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REVIEW

Tropical Phytochemicals in ZnO Nanoparticle Synthesis: Antibacterial Action, UV Protection and Future Perspectives

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Zinc oxide nanoparticles (ZnO NPs) are widely studied with diverse applications in biomedicine, cosmetics and environmental technologies due to their unique physico-chemical properties, including a tunable bandgap (3.2-3.4 eV), high exciton binding energy (~60 meV) and strong photocatalytic activity. Conventional synthesis methods often rely on toxic chemicals and energy-intensive conditions, whereas plant-mediated green synthesis offers a sustainable and eco-friendly alternative. This review systematically evaluates and focused only on the biosynthesis of ZnO NPs using tropical plant extracts, with particular emphasis on the roles of phytochemicals including flavonoids, phenolic acids, terpenoids and alkaloids, in regulating nanoparticle nucleation, growth and stabilisation. Current evidence indicates that ZnO NPs formation primarily follows a hydrolysis–dehydration pathway involving zinc hydroxide intermediates rather than the direct reduction of Zn^{2+} to metallic zinc. Comparative analysis of reported studies shows that green-synthesised ZnO NPs typically exhibit particle sizes of 10-50 nm and demonstrate strong antibacterial activity (MIC 22-40 μg/mL) through reactive oxygen species generation, membrane disruption and metabolic interference. In addition to antimicrobial activity, ZnO NPs provide broad-spectrum UV protection and have potential applications in drug delivery, wound healing and active food packaging. Despite these advantages, challenges remain in standardizing synthesis, achieving scalability and evaluating long-term safety. Future research integrating artificial intelligence–assisted optimisation and hybrid nanocomposite design may improve the reproducibility and functional performance of plant-mediated ZnO nanomaterials for sustainable biomedical and industrial applications.

Keywords: Zinc oxide nanoparticles, Green synthesis, Tropical plants, Sustainability, Human health.

INTRODUCTION

Owing to their versatile surface chemistry, intrinsic defect structure and tunable electronic characteristics, zinc oxide nanoparticles (ZnO NPs) have emerged a key functional nanomaterials. These unique physico-chemical attributes impart favorable optical, catalytic & semiconducting properties, facilitating efficient light absorption and enhanced photocatalytic performance [1]. In addition, the ability of ZnO NPs to generate reactive oxygen species (ROS) under appropriate conditions has stimulated extensive research into their biomedical and antimicrobial potential. Consequently, ZnO NPs have found widespread applications in antimicrobial environmental remediation, coatings, optoelectronic devices, biosensing, cosmetics, energy-related technologies and targeted drug delivery systems [2-4].

Initially, ZnO NPs gained considerable attention for their diverse biological activities, particularly their antimicrobial, anticancer, anti-inflammatory and wound-healing properties [5,6]. Among these, their antimicrobial potential has been

extensively investigated owing to their ability to combat a broad spectrum of pathogenic microorganisms. The antimicrobial activity of ZnO NPs is primarily mediated through multiple interconnected mechanisms, including the generation of reactive oxygen species (ROS), disruption of microbial cell membranes *via* lipid peroxidation and the controlled release of Zn^{2+} ions. These processes induce oxidative stress, impair vital cellular functions and ultimately inhibit microbial growth and biofilm formation [7]. As a result, ZnO NPs have demonstrated significant antibacterial activity against various pathogens with reported minimum inhibitory concentrations (MICs) as low as 20 μg/mL [8-10]. In addition to their antimicrobial efficacy, the favourable optical properties of ZnO NPs have promoted their application in dermatological and cosmetic formulations as effective UV-blocking agents. Their ability to absorb and scatter both UVA and UVB radiation provides broad-spectrum photoprotection while maintaining a favourable safety profile due to their limited penetration through the epidermal barrier [11-13]. Furthermore, the pH-responsive dissolution behaviour of ZnO NPs in acidic environments such as tumor microenvironments, has expanded their biomedical utility in targeted drug delivery systems, where controlled drug release can enhance therapeutic efficacy and improve treatment outcomes [14-16].

