

# Synthesis Approaches and Recent Advancement of CeO<sub>2</sub> Nanoparticles: A Short Review

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## Abstract:

Cerium dioxide (CeO<sub>2</sub>), also known as ceric oxide, ceric dioxide, ceria, or cerium oxide, is a rare-earth metal oxide that functions as an n-type semiconductor with a band gap of approximately 2.9 eV. It has attracted considerable attention due to its unique band characteristics, remarkable adsorption capacity, radiation stability, and versatile surface chemistry. The exceptional durability, biocompatibility, and reactivity of cerium oxide nanoparticles (CeO<sub>2</sub> NPs) further enhance their importance in advanced research and technological applications. Owing to these properties, CeO<sub>2</sub> NPs are extensively explored across diverse fields such as agriculture, medicine, sensing devices, cellular systems, and targeted drug delivery. Their high reactivity and distinctive physicochemical behavior make them promising candidates for agricultural applications, contributing to improved ecological balance and food productivity. Their proven biocompatibility, as evidenced by both *in vitro* and *in vivo* studies, supports their utilization in biomedical applications. This review highlights various synthesis approaches and discusses the advancement of cerium dioxide nanoparticles.

**Keywords:** ceric oxide, biocompatibility, synthesis approaches, nanoparticles.

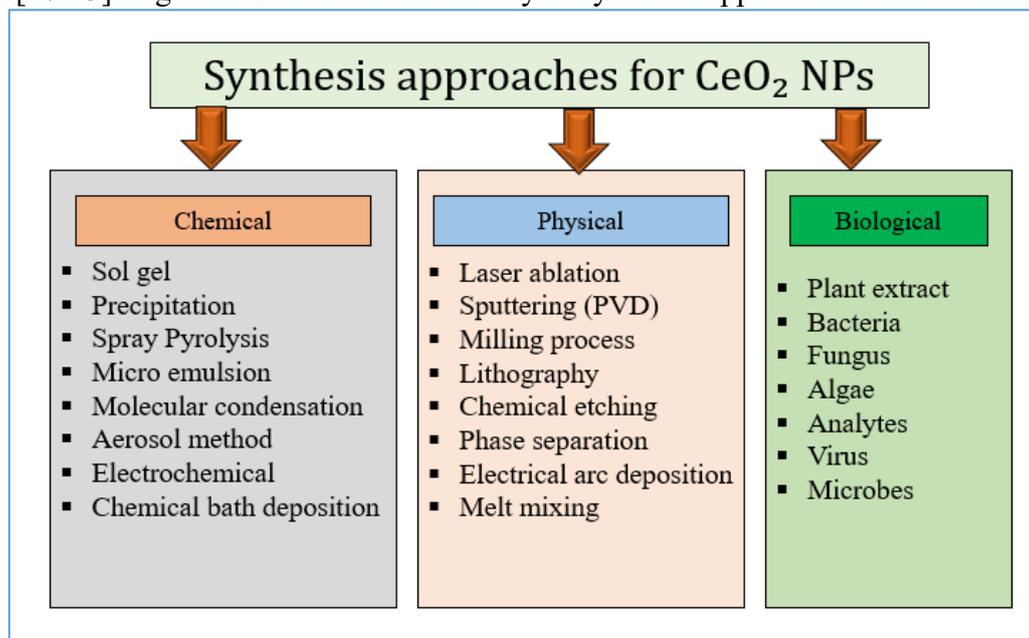
## 1. INTRODUCTION:

Nanotechnology has emerged as one of the most significant and rapidly expanding fields of research, attracting immense interest across every branch of science and technology. Its diverse applications span electronics, communications, industrial processes, energy, and biomedical sciences [1]. Within this domain, cerium oxide nanoparticles (CeO<sub>2</sub> NPs) have gained remarkable attention owing to their multifunctional nature and the possibility of synthesizing them through a variety of approaches, including chemical, physical, and biological methods [1,2]. CeO<sub>2</sub> is a rare-earth metal oxide, is particularly intriguing due to its unusual electrical and optical properties that stem from its unique 4f electron configuration. While the theoretical band gap of CeO<sub>2</sub> is about 6.0 eV, experimental studies have reported values ranging between 2.76 and 3.19 eV, which vary depending on the choice of precursor materials and synthesis techniques employed [3, 4]. A key factor underlying the functional versatility of CeO<sub>2</sub> is the presence of abundant surface oxygen vacancies. These vacancies not only act as active catalytic sites for adsorbate interactions but also enable facile oxygen storage and release, making CeO<sub>2</sub> a preferred material in catalysis, energy storage, and environmental applications [4, 5]. The concentration of oxygen vacancies can be enhanced either by reducing pure CeO<sub>2</sub> in oxygen-deficient environments or by introducing suitable dopant elements. However, for effective doping, the choice of dopants with appropriate ionic radii and concentrations is crucial, since these parameters directly affect the stability of the CeO<sub>2</sub> lattice and the distribution of defects [6, 7]. Compared with bulk ceria, nanocrystalline CeO<sub>2</sub> exhibits a much higher density of structural defects spread across the surface, grain boundaries, and lattice, which strongly governs its physicochemical behavior [8, 9]. These defects, along with tailored doping strategies, significantly modify the redox, electronic, and catalytic properties of CeO<sub>2</sub>, thereby broadening its applicability across multiple scientific and technological sectors.

