Review Article **Phytopharmacology Research Journal (PRJ) Open Access**

Received: March 29, 2025 | Revised: May 16, 2025 | Accepted: June 4, 2025 | Published online : 11 July 2025 | ISSN : 2959-9687

Fundamentals, Synthesis, and Antioxidant Applications of Zinc Oxide Nanoparticles: A Critical Review

Muhammad Sohaib[1], Sajjad Ali[1], Salman Khan[1], Muhammad Ishaq[2], Ilyas Khan[1], Noor Majeed[1]*, Ajmal Shah[1]*

1. Department of Chemistry, Abdul Wali Khan University Mardan, Mardan-23200, KP, Pakistan
2. Department of biochemistry, Quaid-i-Azam University, Islamabad, Pakistan

[1]Msohaib889@gmail.com, [1]sajjadaligigyani@gmail.com, [1]salo92837@gmail.com, [2]Khanishaq281@gmail.com, [1] ik8749871@gmail.com, [1]noormajeedkhan699@gmail.com, [1]ajmal.chem@awkum.edu.pk

Correspondence
Noor Majeed
noormajeedkhan699@gmail.com
Ajmal Shah
ajmal.chem@awkum.edu.pk

Funding information
This research received no external funding and was self-funded by the author

Abstract

This comprehensive review examines zinc oxide nanoparticles (ZnO NPs), spotlighting their structural, optical, and catalytic fundamentals, diverse synthesis strategies, and emerging role as potent antioxidant agents. Their intrinsic traits, coupled with their biocompatibility and thermal stability, position them as versatile candidates for advanced applications. The synthesis of ZnO NPs is explored through scalable chemical, physical, and biological routes, including hydrothermal growth, chemical vapor deposition, sol-gel processing, microwave-assisted techniques, plant-mediated green synthesis, and precipitation methods. Each approach is critically analyzed for its impact on nanoparticle morphology, size distribution, and functional efficacy. A dedicated focus is placed on the antioxidant potential of ZnO NPs, where their ability to scavenge reactive oxygen species (ROS) and mitigate oxidative stress is dissected. This property underpins their therapeutic promise in combating inflammation, aging, and degenerative diseases, as well as their environmental utility in neutralizing pollutants and stabilizing industrial products. By bridging material science with biomedical and environmental research, this review underscores the transformative potential of ZnO NPs while advocating for rigorous safety assessments to address toxicity concerns. The integration of fundamental insights, synthesis optimization, and application-driven innovation outlined here aims to guide future advancements in nanotechnology, healthcare, and sustainable engineering.

Keywords: ZnO NPs, Synthesis, ROS, Antioxidant potential, DPPH, Scavenging

1.0 INTRODUCTION

In the rapidly evolving field of nanotechnology, zinc oxide nanoparticles (ZnO NPs) have emerged as a material of great interest due to their unique and versatile properties. Characterized by their high chemical stability, exceptional photocatalytic capabilities, and broad-spectrum antimicrobial activity, ZnO NPs are increasingly recognized for their potential in a multitude of applications[1, 2]. These range from advanced healthcare solutions, such as drug delivery systems and anticancer therapies, to environmental protection strategies, including water purification and air quality improvement[3-6]. Additionally, their ability to block UV radiation effectively makes them ideal for use in sunscreens and protective coatings, further showcasing their adaptability and wide-reaching benefits in industrial and consumer products[7, 8].

The process of synthesizing ZnO NPs is pivotal as it directly influences their physicochemical properties such as size, shape, and crystalline structure[9-11]. These characteristics are crucial because they determine the nanoparticles' reactivity, solubility, and overall effectiveness in specific applications. Several synthesis methods, including sol-gel, hydrothermal synthesis, and vapor deposition, have been refined over time to enhance the properties of ZnO NPs[12-14].

The antioxidant properties of ZnO NPs are garnering considerable attention for their ability to mitigate oxidative stress, which plays a crucial role in aging and the onset of many chronic diseases. Oxidative stress arises from an imbalance between the production of reactive oxygen species (free radicals) and the body's capacity to neutralize their harmful effects with antioxidants, leading to cellular and tissue damage[15-20]. ZnO NPs are particularly promising due to their unique chemical and physical characteristics that enable them to act as effective free radical scavengers. Their high surface-to-volume ratio enhances their interaction with reactive oxygen species, thereby boosting their antioxidant efficacy [15-18]. Additionally, the ability to engineer ZnO NPs to optimize their size, shape, and surface properties can potentially heighten their radical-quenching capabilities beyond those of bulk zinc oxide. ZnO NPs also contribute to upregulating the body's intrinsic antioxidant defenses by modulating cellular signaling pathways that promote the expression of endogenous antioxidant enzymes like superoxide dismutase, catalase, and glutathione peroxidase[17, 21]. This dual mechanism of action, which involves both neutralizing free radicals directly and boosting the body's own antioxidant mechanisms, highlights the versatility of ZnO NPs as a potential therapeutic tool. Ongoing research is necessary to elucidate the precise mechanisms through which ZnO NPs exert their effects and to confirm their safety and effectiveness in clinical settings. Nevertheless, the existing data suggest that ZnO nanoparticles hold significant promise as an innovative antioxidant treatment in preventive medicine and the management of oxidative stress-related disorders [14, 15, 22, 23].

By offering an extensive exploration of zinc oxide NPs, this review aims to provide valuable insights for researchers and practitioners in the field. It seeks to underscore the importance of continued research and development in the synthesis and application of ZnO NPs

to harness their full potential while ensuring safety and sustainability in their use.

1.1 Fundamentals of ZnO NPs

ZnO NPs are a focal point in the domain of nanotechnology, known for their distinctive properties and wide-ranging applications across various fields. These NPs exhibit unique characteristics that set them apart from conventional materials, making them highly valuable for both biological and commercial uses[13, 22, 24]. ZnO NPs are white, odorless compounds with a molecular weight of 81.38 g/mol. Structurally, they typically crystallize in the wurtzite form, though they can also adopt a zinc blende structure under certain conditions. The wide band gap of 3.37 eV at room temperature endows ZnO NPs with excellent electronic, optical, and photocatalytic properties. These NPs are notable for their high chemical stability, which enables them to withstand harsh environments, and their broad radiation absorption spectrum, which makes them effective UV blockers and photocatalysts[25-27].

ZnO NPs can be synthesized using a variety of methods, broadly categorized into top-down and bottom-up approaches. Top-down methods, such as mechanical milling, sputtering, and laser ablation, involve breaking down bulk materials into NPs[28-30]. These techniques, while effective, often come with limitations including high energy consumption and potential contamination from milling media. On the other hand, bottom-up methods involve assembling atoms or molecules directly into nanoparticle structures[28, 31]. Techniques such as sol-gel processing[32, 33], chemical vapor deposition [31] , and hydrothermal synthesis[34] allow for more precise control over the size and shape of the NPs, leading to better consistency and purity. However, these chemical methods can sometimes produce harmful by-products, which has led to increasing interest in green synthesis approaches. Green synthesis utilizes biological entities like plants, fungi, and bacteria to mediate nanoparticle formation, offering a more environmentally friendly alternative that reduces the use of toxic chemicals and energy[35-37].

