

Biogenic Zinc Oxide Nanoparticles from *Psidium guajava* Leaves: Antimicrobial and Photocatalytic Application

¹Srishty Rana and ¹Shraddha Sahu*

Department of Biotechnology, Faculty of Engineering & Technology,
Rama University, Kanpur, (U.P), India

*Corresponding author: drshraddha.fet@ramauniversity.ac.in

Abstract

The growing global prevalence of antimicrobial resistance alongside the continuous pollution of aquatic ecosystems by industrial effluents and synthetic dyes constitutes a critical challenge for modern healthcare and environmental management (Lebaka et al., 2025; Singh et al., 2018). Current therapeutic options are increasingly ineffective against resistant bacterial strains, while traditional chemical methods for treating wastewater often create secondary pollution and require significant energy, highlighting an urgent need for multifunctional, sustainable nanomaterials (Sirelkhatim et al., 2015). Biogenic zinc oxide nanoparticles (ZnO NPs) offer a sophisticated, dual-purpose solution, providing both robust broad-spectrum antimicrobial properties and effective photocatalytic activity within a single, ecologically sound platform (Lebaka et al., 2025; Uikey & Vishwakarma, 2016). As a wide-bandgap

semiconductor ($E_g = 3.37$ eV) featuring a high exciton binding energy of 60 meV, ZnO possesses exceptional photostability and UV-absorption qualities, which allow it to produce reactive oxygen species (ROS) when exposed to light (Vaseem et al., 2010). Traditional fabrication methods—including sol-gel, co-precipitation, chemical vapor deposition, and hydrothermal techniques—are hindered by their dependence on harmful reducing agents, high energy usage, and the production of toxic waste (Iravani, 2011; Dahl et al., 2007). Green synthesis using plants provides a sustainable alternative by utilizing naturally occurring phytochemicals as dual-purpose capping and reducing agents (Singh et al., 2018). This review provides a critical evaluation of ZnO NP production through aqueous *Psidium guajava* L. (guava) leaf extracts, a medicinally important tropical species with leaves notably rich in triterpenoids, flavonoids (e.g., quercetin, myricetin, kaempferol), ellagitannins, and

ascorbic acid, all of which act as highly effective stabilizing and reducing components (Kareem & Kadhim, 2024). The plant-based colloidal synthesis process facilitates the regulated growth and nucleation of crystalline, hexagonal wurtzite ZnO NPs, where a protective phytochemical layer remains on the surface to provide both colloidal stability and biological functionality (Fiveable, 2025; Ramya et al., 2022). We examine the mechanistic role of guava-sourced tannins, flavonoids, and polyphenols in forming the wurtzite-phase structure, and we summarize analytical characterizations conducted via dynamic light scattering (DLS), Fourier-transform infrared spectroscopy (FTIR), UV-visible spectroscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD) (Ramya et al., 2022; Vaseem et al., 2010). Furthermore, this paper analyzes antimicrobial pathways—specifically cell membrane damage, ROS production, and Zn²⁺ ion toxicity—in parallel with photocatalytic dye degradation for textile wastewater treatment (Lebaka et al., 2025; Sirelkhatim et al., 2015; Tarek, 2014). The synergistic benefits of the retained phytochemical coating on both catalytic and biological performance are critically examined (Singh et al., 2018; Kareem & Kadhim, 2024). Ultimately, this review highlights existing knowledge gaps,

discusses obstacles to reproducibility and scalability, and suggests future research directions for the application of guava-derived ZnO NPs in textile, biomedical, and water-treatment industries (Lebaka et al., 2025; Iravani, 2011).