Given these unique attributes, cerium oxide nanoparticles have been applied in diverse areas including catalysis, fuel cells, gas sensing, photocatalysis, environmental remediation, biomedical engineering, and drug delivery. Their structural tunability through controlled synthesis and doping strategies makes them one of the most promising multifunctional nanomaterials of current research interest. Therefore, this review paper emphasizes the synthesis strategies and highlights the recent advancements in the applications of CeO<sub>2</sub> nanoparticles across different interdisciplinary fields.

## 2. SYNTHESIS METHODS OF CERIUM DIOXIDE

CeO<sub>2</sub> NPs have attracted significant research interest due to their cost-effectiveness, catalytic durability, and stability under harsh environmental conditions. A wide range of synthesis methods have been reported in the literature, including spray pyrolysis, solvothermal evaporation, precipitation, hydrothermal processing, chemical bath deposition, microemulsion method, physical vapor deposition, sputtering, thermal oxidation, reversed micelle route, co-precipitation, forced hydrolysis, solvo-thermal synthesis, and the sol-gel method [10, 11]. These techniques allow the preparation of nanoparticles with desirable features such as high crystallinity, controlled particle size, large surface area, and fine crystallite dimensions. The choice of synthesis route plays a decisive role in tailoring the structural, morphological, and physicochemical characteristics of CeO<sub>2</sub>, which in turn directly influences its performance in specific applications. Since different synthesis approaches yield products with distinct surface morphologies, oxygen vacancy concentrations, and porosity, it is necessary to align the selected method with the intended application of the nanomaterials [10-13]. Figure 1 illustrates the diversity of synthesis approaches for CeO<sub>2</sub> NPs.



**Figure 1.** Synthesis approaches for CeO<sub>2</sub> nanoparticles

## 3. HISTORY AND LITERATURE SURVEY

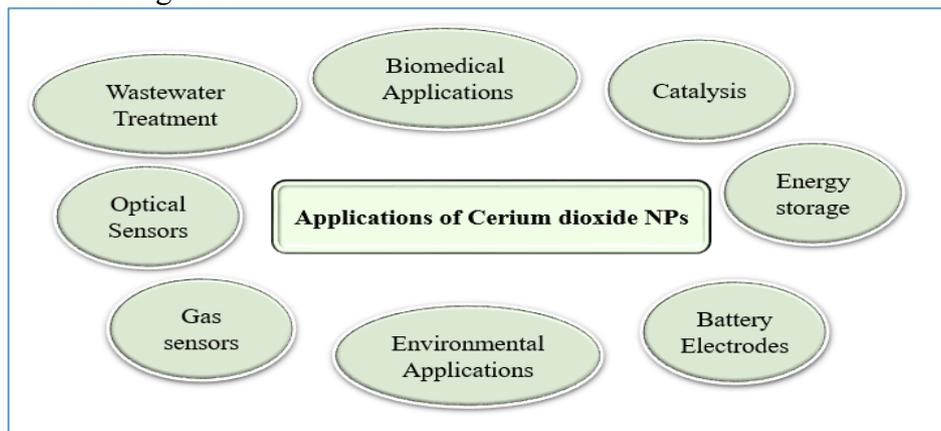
Cerium dioxide also known as ceria, is one of the most studied rare-earth oxides due to its unique fluorite-type crystal structure, high oxygen storage/release capability, and the facile redox transition between Ce<sup>4+</sup> and Ce<sup>3+</sup> oxidation states. The history of cerium dioxide applications dates back to the late 19th century, when ceria was used in gas mantles for lighting owing to its high thermal stability and luminescent properties [13]. During the early 20<sup>th</sup> century, CeO<sub>2</sub> gained industrial importance as a glass decolorizer and polishing agent, particularly for optical and precision polishing applications [14]. However, the major turning point in ceria research came in the 1970s, with the introduction of CeO<sub>2</sub> into automotive three-way catalysts (TWCs) to reduce exhaust emissions. In this system, CeO<sub>2</sub> functioned as an oxygen buffer, reversibly storing and releasing oxygen under lean and rich fuel conditions. This breakthrough firmly established ceria as a material of central importance in heterogeneous catalysis [15, 16]. The foundation for ceria catalysis was laid by the pioneering works of Trovarelli and co-workers, who comprehensively studied the redox behavior and structure-activity correlations of CeO<sub>2</sub>-based materials [17]. They demonstrated that the oxygen storage