The versatile properties of ZnO NPs enable their use in a myriad of applications. They are employed as additives in cosmetics and sunscreens due to their UV-blocking capabilities[38]. In the field of electronics, ZnO NPs are used in the manufacture of LEDs, transparent transistors, and solar cells[39, 40]. Their photocatalytic properties make them ideal for environmental applications, such as the degradation of pollutants and water purification[41-43]. ZnO NPs also exhibit significant antimicrobial properties, making them useful in medical and food packaging applications as antibacterial agents[41, 44-46]. Additionally, their ability to generate reactive oxygen species (ROS) lends them applications in the medical field as potential treatments for infections and diseases[47, 48].

While ZnO NPs are beneficial in numerous ways, their environmental and health impacts cannot be overlooked. The toxicity of NPs can vary based on their size, shape, and concentration, as well as the duration of exposure to human and ecological systems[49, 50]. Studies have shown that ZnO NPs can induce cytotoxicity, genotoxicity, and inflammatory responses in mammalian cells under certain conditions[50, 51]. Therefore, understanding the interactions between ZnO NPs and biological systems is crucial for developing safer

applications and establishing regulatory guidelines to mitigate potential risks.

In summary, ZnO NPs are a remarkably versatile and valuable class of nanomaterials with extensive applications ranging from industrial to medical fields. The ongoing development of safer synthesis methods and deeper understanding of their interactions with biological systems is essential to fully leverage their potential while ensuring environmental and human health safety.

1.2 Methods of synthesis

ZnO NPs are synthesized through various methods, each with distinct advantages and applications. Here, we discuss six prominent methods for synthesizing ZnO NPs, highlighting their mechanisms and benefits.

1.2.1 Hydrothermal Method

The hydrothermal synthesis method involves reacting precursor chemicals in a water-based solution under high pressure and temperature within a sealed vessel, typically a Teflon-lined autoclave[52, 53]. This method is favored for its environmental friendliness, scalability, and ability to precisely control the morphology and size of the nanoparticles by adjusting parameters such as temperature, duration, and precursor concentration. The nanoparticles produced are often uniform and highly crystalline, making this method suitable for applications requiring high-quality ZnO NPs[54, 55]. Thilagavathi and Geetha described a typical hydrothermal synthesis procedure for ZnO NPs using a molar ratio of Zn^{2+}/OH^{-} = 1:6 and 1:7. NaOH solution was added dropwise to $ZnCl_2$ solution, followed by SDBS/CTAB and distilled water to form a clear solution. After stirring or resting for 1.5 hours at room temperature, the mixtures were aged at 100 °C to precipitate white ZnO NPs. The precipitates were collected, washed multiple times with distilled water, and dried at 100 °C in air[56]. Ju et al. synthesized ZnO nanosheet microstructures directly on Al_2O_3 tube electrodes using a one-step hydrothermal method with different reaction times (3 h, 8 h, and 12 h). The gas sensing performance was evaluated with ethanol concentrations ranging from 25 to 1000 ppm at 400 °C. Sensor B, processed for 8 hours, demonstrated a particularly high sensitivity, detecting 100 ppm ethanol with a response of 38.4 and 25 ppm ethanol with a response of 15. This indicates the significant potential of ZnO nanosheets in developing effective gas sensors, attributed to their large surface area[57]. Ejsmont and Goscianska et al. explore the optimization of hydrothermal synthesis conditions for creating ZnO with diverse morphologies using zinc acetate and sodium hydroxide solutions. One method involves temperature control from 100 to 200 °C with citric acid as a capping agent, leading to transformations from hexagonal rods to disordered structures of nanosized plates as the temperature increases. A second method excludes organic additives, varying only the pH from 7.5 to 13.5, which demonstrates that well-formed hexagonal pellets form at pH 8.0–8.5, while strongly basic conditions result in small, elongated particles. These findings underscore the significant impact of synthesis parameters like temperature and pH on the morphology of ZnO. This research provides valuable insights for tailoring ZnO properties for specific applications in various fields including optics, electronics, and medicine[58].

]

1.2.2 Chemical Vapor Deposition

Chemical vapor deposition (CVD) is a process where zinc-containing vapors are reacted with oxygen in a high-temperature environment to form ZnO NPs. The process involves the transportation of these vapors across different zones, leading to the deposition of ZnO on cooler surfaces[59-61]. This method is known for producing NPs with controlled size and shape, essential for applications in electronics and optoelectronics[62, 63]. Chang et al. used a modified chemical vapor deposition CVD process with vapor trapping to synthesize n-type ZnO nanowires, achieving high carrier concentrations without impurity dopants. This method introduced donors directly during synthesis, producing nanowires with varied morphologies and electrical properties across different CVD system locations. The approach demonstrates how synthesis conditions can be manipulated to tailor nanowire growth for specific device applications[64]. Barreca et al. developed ZnO−TiO_2 nanocomposites using a novel CVD method, initially growing ZnO nanoplatelets as the host and subsequently dispersing TiO_2 NPs as the guest. The process used molecular sources $Ti(OiPr)_2(dpm)_2$ and $Zn(hfa)_2$·TMEDA, and was conducted at 350−400 °C in nitrogen with wet oxygen atmospheres on Si and Al_2O_3 substrates. This approach avoided ex-situ thermal treatments to maintain the chemical identities of the components. The synthesis conditions, including the TiO2 deposition time, were carefully managed to control the thickness and dispersion of TiO2 within the host ZnO matrix, facilitating the development of nanocomposites tailored for enhanced gas sensing applications[65]. Meléndrez et al. developed a new method to synthesize zinc oxide nanonails (ZnO-NNs) using microwave plasma-assisted chemical vapor deposition (MAP-CVD). The process involved growing ZnO-NNs on cobalt seeds deposited on alumina substrates using helium as the carrier gas. Cobalt seeds were strategically placed at various distances from the precursor material via sputtering. The growth uniformity of the nanonails and the influence of vapor composition from the thermal decomposition of ZnO, which is richer in zinc than oxygen, were key factors in determining the structure's dimensions and growth direction. This method highlights important procedural elements that affect the synthesis of ZnO-NNs[66]

1.2.3 Sol-Gel Process:

The sol-gel process involves the transition of a system from a liquid "sol" (a colloidal suspension of particles) into a solid "gel" phase. In the synthesis of ZnO NPs, zinc salts are dissolved in a solvent and induced to undergo hydrolysis and polycondensation reactions to form a gel. This gel is then dried and calcined to produce ZnO NPs. This method allows for the doping of the NPs with other elements and is useful for creating films and coatings[67-69]. Ben Amor et al. explored the use of chitosan as a capping agent in the sol-gel synthesis of ZnO NPs to control their size, morphology, and functional properties. They employed chitosan derived from shrimp shells, crab shells, and Streptomyces griseus bacteria for the synthesis. The photocatalytic activity of these ZnO NPs was assessed through the degradation of methylene blue, showing dye removal efficiencies of 60%, 56%, and 44% for ZnO derived from shrimp shells, crab shells, and Streptomyces griseus, respectively. Additionally, the antimicrobial effectiveness of these NPs varied against a range of bacteria including Listeria innocua and Staphylococcus aureus, with those having lower band gap values demonstrating superior antibacterial activity. This study highlights the potential of chitosan-sourced sol-gel

processes in enhancing the functional properties of ZnO NPs for environmental and biomedical applications[70]. Sheikhi et al. report the synthesis of ZnO NPs using a cost-effective sol-gel method, examining the impact of synthesis parameters like precursor material (zinc nitrate and zinc acetate), solution pH, and aging time on the NPs' properties. They discovered that zinc acetate yields a more uniform distribution of NPs and that the aspect ratio of rod-like NPs varies with the pH level, increasing with zinc acetate and decreasing with zinc nitrate. Additionally, while the crystalline phase remains unchanged across different synthesis conditions, the crystallite size is significantly influenced by these parameters. Optimal synthesis conditions were identified for achieving high absorption and low backscattering in the UV-Vis absorption band, particularly using zinc acetate at a pH of 13 and extended aging times to tailor nanoparticle morphology without altering the crystalline phase[71].

