

# From Precursors to Performance: Diverse Synthesis Strategies for Cerium Oxide Nanoparticles

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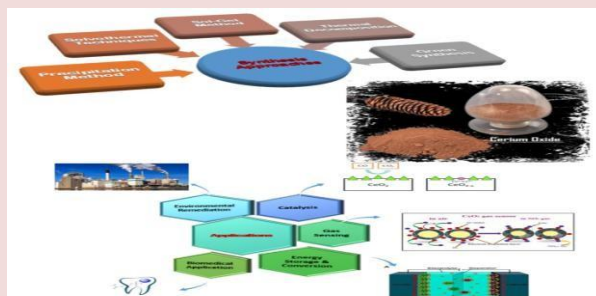
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## Abstract

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) have garnered significant attention owing to their unique redox properties, high surface-to-volume ratio, and exceptional biocompatibility. This review systematically explores the diverse methodologies employed for the synthesis of CeO<sub>2</sub> NPs, including conventional physicochemical techniques and emerging green synthesis approaches leveraging plant extracts and biomolecular mediators for sustainable production. The multifunctional applications of CeO<sub>2</sub> NPs are critically examined, with a focus on their catalytic efficiency, environmental remediation capabilities, and roles in energy storage systems. Additionally, their biomedical applications, particularly in oxidative stress modulation, anti-inflammatory therapies, and wound healing, are highlighted. Advanced applications such as photocatalytic degradation of pollutants and their integration into hybrid nanocomposites for energy storage and conversion are discussed in detail. The review also addresses current limitations in the scalability and functional optimization of CeO<sub>2</sub> NPs, offering insights into prospective research directions. This comprehensive analysis underscores the pivotal role of CeO<sub>2</sub> NPs in advancing sustainable nanotechnologies and fostering interdisciplinary innovation.



**KEYWORDS:** Cerium Oxide Nanoparticles, Green Synthesis, Redox Properties, Biomedical Applications, Environmental Remediation, Photocatalysis, Energy Storage

## 1. Introduction

Nanotechnology has transformed material science and engineering, enabling the design and application of materials at the atomic and molecular levels. Among these materials, cerium oxide nanoparticles ( $\text{CeO}_2$  NPs) have emerged as one of the most promising and versatile nanomaterials due to their unique physicochemical properties and wide applicability across multiple scientific domains [1].  $\text{CeO}_2$  NPs, derived from cerium, a rare earth element, exhibit exceptional redox properties, high oxygen storage capacity, and the ability to alternate between  $\text{Ce}^{3+}$  and  $\text{Ce}^{4+}$  oxidation states. These attributes render them ideal candidates for catalytic, environmental, biomedical, and energy applications [2]. The widespread interest in  $\text{CeO}_2$  NPs can be attributed to their remarkable reactivity and adaptability in different functional environments [3]. Their redox potential, combined with their ability to scavenge free radicals, positions them as effective agents in mitigating oxidative stress, an underlying factor in many degenerative diseases. In addition to their biomedical utility,  $\text{CeO}_2$  NPs have demonstrated efficacy in catalysis, particularly in automotive catalytic converters, where they facilitate the oxidation of harmful gases, contributing to pollution control [4]. Furthermore, their role in energy applications, such as supercapacitors and solid oxide fuel cells, underlines their importance in addressing critical energy and environmental challenges. Synthesis techniques for  $\text{CeO}_2$  NPs have evolved significantly to meet the growing demand for precise control over their size, morphology, and functional properties [5]. Traditional physicochemical methods, including sol-gel, hydrothermal, and precipitation techniques, offer high precision but are often energy-intensive and reliant on hazardous chemicals, which raises concerns about their environmental footprint. Consequently, researchers have turned to green synthesis approaches, which employ plant extracts, microorganisms, and other bio-based agents [6]. These eco-friendly methods not only reduce environmental impact but also impart biocompatibility and enhanced functional properties to the nanoparticles, making them suitable for

biomedical applications. The applications of  $\text{CeO}_2$  NPs span diverse fields, demonstrating their multifunctionality and transformative potential [7]. In environmental remediation, they are widely used in photocatalytic processes for degrading organic pollutants and improving water quality. In energy technology,  $\text{CeO}_2$  NPs contribute to the development of advanced electrodes for supercapacitors, hybrid batteries, and fuel cells [8]. In biomedicine, their antioxidant and anti-inflammatory properties have led to their use in therapies targeting oxidative stress, neurodegenerative diseases, and cancer [9]. The development of composite materials incorporating  $\text{CeO}_2$  NPs has further expanded their applications, providing solutions for advanced coatings, sensors, and medical implants [10]. Despite their immense potential, several challenges hinder the widespread adoption and optimal utilization of  $\text{CeO}_2$  NPs. Scalability remains a significant hurdle, as conventional synthesis methods often struggle to meet industrial-scale production requirements without compromising quality [11]. Additionally, achieving consistent surface functionalization and addressing potential cytotoxicity concerns are critical for advancing their biomedical applications.

Furthermore, the environmental and economic sustainability of  $\text{CeO}_2$  NPs production requires further exploration, particularly in light of the increasing demand for rare earth elements [12]. This review aims to provide a comprehensive analysis of the synthesis strategies, properties, and applications of  $\text{CeO}_2$  NPs while addressing the challenges and opportunities in this rapidly evolving field. By integrating insights from recent research, this work highlights the transformative potential of  $\text{CeO}_2$  NPs in catalysis, energy, biomedicine, and environmental applications [13]. Moreover, it identifies key gaps in current knowledge and proposes future research directions to unlock the full capabilities of  $\text{CeO}_2$  NPs. Through this effort, the review seeks to underscore the critical role of  $\text{CeO}_2$  NPs in advancing nanotechnology and driving innovation in sustainable and interdisciplinary scientific domains.

### 1.1) Unique Properties of Cerium Oxide Nanoparticles

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) possess unique properties that underpin their wide- ranging applications. Their rapid redox cycling between Ce<sup>3+</sup> and Ce<sup>4+</sup> oxidation states enables them to participate efficiently in catalytic reactions by readily donating or accepting electrons, significantly enhancing catalytic performance in processes such as pollutant degradation and automotive catalytic conversions[14]. Additionally, CeO<sub>2</sub> NPs demonstrate the ability to reversibly store and release oxygen within their lattice structure, a characteristic crucial for applications in three- way catalysis and solid oxide fuel cells[15]. This oxygen buffering capacity supports the simultaneous oxidation of hydrocarbons and carbon monoxide while reducing nitrogen oxides, playing a critical role in energy and environmental technologies[16]. At the nanoscale, cerium oxide exhibits a high surface area with abundant surface-active sites, which enhances molecular interactions and improves the efficiency of catalytic and adsorption processes. This increased surface area is essential for applications in environmental remediation, energy conversion, and storage technologies[17]. Furthermore, emerging research highlights the biocompatibility of CeO<sub>2</sub> NPs, emphasizing their potential in biomedical applications. Their inherent antioxidant properties allow them to scavenge reactive oxygen species (ROS), mitigating oxidative stress and offering therapeutic potential for conditions such as neurodegenerative diseases and cancer[18]. This biocompatibility also extends their utility in diagnostics and drug delivery systems. These remarkable properties make CeO<sub>2</sub> NPs a transformative material, bridging critical advancements across catalysis, energy, biomedicine, and environmental science. Their multifunctionality positions them as an indispensable component in the development of sustainable and innovative nanotechnological solutions[19].

### 2.0 SYNTHESIS APPROACHES

Synthesis methods significantly influence the

physico- chemical properties—such as crystallite size, shape, surface defects, and oxygen vacancy concentration of CeO<sub>2</sub> NPs. Below are some of the most widely adopted techniques.