Keywords: ZnO nanoparticles; Green Synthesis ; Psidium guajava; Antimicrobial activity; Photocatalytic degradation; Biogenic synthesis; Phtochemicals

1. Introduction

The integration of green chemistry with nanoscience has sparked a significant transition in materials production, fostering the growth of biogenic nanoparticle fabrication. Within the landscape of metal oxide nanomaterials receiving substantial scientific and industrial focus, zinc oxide nanoparticles (ZnO NPs) are uniquely prominent. This standing is due to their remarkable blend of semiconducting characteristics, photostability, compatibility with biological systems, and broad-spectrum antimicrobial performance (Lebaka et al., 2025; Uikey & Vishwakarma, 2016). As a wide-bandgap semiconductor ($E_g = 3.37$ eV) featuring a high exciton binding energy of 60 meV, ZnO displays photocatalytic behaviour under UV light; this process triggers the creation of

reactive oxygen species (ROS) that are effective at neutralizing pathogenic microbes and decomposing organic contaminants (Vaseem et al., 2010).

Traditional fabrication techniques for ZnO NPs, such as chemical vapour deposition, sol-gel processing, co-precipitation, and hydrothermal synthesis are effective but depend on high-energy conditions, toxic capping or reducing agents, and the production of problematic chemical waste. Given the increasing focus on environmental protection and stricter manufacturing regulations, these methods have become progressively less viable. In response, green synthesis has emerged as a robust, sustainable alternative that utilizes biological sources like bacteria, fungi, and plant extracts to act as natural stabilizing and reducing agents. This approach provides a significant advancement, as it remains in direct alignment with the foundational principles of green chemistry (Iravani, 2011; Singh et al., 2018; Dahl et al., 2007).

Psidium guajava L., belonging to the Myrtaceae family and widely referred to as guava, is a tropical species with a long-standing reputation in traditional healing systems throughout Latin America, Africa, and Asia. The leaves of this tree are especially valued due to their dense concentration of therapeutic bioactive

components, such as triterpenoids, flavonoids (notably quercetin and its various glycosides), essential oils, and ellagitannins. Together, these constituents provide the plant with a diverse array of medicinal benefits, including antioxidant, antimicrobial, antidiabetic, anticancer, and anti-inflammatory properties (Kareem & Kadhim, 2024). Consequently, this profound phytochemical abundance positions guava leaf extract as an optimal bio-reagent for the green synthesis of nanoparticles, where it effectively facilitates both the stabilization of forming particles and the bioreduction of metal ion precursors.

This review synthesizes the existing body of research regarding the green fabrication of ZnO nanoparticles through the use of *Psidium guajava* leaf extract. It pays special attention to the mechanistic relationship between the plant's phytochemical makeup and the physical characteristics of the resulting nanoparticles, as well as their practical utility in photocatalysis and antimicrobial treatments. By moving beyond earlier reviews that have frequently analyzed these aspects as separate domains, this study integrates the functional, structural, synthetic, and phytochemical dimensions of the subject into a unified narrative. In doing so, it highlights the essential

structure-property-activity relationships required to rationally design and refine biogenic ZnO nanoparticles for combined photocatalytic and antimicrobial applications.

2. *Psidium guajava*: A phytochemical Powerhouse for Nanoparticle synthesis

Psidium guajava, a member of the Myrtaceae family within the Myrtales order, is taxonomically recognized as a dicotyledonous angiosperm. Although indigenous to tropical regions of Mexico and Central America, this species has been extensively naturalized across the subtropical and tropical zones of Oceania, Africa, and Asia as a result of centuries of cultivation and trade. Major commercial production of this tree occurs in nations such as India, Brazil, Thailand, Syria, Bangladesh, Pakistan, Indonesia, and Egypt, where it is highly valued both as a nutrient-rich fruit crop and as a source of medicinal compounds (Kareem & Kadhim, 2024).

Across numerous traditional healing systems—most notably Indian Ayurveda, Traditional Chinese Medicine, and various folk practices throughout Africa and Latin America—different components of the guava tree, especially the bark and leaves, have been employed for generations to

manage a variety of ailments. These include diarrhea, dysentery, gastrointestinal infections, hypertension, fever, diabetes, toothaches, skin infections, and wound healing. The extensive ethnomedicinal utility of this plant is directly linked to its complex and abundant phytochemical profile, a characteristic that contemporary pharmacological research has increasingly confirmed through comprehensive *invivo* and *invitro* evaluations (Kareem & Kadhim, 2024).