Despite their considerable potential, the large-scale production of ZnO NPs has traditionally relied on physicochemical synthesis routes such as sol-gel, hydrothermal, coprecipitation and chemical reduction methods. Although these approaches provide good control over particle size and morphology, they frequently require high reaction temperatures, elevated pressures, substantial energy input and the use of hazardous chemical reagents or stabilizing agents [17,18]. Furthermore, the formation of toxic byproducts and residual contaminants may limit their environmental compatibility and biomedical applicability [19-21]. These limitations have stimulated growing interest in the development of green and sustainable synthesis strategies that minimise environmental impact while adhering to the fundamental principles of green chemistry.

In view of these considerations, the selection of plant species becomes a crucial determinant in the success of green ZnO NPs synthesis, with tropical plants emerging as particularly promising candidates due to their exceptional phytochemical richness. The abundance of polyphenols, flavonoids, terpenoids and alkaloids in these species contributes significantly to nanoparticle formation, stabilisation and functional performance [22,23]. In addition to serving as natural reducing and capping agents, these bioactive compounds can remain adsorbed on the nanoparticle surface, enhancing colloidal stability and imparting supplementary biological functionalities such as antioxidant, antimicrobial and anti-inflammatory activities. Consequently, the phytochemical profile of a plant extract plays a decisive role in determining the physicochemical characteristics and biological performance of the resulting ZnO NPs [2].

Among the diverse botanical resources investigated for green nanotechnology, tropical plant species have attracted particular attention owing to their exceptional richness in secondary metabolites. Plants such as *Etlingera elatior* (torch ginger), *Azadirachta indica* (neem), *Psidium guajava* (guava), *Aloe vera*, *Moringa oleifera* and numerous other tropical species contain abundant polyphenols, flavonoids, terpenoids and alkaloids capable of regulating nanoparticle formation [24-26]. These phytochemicals influence critical processes including metal-ion complexation, nucleation kinetics, particle growth and surface stabilisation, thereby governing nanoparticle size, morphology, crystallinity and dispersibility [23,27-29]. As a result, ZnO NPs synthesised using tropical plant extracts commonly exhibit particle sizes ranging from 10 to 50 nm, spherical, rod-shaped or hexagonal morphologies and well-defined crystalline structures [30,31].

Beyond their favourable physico-chemical characteristics, plant-derived ZnO NPs have demonstrated promising biological compatibility [25,32,33]. Toxicological studies suggest that phytochemical-capped ZnO NPs often exhibit lower cytotoxicity than chemically synthesised counterparts due to the absence of hazardous synthetic reagents and the presence of naturally occurring biomolecules on the nanoparticle surface [20,31,34,35]. For example, ZnO NPs synthesised using *A. vera* extract maintained more than 90% cell viability in HaCaT keratinocyte cell lines at concentrations up to 50 mg mL^{-1}, which reflects good biocompatibility and suitability for biomedical applications such as wound dressings tissue engineering scaffolds and antimicrobial therapeutics [36]. However, the toxicological behaviour of ZnO NPs remains highly dependent on factors such as particle size, morphology, surface characteristics, concentration and exposure duration, which can influence cellular uptake, ROS generation and oxidative stress responses [37]. Several challenges continue to limit the widespread adoption of plant-mediated ZnO NP synthesis. Variations in the phytochemical compositions among plant species and harvesting conditions affect reproducibility and nanoparticle characteristics [38,39]. The mechanisms governing phytochemical–metal interactions remain incompletely understood while long-term toxicity and safety data are still limited. The absence of standardised protocols for large-scale production and safety evaluation presents an additional barrier to clinical and industrial translation [40,41].

