Advanced Nano Research
Volume 9, Issue 1, pp. 1-16, 2026
DOI: https://doi.org/10.21467/anr.9.1.1-16

ISSN: 2581-5164

REVIEW ARTICLE

Advances in Zinc Oxide Nanoparticles: Synthesis, Characterization, Applications, and Future Prospects

Islam Uddin

Department of Applied Sciences and Humanities, Faculty of Engineering and Technology, JMI, New Delhi

*Corresponding author's email: islamftp@gmail.com

Received: 19 November 2025 / Revised: 15 March 2026 / Accepted: 23 March 2026 / Published: 28 March 2026

Abstract

Zinc oxide (ZnO) is a multifunctional semiconductor nanomaterial that has attracted considerable attention due to its unique optical, electrical, piezoelectric, and catalytic properties. Its wide band gap (3.37 eV) and high exciton binding energy (60 meV) make it suitable for diverse applications in photocatalysis, sensing, optoelectronics, environmental remediation, and biomedicine. Recent advances in synthesis techniques have enabled precise control over the size, morphology, crystallinity, and surface characteristics of ZnO nanoparticles, significantly influencing their functional performance. This review summarizes recent developments in ZnO nanoparticle synthesis, characterization, and emerging applications. Conventional synthesis methods, including precipitation, hydrothermal, sol–gel, electrochemical, and microwave-assisted approaches, are discussed alongside environmentally friendly green synthesis strategies based on biological resources. Key characterization techniques such as XRD, FTIR, SEM, TEM, AFM, and UV–Visible spectroscopy are highlighted for their roles in evaluating structural, morphological, and optical properties. The review also highlights the expanding use of ZnO nanomaterials across a wide range of fields, including antibacterial and anticancer treatments, photocatalysis, sensing applications, environmental cleanup, and optoelectronic technologies. Furthermore, it examines key challenges such as toxicity concerns, reproducibility issues, and the difficulties associated with large-scale production.

Keywords: Zinc oxide; ZnO nanoparticles; green synthesis.

1 Introduction

Nanotechnology has revolutionized modern materials research by enabling the design and development of materials with unique physicochemical properties at the nanoscale. Nanoparticles, typically ranging from 1 to 100 nm in size, exhibit characteristics that differ significantly from those of their bulk counterparts due to quantum confinement effects, increased surface area, and enhanced surface reactivity. Depending on their dimensionality, nanomaterials can exist as zero-dimensional structures such as quantum dots, one-dimensional nanorods and nanotubes, two-dimensional thin films, and three-dimensional nanocomposites and nanofibers. These distinctive features have opened new opportunities in fields such as electronics, energy storage, environmental remediation, catalysis, and biomedicine [1]. The growing interest in ZnO nanoparticles is largely attributed to their remarkable versatility and the ability to tailor their properties through controlled synthesis. At the nanoscale, ZnO exhibits enhanced surface-to-volume ratio, improved catalytic efficiency, tunable optical characteristics, and unique biological activity. These features have enabled their incorporation into a wide range of applications, including antimicrobial coatings, cosmetic products, food packaging materials, drug-delivery systems, biosensors, photocatalysts, and electronic devices [2].

Recent advances in synthesis methodologies have played a crucial role in enhancing the performance of ZnO nanomaterials. Conventional physicochemical approaches such as precipitation, hydrothermal synthesis, sol–gel processing, electrochemical deposition, and microwave-assisted synthesis have been widely employed to produce ZnO nanoparticles with controlled size, morphology, and crystallinity [2]. By carefully adjusting synthesis parameters, researchers can tailor the structural and functional properties of ZnO for specific applications. However, many traditional synthesis routes involve high energy consumption, toxic chemicals, or complex processing conditions, which has encouraged the development of more sustainable alternatives. Recently, green synthesis has emerged as a promising and environmentally friendly approach for the production of ZnO nanoparticles. This method utilizes biological resources such as plant extracts, microorganisms, algae, and other renewable materials as reducing and stabilizing agents, thereby minimizing the use of hazardous chemicals and reducing environmental. Beyond sustainability, green synthesis often improves the biocompatibility of ZnO nanoparticles, making them particularly attractive for biomedical and pharmaceutical applications. Consequently, significant research efforts have been directed toward understanding the mechanisms and optimizing the conditions of biologically mediated ZnO synthesis [3-5].

Among the various metal oxide nanomaterials, zinc oxide (ZnO) has attracted considerable scientific and technological interest because of its exceptional optical, electrical, piezoelectric, and catalytic properties. ZnO is a II–VI semiconductor characterized by a wide direct band gap of approximately 3.37 eV and a high exciton binding energy of about 60 meV at room temperature. These properties make it highly suitable for optoelectronic devices, ultraviolet (UV) photodetectors, solar cells, sensors, and photocatalytic systems. Furthermore, ZnO predominantly crystallizes in a hexagonal wurtzite structure, which contributes to its unique electronic behavior and structural stability [6]. Alongside advances in synthesis, substantial progress has been made in the characterization of ZnO nanomaterials. A wide range of analytical techniques is employed to investigate their structural, morphological, optical, and chemical properties. Techniques such as X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM), and UV–Visible spectroscopy provide valuable information regarding crystallinity, particle size, morphology, elemental composition, surface chemistry, and optical behavior [7]. Comprehensive characterization is essential for establishing structure–property relationships and optimizing material performance for targeted applications.

The broad applicability of ZnO nanoparticles has further accelerated research in this field. In the biomedical sector, ZnO nanoparticles have demonstrated promising antibacterial, antifungal, anticancer, anti-inflammatory, and drug-delivery capabilities. Their photocatalytic activity has also been extensively explored for environmental remediation, wastewater treatment, and pollutant degradation. Moreover, the unique optical and electronic properties of ZnO make it an attractive material for sensors, photodetectors, light-emitting devices, and other advanced optoelectronic systems [8]. The continuous expansion of these applications highlights the importance of developing efficient synthesis methods and comprehensive characterization strategies. Given the rapid growth of ZnO-related research and the increasing demand for high-performance nanomaterials, a comprehensive assessment of recent developments is both timely and necessary. This review aims to provide an updated overview of the latest advances in ZnO nanoparticle synthesis, characterization techniques, and emerging applications. Particular emphasis is placed on comparing conventional and green synthesis approaches, discussing modern characterization tools, and highlighting recent progress in biomedical, environmental, catalytic, sensing, and optoelectronic applications. In addition, current challenges and future research directions are examined to provide insights into the continued development and practical implementation of ZnO-based nanomaterials.

2 Structure-Dependent Properties of ZnO Nanoparticles

The exceptional performance of zinc oxide (ZnO) nanoparticles in a wide range of applications is closely linked to their crystal structure and size-dependent properties. ZnO is a II–VI semiconductor that predominantly crystallizes in the hexagonal wurtzite structure, which is thermodynamically stable under ambient conditions. This crystal structure consists of alternating planes of zinc (Zn^{2+}) and oxygen (O^{2-}) ions arranged along the c-axis, resulting in a non-centrosymmetric lattice. Such a structural arrangement gives rise to several unique properties, including piezoelectricity, pyroelectricity, and strong optical activity [2]. At the nanoscale, ZnO exhibits physicochemical characteristics that differ significantly from those of bulk materials. The reduction in particle size leads to an increase in surface-to-volume ratio, exposing a larger number of active surface sites. As a result, ZnO nanoparticles often demonstrate enhanced catalytic activity, improved adsorption capacity, greater chemical reactivity, and superior interaction with biological systems. These features make ZnO nanomaterials particularly attractive for applications in catalysis, environmental remediation, sensing, and biomedicine [1].