#### 2.1) Precipitation Method

The precipitation method, also known as co-precipitation, is a widely employed technique for synthesizing cerium oxide nanoparticles (CeO<sub>2</sub> NPs) due to its simplicity, cost- effectiveness, and scalability[20]. In this process, a cerium precursor, such as cerium nitrate or cerium chloride, is dissolved in an aqueous solution. Subsequently, a base, commonly ammonia or sodium hydroxide, is introduced to the solution, triggering the precipitation of cerium hydroxide[21]. This intermediate is then thermally treated to yield cerium oxide nanoparticles. This method is particularly attractive because of its straightforward procedure and low operational costs, making it suitable for large-scale production [22]. However, there are inherent challenges associated with the technique. Achieving precise control over particle size distribution can be difficult, and the resulting nanoparticles often exhibit a tendency to agglomerate, which may limit their applicability in certain advanced fields. Despite these limitations, careful tuning of synthesis parameters can mitigate these issues and significantly enhance the quality of the resulting nanoparticles[23]. Key parameters that influence the precipitation process include temperature, pH, and the choice of cerium precursor[24]. Temperature plays a critical role in determining the kinetics of the precipitation reaction and subsequent crystal growth. Lower temperatures may yield smaller particles, whereas higher temperatures can promote crystallinity[25]. The pH of the reaction medium directly impacts the rate of nucleation and growth, with optimal pH levels required to produce uniform and monodisperse nanoparticles[26]. Additionally, the type of precursor used can influence the solubility, purity, and morphology of the final CeO<sub>2</sub> NPs, necessitating careful selection based on the intended application[27]. By fine-tuning these parameters,

researchers can improve particle uniformity, minimize agglomeration, and tailor the properties of CeO<sub>2</sub> NPs for specific applications. Despite its limitations, the precipitation method remains a cornerstone in nanoparticle synthesis, offering a balance between cost-efficiency and the ability to produce high-quality materials at scale[28].

## 2.2) Hydrothermal and Solvothermal Techniques

Hydrothermal and solvothermal synthesis methods have become indispensable for the production of high-quality cerium oxide nanoparticles (CeO<sub>2</sub> NPs) due to their ability to offer precise control over nanoparticle properties [29, 30]. These methods utilize sealed, high-pressure environments, typically within an autoclave, where reactions occur under elevated temperatures and pressures. The hydrothermal method employs water as the reaction medium, whereas solvothermal synthesis extends to the use of organic solvents, enabling a broader range of reaction conditions and tunability[31]. The controlled reaction environment in hydrothermal and solvothermal methods significantly enhances the crystallinity of CeO<sub>2</sub> NPs[32]. Under high-temperature and high-pressure conditions, uniform nucleation and growth processes occur, suppressing the formation of structural defects and improving the nanoparticles' overall stability and performance. These conditions also allow the fine-tuning of nanoparticle size and shape, which is critical for tailoring their functionality for specific applications[33]. By adjusting synthesis parameters such as temperature, pressure, reaction time, and solvent type, researchers can produce nanoparticles with various morphologies, including nanocubes, nanorods, nanospheres, and hierarchical structures[34]. Each morphology provides unique surface properties and interaction dynamics, making these techniques highly versatile for customizing nanoparticles to optimize their performance in diverse fields such as catalysis, energy storage, and biomedical applications[35]. Advantages of hydrothermal and solvothermal methods are particularly evident in their ability to produce nanoparticles with uniform size distribution and

highly crystalline structures[36]. These properties are essential for applications that demand high surface activity and stability, such as photocatalysis, fuel cell technology, and antioxidative therapies. The solvothermal method, in particular, allows for the use of non-aqueous solvents, which can influence the solubility and reactivity of precursors, providing additional control over the properties of the synthesized nanoparticles [37]. However, these methods are not without limitations. The requirement for specialized equipment, such as high-pressure autoclaves, increases the initial cost and complexity of these techniques, potentially limiting their accessibility[38]. Moreover, the reaction times are typically long, often extending to several hours or even days, and the high energy demands for maintaining elevated temperatures and pressures can increase operational costs. These factors make hydrothermal and solvothermal methods less favorable for large-scale, cost-sensitive production scenarios[39]. Despite these challenges, the unique advantages of hydrothermal and solvothermal techniques make them a cornerstone in the synthesis of cerium oxide nanoparticles[40]. Their ability to deliver superior crystallinity, tailored morphologies, and controlled particle sizes makes them ideal for advanced applications. Ongoing research into optimizing these methods aims to address their current limitations, focusing on reducing energy consumption, developing alternative low-cost autoclave designs, and exploring hybrid methods that combine hydrothermal or solvothermal processes with other techniques to enhance scalability[41].

Hydrothermal and solvothermal techniques represent a highly effective approach for the synthesis of CeO<sub>2</sub> NPs, offering unparalleled control over nanoparticle properties. By enabling the precise manipulation of particle size, shape, and crystallinity, these methods continue to drive innovation in the development of nanomaterials for cutting-edge applications in catalysis, energy, biomedicine, and environmental science[42].

## 2.3) Sol-Gel Method

The sol-gel technique is a widely utilized method for synthesizing cerium oxide nanoparticles (CeO<sub>2</sub> NPs), offering excellent control over chemical composition and homogeneity. This technique involves a two-step transformation of a liquid precursor solution ("sol") into a solid three-dimensional network ("gel") through hydrolysis and condensation reactions[43]. The process is particularly attractive for producing highly pure and uniform nanoparticles, making it a preferred approach in advanced material synthesis [44]. The process begins with the hydrolysis of metal alkoxide or metal salt precursors, during which the metal reacts with water to form hydroxyl (M–OH) bonds[45]. This step is followed by condensation reactions, where M–OH groups undergo cross-linking to form a continuous gel-like network. The resulting gel is then aged, dried, and subjected to thermal treatment to produce cerium oxide nanoparticles[46]. This approach provides a high degree of control over particle composition and structure, enabling the synthesis of CeO<sub>2</sub> NPs with desirable properties tailored for specific applications. One of the key advantages of the sol-gel technique is its ability to achieve exceptional chemical homogeneity, ensuring uniform distribution of the precursor materials at the molecular level[47]. Additionally, the process typically occurs at relatively low processing temperatures compared to other synthesis methods, reducing energy consumption and allowing for the integration of temperature-sensitive additives[48]. These features make the sol-gel technique particularly suitable for applications where precise control over material properties is critical, such as in catalysis, coatings, and optical materials. Its benefits, the sol-gel technique has certain drawbacks[49]. The process is time-intensive, requiring extended aging and drying periods to achieve gel stability and prevent structural collapse. Moreover, the drying stage poses a significant risk of cracking due to shrinkage, particularly when dealing with large-scale gels or thick films[50]. These challenges necessitate careful optimization of synthesis parameters, such as the precursor concentration, water-to-precursor ratio,

and drying conditions, to minimize defects and improve yield. The sol-gel technique is a versatile and effective method for synthesizing CeO<sub>2</sub> NPs, offering superior control over chemical composition and structural properties[51]. While it demands longer processing times and careful handling during drying, the benefits of chemical homogeneity, low processing temperatures, and precision make it a valuable tool for producing high-quality nanoparticles for advanced applications in catalysis, energy storage, and functional coatings[52].