Beyond their favourable physico-chemical characteristics, plant-derived ZnO NPs have demonstrated promising biological compatibility. Toxicological investigations indicate that phytochemical-capped nanoparticles often exhibit lower cytotoxicity than chemically synthesised counterparts due to the absence of hazardous synthetic reagents and the presence of naturally occurring biomolecules on the nanoparticle surface [42,43]. For instance, *Aloe vera*-mediated ZnO NPs demonstrated antimicrobial activity against resistant bacterial strains [44], while separate HaCaT keratinocyte studies indicate that ZnO NPs exposure requires careful dose optimisation to minimise cytotoxic effects [45].

Many reviews on green synthesis of metal oxide nanoparticles remain descriptive and provide limited insight into the influence of phytochemical diversity on nanoparticle formation mechanisms and functional properties. This review critically examines tropical plant-mediated synthesis of ZnO NPs with emphasis on the roles of flavonoids phenolic acids terpenoids and alkaloids in nanoparticle nucleation growth stabilisation and biological activity. Recent applications of

artificial intelligence (AI) and machine learning (ML) in synthesis optimisation and prediction of nanoparticle characteristics are discussed alongside emerging applications of ZnO-based hybrid nanocomposites in antimicrobial coatings wound-healing materials and active food packaging. Future research should focus on clarifying the molecular mechanisms of phytochemical-mediated nanoparticles synthesis while establishing standardised and scalable production methods together with comprehensive toxicological and regulatory frameworks. Progress in these areas will facilitate the transition of green synthesis strategies from laboratory studies to sustainable applications in healthcare environmental remediation and industry.

Methodology: This review was conducted in accordance with the general principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to promote transparency and reproducibility during literature identification and selection [46]. A comprehensive literature survey was performed using the Web of Science, Scopus, PubMed and Google Scholar databases to ensure broad coverage of peer-reviewed publications related to the green synthesis of zinc oxide nanoparticles (ZnO NPs). The search was restricted to studies published between 2008 and 2026, a period marked by substantial growth in research on plant-mediated synthesis of ZnO NPs.

The literature search employed combinations of keywords such as "zinc oxide nanoparticles", "ZnO nanoparticles", "green synthesis", "plant-mediated synthesis", "tropical plants", "biosynthesis of ZnO nanoparticles", "phytochemical synthesis", "antibacterial ZnO nanoparticles" and "ZnO nanoparticles UV protection". Boolean operators were used to refine the search strategy with representative search strings taking the form: ("ZnO nanoparticles" OR "zinc oxide nanoparticles") AND ("green synthesis" OR "plant-mediated synthesis") AND ("phytochemicals" OR "tropical plants").

Study selection process: Data collected from the selected studies comprised the plant species used for ZnO NPs synthesis, the principal phytochemicals responsible for nanoparticle formation and stabilisation, the experimental conditions governing synthesis and the physicochemical properties of the synthesised nanoparticles, including particle size, morphology and crystallinity. This review has considered peer-reviewed journal articles published in English that reported the plant-mediated synthesis of ZnO NPs together with evidence related to phytochemical mechanisms physicochemical characterisation or biological activity. Conference abstracts without accompanying full-text articles studies restricted to chemical or physical synthesis routes in the absence of plant extracts publications lacking experimental characterisation of ZnO NPs and duplicate records identified across multiple databases were removed during the screening process.

The selection procedure was performed through successive stages of evaluation. The initial database search retrieved approximately 557 publications relevant to the objectives of the review. Elimination of duplicate records reduced the number of eligible articles to 373, which were subjected to title and abstract assessment. Screening at this stage led to the exclusion of 227 publications, which did not satisfy the predefined eligibility criteria mainly since they focused on non-plant synthesis methods or contained insufficient experimental evidence. Detailed full-text examination of the remaining 146 studies resulted in the final inclusion of 96 articles that contributed substantial information on phytochemical-mediated ZnO NPs synthesis strategies, characterization, mechanism, antibacterial activity and emerging applications.