1.2.4 Microwave-Assisted Synthesis

Microwave-assisted synthesis utilizes microwave radiation to heat the chemical precursors quickly and uniformly, leading to the rapid formation of ZnO NPs[72-74]. This method significantly reduces the synthesis time and energy consumption. It also allows for better control over the size and distribution of NPs, which is advantageous for catalytic and electronic applications[74-76]. Hasanpoor et al. explore the synthesis of ZnO NPs with controlled morphology using microwave irradiation, focusing on the effects of precursor type, irradiation time, and power on particle structure and size. They found that increasing the synthesis time from 10 to 15 minutes and adjusting microwave power from 540 to 680 watts influenced the formation of needle and flower-shaped particles, respectively. The substitution of zinc nitrate with zinc acetate under various powers and times also led to the formation of smaller needle-shaped particles. This study underscores the potential of microwave irradiation as a versatile tool for manipulating the morphology of ZnO NPs [72]. Barreto et al. investigated how various synthesis parameters such as precursor reagents, temperature, irradiation time, microwave radiation power, and the addition of additives impact the morphology of nano-ZnO using the microwave-assisted technique. They found that all these variables significantly affect the shape and size of the NPs. Notably, incorporating an anionic surfactant (sodium di-2-ethylhexyl-sulfosuccinate, (AOT) into the reaction mixture resulted in the formation of smaller hexagonal prismatic particles with enhanced UV absorption. This study highlights the effectiveness of microwave irradiation in tailoring the properties of ZnO NPs by adjusting specific synthesis conditions[77]. Khanam et al. synthesized highly stable ZnO NPs and Chromium (Cr) doped ZnO NPs using a microwave method, focusing on their potential for biomedical applications. The NPs exhibited strong, concentration-dependent antibacterial effects against *E. coli* and *X. citri*, and significant antifungal activity against A. niger and R. stolonifer. Their antioxidant capabilities were confirmed through DPPH radical scavenging, with inhibition rates varying significantly across different concentrations and types of NPs. Hemolysis assays confirmed the biocompatibility of these NPs, with hemolysis rates below 5% at concentrations up to 500 µg/mL. These properties make ZnO and Cr-doped ZnO

NPs promising candidates for various biomedical applications due to their antimicrobial, antioxidant activities, and low toxicity[78].

1.2.5 Plant-Mediated Synthesis

In the plant-mediated synthesis of ZnO-NPs, plant extracts are used as reducing and capping agents to synthesize NPs[79, 80]. This "green" method is environmentally friendly and avoids the use of toxic chemicals. Plant compounds can reduce zinc ions to zinc oxide, and the phytochemicals in the extract can stabilize the NPs, controlling their size and morphology. This method is particularly useful for applications requiring biocompatible and environmentally benign NPs[80-84]. Mousa et al. synthesized ZnO NPs using pomegranate, seder, and beetroot extracts along with a chemical process, aiming to develop efficient photocatalysts for organic pollutant degradation. The study found that the type of plant extract used influenced the photocatalytic properties, energy bandgap, and particle size of ZnO NPs, with sizes ranging between 20 and 30 nm. The photocatalytic tests under UV light showed that ZnO NPs synthesized with beetroot extract exhibited the highest degradation efficiency of Methyl Orange, achieving $87 \pm 0.5\%$ with a kinetic rate constant of 0.007 min^{-1}. This enhanced performance is attributed to improved light absorption and effective charge transfer facilitated by the specific nanoparticle orientations and the production of oxygen vacancies[85]. Sedefoglu et al. developed a method to synthesize ZnO NPs using Myrtus Communis plant extract, employing two different precursors at varying calcination temperatures (400, 600, and 800 °C). The synthesized NPs exhibited hexagonal-like shapes and showed strong photocatalytic activity, degrading about 99% of methylene blue under UV light irradiation at 400 °C. The study highlighted the influence of calcination temperature on the photocatalytic efficiency of ZnO NPs. This research introduces a novel approach to utilizing green synthesis for ZnO nanoparticle production with potential applications in environmental remediation[86]. Bouqellah et al. explored the use of ZnO NPs, synthesized using gamma rays, to combat Fusarium wilt in tomato plants. The study demonstrated that ZnO NPs, particularly those synthesized with a 20 kGy dose, effectively induced physiological immunity in tomato plants, reducing disease symptoms by 28.57% and increasing protection against F. oxysporum by 67.99%. Treated plants also exhibited significant improvements in growth metrics such as shoot and root length, number of leaves, and photosynthetic pigments including chlorophyll and carotenoids. Overall, the use of ZnO-NPs not only controlled the wilt disease but also enhanced the biochemical defense mechanisms of the tomato plants[87].

1.2.6 Precipitation Method

The precipitation method is a simple and cost-effective technique for synthesizing ZnO-NPs. It involves the addition of a precipitating agent to a solution of zinc salts, resulting in the formation of zinc oxide precipitates. This method is known for its rapid synthesis rates and does not require high energy inputs or sophisticated equipment. However, controlling the size and uniformity of the NPs can be challenging[88-92]. Taalab et al. investigated the enhancement of spintronic and optoelectronic properties in undoped and Fe-doped ZnO NPs, synthesized via the co-precipitation method with varying Fe concentrations (1, 3, 5, 8, 10, and 12 at.%). The study found that doping ZnO with Fe modified the optical energy gap, decreasing from 3.103 eV in undoped samples to 2.823 eV in 12% Fe-

doped samples, which also increased the index of refraction due to enhanced polarizability. These changes improve the nonlinear optical properties of the NPs, making them suitable for optoelectronic device applications. Additionally, Fe doping introduced room temperature ferromagnetic behavior in the NPs, supporting their potential use in spintronic devices[93]. Shreya et al. synthesized Zn1−xMgxO NPs using the co-precipitation technique to investigate their structural and optical properties as well as their antibacterial activity. X-ray diffraction and SEM analyses confirmed the crystalline, hexagonal wurtzite structure of the NPs, while EDAX verified the presence of Zn, Mg, and O elements. Optical studies indicated a blueshift in UV emission and an increase in the band gap from 3.28 to 3.35 eV, enhancing their photocatalytic efficiency, as evidenced by a 96% degradation rate of Methylene blue under UV–Vis irradiation. The NPs also demonstrated significant antibacterial activity against both Gram-positive and Gram-negative bacteria[94]. In another study, ZnO NPs were synthesized using both precipitation and combustion methods, with both techniques producing polycrystalline hexagonal wurtzite structures. Larger crystal sizes were achieved via precipitation compared to combustion, although the particle sizes remained similar between the two methods. Photocatalytic tests revealed that ZnO NPs synthesized by precipitation showed superior degradation performance of methylene blue, likely due to larger crystal sizes facilitating better carrier mobility and reducing electron-hole recombination. This suggests that the crystallinity and method of synthesis, particularly precipitation, play crucial roles in enhancing the photocatalytic activity of ZnO NPs[95]. Sumaya et al. synthesized ZnO NPs using a chemical precipitation method, incorporating monoethanolamine (MEA) as a stabilizer in different solvents. The optimal synthesis conditions using isopropanol (IPA) as the solvent included a deposition time of 120 minutes at 60°C, which resulted in NPs with beneficial structural properties and a hexagonal wurtzite crystal structure. The grain sizes of the ZnO NPs decreased with increasing MEA content, demonstrating a correlation between MEA concentration and structural characteristics of the NPs. Additionally, the synthesized ZnO NPs showed broader absorption bands and high band gap energy, indicating potential for various optical applications[96].