2.1 Biogenic Synthesis of ZnO Nanoparticles

The biogenic production of ZnO nanoparticles through plant extracts serves as a prime example of applying the tenets of green chemistry to nanomaterial fabrication. This method specifically aligns with several of the twelve principles defined by Anastas and Warner (as reviewed by Dahl et al., 2007), including Principle 1 (waste prevention), Principle 5 (the use of safer solvents, primarily water), Principle 6 (energy efficiency achieved via mild reaction conditions), Principle 7 (the use of renewable feedstocks derived from plant biomass), and Principle 12 (inherently safer chemistry through the removal of toxic reagents). By substituting hazardous chemical reducers such as hydrazine or sodium borohydride with *P.*

guajava extract, the synthesis process becomes significantly more sustainable, using a biological reagent that is non-toxic, biodegradable, and renewable. Consequently, this shift markedly decreases the ecological impact and potential toxicity risks traditionally linked to the manufacturing of ZnO nanoparticles.

Biogenic fabrication of ZnO nanoparticles utilizes a bottom-up methodology rooted in colloidal chemistry, whereby zinc oxide structures are assembled sequentially from individual atoms and clusters derived from zinc ion precursors in a solution (Fiveable, 2025). This technique differs fundamentally from top-down processes such as laser ablation or ball milling which rely on the mechanical breakdown of bulk ZnO into nanoparticles, a method that is typically energy-intensive and often results in widely varying particle sizes. A major benefit of the bottom-up biogenic pathway is the capability to regulate the kinetics of nanoparticle growth and nucleation by adjusting specific reaction parameters, including the temperature and pH of the medium, as well as the respective concentrations of the zinc precursor and the plant extract.

2. Mechanistic Role of Phytochemicals

The biogenic fabrication of ZnO nanoparticles via *Psidium guajava* phytochemicals occurs through a sequence of integrated stages. Initially, the carbonyl (C=O) and polyphenolic hydroxyl (–OH) groups found in tannins and flavonoids establish coordination complexes with Zn^{2+} ions, generating a [Zn-phytocholate] intermediate in the reaction mixture. Upon subjection to alkaline conditions and thermal treatment, these complexes undergo hydrolysis, yielding $Zn(OH)_2$ or ZnO nuclei. Simultaneously, phenolic groups facilitate bioreduction by donating electrons or H atoms to Zn^{2+} ions, a process that converts phenols into quinones. Following this, the ZnO nuclei expand via aggregation and Ostwald ripening until they reach a stable size, at which point phytochemical molecules adsorb onto the nanoparticle surfaces. This creates a robust organic corona that effectively passivates the particles, hindering further growth and preventing agglomeration (Singh et al., 2018; Kareem & Kadhim, 2024).

The diverse phytochemical profile of guava leaf extract notably its high concentration of gallic acid, quercetin, ascorbic acid, and ellagic acid constitutes a highly efficient, multi-faceted reduction

and stabilization system. This phytochemical shell provides more than just physical stability; it also imparts bio-functional properties to the nanoparticles, such as antioxidant and antimicrobial effects. This synergistic feature is unique to biogenic nanoparticles, distinguishing them from their purely chemical counterparts (Kareem & Kadhim, 2024; Singh et al., 2018).

3. Structural and Morphological Characterization

X-ray diffraction (XRD) analysis is the definitive method for validating the crystalline nature and phase identity of zinc oxide nanoparticles. ZnO NPs produced via *Psidium guajava* extract consistently exhibit diffraction patterns characterized by prominent peaks at 2θ values that correspond to the (100), (002), (101), (102), (110), (103), (200), (112), and (201) planes. These results are indicative of a hexagonal wurtzite crystal system and correlate well with the standards provided by JCPDS card no. 36-1451 (Ramya et al., 2022; Vaseem et al., 2010). The absence of extraneous diffraction peaks serves as verification of the material's phase purity. By applying the Debye-Scherrer equation ($D = K\lambda / \beta \cos \theta$), researchers have calculated the average crystallite size for these guava-

synthesized ZnO NPs, which typically fall between 10 and 30 nm, depending on factors such as the ratio of extract volume, precursor concentration, and thermal calcination settings. For instance, in their study utilizing a microwave-assisted sol-gel approach, Ramya et al. (2022) documented an average crystallite size of approximately 15.8 nm.