One of the most important properties of ZnO is its wide direct band gap of approximately 3.37 eV and high exciton binding energy of about 60 meV at room temperature. These characteristics enable efficient absorption of ultraviolet radiation while maintaining optical transparency in the visible region, making ZnO highly suitable for UV photodetectors, solar cells, photocatalysts, and transparent electronic devices [2,5]. Furthermore, the high exciton binding energy allows excitonic emissions to remain stable at room temperature, which is advantageous for optoelectronic applications. The photocatalytic behavior of ZnO is closely associated with its electronic band structure. When ZnO nanoparticles are exposed to ultraviolet or high-energy visible light, electrons in the valence band become excited and transition to the conduction band, leaving behind positively charged holes in the valence band. This process generates electron–hole pairs that participate in various oxidation and reduction reactions at the nanoparticle surface. The photogenerated electrons typically react with dissolved oxygen molecules to form superoxide radicals ($\bullet O_2^-$), while the holes react with water molecules or hydroxide ions to generate hydroxyl radicals ($\bullet OH$) [2]. These reactive oxygen species (ROS) are highly oxidative and play a crucial role in photocatalytic degradation of pollutants, antimicrobial activity, and cancer cell destruction. The ability of ZnO nanoparticles to generate ROS has attracted significant attention in biomedical research. Reactive oxygen species can induce oxidative stress within microbial cells, resulting in membrane damage, protein denaturation, and DNA disruption. Consequently, ZnO nanoparticles exhibit strong antibacterial and antifungal properties against a wide range of pathogenic microorganisms. Similarly, controlled ROS generation can trigger apoptosis and inhibit proliferation in cancer cells, making ZnO-based nanomaterials promising candidates for anticancer therapies. In addition to ROS-mediated mechanisms, ZnO nanoparticles can gradually release Zn^{2+} ions when exposed to biological or aqueous environments. These released ions interact with proteins, enzymes, and cellular membranes, influencing various biochemical pathways. The combined effects of ion release and ROS generation contribute significantly to the antimicrobial and cytotoxic activities of ZnO nanoparticles [2]. However, these same mechanisms also raise concerns regarding potential toxicity, highlighting the need for careful evaluation of dosage, exposure conditions, and long-term biological effects.

The morphology of ZnO nanostructures is another critical factor governing their functional performance. Depending on the synthesis method and reaction conditions, ZnO can be fabricated in various forms, including nanoparticles, nanorods, nanowires, nanoflowers, nanotubes, nanosheets, and hierarchical architectures. Different morphologies exhibit distinct surface areas, crystal facets, charge transport characteristics, and optical properties, which directly influence their performance in photocatalytic, sensing, and biomedical applications [2]. For example, nanorods and nanowires provide efficient pathways for electron transport, whereas nanoflower structures offer a larger active surface area that enhances catalytic and antibacterial activity. Surface characteristics also play a vital role in determining the behavior of ZnO nanoparticles. Factors such as surface charge, defect concentration, porosity, and surface functionalization influence nanoparticle stability, dispersibility, and interactions with surrounding environments. Surface modification with polymers, biomolecules, or inorganic coatings can improve biocompatibility, reduce aggregation, and enhance targeting efficiency in drug-delivery applications. Moreover, engineered surface defects can alter optical absorption and charge separation processes, thereby improving photocatalytic and sensing performance [1].

The luminescence properties of ZnO nanoparticles further contribute to their technological importance. ZnO exhibits strong near-band-edge ultraviolet emission as well as visible emissions arising from intrinsic defects such as oxygen vacancies and zinc interstitials. These optical characteristics have been exploited in bioimaging, light-emitting devices, and optical sensors. The intensity and wavelength of emission can be tuned by controlling particle size, morphology, doping, and synthesis conditions, providing additional flexibility for advanced applications [2]. The remarkable versatility of ZnO nanoparticles originates from the strong interplay between their crystal structure, electronic properties, surface chemistry, and morphology. Understanding these structure–property relationships is essential for tailoring ZnO nanomaterials to specific applications and for designing next-generation functional materials with enhanced performance. Continued research in this area is expected to further expand the capabilities of ZnO-based systems across biomedical, environmental, catalytic, and optoelectronic fields.

3 Recent Advances in Synthesis Methods

The functional performance of ZnO nanoparticles is strongly influenced by their size, morphology, crystallinity, and surface characteristics, all of which are determined by the synthesis route employed. Consequently, considerable research efforts have been directed toward developing reliable and controllable methods for producing ZnO nanomaterials with tailored properties. Over the years, a variety of physicochemical and biological synthesis techniques have been reported, each offering distinct advantages and limitations. Conventional physicochemical methods remain widely used because of their reproducibility, scalability, and ability to provide precise control over nanoparticle characteristics. More recently, environmentally sustainable green synthesis approaches have emerged as attractive alternatives that address concerns associated with toxic chemicals and energy-intensive processes.

3.1 Conventional Physicochemical Synthesis Methods

3.1.1 Precipitation Method

Among the numerous methods available for ZnO nanoparticle synthesis, the precipitation technique is one of the simplest, most economical, and widely adopted approaches. The method generally involves the reaction of a zinc precursor, such as zinc nitrate or zinc acetate, with a precipitating agent under controlled conditions of pH, temperature, and concentration. The resulting precipitate is subsequently filtered, washed, dried, and calcined to obtain ZnO nanoparticles. The popularity of the precipitation method stems from its operational simplicity and suitability for large-scale production. Unlike many advanced synthesis routes, it does not require sophisticated instrumentation or expensive processing conditions, making it attractive for industrial applications. Moreover, reaction parameters can be adjusted to influence particle size and morphology. For instance, studies have reported the synthesis of ZnO nanoparticles with average particle sizes around 30 nm without the use of surfactants or complex stabilizing agents [9,10]. Despite these advantages, the precipitation method often produces particles with broad size distributions and a tendency toward agglomeration. Achieving uniform morphology requires careful optimization of synthesis parameters, particularly pH and reaction temperature. Nevertheless, the method remains an important route for the large-scale production of ZnO nanoparticles due to its cost-effectiveness and ease of implementation.

3.1.2 Hydrothermal Synthesis

Hydrothermal synthesis has emerged as one of the most effective techniques for producing highly crystalline ZnO nanostructures with well-defined morphologies. In this method, chemical reactions occur in sealed vessels under elevated temperature and pressure conditions, promoting controlled crystal growth and enhanced crystallinity. A major advantage of hydrothermal synthesis is its ability to precisely tailor nanoparticle morphology by controlling parameters such as precursor concentration, reaction temperature, pressure, and synthesis duration. Depending on these conditions, ZnO can be synthesized in the form of nanorods, nanowires, nanoflowers, nanotubes, and hierarchical structures. Such morphological diversity is particularly important because particle shape significantly influences optical, catalytic, and sensing performance. Recent studies have demonstrated that hydrothermal processing can produce extremely small and highly crystalline ZnO nanoparticles. For example, zinc nitrate-based systems reacted with sodium hydroxide at approximately 120°C for several hours have yielded nanoparticles with excellent structural uniformity and enhanced functional properties [11]. Furthermore, hydrothermal synthesis has recently been extended to the utilization of recycled and sustainable precursor materials, highlighting its potential contribution to greener nanomaterial production [12]. However, the requirement for specialized pressure-resistant reactors and relatively long reaction times may limit large-scale implementation. Despite these challenges, hydrothermal synthesis remains one of the preferred methods for producing high-quality ZnO nanostructures for advanced applications.