#### 2.4) Thermal Decomposition

Thermal decomposition is a straightforward and efficient method for synthesizing cerium oxide nanoparticles (CeO<sub>2</sub> NPs), widely used for its simplicity and scalability[53]. The process involves the thermal treatment of cerium precursors, such as cerium acetate or cerium oxalate, under controlled conditions. When heated, these precursors decompose to release gaseous byproducts, leaving behind cerium oxide in its crystalline form[54]. This method is particularly well-suited for producing nanoparticles on a large scale, making it attractive for industrial applications. Primary advantages of thermal decomposition is its simplicity. The process requires relatively minimal equipment and straightforward operational steps, which lowers production costs and enables scalability. Additionally, the direct conversion of precursors into cerium oxide makes this method efficient for producing high-purity nanoparticles with minimal contamination. The ability to scale up production further enhances its applicability in areas such as catalysis, coatings, and energy storage[55]. This method has several challenges that need to be addressed for optimal outcomes. Precise temperature control is critical to ensure the complete decomposition of precursors and to prevent the formation of undesired phases, such as cerium hydroxide or intermediate oxides. Failure to maintain accurate temperature settings can lead to impurities, reducing the performance and functionality of the nanoparticles. Moreover, high

temperatures used during decomposition often promote agglomeration of nanoparticles, resulting in larger particles with reduced surface area, which can diminish their catalytic efficiency and other desirable properties[56]. To mitigate these drawbacks, several strategies can be employed. Temperature ramping techniques, where the temperature is gradually increased, can help achieve uniform decomposition and minimize agglomeration. Additionally, incorporating stabilizing agents or surfactants during the synthesis process can further reduce particle aggregation, ensuring a more uniform product. Thermal decomposition offers a straightforward and scalable approach for synthesizing cerium oxide nanoparticles, making it a practical choice for industrial-scale production. While challenges such as phase control and agglomeration at high temperatures exist, careful optimization of synthesis parameters can enhance the quality and performance of the nanoparticles. This method remains a valuable tool in the development of CeO<sub>2</sub> NPs for a variety of applications in catalysis, energy storage, and environmental remediation[57].

### 2.5) Green Synthesis

Green or bio-inspired synthesis represents a sustainable and environmentally conscious method for the production of cerium oxide nanoparticles (CeO<sub>2</sub> NPs). This approach utilizes biological resources, such as plant extracts, microorganisms, and other biogenic materials, to reduce cerium salts into nanoparticles[58]. The natural components in these biological agents serve dual roles as reducing and stabilizing agents, facilitating the formation of nanoparticles under mild reaction conditions. This method aligns with the principles of green chemistry, emphasizing minimal environmental impact and reduced use of hazardous reagents[59]. The process typically involves the use of phytochemicals in plant extracts, enzymes in microbial systems, or other biogenic compounds to mediate the synthesis. Phytochemicals such as polyphenols, alkaloids, and flavonoids reduce cerium ions, while simultaneously acting as capping agents to stabilize the nanoparticles. The mild

reaction conditions, including ambient temperatures and neutral pH, contribute to the eco-friendly nature of this synthesis method. These characteristics make green synthesis particularly suited for applications in fields requiring biocompatible and non-toxic materials, such as biomedicine and environmental remediation[60]. The advantages of green synthesis are significant. It offers an environmentally sustainable alternative to conventional methods by eliminating the need for harsh chemicals and reducing energy consumption. The inherent biocompatibility of nanoparticles synthesized using biological agents enhances their suitability for therapeutic applications, including drug delivery, antioxidant therapies, and biomedical imaging[61]. The surface functionalization imparted by natural capping agents improves the colloidal stability and reactivity of the nanoparticles, broadening their applicability across various fields. These properties make green synthesis an attractive method for producing nanoparticles that meet both ecological and functional criteria[62]. Challenges associated with green synthesis include variability in biological resources, which can lead to inconsistencies in nanoparticle properties such as size, shape, and yield[63]. The composition of plant extracts and microbial systems is influenced by factors like geographical origin, seasonal changes, and environmental conditions, introducing variability into the synthesis process. This lack of reproducibility poses difficulties for standardization, especially in applications that demand precise control over nanoparticle characteristics[64]. Additionally, scaling up the synthesis for industrial applications requires significant quantities of biological materials, which may be resource-intensive and introduce logistical challenges[65]. Recent research focuses on standardizing the synthesis process by utilizing engineered biological systems or synthetic analogs of natural compounds to enhance reproducibility. The development of robust and reproducible protocols, including the use of well-characterized and consistent biological resources, is essential for addressing these challenges[66]. Combining green synthesis with complementary techniques, such as hydrothermal or solvothermal methods, is being explored to

overcome scalability limitations and achieve improved control over nanoparticle properties. Green or bio-inspired synthesis offers a promising alternative to traditional methods for producing cerium oxide nanoparticles. Its emphasis on sustainability, reduced toxicity, and compatibility with biomedical applications highlights its potential for addressing current demands in nanotechnology and material science. Advances in standardization and hybridization of methods are likely to enhance the feasibility and effectiveness of this approach for large-scale and interdisciplinary applications[67].

### 3.0 APPLICATIONS OF CERIUM OXIDE NANOPARTICLES

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) exhibit remarkable catalytic, antioxidant, and regenerative properties, making them highly versatile in various applications. They are widely used in biomedical fields for drug delivery, neuroprotection, and antioxidant therapies. Their catalytic activity finds relevance in environmental protection, such as wastewater treatment and fuel cells[68]. Additionally, CeO<sub>2</sub> NPs are utilized in industrial applications, including UV shielding, sensors, and as additives in cosmetics and coatings. Some of its applications are as following:

#### 3.1 Catalysis

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) have emerged as critical materials in catalysis due to their exceptional oxygen storage/release capacity, reversible redox behavior (Ce<sup>3+</sup>/Ce<sup>4+</sup>), and high thermal stability[53]. In automotive applications, CeO<sub>2</sub> NPs are integral to three-way catalytic converters, where they dynamically buffer the oxygen concentration by alternately storing and releasing oxygen. This property facilitates the efficient oxidation of carbon monoxide (CO) and hydrocarbons (HCs) into carbon dioxide (CO<sub>2</sub>) and the reduction of nitrogen oxides (NO<sub>x</sub>) into nitrogen (N<sub>2</sub>)[69]. The unique redox capability of CeO<sub>2</sub> thus enhances the catalytic efficiency and contributes to stringent emission control standards. In industrial

catalysis, CeO<sub>2</sub> NPs serve as active catalysts or catalyst supports in reactions such as the water-gas shift reaction (WGS) for hydrogen production and oxidative desulfurization for sulfur removal from fuels. The catalytic activity of CeO<sub>2</sub> is significantly augmented by doping with metals like zirconium (Zr), copper (Cu), or other rare earth elements[70]. These dopants enhance the structural properties, improve oxygen mobility, and increase surface area, which collectively optimize reaction kinetics and stability under harsh operating conditions. The ability of CeO<sub>2</sub> to undergo reversible oxygen exchange, combined with its structural versatility, positions it as a cornerstone material in both automotive and industrial catalytic processes, advancing sustainable energy and environmental technologies[71].

#### 3.2) Energy Storage and Conversion

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) are increasingly recognized for their critical role in energy storage and conversion technologies due to their unique redox properties, high ionic conductivity, and excellent thermal stability. These attributes make CeO<sub>2</sub> a material of choice in advanced systems like solid oxide fuel cells (SOFCs) and solar-driven thermochemical cycles, which are pivotal in the shift toward sustainable energy solutions. The context of solid oxide fuel cells (SOFCs), doped CeO<sub>2</sub> serves as a high-performance electrolyte or interlayer material. SOFCs rely on the transport of oxygen ions across the electrolyte to facilitate electrochemical reactions that convert chemical energy into electrical energy[72]. Conventional SOFCs, which use materials like yttria-stabilized zirconia (YSZ) as electrolytes, require operating temperatures exceeding 800°C. However, these high temperatures often result in thermal degradation and reduced system longevity. CeO<sub>2</sub>, particularly when doped with trivalent ions such as gadolinium (Gd<sup>3+</sup>) or samarium (Sm<sup>3+</sup>), exhibits significantly higher ionic conductivity at intermediate temperatures (500–700°C). This improvement arises from the increased concentration of oxygen vacancies introduced by