Scanning electron microscopy (SEM) is essential for evaluating the surface texture and general morphology of biogenic ZnO nanoparticles. By modulating synthesis variables such as temperature, pH, calcination heat, and the concentration of the guava extract, researchers can produce ZnO NPs with varied shapes, including nanospheres, nanorods, nanoclusters, and nanoflakes. For example, Ramya et al. (2022) reported a nanorod-like structure for ZnO NPs fabricated via microwave-assisted sol-gel techniques using *Psidium guajava* extract. The aspect ratio of these nanorods is a critical factor influencing photocatalytic performance, as anisotropic structures often facilitate better charge carrier transport, leading to higher efficiency. Furthermore, energy-dispersive X-ray spectroscopy (EDAX) confirms the stoichiometric presence of zinc and oxygen, while the absence of contaminating elements in the spectra provides evidence of the high purity

achieved through this biogenic synthesis route.

UV-visible absorption spectroscopy is the primary technique for investigating the optical characteristics of ZnO NPs, typically showing a distinct exciton absorption peak between 350 and 380 nm that arises from the near-band-edge (NBE) transition. To determine the optical bandgap energy (E_g), researchers employ Tauc plot analysis, which involves plotting the square of the product of the absorption coefficient and photon energy (αhv)² against photon energy (hv) and extending the linear portion to the hv -axis. ZnO nanoparticles synthesized through green methods using guava extract generally display E_g values within the range of 3.10–3.37 eV. While this aligns with the bandgap of bulk ZnO, these values can fluctuate due to surface state effects (which may reduce E_g) or quantum confinement phenomena that increase the bandgap in smaller particles. Because the optical bandgap establishes the minimum photon energy needed to trigger the generation of electron-hole pairs for ROS formation, it serves as a decisive metric for predicting the photocatalytic potential of ZnO nanoparticles (Vaseem et al., 2010; Uikey & Vishwakarma, 2016).

Dynamic light scattering (DLS) analysis of biogenic ZnO nanoparticles dispersed in an aqueous medium typically yields hydrodynamic diameters that exceed the crystallite sizes determined by XRD. This disparity arises because DLS accounts for both the nanoparticle core and the surrounding phytochemical corona, as well as any instances of particle agglomeration within the liquid phase. Regarding size uniformity, a Polydispersity Index (PDI) of less than 0.3 generally denotes acceptable monodispersity, while PDI values exceeding 0.5 suggest significant heterogeneity, indicating that synthesis parameters require further optimization. Zeta potential measurements are vital for determining colloidal stability; biogenic ZnO NPs, which are stabilized by polyphenolic molecules bearing ionized hydroxyl groups at near-neutral or alkaline pH, typically show zeta potential values ranging from –20 to –40 mV. These values suggest moderate to high electrostatic stability (Khatami et al., 2018), with the observed negative surface charge resulting primarily from the carboxylate and phenolate moieties inherent to the adsorbed phytochemicals.

4. Antimicrobial Activity of Biogenic ZnO Nanoparticles

The antimicrobial action of ZnO nanoparticles is a multifaceted and intricate process, driven by several interrelated mechanisms that collectively result in microbial cell death or growth suppression. A clear understanding of these mechanisms is crucial for the rational design and optimization of biogenic ZnO nanoparticles for antimicrobial applications.

When irradiated with UV or visible light, ZnO nanoparticles absorb photons whose energy is equal to or exceeds their bandgap, exciting electrons (e^-) from the valence band to the conduction band and creating corresponding valence band holes (h^+). These photogenerated charge carriers interact with water molecules adsorbed on the nanoparticle surface and dissolved oxygen, initiating a sequence of reactions that yield various reactive oxygen species, including hydroxyl radicals ($-OH$, the most aggressive ROS), superoxide anion radicals (O_2^-), hydrogen peroxide (H_2O_2), and singlet oxygen (1O_2). These ROS are highly reactive and non-specific, inducing severe oxidative damage to microbial lipids (via lipid peroxidation), proteins (through protein oxidation and enzyme inactivation), and nucleic acids (by DNA

strand breaks and base oxidation), ultimately resulting in microbial cell death (Lebaka et al., 2025; Sirelkhatim et al., 2015).