3.1.3 Sol–Gel Method

The sol–gel process is widely recognized as a versatile and highly controllable method for synthesizing ZnO nanoparticles. The technique involves the transformation of a colloidal solution (sol) into a three-dimensional network structure (gel), followed by drying and heat treatment to obtain the final oxide material. One of the major advantages of the sol–gel method is its ability to produce highly homogeneous materials with excellent compositional uniformity. Researchers can carefully control hydrolysis and condensation reactions, enabling precise regulation of particle size, porosity, and crystallinity. Consequently, ZnO nanoparticles synthesized through sol–gel processing often exhibit high purity, small particle size, and large specific surface area, characteristics that are desirable for photocatalytic and sensing applications. Recent investigations have shown that stable ZnO nanoparticle gels can be obtained under mild conditions using zinc acetate precursors, particularly at near-room temperature and slightly alkaline pH values [13]. Although the sol–gel method offers excellent control over material properties, it may involve lengthy processing times and post-synthesis heat treatment steps. Nevertheless, its reproducibility and flexibility continue to make it one of the most extensively employed approaches for ZnO synthesis.

3.1.4 Electrochemical Deposition

Electrochemical deposition represents a relatively simple and cost-effective route for the preparation of ZnO nanostructures. The process involves the electrochemically induced precipitation of ZnO from aqueous solutions containing zinc salts such as zinc chloride or zinc nitrate. By applying an external potential, ZnO can be deposited directly onto conductive substrates, enabling the fabrication of thin films and nanostructured coatings [14]. A notable advantage of this technique is its low-temperature operation, which reduces energy consumption and allows deposition on temperature-sensitive substrates. Additionally, electrochemical methods offer excellent control over film thickness, morphology, and crystal orientation through adjustment of deposition parameters such as current density, electrolyte composition, and deposition time. Recent developments have focused on process optimization strategies, including statistical approaches such as TOPSIS–Taguchi analysis, to improve nanoparticle quality and production efficiency. Electrochemical deposition has also been successfully employed for the fabrication of ZnO nanorods and other one-dimensional nanostructures with potential applications in sensing and optoelectronic devices [15].

3.1.5 Microwave-Assisted Synthesis

Microwave-assisted synthesis has gained increasing attention as a rapid and energy-efficient alternative to conventional heating techniques. Unlike traditional heating methods, which rely on heat transfer from the external environment, microwave irradiation directly interacts with reactant molecules, resulting in uniform volumetric heating and accelerated reaction kinetics. The most significant advantage of microwave-assisted synthesis is the dramatic reduction in reaction time while maintaining excellent control over particle size and morphology. Uniform heating minimizes temperature gradients within the reaction medium, leading to homogeneous nucleation and improved particle distribution. Consequently, ZnO nanoparticles synthesized using microwave irradiation often exhibit superior crystallinity and reduced agglomeration compared with those produced by conventional methods [16]. Recent studies have successfully combined microwave and hydrothermal approaches to synthesize morphology-controlled ZnO nanostructures with enhanced gas-sensing and photocatalytic performance [11]. The method is particularly attractive for industrial applications because of its reduced energy consumption and high production efficiency.

3.1.6 Comparative Overview of Conventional Synthesis Methods

Each physicochemical synthesis route offers distinct advantages and challenges. Precipitation methods are inexpensive and suitable for large-scale production but may suffer from poor size uniformity. Hydrothermal synthesis provides exceptional control over morphology and crystallinity, although it requires specialized equipment and elevated temperatures. Sol–gel processing yields highly pure and homogeneous nanoparticles but often involves longer processing times. Electrochemical deposition is particularly useful for thin-film fabrication, while microwave-assisted synthesis offers rapid production and improved energy efficiency. The choice of synthesis method ultimately depends on the intended application of the ZnO nanomaterial. Applications requiring highly crystalline and morphology-controlled structures, such as photocatalysis and sensing, often favor hydrothermal and microwave-assisted techniques. In contrast, large-scale industrial production may benefit from precipitation and sol–gel approaches due to their simplicity and cost-effectiveness. Therefore, continued optimization of these methods remains essential for meeting the growing demand for high-performance ZnO nanomaterials.

3.2 Green and Biological Synthesis

Growing environmental concerns associated with conventional chemical synthesis methods have accelerated the search for sustainable and eco-friendly alternatives for nanoparticle production. In this context, green synthesis has emerged as a promising approach for the fabrication of ZnO nanoparticles. Unlike traditional physicochemical methods, green synthesis utilizes biological resources such as plant extracts, microorganisms, algae, fungi, and other naturally derived materials as reducing, stabilizing, and capping agents. This approach minimizes the use of hazardous chemicals, reduces energy consumption, and offers an environmentally benign route for nanoparticle production [3]. The increasing interest in green synthesis is driven not only by environmental considerations but also by the enhanced biocompatibility of the resulting nanoparticles. Biological molecules present in natural extracts often remain adsorbed on the nanoparticle surface, improving colloidal stability and reducing toxicity. As a result, green-synthesized ZnO nanoparticles have gained considerable attention for biomedical, pharmaceutical, agricultural, and environmental applications [17].

3.2.1 Plant-Mediated Synthesis

Among various biological approaches, plant-mediated synthesis is the most extensively investigated method for producing ZnO nanoparticles. Plant extracts contain a diverse range of bioactive compounds, including flavonoids, phenolic acids, alkaloids, terpenoids, proteins, carbohydrates, and polyphenols. These naturally occurring phytochemicals participate in the reduction of zinc ions and simultaneously act as stabilizing agents, facilitating nanoparticle formation without the need for additional chemicals. The synthesis process typically involves mixing an aqueous plant extract with a zinc precursor solution, followed by controlled heating and pH adjustment. During the reaction, phytochemicals interact with zinc ions, promoting nucleation and growth of ZnO nanoparticles. The final particle characteristics are strongly influenced by factors such as extract composition, precursor concentration, temperature, reaction time, and pH. A wide variety of plant species have been successfully employed for ZnO nanoparticle synthesis. Reports have described the use of extracts derived from *Psidium guajava*, *Azadirachta indica* (neem), *Aloe vera*, *Hibiscus sabdariffa*, *Gymnema sylvestre*, *Citrus hystrix*, *Pedalium murex*, and *Artemisia haussknechti*, among many others. These studies have demonstrated that plant-derived biomolecules not only facilitate nanoparticle formation but also influence particle size, morphology, crystallinity, and biological activity [3,18]. Recent investigations have highlighted the potential of novel phytochemical-rich plant resources for producing ZnO nanoparticles with enhanced antimicrobial, antioxidant, and photocatalytic properties. Such findings suggest that the selection of plant species plays a critical role in determining the final characteristics and functionality of the synthesized nanomaterials.