doping, which enhances oxygen ion transport[73]. By enabling SOFCs to operate efficiently at lower temperatures, doped CeO<sub>2</sub> reduces thermal stress, improves durability, and lowers manufacturing and operational costs. Furthermore, its role as an interlayer minimizes undesired reactions between other cell components, further enhancing the performance and longevity of the SOFC system. Solar-driven thermochemical cycles, in which CeO<sub>2</sub> stands out for its ability to harness concentrated solar energy for the splitting of water (H<sub>2</sub>O) and carbon dioxide (CO<sub>2</sub>). These cycles operate by leveraging the redox flexibility of cerium oxide, which alternates between its reduced (Ce<sup>3+</sup>) and oxidized (Ce<sup>4+</sup>) states. Under high-temperature solar irradiation, CeO<sub>2</sub> undergoes a thermochemical reduction, releasing oxygen and creating oxygen vacancies within its lattice structure[74]. In the subsequent oxidation step, the reduced CeO<sub>2</sub> reacts with H<sub>2</sub>O or CO<sub>2</sub> to produce hydrogen (H<sub>2</sub>) or carbon monoxide (CO), respectively. The hydrogen produced can serve as a clean fuel, while the carbon monoxide can be combined with hydrogen to synthesize syngas, a versatile precursor for a variety of fuels and chemicals. This process not only provides a pathway for storing solar energy in chemical form but also offers a means for recycling CO<sub>2</sub>, contributing to the development of carbon-neutral energy technologies. The high thermal stability of CeO<sub>2</sub>, combined with its rapid redox kinetics and scalability, makes it particularly well-suited for integration into large-scale solar reactors. Furthermore, advancements in material engineering, such as nanoscale structuring and doping with elements like zirconium (Zr) or hafnium (Hf), have further optimized its performance by enhancing its redox capacity and reaction rates. These innovations ensure that CeO<sub>2</sub>-based thermochemical systems can operate efficiently under the extreme conditions required for solar fuel production. The versatility and efficiency of CeO<sub>2</sub> NPs in energy storage and conversion underscore their importance in advancing clean energy technologies. Their integration into SOFCs and solar thermochemical cycles represents a significant step toward achieving sustainable energy systems, highlighting the material's transformative potential in addressing

### 3.3) Environmental Remediation

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) have demonstrated significant potential in environmental remediation due to their surface chemistry, redox properties, and photocatalytic capabilities[76]. Their high reactivity and ability to neutralize pollutants make them an effective material for mitigating environmental contamination in water, soil, and air. One of the key applications of CeO<sub>2</sub> NPs is the adsorption of pollutants. The surface of CeO<sub>2</sub> exhibits a high density of oxygen vacancies, which act as active sites for binding various contaminants. These include heavy metal ions such as lead (Pb<sup>2+</sup>), mercury (Hg<sup>2+</sup>), and arsenic (As<sup>3+</sup>), as well as organic dyes like methylene blue and rhodamine B, which are prevalent in industrial wastewater[77]. The nanoscale dimensions of CeO<sub>2</sub> provide a high surface area, enhancing its adsorption efficiency and enabling effective removal of pollutants from contaminated media. CeO<sub>2</sub> NPs also exhibit strong photocatalytic activity, making them suitable for the degradation of organic pollutants under UV or visible light. Upon light exposure, CeO<sub>2</sub> generates electron-hole pairs, which interact with water and oxygen molecules to produce reactive oxygen species (ROS), such as hydroxyl radicals (•OH) and superoxide anions (O<sub>2</sub><sup>-•</sup>). These ROS oxidize and break down complex organic molecules into simpler, less harmful compounds, ultimately mineralizing them into CO<sub>2</sub> and water[78]. CeO<sub>2</sub> is effective in degrading persistent pollutants like pesticides, pharmaceuticals, and aromatic hydrocarbons. The photocatalytic efficiency of CeO<sub>2</sub> can be enhanced by doping with metals such as zinc or titanium or coupling with other semiconductors like TiO<sub>2</sub> or ZnO, which extend its light absorption range into the visible spectrum and improve its performance under natural sunlight. The redox flexibility of CeO<sub>2</sub>, enabled by the reversible transition between Ce<sup>3+</sup> and Ce<sup>4+</sup> states, allows it to catalytically reduce toxic substances such as nitrogen oxides (NO<sub>x</sub>) or sulfur oxides (SO<sub>x</sub>) in gaseous emissions. This makes CeO<sub>2</sub> an effective

material for both water treatment and air purification, as well as for controlling industrial emissions[79]. The multifunctional properties of CeO<sub>2</sub> NPs in pollutant adsorption and photocatalysis highlight their significance in environmental remediation. Research efforts aimed at improving their efficiency through doping, nanoscale engineering, and composite development are likely to expand their applications in sustainable environmental management[80].

### 3.4) Gas Sensing

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) are highly effective materials for gas sensing applications due to their exceptional redox properties and surface reactivity. The redox cycling of cerium ions between Ce<sup>3+</sup> and Ce<sup>4+</sup> states enables dynamic detection of gaseous analytes, such as carbon monoxide (CO), hydrogen (H<sub>2</sub>), and volatile organic compounds (VOCs)[81]. This redox activity facilitates gas adsorption and reaction on the CeO<sub>2</sub> surface, leading to measurable changes in electrical conductivity or other properties, which form the foundation of gas-sensing mechanisms[82]. The performance of CeO<sub>2</sub>-based gas sensors is strongly influenced by particle size, defect density, and surface characteristics. Smaller particle sizes increase the specific surface area, providing more active sites for gas interactions. High oxygen vacancy density enhances adsorption and promotes redox reactions with target gases, improving sensitivity and reducing detection limits. Optimizing these structural features is crucial for achieving efficient and reliable gas sensing[83].

Material modifications often improve sensor performance. Doping CeO<sub>2</sub> with transition metals such as copper or iron, or rare earth elements like gadolinium or samarium, enhances redox activity and electronic properties. These modifications increase oxygen vacancies and alter the electronic structure, leading to stronger and more specific interactions with certain gases. Coupling CeO<sub>2</sub> with other semiconductors, such as ZnO, SnO<sub>2</sub>, or TiO<sub>2</sub>, creates heterojunctions that facilitate charge

transfer, improve response times, and enhance selectivity. CeO<sub>2</sub>-based sensors are known for their stability and ability to operate under varying environmental conditions, including fluctuations in temperature and humidity[84]. This versatility makes them suitable for a wide range of applications, such as industrial safety, environmental monitoring, and healthcare diagnostics, where detecting harmful gases or air composition changes is critical. CeO<sub>2</sub>'s tunable properties, high stability, and capability to detect multiple gases make it a key material for gas-sensing technologies[85]. Advances in nanotechnology, such as the synthesis of ultra-small CeO<sub>2</sub> particles or hybrid nanostructures, continue to enhance sensor performance. These developments strengthen the role of CeO<sub>2</sub> NPs in next-generation gas sensors, contributing to improved safety, environmental sustainability, and public health[86].