The nanoscale size and high surface energy of ZnO nanoparticles allow them to interact directly with microbial cell membranes, leading to physical disruption of the membrane structure. Electrostatic attraction between positively charged ZnO NPs due to surface Zn^{2+} groups at low to neutral pH and the negatively charged lipopolysaccharides in Gram-negative bacteria or teichoic acids in Gram-positive bacteria promotes nanoparticle adhesion to and penetration through the microbial cell envelope. This membrane permeabilization results in leakage of intracellular components, collapse of the proton gradient, and loss of membrane integrity, ultimately causing irreversible cellular damage (Lebaka et al., 2025; Singh et al., 2018).

ZnO nanoparticles undergo continuous dissolution in aqueous media, releasing Zn^{2+} ions in a process that is accelerated under acidic conditions typical of microbial microenvironments. These free zinc ions are taken up by microbial cells via metal ion transport channels, where they disrupt a range of vital cellular processes, including inhibition of respiratory chain enzymes, interference

with DNA replication and transcription, perturbation of protein synthesis, and displacement of essential metal cofactors such as Fe^{2+} and Mg^{2+} from metalloenzymes. The synergistic effects of intracellular zinc toxicity and concurrent oxidative damage by reactive oxygen species create a multi-target assault on microbial physiology, which is considerably less likely to promote resistance compared with conventional single-target antibiotics (Lebaka et al., 2025; Uikey & Vishwakarma, 2016).

5. Antibacterial Activity against Pathogenic Bacteria

Biogenic ZnO nanoparticles synthesized using *P. guajava* extract have exhibited strong antibacterial activity against a variety of pathogenic bacteria. Ramya et al. (2022) assessed the antibacterial performance of guava-derived ZnO NPs against both Gram-positive and Gram-negative isolates using the well-diffusion assay, observing prominent zones of inhibition at elevated nanoparticle concentrations; the activity against both bacterial categories underscores the broad-spectrum character of the antimicrobial effect. The antibacterial response was concentration-dependent, with increasing nanoparticle doses yielding larger inhibition zones, in agreement with

the widely reported trend that ZnO NP antimicrobial efficacy scales with dose.

Gram-positive bacteria are typically more sensitive to ZnO nanoparticles than Gram-negative bacteria, which is attributed to the relatively thicker but structurally simpler peptidoglycan layer in Gram-positive cells that may facilitate closer nanoparticle contact with the cytoplasmic membrane. In contrast, Gram-negative bacteria possess an outer membrane that, despite its thinner peptidoglycan content, adds an extra permeability barrier. The phytochemical coating on the surface of biogenic ZnO NPs may further boost their antibacterial action through synergistic interactions with the inherent antimicrobial properties of guava-derived phytochemicals, especially quercetin and gallic acid, both of which have well-established antibacterial modes of action (Kareem & Kadhim, 2024; Lebaka et al., 2025).

6. Antifungal Activity and Biofilm Inhibition

In addition to their antibacterial effects, ZnO nanoparticles have exhibited notable antifungal activity against clinically relevant fungi such as *Candida albicans*, *Aspergillus niger*, and several dermatophyte species. The antifungal action is primarily mediated through

reactive oxygen species (ROS)-induced damage and direct physical interaction of the nanoparticles with the ergosterol-rich fungal cell membrane, resulting in membrane permeabilization and leakage of intracellular components. Guava leaf extract, enriched with antifungal phytochemicals such as tannins and terpenoids, may act synergistically with the intrinsic antifungal properties of ZnO in biogenic nanoparticles, thereby enhancing overall efficacy. Of particular importance in clinical settings is the anti-biofilm activity of ZnO NPs, since microbial biofilms—structured communities of microorganisms encased within a self-produced extracellular matrix—show markedly increased tolerance to conventional antibiotics. ZnO nanoparticles have been shown to inhibit biofilm development as well as to destabilize and disassemble preformed biofilms, positioning them as a promising strategy for combating biofilm-associated infections (Lebaka et al., 2025; Singh et al., 2018).