3.2.2 Microbial-Mediated Synthesis

Microorganisms, including bacteria, fungi, yeasts, and algae, have also been explored as biological factories for nanoparticle production. Microbial synthesis relies on the natural metabolic processes of living organisms, which can transform metal ions into stable nanoparticles through intracellular or extracellular mechanisms. Fungal-mediated synthesis has attracted particular attention because fungi secrete large quantities of enzymes and proteins that facilitate nanoparticle formation and stabilization. Similarly, bacterial systems offer advantages such as rapid growth, ease of cultivation, and scalability. Although microbial synthesis is generally more complex than plant-mediated approaches, it provides excellent control over nanoparticle morphology and may enable the production of highly uniform nanostructures [2]. Despite these advantages, challenges associated with microbial cultivation, contamination control, and purification of synthesized nanoparticles currently limit large-scale commercialization. Nevertheless, ongoing advances in biotechnology and microbial engineering are expected to improve the practicality of this approach in the future.

3.2.3 Mechanism of Green Synthesis

The exact mechanism of green synthesis varies depending on the biological source employed; however, the process generally involves three key stages: reduction, nucleation, and stabilization. Initially, biomolecules present in plant extracts or microbial metabolites interact with zinc ions and facilitate their conversion into ZnO nuclei. These nuclei subsequently grow through controlled aggregation and crystallization processes. Finally, various biological compounds adsorb onto the nanoparticle surface, acting as natural capping agents that prevent excessive growth and agglomeration [3]. The presence of these surface-bound biomolecules often contributes to improved stability, enhanced biological activity, and reduced cytotoxicity. Furthermore, the functional groups associated with biological capping agents can provide additional opportunities for surface modification and targeted applications in drug delivery and biomedical engineering.

3.2.4 Advantages of Green Synthesis

Green synthesis offers several advantages over conventional physicochemical methods. First, it eliminates or significantly reduces the use of toxic chemicals, making the process safer for both human health and the environment. Second, many biological synthesis routes operate under mild reaction conditions, reducing energy consumption and overall production costs. Third, the use of renewable biological resources contributes to sustainability and aligns with the principles of green chemistry [5]. Another important advantage is the improved biocompatibility of green-synthesized ZnO nanoparticles. Biological molecules associated with the nanoparticle surface can reduce toxicity while enhancing interactions with biological systems. This characteristic is particularly valuable for applications in medicine, pharmaceuticals, and food-related technologies [17]. Furthermore, green synthesis often generates nanoparticles with unique morphologies and surface functionalities that may be difficult to achieve using conventional methods. Such features can enhance photocatalytic efficiency, antimicrobial activity, and sensing performance.

3.2.5 Current Challenges and Future Perspectives

Despite its considerable advantages, green synthesis faces several challenges that must be addressed before widespread industrial adoption can be achieved. One of the primary limitations is the variability in biological materials. The composition of plant extracts can differ significantly depending on species, geographical location, environmental conditions, and extraction methods, leading to variations in nanoparticle properties and reproducibility [3]. Another challenge involves understanding the complex biochemical mechanisms responsible for nanoparticle formation. While numerous studies have demonstrated successful synthesis, the specific roles of individual biomolecules often remain unclear. Greater mechanistic understanding is necessary for improving process control and reproducibility. Scale-up and standardization also represent major obstacles. Most green synthesis studies remain confined to laboratory-scale investigations, and there is currently a lack of standardized protocols for large-scale production. Future research should focus on process optimization, quality control, and industrial feasibility assessments. The integration of artificial intelligence (AI), machine learning, and advanced process modeling offers exciting opportunities for overcoming these challenges. AI-assisted optimization could help predict synthesis conditions, control nanoparticle characteristics, and improve reproducibility, thereby accelerating the development of next-generation sustainable nanomaterials.

4 Characterization Techniques

The successful synthesis of ZnO nanoparticles must be accompanied by comprehensive characterization to understand their structural, morphological, optical, and chemical properties. Since the performance of ZnO nanomaterials is strongly influenced by factors such as particle size, crystallinity, surface chemistry, and defect concentration, the use of appropriate characterization techniques is essential for establishing structure–property relationships. A combination of analytical tools is typically employed to obtain a complete understanding of the synthesized nanomaterials and to evaluate their suitability for specific applications [1].

4.1 X-Ray Diffraction (XRD)

X-ray diffraction (XRD) is one of the most widely used techniques for investigating the crystalline structure of ZnO nanoparticles. It provides valuable information regarding crystal phase, crystallite size, lattice parameters, and phase purity. The technique is based on the diffraction of X-rays by the atomic planes within a crystalline material, producing characteristic diffraction patterns that can be used to identify crystal structures. For ZnO nanoparticles, XRD patterns typically exhibit distinct diffraction peaks corresponding to the hexagonal wurtzite phase. The presence of sharp and intense peaks generally indicates high crystallinity and successful nanoparticle formation, whereas the absence of impurity peaks confirms phase purity. In addition, the average crystallite size can be estimated using the Debye–Scherrer equation, making XRD an important tool for evaluating the influence of synthesis conditions on crystal growth [7,18]. Beyond structural identification, XRD analysis provides insights into crystal defects, strain, and lattice distortions that may affect the optical, electronic, and photocatalytic properties of ZnO nanomaterials. Consequently, it remains one of the fundamental characterization techniques in ZnO research.

4.2 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) is commonly employed to identify chemical bonds, functional groups, and surface species present in ZnO nanoparticles. The technique measures the absorption of infrared radiation by molecular vibrations, allowing the identification of specific chemical functionalities. In ZnO nanoparticles, characteristic absorption bands are typically observed in the range of 400–600 cm^{-1}, corresponding to Zn–O stretching vibrations and confirming the formation of ZnO structures. For green-synthesized nanoparticles, FTIR analysis is particularly important because it helps identify phytochemicals, proteins, or other biomolecules attached to the nanoparticle surface. These biomolecules often act as reducing and stabilizing agents during synthesis and may significantly influence nanoparticle stability and biological activity [17]. Furthermore, FTIR provides valuable information regarding surface modification, functionalization, and interactions between ZnO nanoparticles and other materials, making it an indispensable tool for the development of nanocomposites and biomedical systems.

4.3 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is widely used to examine the surface morphology and microstructural features of ZnO nanoparticles. The technique generates high-resolution images by scanning a focused electron beam across the sample surface and detecting emitted electrons. SEM analysis provides information regarding particle shape, size distribution, surface texture, and aggregation behavior. Depending on the synthesis method employed, ZnO nanomaterials may exhibit a variety of morphologies, including spherical particles, nanorods, nanowires, nanoflowers, nanosheets, and hierarchical structures [11]. Understanding these morphological variations is important because nanoparticle shape and surface characteristics significantly influence photocatalytic activity, antimicrobial performance, and sensing efficiency. Field-emission scanning electron microscopy (FE-SEM), an advanced form of SEM, offers even higher spatial resolution and has become a preferred tool for detailed examination of ZnO nanostructures. SEM observations are frequently combined with elemental analysis techniques such as energy-dispersive X-ray spectroscopy to obtain complementary information regarding composition and morphology [19,20].

4.4 Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is one of the most powerful techniques for nanoscale characterization. Unlike SEM, which primarily examines surface features, TEM provides direct visualization of internal structure, particle morphology, and crystallographic details at extremely high resolution. TEM images enable accurate determination of nanoparticle size, shape, and distribution. Studies have reported ZnO nanoparticles with dimensions ranging from a few nanometers to several tens of nanometers, depending on synthesis conditions. High-resolution TEM (HRTEM) further allows visualization of lattice fringes, providing detailed information about crystal orientation and structural defects. Selected area electron diffraction (SAED), often integrated with TEM analysis, can be used to confirm crystallinity and crystal phase. Together, TEM and HRTEM play a crucial role in understanding the nanoscale architecture of ZnO materials and validating structural information obtained from XRD analysis [20] .