### 3.5) Biomedical Applications

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) have garnered significant interest in biomedical research due to their unique redox properties, biocompatibility, and ability to interface with complex biological systems[87]. These properties have enabled their exploration for diverse applications, including antioxidant therapy, drug delivery, and anti-inflammatory treatments, demonstrating their potential to address a range of challenging medical conditions. The antioxidant properties of CeO<sub>2</sub> NPs are derived from their reversible redox cycling between Ce<sup>3+</sup> and Ce<sup>4+</sup> states, enabling them to act as highly effective scavengers of reactive oxygen species (ROS) such as superoxide anions, hydroxyl radicals, and hydrogen peroxide[88]. ROS are implicated in the pathogenesis of various oxidative stress-related diseases, including neurodegenerative disorders like Alzheimer's and Parkinson's, cardiovascular diseases, and certain cancers. CeO<sub>2</sub> NPs exhibit a self-regenerating capacity to continuously neutralize ROS, maintaining oxidative balance over extended periods[89]. This capability positions them as promising therapeutic agents for managing

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oxidative stress and its associated diseases. Their nanoscale size allows for cellular uptake and effective interaction with intracellular ROS, offering an innovative approach to mitigating oxidative damage in biological systems. CeO<sub>2</sub> NPs also show significant potential in drug delivery applications, leveraging their intrinsic biocompatibility and ability to be functionalized for specific biomedical purposes[90]. Surface modifications with biopolymers, peptides, antibodies, or ligands enhance their stability, targeting ability, and therapeutic payload capacity. This functionalization enables the nanoparticles to recognize and bind to specific cellular receptors or biomarkers, facilitating targeted drug delivery with high precision. For example, functionalized CeO<sub>2</sub> NPs have been explored for delivering chemotherapeutic agents directly to tumor sites, minimizing systemic toxicity and improving treatment efficacy[91]. Their ability to respond to environmental stimuli, such as pH changes in the tumor microenvironment, further enhances their role in controlled drug release. Additionally, CeO<sub>2</sub> NPs can be engineered for dual-functionality in theranostics, combining drug delivery with imaging capabilities for real-time monitoring of therapeutic outcomes[92]. Emerging research indicates that CeO<sub>2</sub> NPs also possess anti-inflammatory properties, making them a potential tool for treating inflammatory diseases. By modulating cellular signaling pathways, CeO<sub>2</sub> NPs can suppress the release of pro-inflammatory cytokines and reduce the activation of immune cells involved in chronic inflammation[93]. This modulation is attributed to their ROS-scavenging activity, which interrupts oxidative signaling cascades that exacerbate inflammation. These anti-inflammatory effects make CeO<sub>2</sub> NPs promising candidates for managing conditions such as rheumatoid arthritis, inflammatory bowel disease, and chronic obstructive pulmonary disease (COPD). The ability of CeO<sub>2</sub> NPs to reduce inflammation without compromising immune system function enhances their appeal as a novel therapeutic strategy. The versatility of CeO<sub>2</sub> NPs stems from their unique physicochemical properties, tunability through surface modifications, and biocompatibility[94].

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Their multifunctional nature allows for integration into a wide array of biomedical applications, from therapeutic interventions to diagnostic tools[95]. However, further research is required to optimize their synthesis, ensure safety and efficacy, and understand their long-term biological interactions. As advancements continue, CeO<sub>2</sub> NPs hold the potential to revolutionize the treatment of oxidative stress-related disorders, inflammatory diseases, and targeted drug delivery systems, paving the way for innovative approaches in modern medicine[96].

### 4.0 CONCLUSION AND FUTURE PERSPECTIVES

Cerium oxide nanoparticles (CeO<sub>2</sub> NPs) have emerged as a versatile material with diverse applications spanning catalysis, energy storage, environmental remediation, gas sensing, and biomedicine. Their exceptional redox properties, high oxygen storage capacity, thermal stability, and tunable surface chemistry make them indispensable for various technological and industrial advancements. The synthesis methods, including precipitation, hydrothermal, sol-gel, thermal decomposition, and green synthesis, offer tailored approaches to optimize the size, shape, and functionality of CeO<sub>2</sub> NPs, enabling their adaptation to specific applications. In catalysis, CeO<sub>2</sub> NPs have demonstrated superior performance in automotive exhaust systems and industrial chemical reactions, while their role in energy storage and conversion highlights their potential to advance sustainable energy solutions, including solid oxide fuel cells and solar thermochemical cycles. In environmental remediation, CeO<sub>2</sub> NPs are effective in pollutant adsorption and photocatalysis, making them invaluable in water and air purification. Their sensitivity to gaseous analytes underpins their utility in gas sensing applications, and their biocompatibility, coupled with antioxidant and anti-inflammatory properties, establishes them as promising candidates for biomedical innovations. Despite these advancements, several challenges remain. The long-term environmental and biological safety of CeO<sub>2</sub> NPs requires comprehensive evaluation to ensure their sustainable use, particularly in biomedical and

environmental applications. Scalability and cost-effectiveness of synthesis methods also need improvement to facilitate industrial adoption. Moreover, a deeper understanding of their interaction with biological systems and their fate under environmental conditions is crucial for realizing their full potential. Future research should focus on developing more efficient and eco-friendly synthesis methods, such as green synthesis, to minimize environmental impact. Advances in surface engineering and doping strategies can further enhance the performance of CeO<sub>2</sub> NPs for specific applications, such as extending their photocatalytic activity into the visible light range or improving their ionic conductivity for energy applications. In the biomedical field, efforts should be directed toward achieving precise control over particle size, surface charge, and functionalization to maximize therapeutic efficacy while minimizing potential cytotoxicity. In conclusion, the multifunctional nature of CeO<sub>2</sub> NPs, combined with ongoing innovations in their synthesis and application, positions them as a cornerstone material in addressing global challenges related to energy, environment, and health. By addressing current limitations and exploring new frontiers, CeO<sub>2</sub> NPs hold immense promise for driving transformative advances across a wide spectrum of scientific and industrial domains.

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- **Hao Sun:** Conceptualization, Investigation, Formal analysis, Writing
- **Aamir Sohail:** Methodology, Investigation, Data Curation
- **Ajmal Shah:** Resources, Validation, Writing – Review & Editing
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## REFERENCES

- [1] H.S. Das, A. Basak, S. Maity, *Materials Science and Nanotechnology*, in: *Innovations in Energy Efficient Construction Through Sustainable Materials*, IGI Global, 2025, pp. 175-206.
- [2] S. Selvaraj, A. Chauhan, A. Radhakrishnan, G. Rana, V. Dutta, K.M. Batoo, S.J.J.o.I. Ghotakar, O. Polymers, *Materials, Cerium oxide nanoparticles and their polymeric composites: advancements in biomedical applications*, (2024) 1-27.
- [3] A. Yadav, K.J.J.E.N. Yadav, *Exploring the Effect of Engineered Nanomaterials on Soil Microbial Diversity and Functions: A Review*, 13 (2024) 48-62.
- [4] A.B. Shcherbakov, V.V. Reukov, A.V. Yakimansky, E.L. Krasnopeeva, O.S. Ivanova, A.L. Popov, V.K.J.P. Ivanov, *CeO<sub>2</sub> nanoparticle-containing polymers for biomedical applications: A review*, 13 (2021) 924.
- [5] M. Melchionna, A. Trovarelli, P. Fornasiero, *Synthesis and properties of cerium oxide-based materials*, in: *Cerium Oxide (CeO<sub>2</sub>): Synthesis, Properties and Applications*, Elsevier, 2020, pp. 13-43.
- [6] M. Shah, A. Hameed, M. Kashif, N. Majeed, J. Muhammad, N. Shah, T. Rehan, A. Khan, J. Uddin, A.J.C.P. Khan, *Advances in agar-based composites: A comprehensive review*, (2024) 122619.
- [7] T. Rajamuthuramalingam, W. da Silva, N. Zuverza-Mena, C. Dimkpa, J.C.J.N. White, *Nano-sized Metal Oxide Fertilizers for Sustainable Agriculture: Balancing Benefits, Risks, and Risk Management Strategies*, (2024).
- [8] M. Ramesh, L. Rajeshkumar, D. Balaji, V.J.C.A.C. Bhuvaneshwari, *Sustainable and renewable nano-biocomposites for sensors and actuators: a review on preparation and performance*, 19 (2023) 38-69.
- [9] F. Corsi, G. Deidda Tarquini, M. Urbani, I. Bejarano, E. Traversa, L.J.N. Ghibelli, *The Impressive Anti-Inflammatory Activity of Cerium Oxide Nanoparticles: More than Redox?*, 13 (2023) 2803.
- [10] L. Yi, L. Yu, S. Chen, D. Huang, C. Yang, H. Deng, Y. Hu, H. Wang, Z. Wen, Y.J.F.i.P. Wang, *The regulatory mechanisms of cerium oxide nanoparticles in*