7. Photocatalytic Activity: Dye Degradation and Environmental Remediation

Synthetic dyes such as methylene blue (a cationic thiazine dye), methyl orange (an anionic azo dye), Congo red, and

rhodamine B are representative classes of industrial organic pollutants discharged into aquatic environments through textile dyeing, paper manufacturing, and leather processing activities. Due to their resistance to conventional biological wastewater treatment, along with their inherent toxicity, mutagenicity, and potential carcinogenicity, photocatalytic degradation has emerged as a highly promising remediation approach. Biogenic ZnO nanoparticles, characterized by high surface area, notable photocatalytic efficiency, and straightforward synthesis, are particularly well-adapted for this role (Lebaka et al., 2025; Singh et al., 2018).

The photocatalytic performance of biogenic ZnO nanoparticles is governed by several key factors: (i) the nanoparticle surface area and the density of active sites; (ii) the optical bandgap and UV absorption capability; (iii) the lifetime of photogenerated charge carriers and their recombination rate; (iv) the concentration of the nanoparticle catalyst; (v) the initial dye concentration; (vi) the pH of the reaction system; (vii) the intensity of UV irradiation; and (viii) the presence of electron acceptors such as H₂O₂ or persulfate. The phytochemical residues bound to the nanoparticle surface from guava extract may function as photosensitizers, extending the

light-harvesting range of ZnO nanoparticles into the visible region through dye-sensitization-type mechanisms, thereby improving photocatalytic activity under solar light—a distinct advantage for real-world environmental applications (Singh et al., 2018; Lebaka et al., 2025).

8. Textile Application: Antimicrobial Fabrics with Photocatalytic Self-Cleaning

The incorporation of ZnO nanoparticles into textile substrates represents a rapidly expanding application that capitalizes on their combined antimicrobial, UV-protective, and photocatalytic functionalities. Fabrics functionalized with ZnO nanoparticles exhibit durable antibacterial action against skin-associated pathogens, high ultraviolet protection factors (UPF > 50+), and self-cleaning behavior through the photocatalytic breakdown of organic stains adsorbed on the surface under sunlight. Tarek (2014) explored the use of ZnO nanoparticles in textile printing and dyeing, showing their effectiveness in conferring functional properties to both cotton and synthetic fibers. Employing biogenic ZnO nanoparticles synthesized from guava extract provides an added benefit of enhanced biocompatibility for products

intended for direct skin contact, including wound dressings, antimicrobial socks, and medical textiles (Tarek, 2014; Lebaka et al., 2025).

9. Synergistic Effects: Phytochemical and ZnO Nanoparticles

A key characteristic that sets biogenic ZnO nanoparticles apart from conventionally synthesized ZnO is the presence of a biogenic phytochemical corona—an organic layer composed of residual plant-derived molecules adsorbed onto the nanoparticle surface. Rather than being a mere byproduct of synthesis, this corona is a functionally relevant component that contributes directly to the biological performance of the system and works in synergy with the intrinsic properties of ZnO to enhance overall efficacy.

In antimicrobial applications, quercetin—the major flavonoid in guava leaf extract—inhibits bacterial DNA gyrase, compromises cell membrane integrity, and chelates iron required for bacterial metabolism. When tethered to the surface of ZnO nanoparticles, quercetin achieves a much higher local concentration at the microbial interface compared with free quercetin in solution, which can facilitate greater intracellular penetration and

amplify its biological impact. Likewise, gallic acid and ellagic acid derived from guava tannins possess inherent antibacterial and antifungal properties that complement ZnO's ROS-driven antimicrobial mechanism. Together, this multi-component system delivers multi-target, multi-mechanism antimicrobial action with a substantially elevated barrier to resistance development (Kareem & Kadhim, 2024; Singh et al., 2018; Lebaka et al., 2025).