4.5 Energy-Dispersive X-Ray Spectroscopy (EDS/EDX)

Energy-dispersive X-ray spectroscopy (EDS or EDX) is commonly used in conjunction with SEM or TEM to determine the elemental composition of ZnO nanoparticles. The technique detects characteristic X-rays emitted from a sample when it is exposed to an electron beam, allowing qualitative and quantitative elemental analysis. For ZnO nanoparticles, EDX spectra typically reveal the presence of zinc and oxygen as the dominant elements, confirming successful synthesis and purity of the material. The absence of unwanted elemental signals indicates minimal contamination and high-quality nanoparticle formation [21]. In addition to confirming composition, EDX analysis is particularly useful for investigating doped ZnO systems and nanocomposites, where precise determination of elemental distribution is necessary for understanding material performance.

4.6 Atomic Force Microscopy (AFM)

Atomic force microscopy (AFM) provides three-dimensional surface topographical information at the nanometer scale. Unlike electron microscopy techniques, AFM does not require conductive coatings and can be used to analyze a wide variety of materials under ambient conditions. The technique operates by scanning a sharp probe across the sample surface and measuring interaction forces between the tip and the material. AFM enables the determination of surface roughness, particle height, grain distribution, and nanoscale surface features. In ZnO research, AFM is particularly useful for evaluating thin films, coatings, and nanostructured surfaces where surface texture significantly influences optical and electronic performance. When combined with SEM and TEM observations, AFM provides a more comprehensive understanding of surface morphology and structural organization [22].

4.7 UV–Visible Spectroscopy

UV–Visible spectroscopy is a fundamental technique for investigating the optical properties of ZnO nanoparticles. The technique measures the absorption and transmission of ultraviolet and visible light by a material, providing information regarding optical band gap, electronic transitions, and light absorption behavior. ZnO nanoparticles typically exhibit strong absorption in the ultraviolet region due to their wide band gap. The position of the absorption edge can be used to estimate band gap energy, which is an important parameter for photocatalytic and optoelectronic applications. Variations in particle size, morphology, and defect concentration often result in shifts in absorption characteristics, providing insight into nanoscale effects. For green-synthesized ZnO nanoparticles, UV–Visible spectroscopy is also frequently employed as a rapid preliminary tool to monitor nanoparticle formation and evaluate optical [23]. The technique remains one of the most widely used methods for assessing the optical performance of ZnO nanomaterials.

4.8 Advanced Characterization Techniques

In addition to the commonly employed techniques discussed above, several advanced analytical methods contribute to a more comprehensive understanding of ZnO nanoparticles. Raman spectroscopy provides information regarding crystal quality, phonon modes, and structural defects, while photoluminescence (PL) spectroscopy is extensively used to investigate electronic transitions, defect states, and emission behavior [24]. Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) are valuable for evaluating thermal stability, decomposition behavior, and phase transformations of ZnO-based materials. Similarly, X-ray photoelectron spectroscopy (XPS) offers detailed information regarding elemental composition, oxidation states, and surface chemical environments, making it particularly useful for studying doped and functionalized ZnO systems [25]. The integration of multiple characterization techniques is essential for obtaining a complete understanding of ZnO nanoparticles. While individual methods provide specific information, their combined application enables researchers to establish robust correlations between synthesis conditions, structural properties, and functional performance. Such comprehensive characterization forms the foundation for the rational design and optimization of ZnO nanomaterials for advanced technological applications.

5 Emerging Applications of ZnO Nanoparticles

The unique combination of optical, electronic, catalytic, and biological properties has positioned ZnO nanoparticles among the most versatile nanomaterials currently under investigation. Their wide band gap, high exciton binding energy, large surface-to-volume ratio, tunable morphology, and ability to generate reactive oxygen species (ROS) enable their use in diverse fields ranging from medicine and environmental remediation to sensing and optoelectronics. Recent advances in synthesis and surface engineering have further expanded the functional capabilities of ZnO nanomaterials, leading to significant progress in both fundamental research and practical applications.

5.1 Biomedical Applications

ZnO nanoparticles have attracted significant attention in biomedical research owing to their biocompatibility, antimicrobial activity, and unique physicochemical properties. Their ability to generate reactive oxygen species (ROS), release Zn^{2+} ions, and interact with biological membranes enables applications in antimicrobial therapy, cancer treatment, anti-inflammatory formulations, bioimaging, and drug delivery [26].

5.1.1 Antibacterial and Antifungal Applications

ZnO nanoparticles exhibit broad-spectrum antimicrobial activity against various Gram-positive and Gram-negative bacteria, including *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*. Their antimicrobial effects arise from ROS generation, membrane disruption, and Zn^{2+} ion release, which collectively impair microbial growth and survival. They also demonstrate antifungal activity against species such as *Candida albicans* and *Aspergillus niger*. Consequently, ZnO nanoparticles are widely explored for applications in wound dressings, antimicrobial coatings, food packaging, and healthcare products [27].

5.1.2 Anticancer Applications

ZnO nanoparticles have shown promising anticancer potential due to their ability to selectively induce oxidative stress in cancer cells. Excessive ROS production leads to DNA damage, mitochondrial dysfunction, and apoptosis through activation of tumor-suppressor and caspase-mediated pathways. Significant anticancer activity has been reported against liver, breast, cervical, colon, and lung cancer cell lines. Furthermore, ZnO-based nanocarriers offer opportunities for targeted drug delivery and improved therapeutic efficacy [28].

5.1.3 Anti-Inflammatory Applications

Recent studies suggest that ZnO nanoparticles possess anti-inflammatory properties by regulating oxidative stress and modulating inflammatory signaling pathways. They can influence cytokine production, suppress inflammatory mediators, and contribute to immune regulation through controlled zinc ion release, highlighting their potential for treating inflammation-related disorders [27].

5.1.4 Bioimaging and Drug Delivery

The strong photoluminescence and surface-functionalization capability of ZnO nanoparticles make them useful for bioimaging applications. Additionally, their high surface area and pH-responsive dissolution behavior enable efficient drug loading and controlled release, particularly in acidic tumor environments. These properties have positioned ZnO nanoparticles as promising platforms for targeted drug delivery and next-generation nanomedicine [26].

5.2 Photocatalytic Applications

Photocatalysis represents one of the most extensively explored application areas of ZnO nanoparticles due to their excellent optical properties, chemical stability, and strong photoactivity. As a wide-band-gap semiconductor, ZnO can absorb ultraviolet radiation and generate electron–hole pairs that participate in oxidation and reduction reactions at the catalyst surface. These reactions produce highly reactive oxygen species capable of degrading a wide range of organic and inorganic contaminants. The photocatalytic mechanism of ZnO is primarily based on the excitation of electrons from the valence band to the conduction band upon irradiation with light of sufficient energy. The resulting photogenerated electrons and holes interact with oxygen and water molecules to form superoxide and hydroxyl radicals, which subsequently oxidize pollutants into less harmful products such as carbon dioxide and water. This process has been widely utilized for the degradation of dyes, pharmaceutical residues, pesticides, and other environmental contaminants [29].