## Review article

## Phytopharmacology Research Journal (PRJ) Open access

- oxidative stress and emerging applications in refractory wound care, 15 (2024) 1439960.
- [11] Z. Zahra, Z. Habib, H. Hyun, H.M.A.J.S. Shahzad, Overview on recent developments in the design, application, and impacts of nanofertilizers in agriculture, 14 (2022) 9397.
- [12] K.A. Bora, S. Hashmi, F. Zulfiqar, Z. Abideen, H. Ali, Z.S. Siddiqui, K.H.J.F.i.P.S. Siddique, Recent progress in bio-mediated synthesis and applications of engineered nanomaterials for sustainable agriculture, 13 (2022) 999505.
- [13] M. Kashif, S. Muhammad, A. Ali, K. Ali, S. Khan, S. Zahoor, M.J.J.o.X.a.S.U. Hamza, Bismuth oxide nanoparticle fabrication and characterization for photocatalytic bromophenol blue degradation, 19 (2023) 521-544.
- [14] M. Zou, K. Yu, Y. Huang, Q. Sheng, Y. Chen, H. Liu, N. Feng, D. Ma, D. Dou, Z.J.E.o.S.M. Zhu, I.o.R. Microbiota, Activation of ROS Signaling Molecule by Agnps: Molecular Mechanisms in Roses Under Abiotic Stress, Exploration of Stress Memory, and Impact on Root Microbiota.
- [15] M. Gul, M. Kashif, K.J.P.R.J. Shahid, Eco-Friendly Approaches in the Synthesis of ZnO Nanoparticles using Plant Extract: A Review, 3 (2024) 1-25.
- [16] A. Shubair, Tuning the Selectivity of Bimetallic NiBi Catalysts for Glycerol Electrooxidation Into Value-Added Products, in, Université d'Ottawa/University of Ottawa, 2021.
- [17] Y. Xu, Y. Zhou, Y. Li, Y. Liu, Z.J.J.o.E.C.E. Ding, Advances in cerium dioxide nanomaterials: Synthesis strategies, property modulation, and multifunctional applications, (2024) 113719.
- [18] Z. Liu, Z. Yao, H. Yang, S. Wu, Z.J.N. Tang, Leveraging the Dual Role of ROS in Liver Disease with Nanomaterials: Clearing and Amplifying for Therapy, (2025).
- [19] K.A. Sanoja-López, R.J.C.A.A.J. Luque, Porous Materials for the heterogeneously catalyzed synthesis of high Value- Added products: latest trends and future prospects, e202401238.
- [20] O. Tammaro, R. Paparo, M. Chianese, I. Ritacco, L. Caporaso, M.F. Camellone, B. Masenelli, A.D. Lamirand, J.-M. Bluet, M.J.C.E.J. Fontana, Reverse micelle strategy for effective substitutional Fe-doping in small-sized CeO<sub>2</sub> nanocrystals: Assessment of adsorption and photodegradation efficiency of ibuprofen under visible light, 479 (2024) 147909.
- [21] M. Kashif, M. Jawad, A.A. Khan, H. Sun, K. Ullah, O. Fakayode, S.J.J.o.A.R.i.W. Azizi, Wastewater, Fe/Ti-codoped strontium oxide nanoparticles for enhanced photocatalytic degradation of methyl orange, 11 (2024) 8-14.
- [22] H.-I. Chen, H.-Y.J.C.I. Chang, Synthesis of nanocrystalline cerium oxide particles by the precipitation method, 31 (2005) 795-802.
- [23] V. Harish, M. Ansari, D. Tewari, A.B. Yadav, N. Sharma, S. Bawarig, M.-L. García-Betancourt, A. Karatutlu, M. Bechelany, A.J.J.o.t.T.I.o.C.E. Barhoum, Cutting-edge advances in tailoring size, shape, and functionality of nanoparticles and nanostructures: A review, 149 (2023) 105010.
- [24] Y. Shlapa, S. Solopan, V. Sarnatskaya, K. Siposova, I. Garcarova, K. Veltruska, I. Timashkov, O. Lykhova, D. Kolesnik, A.J.C. Musatov, S.B. Biointerfaces, Cerium dioxide nanoparticles synthesized via precipitation at constant pH: Synthesis, physical-chemical and antioxidant properties, 220 (2022) 112960.
- [25] J. Li, F.L.J.C.r. Deepak, In situ kinetic observations on crystal nucleation and growth, 122 (2022) 16911-16982.
- [26] N.T. Thanh, N. Maclean, S.J.C.r. Mahiddine, Mechanisms of nucleation and growth of nanoparticles in solution, 114 (2014) 7610-7630.
- [27] R. Kumar, A. Dhar, A. Banerjee, S. Mondal, Scientific Frontiers: Sustainable Practices and Technologies, (2024).
- [28] S. Kaur, A. Rani, A. Sharma, N. Luhakhra, V. Karol, Green Nanomaterials in Energy Storage: Advancements and challenges, in: Materials for Boosting Energy Storage. Volume 3: Advances in Sustainable Energy Technologies, ACS Publications, 2024, pp. 281-307.
- [29] M.L. Hancock, R.A. Yokel, M.J. Beck, J.L. Calahan, T.W. Jarrells, E.J. Munson, G.A. Olaniyan, E.A.J.A.S.S. Grulke, The characterization of purified citrate-coated cerium oxide nanoparticles prepared via hydrothermal synthesis, 535 (2021) 147681.
- [30] J.W. Annis, J.M. Fisher, D. Thompsett, R.I.J.I. Walton, Solvothermal synthesis routes to substituted cerium dioxide materials, 9 (2021) 40.
- [31] M. Kashif, M. Ali, S. Naz, J. Amir, S. Murad, M. Atif, O.A. Khattak, S. Ullah, S. Aleena, N.J.B.J.o.S. Khan, Formulation development and characterization of quercetin loaded poly caprolactone nanoparticles for tumors, 3 (2024) 82-92.
- [32] L. Ndlwana, N. Raleie, K.M. Dimpe, H.F. Ogutu, E.O. Oseghe, M.M. Motsa, T.A. Msagati, B.B.J.M. Mamba, Sustainable hydrothermal and solvothermal synthesis of advanced carbon materials in multidimensional applications: A review, 14 (2021) 5094.