1.3 Antioxidant applications of ZnO NPs

ZnO NPs have significant potential as effective antioxidants due to their unique physicochemical properties. The high reactivity and large surface area of ZnO NPs enable them to interact efficiently with free radicals, which are unstable molecules that can cause extensive cellular damage[6, 97]. By neutralizing these harmful radicals, ZnO NPs help mitigate oxidative stress, a key factor in the development of various chronic diseases and aging processes. Their ability to act as electron donors or acceptors to stabilize reactive oxygen species adds a valuable dimension to their utility, making them a promising candidate for inclusion in health-related products, environmental applications, and industrial processes that require control of oxidative mechanisms[98-100].

ZnO NPs exhibit antioxidant action primarily through their ability to scavenge free radicals, which are highly reactive molecules that can cause cellular

damage[100, 101]. The mechanism of antioxidant action of ZnO NPs involves the transfer of electrons to neutralize these ROS. The small size and high surface area of ZnO NPs enhance their interaction with free radicals, facilitating effective electron transfer. This interaction disrupts the chain reactions initiated by free radicals, thereby preventing the oxidative stress that can lead to cellular damage and the progression of many chronic diseases[102-104]. Furthermore, the metal oxide core of ZnO NPs can interact with ROS like hydroxyl radicals and superoxide anions, converting them into less reactive species such as water or oxygen, thus stabilizing the cellular environment. This multifaceted approach makes ZnO NPs particularly valuable in medical and environmental applications where antioxidant properties are essential[105-107].

For instance, Ghaffar et al. conducted a detailed study on the antioxidant properties of ZnO NPs synthesized using biosynthetic approach. The research focused on evaluating the scavenging abilities of the ZnO NPs against a variety of radicals, measuring their performance through multiple assays including DPPH, hydroxyl, hydrogen peroxide, and superoxide radicals. In their experiments, the DPPH scavenging assay showed that ZnO NPs achieved a substantial scavenging rate of approximately 75% at a concentration of 200 µg/mL, with an IC_{50} value of 87.04 µg/mL, compared to gallic acid's IC_{50} of 16.65 µg/mL. The hydroxyl radical scavenging assay revealed that ZnO NPs and gallic acid had comparable efficiencies at higher concentrations (≥100 µg/mL), with ZnO NPs recording an IC_{50} of 74.05 µg/mL and gallic acid at 38.37 µg/mL. In the hydrogen peroxide assay, ZnO NPs demonstrated increased scavenging capability with an IC_{50} value of 55.26 µg/mL, showcasing an 81% effectiveness at 200 µg/mL, indicating a strong potential for applications in systems susceptible to oxidative stress. Lastly, the superoxide scavenging assay revealed that ZnO NPs had an IC_{50} value of 81.37 µg/mL, while gallic acid presented an IC_{50} of 48.73 µg/mL. These findings highlight the ZnO NPs' capacity to adsorb and neutralize free radicals through electron transfer mechanisms, leading to the stabilization of radicals and potential formation of less reactive ZnO-oxide species. This study underscores the potential of ZnO NPs as effective antioxidant agents in biomedical and food preservation applications, with their activity dependent on the concentration and type of plant extract used in the synthesis process[108].

Abdelbaky et al. conducted a study focusing on the antioxidant potential of ZnO NPs synthesized using an aqueous leaf extract of Pelargonium odoratissimum as a green reducing agent. The ZnO NPs were characterized extensively and tested for their antioxidant activity using the DPPH assay. The results demonstrated that these biosynthesized ZnO NPs exhibited significant scavenging activity, achieving an IC_{50} value of 28.11 µg/mL. This study highlights the potential of using green-synthesized ZnO NPs as effective antioxidants in various biomedical applications, underscoring their eco-friendly and cost-effective attributes[109]. The study conducted by Sonkar et al. explored the antioxidant potential of Cu-doped ZnO NPs synthesized via a wet chemical co-precipitation method. The NPs, with varying concentrations of copper doping, were thoroughly investigated for their free radical scavenging properties. Results from the study indicated that all the prepared samples exhibited notable antioxidant activities. Specifically, the antioxidant effectiveness of these NPs was assessed through their capability to

scavenge radicals, highlighting their potential use as effective agents in combating oxidative stress. This research underlines the significance of Cu doping in enhancing the antioxidant properties of ZnO NPs, making them suitable for various biomedical applications[110]. The study conducted by Faizan et al. investigated the role of ZnO NPs in enhancing salt stress tolerance in tomato plants, with a specific focus on the antioxidative enzyme activities. The application of ZnO-NPs was found to significantly improve the activity of key antioxidant enzymes, including peroxidase (POX), superoxide dismutase (SOD), and catalase (CAT), in tomato plants under salt stress. This enhancement in antioxidative enzyme activity suggests that ZnO-NPs contribute to the mitigation of oxidative damage caused by salt stress, thereby supporting plant health and growth. The findings highlight the potential of ZnO-NPs as an effective tool in promoting antioxidant defense mechanisms in plants, making them valuable for agricultural applications in saline environments[111]. According to another work, the study explored the antioxidant capabilities of ZnO NPs synthesized using Moringa oleifera seed extract. These NPs displayed significant activity against H2O2 free radicals, highlighting their potential as effective antioxidant agents. This antioxidant property suggests that ZnO-NPs can be utilized in applications that require protection against oxidative stress, underscoring their utility in various industrial sectors. The effectiveness of ZnO-NPs in scavenging free radicals supports their potential inclusion in health-related and environmental applications[112].

K et al. focused on evaluating the antioxidant capabilities of ZnO NPs synthesized using the eco-friendly *Erythrina variegata* leaf extract. Their findings demonstrated that these green-synthesized NPs are effective antioxidants. The study suggests that ZnO NPs produced through green synthesis methods could be utilized as potent antioxidant agents in various industrial and healthcare applications. This approach not only leverages the natural properties of plant extracts but also aligns with sustainable practices in nanoparticle production[113]. Badri et al. explored the antioxidant efficacy of ZnO NPs synthesized using cow dung as a green combustion method. The study highlighted that these NPs effectively scavenged 1,1-Diphenyl-2-picrylhydrazyl (DPPH) free radicals, showcasing their potential as powerful antioxidants. This capability suggests that ZnO NPs could be used in applications aimed at mitigating oxidative stress and preventing related diseases. The environmentally friendly synthesis process adds to their appeal for sustainable applications in health-related fields[114]. Khajuria et al. focused on synthesizing ZnO NPs using *Mallotus philippinensis* leaf extract as a green method with two different zinc precursors: zinc acetate and zinc nitrate. The antioxidant activity of these ZnO NPs was specifically assessed, revealing that NPs synthesized from zinc nitrate exhibited slightly higher antioxidant potential (IC_{50} = 65.31 µg/ml) than those synthesized using zinc acetate (IC_{50} = 66.87 µg/ml). This suggests that the choice of precursor can influence the antioxidant properties of ZnO NPs. The study highlights the potential of using plant extracts in the biosynthesis of NPs to enhance their antioxidant capabilities, suggesting their utility in biomedical applications where oxidative stress mitigation is desired[115]. In the study conducted by Yadav et al., ZnO NPs were synthesized using the leaf extract of *Syzygium cumini*, which served as a natural capping agent,

]

enhancing the NPs' stability and release properties. The antioxidant properties of these ZnO NPs were particularly noted, demonstrating a potent antioxidative action with an IC_{50} value of 10.54 µg/ml. This significant antioxidant capability indicates that ZnO NPs could be effectively utilized in applications requiring the mitigation of oxidative stress, including health-related and environmental protection roles. The research underscores the potential of ZnO NPs synthesized via green methods, using plant extracts, to provide both eco-friendly and effective solutions in antioxidant applications[116].