ZnO-based photocatalysts have demonstrated remarkable efficiency in the degradation of common industrial dyes, including methylene blue, methyl orange, and rhodamine B. Their effectiveness is strongly influenced by particle size, morphology, crystallinity, and surface defects, all of which affect charge separation and light absorption efficiency. Nanostructures with high surface areas and reduced electron–hole recombination rates generally exhibit superior photocatalytic performance [30]. Significant efforts have already been devoted to overcome the limitations associated with the wide band gap of ZnO, which restricts its activity primarily to the ultraviolet region of the solar spectrum. Strategies such as metal doping, non-metal doping, heterojunction formation, and coupling with noble metals have been developed to enhance visible-light absorption and improve charge-carrier separation. For example, hybridization with silver, gold, and palladium nanoparticles has been shown to improve photocatalytic efficiency through plasmonic effects and enhanced electron transfer processes [23]. Beyond pollutant degradation, ZnO photocatalysts are being investigated for solar-driven hydrogen production and carbon dioxide reduction. These applications are particularly important in the context of renewable energy and environmental sustainability. Continued research aimed at improving visible-light activity and long-term stability is expected to further expand the role of ZnO in photocatalytic technologies [31].

5.3 Sensing Applications

The unique electronic properties of ZnO nanoparticles have made them highly attractive materials for sensing technologies. Their high electron mobility, large surface area, and sensitivity to surface adsorption processes enable rapid and selective detection of various chemical and biological species. As a result, ZnO-based nanomaterials have been widely investigated for gas sensors, biosensors, environmental monitoring systems, and healthcare diagnostics. Gas sensing is one of the most prominent applications of ZnO nanostructures. The sensing mechanism typically relies on changes in electrical resistance caused by adsorption and desorption of gas molecules on the ZnO surface. Exposure to target gases alters the concentration of charge carriers within the semiconductor, leading to measurable electrical signals. ZnO-based sensors have demonstrated high sensitivity toward gases such as ozone, hydrogen, ammonia, nitrogen oxides, and volatile organic compounds. The performance of ZnO gas sensors is strongly influenced by morphology and surface characteristics. Nanorods, nanowires, nanoflowers, and porous nanostructures often exhibit enhanced sensitivity due to their increased surface area and greater availability of active adsorption sites. Furthermore, surface modification with noble metals or other semiconductors can improve selectivity and lower operating temperatures [32]. In the biomedical field, ZnO nanoparticles have also shown promise for biosensing applications. Their excellent biocompatibility and surface functionalization capability facilitate the immobilization of biomolecules such as enzymes, antibodies, and nucleic acids. These properties have enabled the development of sensors for glucose monitoring, disease diagnostics, and detection of biological markers. As nanotechnology and wearable electronics continue to advance, ZnO-based sensing platforms are expected to play an increasingly important role in next-generation diagnostic devices [33].

5.4 Catalytic Applications

In addition to their photocatalytic activity, ZnO nanoparticles serve as effective catalysts and catalyst supports in various chemical reactions. Their catalytic performance is largely attributed to their amphoteric nature, high surface area, abundance of active surface sites, and ability to facilitate adsorption and activation of reactant molecules. ZnO-based catalysts have been employed in a variety of organic transformations, including oxidation, reduction, condensation, transesterification, and alkylation reactions. The catalytic efficiency can be further enhanced through particle size control, surface modification, and incorporation into composite systems. Recent studies have reported that plant-mediated ZnO nanoparticles exhibit excellent catalytic activity in organic synthesis, demonstrating the potential of green nanotechnology for sustainable chemical processes [25,29]. The integration of ZnO with other catalytic materials has also led to the development of multifunctional catalysts with improved performance. Such hybrid systems often exhibit enhanced stability, selectivity, and reaction rates, making them attractive for industrial and environmental applications. As the demand for environmentally benign catalytic processes continues to grow, ZnO nanomaterials are expected to remain important components of heterogeneous catalyst systems [25].

5.5 Environmental Applications

Environmental remediation has become one of the most important research areas for ZnO nanomaterials due to increasing concerns regarding water pollution, industrial waste, and ecosystem degradation. The combination of photocatalytic activity, adsorption capability, and antimicrobial properties enables ZnO nanoparticles to address multiple environmental challenges simultaneously. One of the most significant environmental applications of ZnO nanoparticles is wastewater treatment. Through photocatalytic degradation, ZnO can effectively remove organic pollutants, dyes, pesticides, pharmaceutical residues, and pathogenic microorganisms from contaminated water. Several studies have reported degradation efficiencies exceeding 90% for common dye pollutants under optimized conditions, highlighting the potential of ZnO-based systems for large-scale water purification [25,29]. ZnO nanoparticles have also demonstrated effectiveness in the removal of toxic heavy metal ions such as lead (Pb^{2+}), copper (Cu^{2+}), and chromium (Cr^{6+}) from aqueous environments. Their high surface area and surface reactivity facilitate adsorption and immobilization of these contaminants, reducing their environmental impact and associated health risks. In addition to water treatment, ZnO nanomaterials have been investigated for soil remediation, air purification, and antimicrobial environmental coatings. The growing emphasis on sustainable technologies has further encouraged the development of green-synthesized ZnO nanoparticles for environmental applications, combining high performance with reduced ecological impact [25,30].

5.6 Optoelectronic Applications

The exceptional optical and electronic properties of ZnO have established it as a key material in the field of optoelectronics. Its wide direct band gap, high exciton binding energy, optical transparency in the visible region, and excellent charge transport characteristics make it suitable for numerous electronic and photonic devices [22,33]. ZnO nanomaterials have been extensively investigated for use in ultraviolet photodetectors, light-emitting diodes (LEDs), laser devices, transparent conductive films, and solar cells. The ability to tailor particle size, morphology, and defect concentration allows precise control over optical absorption and emission properties, enabling the design of materials with application-specific characteristics. Particularly noteworthy is the use of ZnO in photovoltaic devices. As an electron transport material, ZnO facilitates efficient charge separation and transport, contributing to improved solar cell performance. Similarly, ZnO nanostructures have been incorporated into photodetectors due to their strong ultraviolet absorption and rapid photoresponse characteristics [22,25]. Recent advances in nanostructuring, doping, and heterojunction engineering have further expanded the optoelectronic potential of ZnO. The development of flexible electronics, wearable devices, and next-generation photonic systems is expected to create new opportunities for ZnO-based materials in the coming years. Consequently, ZnO continues to be regarded as one of the most promising semiconductor nanomaterials for advanced optoelectronic technologies.

6 Challenges and Future Perspectives

Despite the remarkable progress achieved in the synthesis, characterization, and application of ZnO nanoparticles, several scientific and technological challenges continue to limit their widespread commercialization and practical implementation. Addressing these challenges will be essential for realizing the full potential of ZnO-based nanomaterials in biomedical, environmental, catalytic, and optoelectronic applications [25]. One of the most significant concerns relates to the potential toxicity of ZnO nanoparticles. Although ZnO is generally considered biocompatible and has been approved for use in various consumer products, the biological effects of nanoscale ZnO remain a topic of ongoing investigation. The ability of ZnO nanoparticles to generate reactive oxygen species and release Zn^{2+} ions, while beneficial for antimicrobial and anticancer applications, may also induce oxidative stress and cellular damage under certain conditions. Factors such as particle size, morphology, concentration, surface chemistry, and exposure duration can significantly influence toxicity profiles. Therefore, comprehensive in vitro and in vivo studies are required to establish safe exposure limits and assess long-term environmental and health impacts [21].

