conduction band (CB), together with the formation of a hole (h^+). Furthermore, the interaction between the hole and the solvent, in this case producing OH^- , will lead to the formation

of hydroxyl radicals ($\cdot\text{OH}$). The propagation steps produce more radicals as oxidants to degrade organic compounds or pollutants Figure 13. From the CB site, $\cdot\text{O}_2^-$ is created by the interaction with the solvent. Similar to other metal oxide semiconductors, the photocatalytic activity depends on the physicochemical features of the particles, such as the particle size, which is governed by the synthesis method (Prieur et al., 2020; Mohajeri et al., 2025). With some parameters governing the photoactivity, band gap energy is the main factor, which in many cases also depends on the morphology, particle size, and purity of nanoparticle phases (Fatimah, 2018; Haq et al., 2021). Table 3 summarizes some green synthesized CeO_2 NPs by varied plant extracts and their photocatalytic activity.

Another application of CeO_2 NPs is as an anticancer agent. In some studies, the examination of anticancer activity was correlated with antioxidative and antibacterial activities (Parvathy and BR, 2017; Lu et al., 2022; Mohamed et al., 2025). The antibacterial activity of some plant-mediated synthesized CeO_2 NPs revealed sufficient evidence and potential against many bacterial strains such as *Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus subtilis*, and *Staphylococcus aureus* (Sehar et al., 2020; Zamani et al., 2021; Dar et al., 2022; Khan et al., 2024). The proven activity has been further developed for wound dressing applications (Shabrandi et al., 2017; Li et al., 2025). Chitosan-supported CeO_2 NPs have been applied on cutaneous experimental excisional wounds infected with *Pseudomonas aeruginosa* (Shabrandi et al., 2017; Huang et al., 2018).

The cytotoxicity of CeO_2 NPs has also been confirmed in various cancer cell tests (Chukavin et al., 2023; Yang et al., 2025). The anticancer mechanism of CeO_2 NPs is attributed to their ability to penetrate cancer cells through endocytic pathways Figure 14. Although the mechanism of anticancer activity involves reactive oxygen species (ROS) or reactive nitrogen species (RNS), many experiments tend to suggest that ROS is

primarily responsible for inducing cell stress, mitochondrial dysfunction, endoplasmic reticulum (ER) stress, autophagy, and DNA damage, ultimately leading to apoptosis (Das et al., 2013; Roshani et al., 2023). In addition, metal NPs can inhibit the cell cycle to prevent cancer proliferation. CeO₂ NPs have been reported to actively diminish the viability of breast cancer cell line AMJ13, brain cancer cell line AMGM5, and esophageal cancer cell line SK-GT-4 (Al-attar et al., 2025).

7. FUTURE PERSPECTIVES

Based on the published papers during 2023–2025, research on the green synthesis of CeO₂ NPs shows 331 documents, indicating a rapid growth and high potential for diverse applications in the future. Studies on CeO₂ nanocomposites, doped-CeO₂, and related biomedical applications have gained significant attention. The formation of CeO₂-based nanocomposites with materials such as g-C₃N₄, graphene, and ZSM-5 has been highlighted for their enhanced activity and functionality in environmental and biomedical fields (Huang et al., 2013; Kaur et al., 2016; Barathi et al., 2021). A hybrid material of mesoporous silica-CeO₂ conjugated with iRGD-grafted polyoxyethylene glycol exhibited high stability for wound dressing applications, which was attributed to the antibacterial activity of CeO₂ NPs (Zhou et al., 2022).

Microencapsulation of CeO₂ NPs also represents a promising and challenging direction for future applications (Shcherbakov et al., 2021; Zhang, 2022). However, studies on the integration of green-synthesized CeO₂ NPs into nanocomposites-evaluated not only for their advantages but also their potential drawbacks-remain limited. In many other metal oxide nanocomposites, the combination of functional features enhances their overall applicability, particularly in the context of green chemistry principles.

Nevertheless, reproducibility remains a critical issue, as the inconsistency in physicochemical characteristics of NPs hinders their industrial and medical applications, complicating comparisons across different studies. The variation in secondary metabolite content of plant extracts due to differences in climate, geography, and growth conditions contributes to this problem. Standardization of both the quantity and quality of bioreductive components in plant extracts could serve as a potential solution to improve consistency. Moreover, the scalability of green synthesis approaches for nanoparticle production remains a strategic and necessary focus for future industrial-scale implementation.

8. CONCLUSIONS

Based on bibliometric analysis, the green synthesis of CeO₂ NPs has emerged as one of the critical research focuses in nanoparticle synthesis, offering numerous applications compared to conventional synthesis methods. The utilization of plant extracts for nanoparticle preparation aligns with the principles of green chemistry, including the use of less hazardous chemicals, renewable resources, minimized environmental im-

pact, and safety-oriented design. Several studies have demonstrated the significant potential of CeO₂ NPs synthesis, as reflected by the increasing number of publications and citations. Based on the authors' affiliated countries, researchers from regions with abundant biodiversity have greater opportunities to contribute to this field. The mapping of keywords and co-authorship networks implies that strengthening international collaborations remains essential to enhance the capability of translating green-synthesized CeO₂ NPs into industrial applications.

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