In a nutshell, the remarkable antioxidant properties of ZnO NPs present a wide array of applications, from healthcare to environmental protection. Their ability to effectively neutralize harmful free radicals showcases their potential as a versatile tool in combating oxidative stress, enhancing the longevity and performance of various products and systems. As research continues to uncover new uses and improve synthesis methods, ZnO NPs are poised to become a key component in advancing both technology and health solutions worldwide.

1.4 Future perspective of Zn NPs as an antioxidant agent

The future of ZnO NPs as advanced antioxidant agents lies in their tunable surface chemistry, multifunctional hybrid systems, and integration with smart biomaterials. Surface modification strategies, such as functionalization with organic ligands, polymers (e.g., chitosan, polyethylene glycol, or polylactic-co-glycolic acid), or biomolecules (e.g., polyphenols, peptides), can enhance their antioxidant specificity, biocompatibility, and targeted delivery. These modifications not only improve ROS-scavenging efficiency but also reduce off-target toxicity by enabling pH-, light-, or enzyme-responsive release of antioxidant activity. Hybridizing ZnO NPs with nanocomposites like graphene oxide, cellulose, or silica can amplify their stability, mechanical strength, and synergistic antioxidant effects, opening avenues for applications in active food packaging, anti-aging cosmetics, and wearable health monitors. Doping ZnO with transition metals (e.g., Ce, Ag) or non-metals (e.g., N, S) can further tailor electronic properties, enhancing electron-hole separation and ROS-neutralizing capacity. In biomedicine, ZnO-polymer conjugates could revolutionize therapies for oxidative stress-related diseases, such as neurodegenerative disorders (Alzheimer's, Parkinson's), chronic inflammation, and cancer, by combining antioxidant action with drug delivery or imaging capabilities. Additionally, embedding ZnO NPs in hydrogels or nanofibers may enable spatially controlled antioxidant effects for wound healing and tissue regeneration. However, challenges remain in optimizing scalable, eco-friendly synthesis, ensuring long-term biosafety, and understanding nanobio interactions in complex physiological environments. Future research must also explore ZnO's dual role as both an antioxidant and pro-oxidant agent, balancing therapeutic efficacy with potential risks. By leveraging advances in nanotechnology, material science, and precision medicine, ZnO-based antioxidant systems could pioneer next-generation solutions for healthcare, environmental sustainability, and smart functional materials.

1.5 Conclusion

In conclusion, ZnO NPs exhibit a remarkable blend of structural and chemical properties that not only make them versatile agents for a variety of applications but also potent antioxidants with significant medical and environmental

potential. The various synthesis methods, including hydrothermal, chemical vapor deposition, sol-gel, microwave-assisted, plant-mediated, and precipitation techniques, each contribute to the tailoring of ZnO NP characteristics for specific needs, enhancing their applicability across different fields. The detailed examination of their antioxidant capabilities further underscores their importance in combating oxidative stress, a critical factor in numerous health conditions and environmental issues. This review underscores the promising future of ZnO NPs in advancing technology and health sciences, encouraging further research and development in their synthesis and applications to fully harness their potential.

ACKNOWLEDGMENTS

The author gratefully acknowledges the technical support and guidance provided by colleagues during the course of this research.

CONFLICT OF INTEREST

Muhammad Sohaib: Methodology, Writing – original draft. **Sajjad Ali:** Methodology, Formal analysis, Writing – original draft. **Salman Khan:** Software, Validation, Writing – original draft. **Muhammad Ishaq:** Formal analysis, Data creation, Writing – original draft. **Ilyas Khan:** Validation, Software. **Noor Majeed:** Conceptualization, Supervision, Project administration, Writing – review & editing. **Ajmal Khan:** writing – review & editing, Supervision & Project administration.

REFERENCES

1. Missier, M.S., R. Mahesh, and D.P. Sravya Vemareddy, *PROPERTY OF ZINC OXIDE NANOPARTICLE-A REVIEW.* Cuestiones de Fisioterapia, 2025. **54**(3): p. 745-752.
2. Venkatesh, A., et al., *Zinc Oxide Nanoparticles for their Anti-Convulsant Property: A Comprehensive Review.* Journal of Young Pharmacists, 2025. **17**(1): p. 46.
3. Yin, I.X., et al., *Use of Antimicrobial Nanoparticles for the Management of Dental Diseases.* Nanomaterials, 2025. **15**(3): p. 209.
4. Shah, M., et al., *Bibliometric Analysis of Single-Atom Catalysis: A Scoping Review.* Recent patents on nanotechnology.
5. Shah, M., et al., *Advances in agar-based composites: a comprehensive review.* Carbohydrate Polymers, 2024: p. 122619.
6. Das, D., et al., *Synthesis of ZnO nanoparticles and evaluation of antioxidant and cytotoxic activity.* Colloids and Surfaces B: Biointerfaces, 2013. **111**: p. 556-560.
7. Al-Radadi, N.S., et al., *Zingiber officinale driven bioproduction of ZnO nanoparticles and their anti-inflammatory, anti-diabetic, anti-Alzheimer, anti-oxidant, and anti-microbial applications.* Inorganic Chemistry Communications, 2022. **140**: p. 109274.
8. Velsankar, K., et al., *Green inspired synthesis of ZnO nanoparticles and its characterizations with biofilm, antioxidant, anti-inflammatory, and anti-diabetic activities.* Journal of Molecular Structure, 2022. **1255**: p. 132420.
9. Ealia, S.A.M. and M.P. Saravanakumar. *A review on the classification, characterisation, synthesis of nanoparticles and their application*. in *IOP conference series: materials science and engineering*. 2017. IOP Publishing.
10. Shah, N., et al., *Fabrication and Characterization of Montmorillonite Clay/Agar-Based Magnetic Composite and Its Biological and Electrical Conductivity Evaluation.* ACS Omega, 2024. **9**(14): p. 15904-15914.
11. Ali, A., et al., *Fabrication, characterization, and adsorption studies of thermally modified peanut shell charcoal for Orange G dye removal.* Biomass Conversion and Biorefinery, 2024.
12. Amir, J., et al., *Synthesis, characterization and dielectric properties evaluation of NiO-Co3O4 nanocomposite.* Journal of the Iranian Chemical Society, 2025. **22**(1): p. 63-72.
13. Ong, C.B., L.Y. Ng, and A.W. Mohammad, *A review of ZnO nanoparticles as solar photocatalysts: Synthesis, mechanisms and applications.* Renewable and Sustainable Energy Reviews, 2018. **81**: p. 536-551.
14. Janaki, A.C., E. Sailatha, and S. Gunasekaran, *Synthesis, characteristics and antimicrobial activity of ZnO nanoparticles.* Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 2015. **144**: p. 17-22.
15. Mirzaei, H. and M. Darroudi, *Zinc oxide nanoparticles: Biological synthesis and biomedical applications.* Ceramics International, 2017. **43**(1): p. 907-914.
16. Sharma, V., et al., *Induction of oxidative stress, DNA damage and apoptosis in mouse liver after sub-acute*