capacity (OSC) of ceria originates from the ability of  $\text{Ce}^{4+}$  to undergo reversible reduction to  $\text{Ce}^{3+}$ , generating oxygen vacancies that enhance catalytic activity. This concept was further extended to doped systems such as  $\text{Ce-Zr-O}$ , where zirconium doping improved thermal stability and oxygen mobility, leading to the development of advanced ceria-zirconia solid solutions for TWCs [18]. These studies highlighted the importance of nanostructuring, morphology control, and defect engineering to maximize surface activity, particularly for oxidation reactions such as CO oxidation, soot oxidation, and the water-gas shift reaction [19]. With the advent of nanotechnology, research on cerium dioxide shifted toward nanoscale synthesis methods aimed at controlling particle size, shape, and defect concentration. Various synthesis approaches, including co-precipitation, sol-gel, hydrothermal/solvothermal, microemulsion, combustion, and flame spray pyrolysis, have been reported to produce  $\text{CeO}_2$  nanoparticles with controlled properties [20-22]. Hydrothermal synthesis, for instance, enables the fabrication of well-defined nanorods, nanocubes, and octahedra with specific crystallographic facets exposed, which significantly influence the redox properties and catalytic activity [23]. Combustion and solution-combustion routes offer rapid synthesis of highly crystalline ceria with large surface areas, while flame spray pyrolysis provides a scalable pathway for industrial production of nanoceria powders [24]. Moreover, doping with elements such as Zr, Gd, Sm, and Pr has been widely investigated to enhance oxygen vacancy concentration, ionic conductivity, and thermal durability, which are crucial for both catalytic and electrochemical applications [25]. Ceria nanoparticles have also gained significant attention in biomedical sciences due to their enzyme-mimetic or “nanozyme” properties. Early studies revealed that nanoceria could scavenge reactive oxygen species (ROS) through redox cycling between  $\text{Ce}^{3+}$  and  $\text{Ce}^{4+}$ , mimicking superoxide dismutase (SOD) and catalase activities [26]. This antioxidant property has been exploited in therapeutic applications such as neuroprotection, wound healing, antibacterial coatings, and treatment of oxidative stress-related diseases [27, 28]. Interestingly, the biological activity of nanoceria is strongly dependent on particle size, surface chemistry, and  $\text{Ce}^{3+}/\text{Ce}^{4+}$  ratio, which determine whether the nanoparticles behave as antioxidants or pro-oxidants [29]. Despite promising results, challenges remain in understanding long-term toxicity, biodistribution, and biocompatibility, which are essential for clinical translation. In addition to biomedical applications, nanoceria is widely employed in environmental and sensing fields. In gas sensors,  $\text{CeO}_2$ -based materials exhibit good sensitivity toward gases such as CO,  $\text{NO}_2$ ,  $\text{H}_2$ , and volatile organic compounds, owing to the strong interaction of gas molecules with oxygen vacancies on the ceria surface [30]. However, since pure ceria suffers from low electrical conductivity, its sensing performance is often improved by combining it with other oxides ( $\text{SnO}_2$ ,  $\text{ZnO}$ ,  $\text{TiO}_2$ ) or noble metals (Pt, Pd) to form heterostructures with enhanced response and selectivity [31]. Similarly, in photocatalysis and environmental remediation, ceria nanoparticles and composites have shown excellent activity in the degradation of pollutants under UV and visible light, attributed to their unique bandgap and redox cycling capabilities [32]. Another long-standing application of ceria is in the field of chemical-mechanical planarization (CMP) for glass and semiconductor industries. Nanosized ceria slurries are widely used for polishing silicon wafers and optical glass, where  $\text{Ce-O-Si}$  interactions at the surface, combined with mechanical abrasion, enable efficient and defect-free polishing [31, 32]. Recent studies have focused on optimizing slurry stability, dispersion, and interfacial chemistry to improve CMP performance for advanced electronic materials [33]. The literature reveals that cerium dioxide has evolved from a simple polishing and decolorizing agent to a multifunctional nanomaterial with applications in catalysis, energy, sensing, environmental remediation, and biomedicine. The key unifying theme across these domains is the control of oxygen vacancies and the  $\text{Ce}^{3+}/\text{Ce}^{4+}$  redox cycle, which govern the material’s physicochemical and functional properties. Recent advances in synthesis and defect engineering have opened new opportunities to tailor ceria nanoparticles for specific applications, while ongoing challenges such as scalability, reproducibility, and safety assessment must be addressed to fully exploit their potential.