Another important challenge is associated with the intrinsic electronic properties of ZnO. Although its wide band gap and high exciton binding energy are advantageous for many applications, they also restrict light absorption primarily to the ultraviolet region, which represents only a small fraction of the solar spectrum. Furthermore, rapid recombination of photogenerated electron–hole pairs often reduces photocatalytic efficiency and limits the overall performance of ZnO-based systems. To overcome these limitations, future research should focus on defect engineering, doping strategies, heterojunction design, and the development of hybrid nanostructures capable of extending light absorption into the visible region while improving charge separation efficiency [23]. Reproducibility and process control remain major challenges in nanoparticle synthesis. Small variations in reaction conditions can result in significant differences in particle size, morphology, crystallinity, and surface properties, ultimately affecting material performance. This issue is particularly evident in green synthesis approaches, where the composition of biological extracts can vary depending on plant species, geographical location, growth conditions, and extraction procedures. Establishing standardized synthesis protocols and quality-control measures will therefore be critical for ensuring reproducibility and facilitating industrial-scale production [19]. Scalability represents another key obstacle. While numerous laboratory-scale studies have demonstrated successful synthesis of ZnO nanoparticles with desirable properties, translating these methods to commercial production remains challenging. Conventional physicochemical techniques often require high temperatures, specialized equipment, or significant energy inputs, whereas biological synthesis approaches may suffer from lower yields and inconsistent product quality. Future efforts should prioritize the development of cost-effective, energy-efficient, and scalable manufacturing processes capable of producing high-quality ZnO nanomaterials on an industrial scale [19,25]. The characterization of ZnO nanoparticles also presents challenges. Although a wide range of analytical techniques is available, inconsistencies in measurement protocols and data interpretation frequently complicate comparisons between studies. The establishment of standardized characterization methodologies would improve reproducibility and facilitate more accurate assessment of nanoparticle properties across different research groups and applications. The integration of advanced computational approaches has emerged as a promising direction for ZnO research. Artificial intelligence (AI), machine learning (ML), and data-driven materials design have the potential to accelerate the discovery and optimization of nanomaterials by predicting synthesis conditions, identifying structure–property relationships, and guiding experimental design. Such approaches may significantly reduce experimental costs and development times while enabling more precise control over nanoparticle characteristics [26] .

Future research is also expected to focus on the development of multifunctional ZnO-based nanocomposites and hybrid materials. The incorporation of ZnO with other semiconductors, metals, polymers, carbon-based nanomaterials, and biomolecules can enhance performance and introduce new functionalities. These advanced materials are likely to play a central role in next-generation technologies related to renewable energy, environmental remediation, smart sensing systems, targeted drug delivery, and precision medicine. Furthermore, increasing emphasis on sustainability and green chemistry will continue to drive innovation in environmentally friendly synthesis methods. The combination of biological synthesis routes with modern process optimization strategies may provide an effective pathway toward the large-scale production of high-performance ZnO nanomaterials with reduced environmental impact. As interdisciplinary collaboration between materials scientists, chemists, biologists, engineers, and data scientists continues to expand, the future prospects for ZnO nanotechnology remain highly promising.

7 Conclusion

Zinc oxide (ZnO) nanoparticles are among the most widely studied semiconductor nanomaterials due to their unique optical, electronic, catalytic, and biological properties. Advances in synthesis methods, including conventional physicochemical techniques and environmentally friendly green approaches, have enabled the production of ZnO nanostructures with tailored morphologies and functionalities for diverse applications. Comprehensive characterization using techniques such as XRD, FTIR, SEM, TEM, AFM, and UV–Visible spectroscopy has provided valuable insights into the structural, morphological, and optical properties of ZnO nanoparticles, facilitating their optimization for specific applications. Owing to these properties, ZnO nanoparticles have found extensive applications in biomedicine, photocatalysis, environmental remediation, sensing technologies, catalysis, and optoelectronics. Despite significant progress, challenges related to toxicity, reproducibility, scalability, and visible-light utilization remain. Future research focusing on sustainable synthesis, advanced nanocomposite design, and data-driven material optimization is expected to enhance the performance and commercial viability of ZnO-based systems. Overall, ZnO nanoparticles continue to hold great promise for addressing emerging challenges in healthcare, energy, environmental sustainability, and advanced technologies.

8 Declarations

8.1 Competing Interests

The author declares that there is no conflict of interest.

8.2 Publisher's Note

AIJR remains neutral with regard to jurisdictional claims in published institutional affiliations.

How to Cite this Article:

Islam Uddin, " Advances in Zinc Oxide Nanoparticles: Synthesis, Characterization, Applications, and Future Prospects", *Adv. Nan. Res.*, vol. 9, no. 1, pp. 1–16, Mar. 2026. https://doi.org/10.21467/anr.9.1.1-16

References

[1] S. Bhosale, N. Kannor, N. Shinde, and N. Sahane, "Recent advances in zinc oxide nanoparticles: synthesis methods, characterization techniques, and emerging applications," *Current Catalysis*, vol. 13, no. 2, Oct. 2024, doi: 10.2174/0122115447323237241016100917.

[2] J. Xie, H. Li, T. Zhang, B. Song, X. Wang, and Z. Gu, "Recent advances in ZNO Nanomaterial-Mediated Biological Applications and Action Mechanisms," *Nanomaterials*, vol. 13, no. 9, p. 1500, Apr. 2023, doi: 10.3390/nano13091500.

[3] D. Kirubakaran *et al.*, "A Comprehensive review on the green Synthesis of Nanoparticles: Advancements in biomedical and environmental applications," *Biomedical Materials & Devices*, vol. 4, no. 1, pp. 388–413, Feb. 2025, doi: 10.1007/s44174-025-00295-4.

[4] K. S. Ahmad, S. Yaqoob, and M. M. Gul, "Dynamic green synthesis of iron oxide and manganese oxide nanoparticles and their cogent antimicrobial, environmental and electrical applications," *Reviews in Inorganic Chemistry*, vol. 42, no. 3, pp. 239–263, Nov. 2021, doi: 10.1515/revic-2021-0033.

[5] S. Jadoun, J. Yáñez, R. Aepuru, M. Sathish, N. K. Jangid, and S. Chinnam, "Recent advancements in sustainable synthesis of zinc oxide nanoparticles using various plant extracts for environmental remediation," *Environmental Science and Pollution Research*, vol. 31, no. 13, pp. 19123–19147, Feb. 2024, doi: 10.1007/s11356-024-32357-3.

[6] K. P. Bhandari, D. R. Sapkota, M. K. Jamarkattel, Q. Stillion, and R. W. Collins, "Zinc Oxide Nanoparticles—Solution-Based Synthesis and Characterizations," *Nanomaterials*, vol. 13, no. 11, p. 1795, Jun. 2023, doi: 10.3390/nano13111795.

[7] M. K. Alam *et al.*, "Morphological change of ZnO using hydrothermal technique and organic modifiers," *Nano-Structures & Nano-ObjectsNano-Structures & Nano-Objects*, vol. 41, p. 101436, Feb. 2025. https://doi.org/10.1016/j.nanoso.2025.101436

[8] F. Güell *et al.*, "ZnO-based nanomaterials approach for photocatalytic and sensing applications: recent progress and trends," *Materials Advances*, vol. 4, no. 17, pp. 3685–3707, Jan. 2023, doi: 10.1039/d3ma00227f.

[9] R. K. Sharma and R. Ghose, "Synthesis of zinc oxide nanoparticles by homogeneous precipitation method and its application in antifungal activity against Candida albicans," *Ceramics International*, vol. 41, no. 1, pp. 967–975, Sep. 2014, doi: 10.1016/j.ceramint.2014.09.016.