- [33] K.-J. Wu, C. Edmund, C. Shang, Z.J.P.i.M.S. Guo, Nucleation and growth in solution synthesis of nanostructures– from fundamentals to advanced applications, 123 (2022) 100821.
- [34] I. Ghani, M. Kashif, O.A. Khattak, M. Shah, S. Nawaz, S. Ullah, S. Murad, S. Naz, H.W. Khan, S.J.J.o.X.a.S.U. Muhammad, Hydrothermal synthesis and characterization of Cobalt doped Bismuth oxide NPs for photocatalytic degradation of methyl orange dye, 19 (2023) 1195-1217.
- [35] X. Wang, J. Feng, Y. Bai, Q. Zhang, Y.J.C.r. Yin, Synthesis, properties, and applications of hollow micro-/nanostructures, 116 (2016) 10983-11060.
- [36] S. Zaman, M. Kashif, M. Shah, A. Hameed, N. Majeed, M. Ismail, I. Khan, S. Ullah, N.J.B.J.o.S. Khan, Investigating the enhanced photocatalytic degradation of bromophenol blue using Ni/Zn co-doped Strontium Oxide nanoparticles synthesized via hydrothermal method, 3 (2024) 102-114.
- [37] C.A. Zito, M.O. Orlandi, D.P.J.J.o.E. Volanti, Accelerated microwave-assisted hydrothermal/solvothermal processing: fundamentals, morphologies, and applications, 40 (2018) 271-292.
- [38] M. Jamal, G.A.K. Nabi, H. Sun, K. Ullah, O.A. Khattak, M. Kashif, S. Khan, M. Alam, S. Hussain, M.J.A.o.A.E.S. Ullah, Preparation of Manganese-Doped Bismuth Oxide for the Photocatalytic Degradation of Methylene Blue, (2024) 1-7.
- [39] R. McGonigle, C. Houston, I. Cameron, C. Homann, D. Black, R. Pal, L. MacKenzie, Lessons learned in autoclave synthesis of upconversion nanoparticles: unreported variables and safety considerations, (2024).
- [40] M. Ahsan, S. Qasim, A. Shah, I. Nawaz, M. Kashif, W.J.B.J.o.S. Ahmad, Loading of anticancer drug anastrozole using Fe<sub>3</sub>O<sub>4</sub>@ SiO<sub>2</sub>, 3 (2024) 93-101.
- [41] S. Kogularasu, Y.Y. Lee, B. Sriram, S.F. Wang, M. George, G.P. Chang-Chien, J.K.J.A.C. Sheu, Unlocking catalytic potential: exploring the impact of thermal treatment on enhanced electrocatalysis of nanomaterials, 136 (2024) e202311806.
- [42] S. Pundir, R. Priya, K. Singh, H. Kaur, P. Choudhary, A systematic study on synthesis of CeO<sub>2</sub> nanoparticles by various routes, in: IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2023, pp. 012030
- [43] A.S. Fudala, W.M. Salih, F.F.J.M.T.P. Alkazaz, Synthesis different sizes of cerium oxide CeO<sub>2</sub> nanoparticles by using different concentrations of precursor via sol–gel method, 49 (2022) 2786-2792.
- [44] A.E. Danks, S.R. Hall, Z.J.M.H. Schnepf, The evolution of ‘sol–gel’ chemistry as a technique for materials synthesis, 3 (2016) 91-112.
- [45] M. Kashif, A.A. Khan, H. Sun, J. Kamal, M.I.A. Shah, S. Hussain, J. Amir, Y. Jamal, T.J.B.J.o.S. Ahmad, Synthesis and characterization of Fe-doped CuO nanoparticles: Catalytic efficiency in crystal violet dye degradation and exploration of electrical properties, 3 (2024) 1-18.
- [46] H.-W. He, X.-Q. Wu, W. Ren, P. Shi, X. Yao, Z.-T.J.C.I. Song, Synthesis of crystalline cerium dioxide hydrosol by a sol–gel method, 38 (2012) S501-S504.
- [47] A.S. Finny, A. Othman, S. Andreescu, Cerium oxide nanoparticles for chemical and biological sensors: properties, sensing designs, and applications, in: Cerium Oxide (CeO<sub>2</sub>): Synthesis, Properties and Applications, Elsevier, 2020, pp. 259-277.
- [48] S. Muhammad, A. Ali, S. Zahoor, X. Xinghua, J. Shah, M. Hamza, M. Kashif, S. Khan, B.K.A. Khel, A.J.A.S.A.P.V. Iqbal, Synthesis of Silver Oxide Nanoparticles and its Antimicrobial, Anticancer, Anti-inflammatory, Wound Healing, and Immunomodulatory Activities-A Review, 3 (2023).
- [49] N. Keller, J. Ivanez, J. Highfield, A.M.J.A.C.B.E. Ruppert, Photo-/thermal synergies in heterogeneous catalysis: Towards low-temperature (solar-driven) processing for sustainable energy and chemicals, 296 (2021) 120320.
- [50] S. Muhammad, A. Ali, J. Shah, M. Hamza, M. Kashif, B.K.A. Khel, A.J.N. Iqbal, A.S.I. Journal, Using Moringa oleifera stem extract for green synthesis, characterization, and anti-inflammatory activity of silver oxide nanoparticles, 4 (2023) 80-97.
- [51] M. Parashar, V.K. Shukla, R.J.J.o.M.S.M.i.E. Singh, Metal oxides nanoparticles via sol–gel method: a review on synthesis, characterization and applications, 31 (2020) 3729-3749.
- [52] Y. Khan, H. Sadia, S.Z. Ali Shah, M.N. Khan, A.A. Shah, N. Ullah, M.F. Ullah, H. Bibi, O.T. Bafakeeh, N.B.J.C. Khedher, Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review, 12 (2022) 1386.
- [53] H. Lalithamba, G. Prashanth, H. Latha, A. Siddekha, G.J.C.P. Nagendra, Cerium oxide nanoparticles: sustainable synthesis and diverse applications in electrical properties, catalysis and biomedicine, (2024)

## Review article

1-17.

[54] C. Cau, Y. Guari, T. Chave, J. Larionova, S.I.J.U.s. Nikitenko, Thermal and sonochemical synthesis of porous (Ce, Zr) O<sub>2</sub> mixed oxides from metal  $\beta$ -diketonate precursors and their catalytic activity in wet air oxidation process of formic acid, 21 (2014) 1366-1373.

[55] A.T.J.B.c. Odularu, applications, Metal nanoparticles: thermal decomposition, biomedical applications to cancer treatment, and future perspectives, 2018 (2018) 9354708

[56] P.G. Jamkhande, N.W. Ghule, A.H. Bamer, M.G.J.J.o.d.d.s. Kalaskar, technology, Metal nanoparticles synthesis: An overview on methods of preparation, advantages and disadvantages, and applications, 53 (2019) 101174.

[57] A.V. Rane, K. Kanny, V. Abitha, S. Thomas, Methods for synthesis of nanoparticles and fabrication of nanocomposites, in: Synthesis of inorganic nanomaterials, Elsevier, 2018, pp. 121- 139.

[58] U.L.J.M.R.F. Usman, Green synthesis and applications of ceria-based nanomaterials, 169 (2024).

[59] M. Sen, M. Mukherjee, Bioinspired and Green Synthesis of Nanostructures: A Sustainable Approach, John Wiley & Sons, 2023.

[60] S.H.J.J.o.C.S. Gebre, Bio-inspired synthesis of metal and metal oxide nanoparticles: the key role of phytochemicals, 34 (2023) 665-704.

[61] M. Gul, F. Jan, A. Alam, I. Ahmad, U. Habib, M. Khan,

A.F. AlAsmari, F. Alasmari, A. Khan, A.J.R.J.o.B.C. Al-Harrasi, Synthesis and Evaluation of Some Novel 1, 3- Dimethylbarbituric Acid Derivatives as Potent Anti-Urease Agents: Comprehension through In Vitro, Molecular Docking, and DFT Investigations, 50 (2024) 1609-1626.

[62] K. Parveen, V. Banse, L. Ledwani, Green synthesis of nanoparticles: Their advantages and disadvantages, in: AIP conference proceedings, AIP Publishing, 2016.

[63] J. Amir, S. Muhammad, M. Kashif, A.A. Khan, M. Gul, H. Sun, M. Shah, S. Azizi, M.J.J.o.t.I.C.S. Maaza, Synthesis, characterization and dielectric properties evaluation of NiO- Co<sub>3</sub>O<sub>4</sub> nanocomposite, (2024) 1-10.

[64] S.F. Ahmed, M. Mofijur, N. Rafa, A.T. Chowdhury, S. Chowdhury, M. Nahrin, A.S. Islam, H.C.J.E.R. Ong, Green approaches in synthesising nanomaterials for environmental nanobioremediation: Technological advancements, applications, benefits and challenges, 204 (2022) 111967.

[65] H.C. Erythropel, J.B. Zimmerman, T.M. de Winter, L. Petitjean, F. Melnikov, C.H. Lam, A.W.

## Phytopharmacology Research Journal (PRJ) Open access

Lounsbury, K.E. Mellor, N.Z. Janković, Q.J.G.c. Tu, The Green ChemisTREE: 20 years after taking root with the 12 principles, 20 (2018) 1929-1961.