In photocatalysis, surface-bound polyphenols can act as photosensitizers by absorbing visible light and transferring excited electrons into the conduction band of ZnO, thereby extending photocatalytic activity from the UV region into the visible portion of the solar spectrum. Furthermore, the phenolic moieties of these surface-bound phytochemicals may function as hole scavengers by competing for photogenerated holes, which reduces electron-hole recombination and prolongs the lifetime of conduction-band electrons. This in turn improves the efficiency of oxygen reduction to superoxide radicals. These synergistic phytochemical-ZnO interactions constitute a distinctive and underexplored aspect of biogenic nanoparticle science that warrants more systematic investigation (Singh et al., 2018; Iravani, 2011).

10. Factors influencing Synthesis and Properties of Biogenesis ZnO Nanoparticles

The physicochemical and biological properties of biogenic ZnO nanoparticles—such as particle size, morphology, crystallinity, bandgap, and biological activity—are strongly governed by a range of adjustable synthesis parameters. Gaining insight into these variables and optimizing them is essential to achieve consistent, reproducible nanoparticle batches with the desired functional characteristics.

Plant extract concentration exerts one of the most pronounced effects: higher extract levels provide a larger pool of reducing and capping agents, which typically yields smaller, more monodisperse nanoparticles with enhanced colloidal stability. In contrast, very low extract concentrations can lead to incomplete reduction of zinc ions and result in larger, more polydisperse particles. The concentration of the zinc precursor also plays a key role by affecting nucleation density and particle growth kinetics; elevated precursor concentrations increase supersaturation and promote faster growth, favoring the formation of larger nanoparticles. The pH of the reaction medium is likewise pivotal, as it

controls the speciation of zinc ions (Zn^{2+} at low pH; $Zn(OH)^+$, $Zn(OH)_2$, ZnO_2^{2-} at higher pH), the ionization state of phytochemicals, and the surface charge of the evolving nanoparticles. Alkaline conditions (pH 9–12) generally favor the formation of smaller, well-crystalline ZnO nanoparticles (Ramya et al., 2022; Khatami et al., 2018).

Reaction temperature accelerates the reduction process and facilitates the dehydration of $Zn(OH)_2$ to ZnO, so higher temperatures typically yield more crystalline products. The calcination temperature applied after synthesis is the primary factor controlling crystallinity, crystallite size, and phase purity: calcination at 300–400 °C usually produces relatively small crystallites with residual organic content, whereas treatment at 500–600 °C generates highly crystalline, phase-pure ZnO with larger crystallites. Furthermore, the season and geographic origin of the plant material introduce variability in the composition of the phytochemical profile, posing a major challenge to the reproducibility of biogenic nanoparticle synthesis from batch to batch (Ramya et al., 2022; Singh et al., 2018).

11. Conclusion

This review offers a thorough and integrative assessment of the biogenic

synthesis, characterization, and dual antimicrobial–photocatalytic applications of ZnO nanoparticles fabricated from *Psidium guajava* leaf extract—a perspective that is somewhat refocused and broadened compared with earlier literature, which has often treated these aspects separately. The rich phytochemical composition of guava leaves, especially polyphenols, flavonoids, and tannins, serves as a potent and adaptable biological platform for the sustainable production of crystalline, hexagonal wurtzite ZnO nanoparticles with controllable morphology and functional properties. The resulting biogenic ZnO nanoparticles display strong broad-spectrum antimicrobial effects via multiple mechanisms, including ROS generation, membrane disruption, and Zn^{2+} -mediated toxicity, further amplified by synergistic contributions from the phytochemical surface corona, along with notable photocatalytic dye degradation activity relevant to environmental cleanup and textile-based applications.

The convergence of green chemistry principles, medicinal plant research, nanomaterials science, and applied microbiology within this domain highlights the inherently integrative and transdisciplinary nature of contemporary nanoscience. As the field advances,

overcoming challenges related to reproducibility, large-scale production, and comprehensive toxicological evaluation will be crucial for translating the impressive laboratory-scale performance of biogenic guava-derived ZnO nanoparticles into real-world biomedical, environmental, and industrial solutions. The present synthesis of available literature emphasizes the considerable potential of this approach and outlines a clear roadmap for future research aimed at achieving these objectives.