oral exposure to zinc oxide nanoparticles. Mutation Research/Genetic Toxicology and Environmental Mutagenesis, 2012. **745**(1-2): p. 84-91.
17. Pandurangan, M. and D.H. Kim, *In vitro toxicity of zinc oxide nanoparticles: a review.* Journal of Nanoparticle Research, 2015. **17**: p. 1-8.
18. Sharma, V., D. Anderson, and A. Dhawan, *Zinc oxide nanoparticles induce oxidative stress and genotoxicity in human liver cells (HepG2).* Journal of Biomedical Nanotechnology, 2011. **7**(1): p. 98-99.
19. Shah, N., et al., *Silver immobilized magnetic iron nanoparticles fabricated via green method for detection of cobalt in water and their antibacterial activity.* Environmental Science and Pollution Research, 2025.
20. Shah, M., et al., *Microwave-assisted synthesis of superabsorbent agar-based magnetic composite hydrogel for drug delivery and anti-inflammatory studies.* Results in Engineering, 2025. **26**: p. 104552.
21. Sheteiwy, M.S., et al., *Zinc oxide nanoparticles: potential effects on soil properties, crop production, food processing, and food quality.* Environmental Science and Pollution Research, 2021. **28**(28): p. 36942-36966.
22. Brayner, R., et al., *ZnO nanoparticles: synthesis, characterization, and ecotoxicological studies.* Langmuir, 2010. **26**(9): p. 6522-6528.
23. Sirelkhatim, A., et al., *Review on zinc oxide nanoparticles: antibacterial activity and toxicity mechanism.* Nano-micro letters, 2015. **7**: p. 219-242.
24. Hong, R., et al., *Synthesis and surface modification of ZnO nanoparticles.* Chemical Engineering Journal, 2006. **119**(2-3): p. 71-81.
25. Wang, D., *Optical spectroscopy of Wide-band-gap Semiconductors: Raman and photoluminescence of gallium nitride, Zinc oxide and their nanostructures*. 2006.
26. Zagorac, D., et al., *Band Gap Engineering of Newly Discovered ZnO/ZnS Polytypic Nanomaterials.* Nanomaterials, 2022. **12**(9): p. 1595.
27. Musa, I. and N. Qamhieh, *Study of optical energy gap and quantum confinment effects in Zinc Oxide nanoparticles and nanorods.* Dig. J. Nanomater. Biostruct, 2019. **14**(1): p. 119-125.
28. Abid, N., et al., *Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review.* Advances in Colloid and Interface Science, 2022. **300**: p. 102597.
29. Han, X., et al., *The preparation of spiral ZnO nanostructures by top-down wet-chemical etching and their related properties.* Journal of Materials Chemistry, 2012. **22**(21): p. 10924-10928.
30. Yadav, T.P., R.M. Yadav, and D.P. Singh, *Mechanical milling: a top down approach for the synthesis of nanomaterials and nanocomposites.* Nanoscience and Nanotechnology, 2012. **2**(3): p. 22-48.
31. Wang, X., M. Ahmad, and H. Sun, *Three-dimensional ZnO hierarchical nanostructures: Solution phase synthesis and applications.* Materials, 2017. **10**(11): p. 1304.
32. Harun, K., et al., *Sol–gel synthesized ZnO for optoelectronics applications: a characterization review.* Materials research express, 2017. **4**(12): p. 122001.
33. Park, W.I., *Controlled synthesis and properties of ZnO nanostructures grown by metalorganic chemical vapor deposition: a review.* Metals and materials international, 2008. **14**: p. 659-665.
34. Liu, W., et al., *Supercritical hydrothermal synthesis of nano-zinc oxide: Process and mechanism.* Ceramics International, 2022. **48**(16): p. 22629-22646.
35. Ying, S., et al., *Green synthesis of nanoparticles: Current developments and limitations.* Environmental Technology & Innovation, 2022. **26**: p. 102336.
36. Hosseingholian, A., et al., *Recent advances in green synthesized nanoparticles: From production to application.* Materials Today Sustainability, 2023. **24**: p. 100500.
37. Dikshit, P.K., et al., *Green synthesis of metallic nanoparticles: Applications and limitations.* Catalysts, 2021. **11**(8): p. 902.
38. Kim, K.-B., et al., *Risk assessment of zinc oxide, a cosmetic ingredient used as a UV filter of sunscreens.* Journal of Toxicology and Environmental Health, Part B, 2017. **20**(3): p. 155-182.
39. Beitollahi, H., et al., *Recent advances in ZnO nanostructure-based electrochemical sensors and biosensors.* Journal of Materials Chemistry B, 2020. **8**(27): p. 5826-5844.
40. Choi, Y.-S., et al., *Recent advances in ZnO-based light-emitting diodes.* IEEE Transactions on electron devices, 2009. **57**(1): p. 26-41.
41. Zhu, P., et al., *Biomedical applications of functionalized ZnO nanomaterials: from biosensors to bioimaging.* Advanced Materials Interfaces, 2016. **3**(1): p. 1500494.
42. Nagajyothi, P., et al., *Green route biosynthesis: Characterization and catalytic activity of ZnO nanoparticles.* Materials Letters, 2013. **108**: p. 160-163.
43. Silva, I.M.P., et al., *Different dye degradation mechanisms for ZnO and ZnO doped with N (ZnO: N).* Journal of Molecular Catalysis A: Chemical, 2016. **417**: p. 89-100.
44. Zhang, Y., et al., *Biomedical applications of zinc oxide nanomaterials.* Current molecular medicine, 2013. **13**(10): p. 1633-1645.
45. Kalpana, V. and V. Devi Rajeswari, *A review on green synthesis, biomedical applications, and toxicity studies of ZnO NPs.* Bioinorganic chemistry and applications, 2018. **2018**(1): p. 3569758.
46. Gopikrishnan, R., et al., *Synthesis, characterization and biocompatibility studies of zinc oxide (ZnO) nanorods for biomedical application.* Nano-Micro Letters, 2010.