[66] J. Shah, H. Sun, Z. Qiao, T. Sharif, M.J.B.J.o.S. Gul, Enhanced degradation of methylene blue dye using hydrothermally synthesized Nickel-doped Strontium oxide catalysts, 3 (2024) 13-27.

[67] O.V. Kharissova, B.I. Kharisov, C.M. Oliva González, Y.P. Méndez, I.J.R.S.o.s. López, Greener synthesis of chemical compounds and materials, 6 (2019) 191378.

[68] S.J.M.R.F. Rai, Biomedical applications of green synthesized cerium oxide nanoparticles, 169 (2024).

[69] S.B. Putla, M. Kamali, B. Swapna, B.M. Reddy, P.J.A.A.N.M. Sudarsanam, Review of Shape-Controlled CeO<sub>2</sub> Nanocatalysts for Purification of Auto-Exhaust Pollutants, 7 (2024) 6749-6771.

[70] K. Lorber, Thermal and Combined Photo-Thermal Dry Reforming of Methane (DRM) Over Nanoshaped Ni/CeO<sub>2</sub> Catalysts, University of Nova Gorica (Slovenia), 2023.

[71] P. Kumar, J.K. Ratan, N. Divya, K. Mummaneni, G. Rawat, Investigation of CeO<sub>2</sub>/rGO Nanocomposites as Diesel Additives to Enhance Engine Performance and Reduce Exhaust Emissions, in: 2023 9th International Conference on Signal Processing and Communication (ICSC), IEEE, 2023, pp. 714-719.

[72] P. Umek, M. Dürschnabel, L. Molina-Luna, S. Škapin, R. Cerc Korošec, C.J.M. Bittencourt, The Role of Cerium Valence in the Conversion Temperature of H<sub>2</sub>Ti<sub>3</sub>O<sub>7</sub> Nanoribbons to TiO<sub>2</sub>-B and Anatase Nanoribbons, and Further to Rutile, (2023).

[73] V. Petrovsky, B. Gorman, H. Anderson, T.J.C.T. Petrovsky, Microstructure-Electrical Property Relationship in Nanocrystalline CeO<sub>x</sub> 2 Thin Films, 127 (2002) 127-136.

[74] A.S. SERROUNE, U. Khasani, J. Kakiecwski, M. Brenton, A. SERROUNE, D. Basset, H. SERROUNE, S.J.I.J.o.S.R. Gescot, Management, Development and Characterization of Advanced Nano-Coating with CeO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, ZnO, and TiO<sub>2</sub> Nanoparticles for Enhanced Durability and Corrosion Resistance, 12 (2024) 1228-1269.

[75] J.Y. Kim, B. Jang, M. Lim, J.Y. Park, Y.-H.J.J.o.P.S.

Choa, Enhanced PtRu by CeO<sub>2</sub> hollow nanofibers: Hydrogen gas sensing with CO-resistant in fuel cell, 613 (2024) 234842.

[76] M.J.J.o.E.C.E. Kurian, Cerium oxide based materials for water treatment—A review, 8 (2020) 104439.

- [77] J.T. Dahle, Y.J.I.j.o.e.r. Arai, p. health, Environmental geochemistry of cerium: applications and toxicology of cerium oxide nanoparticles, 12 (2015) 1253-1278.
- [78] S. Pansambal, R. Oza, S. Borgave, A. Chauhan, P. Bardapurkar, S. Vyas, S.J.A.N. Ghotekar, Bioengineered cerium oxide (CeO<sub>2</sub>) nanoparticles and their diverse applications: a review, 13 (2023) 6067-6092.
- [79] M.S. Hassan, R. Khan, T. Amna, J. Yang, I.-H. Lee, M.-Y. Sun, M.H. EL-Newehy, S.S. Al-Deyab, M.-S.J.C.I. Khil, The influence of synthesis method on size and toxicity of CeO<sub>2</sub> quantum dots: Potential in the environmental remediation, 42 (2016) 576-582.
- [80] E. Kalita, J. Baruah, Environmental remediation, in: Colloidal metal oxide nanoparticles, Elsevier, 2020, pp. 525- 576.
- [81] A. Khodadadi, S. Mohajerzadeh, Y. Mortazavi, A.J.S. Miri, A.B. Chemical, Cerium oxide/SnO<sub>2</sub>-based semiconductor gas sensors with improved sensitivity to CO, 80 (2001) 267-271.
- [82] S. Durrani, M. Al-Kuhaili, I.J.S. Bakhtiari, A.B. Chemical, Carbon monoxide gas-sensing properties of electron-beam deposited cerium oxide thin films, 134 (2008) 934-939.
- [83] N. Izu, W. Shin, I. Matsubara, N.J.S. Murayama, A.B. Chemical, The effects of the particle size and crystallite size on the response time for resistive oxygen gas sensor using cerium oxide thick film, 94 (2003) 222-227.
- [84] B. Renganathan, D. Sastikumar, A.C. Bose, R. Srinivasan, A.J.C.A.P. Ganesan, Nanocrystalline cerium oxide coated fiber optic gas sensor, 14 (2014) 467-471.
- [85] N. Nithyavathy, V. Rajendran, L.J. Berchmans, M. Maaza, S. Krithika, S.J.B.o.M.S. Arunmetha, Gas sensing behaviour of cerium oxide and magnesium aluminate composites, 40 (2017) 667-682.
- [86] J.M.J.S. Rzaiz, A.A. Physical, A novel room-temperature nitrogen dioxide gas sensor based on silver-doped cerium oxide thin film, 363 (2023) 114748.
- [87] Rajeshkumar, P.J.B.R. Naik, Synthesis and biomedical applications of cerium oxide nanoparticles—a review, 17 (2018) 1-5
- [88] A. Dhall, W.J.A. Self, Cerium oxide nanoparticles: a brief review of their synthesis methods and biomedical applications, 7 (2018) 97.
- [89] C. Walkey, S. Das, S. Seal, J. Erlichman, K. Heckman, L. Ghibelli, E. Traversa, J.F. McGinnis, W.T.J.E.S.N. Self, Catalytic properties and biomedical applications of cerium oxide nanoparticles, 2 (2015) 33-53.
- [90] K.R. Singh, V. Nayak, T. Sarkar, R.P.J.R.a. Singh, Cerium oxide nanoparticles: properties, biosynthesis and biomedical application, 10 (2020) 27194-27214.
- [91] M. Nyoka, Y.E. Choonara, P. Kumar, P.P. Kondiah, V.J.N. Pillay, Synthesis of cerium oxide nanoparticles using various methods: implications for biomedical applications, 10 (2020) 242.
- [92] Y. Huang, M. Zhang, M. Jin, T. Ma, J. Guo, X. Zhai, Y.J.A.h.m. Du, Recent advances on cerium oxide-based biomaterials: toward the next generation of intelligent Theranostics platforms, 12 (2023) 2300748.
- [93] S.M. Hirst, A.S. Karakoti, R.D. Tyler, N. Sriranganathan, S. Seal, C.M.J.S. Reilly, Anti-inflammatory properties of cerium oxide nanoparticles, 5 (2009) 2848-2856.
- [94] Y. Wu, H.T.J.J.o.M.C.B. Ta, Different approaches to synthesising cerium oxide nanoparticles and their corresponding physical characteristics, and ROS scavenging and anti-inflammatory capabilities, 9 (2021) 7291-7301.
- [95] S. Del Turco, G. Ciofani, V. Cappello, T. Navarra, C. Caselli, M. Gemmi, V. Mattoli, G.J.E.H.J. Basta, Anti-inflammatory and antioxidant effects of cerium oxide nanoparticles in human endothelial cells, 34 (2013) P4174.
- [96] N.J.B. Yadav, Cerium oxide nanostructures: properties, biomedical applications and surface coatings, 12 (2022) 121.