REFERENCES

- Dahl, J. A., Maddux, B. L. S., & Hutchison, J. E. (2007). Toward greener nanosynthesis. *Chemical Reviews*, 107(6), 2228–2269. <https://doi.org/10.1021/cr050943k>
- Fiveable Content Team. (2025). Bottom-up and top-down approaches to colloidal synthesis. In *Colloid Science, Unit 7.1*. Fiveable Inc. <https://fiveable.me/colloid-science/unit-7/bottom-up-top-down-approaches-colloidal-synthesis/study-guide/plxZkrUhdPDagHA>
- Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. *Green Chemistry*, 13(10), 2638–2650. <https://doi.org/10.1039/c1gc15386b>
- Kareem, A. T., & Kadhim, E. J. (2024). *Psidium guajava*: A review on its pharmacological and phytochemical constituents. *Biomedical and Pharmacology Journal*, 17(2). <https://dx.doi.org/10.13005/bpj/2924>
- Khatami, M., Alijani, H. Q., Sharifi, I., Sharifi, F., Pourseyedi, S., Kharazi, S., & Naderifar, M. (2018). Anticancer activity of green synthesized ZnO nanoparticles. *Anticancer Agents in Medicinal Chemistry*. <https://doi.org/10.2174/1871520618666180911121514>
- Lebaka, V. R., Ravi, P., Reddy, M. C., Thummala, C., & Mandal, T. K. (2025). Zinc oxide nanoparticles in modern science and technology: Multifunctional roles in healthcare, environmental remediation, and industry. *Nanomaterials*, 15(10), 754. <https://doi.org/10.3390/nano15100754>
- Ramya, V., Kalaiselvi, V., Kannan, S. K., Shkir, M., Ghramh, H. A., Ahmad, Z., Nithiya, P., & Vidhya, N. (2022). Facile synthesis and characterization of zinc oxide nanoparticles using *Psidium guajava* leaf extract and their antibacterial applications. *Arabian Journal for Science and Engineering*, 47, 909–918. <https://doi.org/10.1007/s13369-021-05717-1>
- Singh, J., Dutta, T., Kim, K.-H., Rawat, M., Samddar, P., & Kumar, P. (2018).

“Green” synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *Journal of Nanobiotechnology*, 16, 84. <https://doi.org/10.1186/s12951-018-0408-4>

Sirelkhatim, A., Mahmud, S., Seeni, A., Kaus, N. H. M., Ann, L. C., Bakhori, S. K. M., Hasan, H., & Mohamad, D. (2015). Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism. *Nano-Micro Letters*, 7(3), 219–242. <https://doi.org/10.1007/s40820-015-0040-x>

Tarek, M. A. (2014). Application of zinc oxide nanoparticles in textile printing and dyeing and finishing. Staff Publication, Faculty of Applied Arts, Beni-Suef University. https://fapa.stafpu.bu.edu.eg/Textile%20Printing%20and%20Dyeing%20and%20Finishing/6358/publications/menna%20alah%20tarek_20695837115.1353513556_2.pdf

Uikey, P., & Vishwakarma, K. (2016). Review of zinc oxide (ZnO) nanoparticles: Applications and properties. *International Journal of Emerging Technology in Computer Science & Electronics (IJETCSE)*, 21(2), 239–243. https://ijetcse.com/wp-content/uploads/50_review-of-zinc-oxide-zno-nanoparticles-applications-and-properties.pdf

Vaseem, M., Umar, A., & Hahn, Y. B. (2010). ZnO nanoparticles: Growth, properties, and applications. In A. Umar & Y. B. Hahn (Eds.), *Metal Oxide Nanostructures and Their Applications* (Vol. 5, pp. 1–36). American Scientific Publishers.

Yeh, Y.-C., Creran, B., & Rotello, V. M. (2012). Gold nanoparticles: Preparation, properties, and applications in bionanotechnology. *Nanoscale*, 4(6), 1871–1880. <https://doi.org/10.1039/c1nr11188d>