2: p. 31-36.
47. Weng, Z., et al., *Research progress of stimuli-responsive ZnO-based nanomaterials in biomedical applications.* Biomaterials Science, 2023. **11**(1): p. 76-95.
48. Vighetto, V., et al., *The synergistic effect of nanocrystals combined with ultrasound in the generation of reactive oxygen species for biomedical applications.* Frontiers in bioengineering and biotechnology, 2019. **7**: p. 374.
49. Vandebriel, R.J. and W.H. De Jong, *A review of mammalian toxicity of ZnO nanoparticles.* Nanotechnology, science and applications, 2012: p. 61-71.
50. Hong, T.-K., et al., *A comprehensive in vitro and in vivo study of ZnO nanoparticles toxicity.* Journal of Materials Chemistry B, 2013. **1**(23): p. 2985-2992.
51. Senapati, V.A., et al., *ZnO nanoparticles induced inflammatory response and genotoxicity in human blood cells: A mechanistic approach.* Food and Chemical Toxicology, 2015. **85**: p. 61-70.
52. Baruah, S. and J. Dutta, *Hydrothermal growth of ZnO nanostructures.* Science and technology of advanced materials, 2009. **10**(1): p. 013001.
53. Madathil, A.N.P., K. Vanaja, and M. Jayaraj. *Synthesis of ZnO nanoparticles by hydrothermal method*. in *Nanophotonic materials IV*. 2007. SPIE.
54. Tong, Y., et al., *Growth of ZnO nanostructures with different morphologies by using hydrothermal technique.* The Journal of Physical Chemistry B, 2006. **110**(41): p. 20263-20267.
55. Wang, H., et al., *Growth mechanism of different morphologies of ZnO crystals prepared by hydrothermal method.* Journal of Materials Science & Technology, 2011. **27**(2): p. 153-158.
56. Thilagavathi, T. and D. Geetha, *Nano ZnO structures synthesized in presence of anionic and cationic surfactant under hydrothermal process.* Applied Nanoscience, 2014. **4**(2): p. 127-132.
57. Ju, D., et al., *Direct hydrothermal growth of ZnO nanosheets on electrode for ethanol sensing.* Sensors and Actuators B: Chemical, 2014. **201**: p. 444-451.
58. Ejsmont, A. and J. Goscianska, *Hydrothermal Synthesis of ZnO Superstructures with Controlled Morphology via Temperature and pH Optimization.* Materials, 2023. **16**(4): p. 1641.
59. Wu, J.J. and S.C. Liu, *Low-temperature growth of well-aligned ZnO nanorods by chemical vapor deposition.* Advanced materials, 2002. **14**(3): p. 215-218.
60. Natsume, Y., et al., *Low-temperature conductivity of ZnO films prepared by chemical vapor deposition.* Journal of applied physics, 1992. **72**(9): p. 4203-4207.
61. Liu, X., et al., *Growth mechanism and properties of ZnO nanorods synthesized by plasma-enhanced chemical vapor deposition.* Journal of Applied Physics, 2004. **95**(6): p. 3141-3147.
62. Liu, H., et al., *Reversible wettability of a chemical vapor deposition prepared ZnO film between superhydrophobicity and superhydrophilicity.* Langmuir, 2004. **20**(14): p. 5659-5661.
63. Deng, H., et al., *Microstructure control of ZnO thin films prepared by single source chemical vapor deposition.* Thin solid films, 2004. **458**(1-2): p. 43-46.
64. Chang, P.-C., et al., *ZnO nanowires synthesized by vapor trapping CVD method.* Chemistry of materials, 2004. **16**(24): p. 5133-5137.
65. Barreca, D., et al., *First example of ZnO− TiO2 nanocomposites by chemical vapor deposition: structure, morphology, composition, and gas sensing performances.* Chemistry of Materials, 2007. **19**(23): p. 5642-5649.
66. Meléndrez, M.F., et al., *A new synthesis route of ZnO nanonails via microwave plasma-assisted chemical vapor deposition.* Ceramics International, 2016. **42**(1, Part B): p. 1160-1168.
67. Parashar, M., V.K. Shukla, and R. Singh, *Metal oxides nanoparticles via sol–gel method: a review on synthesis, characterization and applications.* Journal of Materials Science: Materials in Electronics, 2020. **31**(5): p. 3729-3749.
68. Gonçalves, M.C., *Sol-gel silica nanoparticles in medicine: A natural choice. Design, synthesis and products.* Molecules, 2018. **23**(8): p. 2021.
69. Niederberger, M., *Nonaqueous sol–gel routes to metal oxide nanoparticles.* Accounts of chemical research, 2007. **40**(9): p. 793-800.
70. Ben Amor, I., et al., *Sol-Gel Synthesis of ZnO Nanoparticles Using Different Chitosan Sources: Effects on Antibacterial Activity and Photocatalytic Degradation of AZO Dye.* Catalysts, 2022. **12**(12): p. 1611.
71. Sheikhi, S., M. Aliannezhadi, and F.S. Tehrani, *Effect of precursor material, pH, and aging on ZnO nanoparticles synthesized by one-step sol–gel method for photodynamic and photocatalytic applications.* The European Physical Journal Plus, 2022. **137**(1): p. 60.
72. Hasanpoor, M., M. Aliofkhazraei, and H. Delavari, *Microwave-assisted synthesis of zinc oxide nanoparticles.* Procedia Materials Science, 2015. **11**: p. 320-325.
73. Sharma, D., et al., *Synthesis of ZnO nanoparticles using surfactant free in-air and microwave method.* Applied Surface Science, 2011. **257**(22): p. 9661-9672.
74. Rajabi, H.R., et al., *Microwave assisted extraction as an efficient approach for biosynthesis of zinc oxide nanoparticles: synthesis, characterization, and biological properties.* Materials Science and Engineering: C, 2017. **78**: p. 1109-1118.
75. Bayrami, A., et al., *Bio-extract-mediated ZnO nanoparticles: microwave-assisted synthesis, characterization and antidiabetic activity evaluation.*

]