[10] S. R. Brintha and M. Ajitha, "Synthesis and characterization of ZNO nanoparticles via aqueous solution, sol-gel and hydrothermal methods," *IOSR Journal of Applied Chemistry*, vol. 8, no. 11, pp. 66–72, 2015, doi: 10.9790/5736-081116672.

[11] S. Wirunchit and W. Koetniyom, "ZNO nanoparticles synthesis and characterization by hydrothermal process for biological applications," *Physica Status Solidi (A)*, vol. 220, no. 10, Oct. 2022, doi: 10.1002/pssa.202200364.

[12] S. Somla, T. Yingnakorn, T. Chandakhiaw, C. Longbutsri, L. Sriklang, and S. Khumkoa, "Hydrothermal synthesis of ZnO nanoparticles from recycled ZnO obtained from electric arc furnace dust: morphology control and applications," *Scientific Reports*, vol. 16, no. 1, Feb. 2026, doi: 10.1038/s41598-026-39138-7.

[13] M. Singh, D. Vadher, V. Dixit, and C. Jariwala, "Synthesis, optimization and characterization of zinc oxide nanoparticles prepared by sol–gel technique," *Materials Today Proceedings*, vol. 48, pp. 690–692, Sep. 2021, doi: 10.1016/j.matpr.2021.08.145.

[14] B. Patella *et al.*, "Electrochemical synthesis of zinc oxide nanostructures on flexible substrate and application as an electrochemical Immunoglobulin-G immunosensor," *Materials*, vol. 15, no. 3, p. 713, Jan. 2022, doi: 10.3390/ma15030713.

[15] H.-D. So, S.-H. Jon, and W.-C. Yang, "Process optimization for electrochemical synthesis of ZnO nanoparticles with respect to productivity and consumption using TOPSIS and Taguchi methods," *Scientific Reports*, vol. 15, no. 1, p. 16619, May 2025, doi: 10.1038/s41598-025-01833-2.

[16] H. Nasir, S. K. Zahra, A. Khan, Ahsan, and S. Naheed, “A REVIEW OF SUSTAINABLE METHODS FOR SYNTHESIZING ZINC OXIDE NANOPARTICLES AND THEIR APPLICATIONS,” *Science Heritage Journal*, vol. 8, no. 1, pp. 27–37, Dec. 2023, doi: 10.26480/gws.01.2024.27.37.

[17] M. El-Saadony *et al.*, “Green Synthesis of Zinc oxide nanoparticles: preparation, characterization, and biomedical applications - a review,” *International Journal of Nanomedicine*, vol. Volume 19, pp. 12889–12937, Dec. 2024, doi: 10.2147/ijn.s487188.

[18] M. Umar *et al.*, “Green synthesis and characterizations of zinc oxide nanoparticles using acorn fruit extract for antimicrobial, larvicidal and in silico activities,” *Scientific Reports*, vol. 16, no. 1, p. 7072, Feb. 2026, doi: 10.1038/s41598-026-36137-6.

[19] M. Swain, D. Mishra, and G. Sahoo, “A review on green synthesis of ZnO nanoparticles,” *Discover Applied Sciences*, vol. 7, no. 9, Aug. 2025, doi: 10.1007/s42452-025-06957-8.

[20] S. Goswami *et al.*, “Recent trends in the synthesis, characterization and commercial applications of zinc oxide nanoparticles- a review,” *Inorganica Chimica Acta*, vol. 573, p. 122350, Aug. 2024, doi: 10.1016/j.ica.2024.122350.

[21] P. Pal and A. Pareek, “Zinc oxide nanoparticles: A comprehensive review on its synthesis, characterization, and role in biomedical applications as well as health risks,” *Inorganic Chemistry Communications*, vol. 181, p. 115314, Aug. 2025, doi: 10.1016/j.inoche.2025.115314.

[22] F. T. Z. Toma, M. S. Rahman, and K. H. Maria, “A review of recent advances in ZnO nanostructured thin films by various deposition techniques,” *Discover Materials*, vol. 5, no. 1, Mar. 2025, doi: 10.1007/s43939-025-00201-1.

[23] A. Baig, M. Siddique, and S. Panchal, “A review of Visible-Light-Active Zinc Oxide Photocatalysts for Environmental Application,” *Catalysts*, vol. 15, no. 2, p. 100, Jan. 2025, doi: 10.3390/catal15020100.

[24] I. Kuryliszyn-Kudelska and W. D. Dobrowolski, “Transition Metal-Doped ZNO and ZRO2 Nanocrystals: Correlations between Structure, Magnetism, and Vibrational Properties—A Review,” *Applied Sciences*, vol. 16, no. 2, p. 786, Jan. 2026, doi: 10.3390/app16020786.

[25] S. Maurya, Anupam, S. Tripathi, S. Chaubey, and A. Soni, “Recent advances in the synthesis and applications of zinc oxide nanomaterials for healthcare energy and environmental systems,” *Discover Chemistry.*, vol. 3, no. 1, Mar. 2026, doi: 10.1007/s44371-026-00570-3.

[26] B. Lee, Y. Lee, N. Lee, D. Kim, and T. Hyeon, “Design of oxide nanoparticles for biomedical applications,” *Nature Reviews Materials*, vol. 10, no. 4, pp. 252–267, Jan. 2025, doi: 10.1038/s41578-024-00767-x.

[27] H. Samadi, R. Z. Mohgadam, and M. G. Shahraki, “Green synthesis of ZnO nanoparticles, photocatalyst activity and its biomedical applications: A review,” *Materials Chemistry and Physics*, vol. 345, p. 131161, Jun. 2025, doi: 10.1016/j.matchemphys.2025.131161.

[28] Łukowiak and E. Stolarczyk, “Green synthesis of zinc oxide nanoparticles and their application in anticancer drug delivery – a review,” *International Journal of Nanomedicine*, vol. Volume 21, pp. 1–24, Jan. 2026, doi: 10.2147/ijn.s566276.

[29] C. Zhu and X. Wang, “Nanomaterial ZNO Synthesis and its Photocatalytic applications: A review,” *Nanomaterials*, vol. 15, no. 9, p. 682, Apr. 2025, doi: 10.3390/nano15090682.

[30] A. R. N. Aina, H. Patel, S. Aich, B. Roy, N. S. Samanta, and B. Pal, “Recent advances in ZnO based photocatalysts for industrial dye degradation,” *Discover Applied Sciences*, vol. 7, no. 9, Aug. 2025, doi: 10.1007/s42452-025-07530-z.

[31] H. M. Rasheed, K. Aroosh, D. Meng, X. Ruan, M. Akhter, and X. Cui, “A review on modified ZnO to address environmental challenges through photocatalysis: Photodegradation of organic pollutants,” *Materials Today Energy*, vol. 48, p. 101774, Dec. 2024, doi: 10.1016/j.mtener.2024.101774.

[32] N. Mustapha, B. B. Abdelaziz, M. Benamara, and M. Hjiri, “Recent advances in doping and polymer hybridization strategies for enhancing ZNO-Based gas sensors,” *Nanomaterials*, vol. 15, no. 21, p. 1609, Oct. 2025, doi: 10.3390/nano15211609.

[33] M. R. C. Sytu and J.-I. Hahm, “Principles and applications of ZNO nanomaterials in optical biosensors and ZNO Nanomaterial-Enhanced biodetection,” *Biosensors*, vol. 14, no. 10, p. 480, Oct. 2024, doi: 10.3390/bios14100480.