#### 4. APPLICATIONS OF CERIUM DIOXIDE

Cerium dioxide nanoparticles have emerged as multifunctional nanomaterials owing to their unique redox properties, oxygen storage capacity, high surface-to-volume ratio, and ability to switch between  $\text{Ce}^{3+}$  and  $\text{Ce}^{4+}$  oxidation states. One of the most important applications of  $\text{CeO}_2$  NPs is in catalysis, particularly in automotive three-way catalytic converters, where they enhance CO oxidation,  $\text{NO}_x$  reduction, and hydrocarbon removal due to their excellent oxygen buffering ability [34, 35]. They are also widely studied as electrolyte and electrode materials in solid oxide fuel cells (SOFCs), where doping strategies have been

employed to improve oxide ion conductivity and thermal stability [36]. In the field of environmental remediation and photocatalysis, CeO<sub>2</sub>-based nanostructures are used for the degradation of organic dyes, wastewater treatment, and air purification under UV and visible light irradiation due to their tunable bandgap and surface reactivity [37]. CeO<sub>2</sub> NPs also demonstrate significant potential in gas sensing, where their oxygen vacancies and surface chemistry enhance sensitivity and selectivity toward toxic gases such as CO, NO<sub>2</sub>, and H<sub>2</sub>, making them suitable for environmental monitoring and industrial safety [38, 39]. Moreover, CeO<sub>2</sub> nanoparticles exhibit remarkable biomedical applications, including antioxidant, anti-inflammatory, antibacterial, and drug delivery properties, attributed to their regenerative radical scavenging capability, which mimics natural enzymes such as superoxide dismutase and catalase [40]. They have also been explored in wound healing, neuroprotection, and cancer therapy. The CeO<sub>2</sub> plays a vital role in chemical–mechanical planarization (CMP) in the semiconductor industry, where its hardness, stability, and surface chemistry make it a preferred abrasive for glass and silicon wafer polishing [41]. The multifunctionality of CeO<sub>2</sub> nanoparticles across catalysis, energy devices, environmental monitoring, biomedicine, and microelectronics underscores their immense technological importance and makes them a key subject of ongoing research. Few applications of CeO<sub>2</sub> NPs are reveal in Figure 2.



**Figure 2.** Applications of CeO<sub>2</sub> nanoparticles

## CONCLUSIONS AND FUTURE SCOPE

The cerium dioxide nanoparticles have emerged as a multifunctional material owing to their tunable physicochemical properties, oxygen storage and release capability, and stability under diverse operating conditions. Various synthesis methods, including sol–gel, hydrothermal, co-precipitation, solvothermal, and microemulsion techniques, have been successfully employed to obtain CeO<sub>2</sub> nanostructures with controlled morphology, crystallinity, and surface chemistry. These tailored nanostructures have found wide applications in catalysis, gas sensing, energy storage, photocatalysis, biomedical fields, and environmental remediation. Despite remarkable progress, challenges remain in achieving large-scale, cost-effective, and environmentally benign synthesis routes that can precisely regulate particle size, oxygen vacancy concentration, and surface activity. The future scope of CeO<sub>2</sub> research lies in the development of green synthesis strategies, doping and composite formation for property enhancement, and advanced surface engineering to improve catalytic and sensing efficiency. Furthermore, integrating CeO<sub>2</sub> nanoparticles into multifunctional nanohybrids and exploring their potential in next-generation energy systems, drug delivery, and agricultural sustainability present promising directions. With continuous advances in synthesis approaches and characterization techniques, CeO<sub>2</sub> nanoparticles are expected to play a vital role in bridging material innovation with real-world applications.

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