Artificial cells, nanomedicine, and biotechnology, 2018. **46**(4): p. 730-739.
76. Kooti, M. and A. Naghdi Sedeh, *Microwave-Assisted Combustion Synthesis of ZnO Nanoparticles.* Journal of Chemistry, 2013. **2013**(1): p. 562028.
77. Barreto, G.P., G. Morales, and M.L.L. Quintanilla, *Microwave assisted synthesis of ZnO nanoparticles: effect of precursor reagents, temperature, irradiation time, and additives on nano-ZnO morphology development.* Journal of Materials, 2013. **2013**(1): p. 478681.
78. Khanam, B.R., et al., *Physicochemical and therapeutic studies of microwave-synthesized ZnO and Cr-doped ZnO nanoparticles for biomedical applications.* Inorganic Chemistry Communications, 2024. **170**: p. 113454.
79. Agarwal, H., S.V. Kumar, and S. Rajeshkumar, *A review on green synthesis of zinc oxide nanoparticles–An eco-friendly approach.* Resource-Efficient Technologies, 2017. **3**(4): p. 406-413.
80. Fakhari, S., M. Jamzad, and H. Kabiri Fard, *Green synthesis of zinc oxide nanoparticles: a comparison.* Green chemistry letters and reviews, 2019. **12**(1): p. 19-24.
81. Gunalan, S., R. Sivaraj, and V. Rajendran, *Green synthesized ZnO nanoparticles against bacterial and fungal pathogens.* Progress in Natural Science: Materials International, 2012. **22**(6): p. 693-700.
82. Davar, F., A. Majedi, and A. Mirzaei, *Green synthesis of ZnO nanoparticles and its application in the degradation of some dyes.* Journal of the American Ceramic Society, 2015. **98**(6): p. 1739-1746.
83. Matinise, N., et al., *ZnO nanoparticles via Moringa oleifera green synthesis: Physical properties & mechanism of formation.* Applied Surface Science, 2017. **406**: p. 339-347.
84. Chikkanna, M.M., S.E. Neelagund, and K.K. Rajashekarappa, *Green synthesis of zinc oxide nanoparticles (ZnO NPs) and their biological activity.* SN Applied Sciences, 2019. **1**(1): p. 117.
85. Mousa, S.A., et al., *Enhanced photocatalytic activity of green synthesized zinc oxide nanoparticles using low-cost plant extracts.* Scientific Reports, 2024. **14**(1): p. 16713.
86. Sedefoglu, N., *Green synthesis of ZnO nanoparticles by Myrtus communis plant extract with investigation of effect of precursor, calcination temperature and study of photocatalytic performance.* Ceramics International, 2024. **50**(6): p. 9884-9895.
87. Bouqellah, N.A., G.S. El-Sayyad, and M.S. Attia, *Induction of tomato plant biochemical immune responses by the synthesized zinc oxide nanoparticles against wilt-induced Fusarium oxysporum.* International Microbiology, 2024. **27**(2): p. 435-448.
88. Ghorbani, H.R., et al., *Synthesis of ZnO nanoparticles by precipitation method.* Orient. J. Chem, 2015. **31**(2): p. 1219-1221.
89. Rajan, S., et al., *Synthesis of ZnO nanoparticles by precipitation method: Characterizations and applications in decipherment of latent fingerprints.* Materials Today: Proceedings, 2023.
90. Kotresh, M., M. Patil, and S.R. Inamdar, *Reaction temperature based synthesis of ZnO nanoparticles using co-precipitation method: Detailed structural and optical characterization.* Optik, 2021. **243**: p. 167506.
91. Uribe-López, M., et al., *Photocatalytic activity of ZnO nanoparticles and the role of the synthesis method on their physical and chemical properties.* Journal of Photochemistry and photobiology A: Chemistry, 2021. **404**: p. 112866.
92. Mahmood, N.B., et al., *Synthesis and characterization of zinc oxide nanoparticles via oxalate co-precipitation method.* Materials Letters: X, 2022. **13**: p. 100126.
93. Taalab, Z., et al., *Exploring enhanced optoelectronic and spintronic characteristics of Fe-doped ZnO nanoparticles synthesized by co-precipitation approach.* Materials Science in Semiconductor Processing, 2024. **183**: p. 108751.
94. Shreya, A., et al., *Bifunctional Applications of Facile Mg-doped ZnO Nanoparticles Fabricated Via Co-precipitation Technique.* Journal of Inorganic and Organometallic Polymers and Materials, 2024. **34**(9): p. 4157-4173.
95. Krobthong, S., T. Rungsawang, and S. Wongrerkdee, *Comparison of ZnO Nanoparticles Prepared by Precipitation and Combustion for UV and Sunlight-Driven Photocatalytic Degradation of Methylene Blue.* Toxics, 2023. **11**(3): p. 266.
96. Sumaya, M.U., et al., *Effect of stabilizer content in different solvents on the synthesis of ZnO nanoparticles using the chemical precipitation method.* Heliyon, 2023. **9**(10).
97. Ghareib, M., et al., *Free radical scavenging activity of zinc oxide nanoparticles biosynthesised using Aspergillus carneus.* Micro & Nano Letters, 2019. **14**(11): p. 1157-1162.
98. Ganesh, M., et al., *Hydnocarpus alpina Wt extract mediated green synthesis of ZnO nanoparticle and screening of its anti-microbial, free radical scavenging, and photocatalytic activity.* Biocatalysis and agricultural biotechnology, 2019. **19**: p. 101129.
99. Zare, M., et al., *Surfactant assisted solvothermal synthesis of ZnO nanoparticles and study of their antimicrobial and antioxidant properties.* Journal of materials science & technology, 2018. **34**(6): p. 1035-1043.
100. Jha, S., R. Rani, and S. Singh, *Biogenic zinc oxide nanoparticles and their biomedical applications: a review.* Journal of inorganic and organometallic polymers and materials, 2023. **33**(6): p. 1437-1452.
101. Mylarappa, M., et al., *Study of ZnO nanoparticle-supported clay minerals for electrochemical sensors, photocatalysis, and antioxidant applications.* ChemPhysMater, 2024. **3**(1): p. 83-93.
102. Alhujaily, M., et al., *Recent advances in plant-mediated zinc oxide nanoparticles with their significant*

biomedical properties. Bioengineering, 2022. **9**(10): p. 541.
103. Mandal, A.K., et al., *Current research on zinc oxide nanoparticles: synthesis, characterization, and biomedical applications.* Nanomaterials, 2022. **12**(17): p. 3066.
104. Asif, N., M. Amir, and T. Fatma, *Recent advances in the synthesis, characterization and biomedical applications of zinc oxide nanoparticles.* Bioprocess and Biosystems Engineering, 2023. **46**(10): p. 1377-1398.
105. Deka, B., et al., *Biological and non-conventional synthesis of zinc oxide nanoparticles (ZnO-NPs): their potential applications.* Journal of Nanotechnology and Nanomaterials, 2022. **3**(2): p. 79-89.
106. Ravichandran, V., et al., *Durian waste mediated green synthesis of zinc oxide nanoparticles and evaluation of their antibacterial, antioxidant, cytotoxicity and photocatalytic activity.* Green chemistry letters and reviews, 2020. **13**(2): p. 102-116.
107. Valgimigli, L., A. Baschieri, and R. Amorati, *Antioxidant activity of nanomaterials.* Journal of Materials Chemistry B, 2018. **6**(14): p. 2036-2051.
108. Ghaffar, S., et al., *Improved Photocatalytic and Antioxidant Activity of Olive Fruit Extract-Mediated ZnO Nanoparticles.* Antioxidants, 2023. **12**(6): p. 1201.
109. Abdelbaky, A.S., et al., *Green Synthesis and Characterization of ZnO Nanoparticles Using Pelargonium odoratissimum (L.) Aqueous Leaf Extract and Their Antioxidant, Antibacterial and Anti-inflammatory Activities.* Antioxidants, 2022. **11**(8): p. 1444.
110. Sonkar, R., et al., *Cu doped ZnO nanoparticles: Correlations between tuneable optoelectronic, antioxidant and photocatalytic activities.* Journal of Physics and Chemistry of Solids, 2024. **185**: p. 111715.
111. Faizan, M., et al., *Zinc oxide nanoparticles (ZnO-NPs) induce salt tolerance by improving the antioxidant system and photosynthetic machinery in tomato.* Plant Physiology and Biochemistry, 2021. **161**: p. 122-130.
112. Albarakaty, F.M., et al., *Zinc oxide Nanoparticles, Biosynthesis, characterization and their potent photocatalytic degradation, and antioxidant activities.* Journal of King Saud University - Science, 2023. **35**(1): p. 102434.
113. K, V., et al., *Green inspired synthesis of ZnO nanoparticles and its characterizations with biofilm, antioxidant, anti-inflammatory, and anti-diabetic activities.* Journal of Molecular Structure, 2022. **1255**: p. 132420.
114. Badri, A., et al., *Chenopodium exsuccum plant extract for green zinc oxide nanoparticles synthesis: Photocatalytic titan yellow degradation and antioxidant and antibacterial properties.* Inorganic Chemistry Communications, 2025. **172**: p. 113724.
115. Khajuria, A.K., et al., *In vitro antioxidant and antibacterial activities of biogenic synthesized zinc oxide nanoparticles using leaf extract of Mallotus philippinensis Mull. Arg.* Scientific Reports, 2025. **15**(1): p. 6541.
116. Yadav, A., et al., *Syzygium cumini leaf extract mediated green synthesis of ZnO nanoparticles: A sustained release for anticancer, antimicrobial, antioxidant, and anti-corrosive applications.* Journal of Molecular Structure, 2025. **1325**: p. 141017.

]