Phytochemistry and reduction mechanisms: The phytochemicals present in tropical plants govern multiple stages of ZnO NPs formation by functioning as reducing, chelating and capping agents that influence nucleation, crystal growth, morphology, stability and biological performance [39]. Flavonoids such as quercetin and kaempferol, identified in *Moringa oleifera* [47] and *Psidium guajava* [47] donate electrons for the conversion of Zn^{2+} ions into ZnO while stabilizing the nanoparticle surface through hydrogen bonding and π-π interactions. Phenolic acids, particularly gallic acid and caffeic acid present in *Lawsonia inermis* [48], *Syzygium cumini* [48] and *Ocimum* sanctum [49], participate in redox processes and coordinate with Zn^{2+} ions, thereby influencing nucleation and crystal growth kinetics. Azadirachtin, a limonoid constituent of *Azadirachta indica*, modifies the nanoparticle surface and contributes to antimicrobial activity through enhanced interactions with bacterial membranes [50]. Terpenoids obtained from *Annona muricata* [51] and *Aegle marmelos* [51] participate in the reduction reactions through their unsaturated functional groups and contribute to surface passivation that favours colloidal stability. Alkaloids occurring in *Catharanthus roseus* [52] and *Tinospora cordifolia* [52] interact with Zn^{2+} ions through nitrogen-containing heterocyclic structures and influence both nanoparticle formation and biological properties. Ascorbic acid (vitamin C) present in *Citrus aurantiifolia* [53] and *Emblica officinalis* [53] serves as an efficient reducing agent and contributes to improved biocompatibility of the resulting nanoparticles. Saponins from *Sapindus mukorossi* [54] function as natural surfactants that minimise particle aggregation and favour homogeneous dispersion. Kaempferol also acts as an effective reducing and capping agent during ZnO NPs synthesis due to the presence of multiple hydroxyl groups that facilitate electron transfer and coordinate with the nanoparticle surface. Its strong free radical scavenging ability contributes to enhanced antioxidant properties and improved stability of ZnO NPs synthesised using *Etlingera elatior* [55] and *Carica papaya* [55]. Similarly, another key type of phytochemicals, eugenol present in *Syzygium aromaticum* [8] also participates in the reduction of Zn^{2+} ions through its phenolic hydroxyl group and stabilizes ZnO NPs by forming surface complexes with zinc atoms. The phenolic structure of eugenol contributes antifungal activity through disruption of fungal cell membranes and interference with cellular metabolism, thereby enhancing the functional properties of the nanoparticles. Table-1 provides a concise overview of the principal phytochemicals from tropical plants involved in ZnO NPs synthesis and their respective functions. It serves as a useful reference for selecting plant sources and understanding the mechanisms underlying green synthesis.

Phytochemical mechanism in the ZnO NPs formation: Plant-mediated synthesis of ZnO NPs proceeds predominantly through a hydrolysis-condensation pathway rather than

TABLE-1
KEY PHYTOCHEMICALS IN TROPICAL PLANTS INVOLVED IN GREEN SYNTHESIS OF ZnO NANOPARTICLES

Phyto-chemical	Function in ZnO NP synthesis	Tropical plants	Ref.
Quercetin	Acts as a substantial electron donor; facilitates the reduction of Zn^{2+} to ZnO NPs	*Moringa oleifera, Psidium guajava*	[47]
Gallic acid	Chelates Zn^{2+} ions; controls nucleation and growth; stabilizes nanoparticles	*Lawsonia inermis, Syzygium cumini*	[48]
Azadirachtin	Provides capping; imparts antimicrobial properties by surface functionalization	*Azadirachta indica*	[49]
Kaempferol	Participates in reduction and capping; improves antioxidant potential of NPs	*Etlingera elatior, Carica papaya*	[50]
Caffeic acid	Acts as a reducing and capping agent; improves dispersion stability	*Ocimum sanctum, Allium sativum*	[51]
Eugenol	Reduces Zn^{2+}; forms stable complexes with ZnO; adds antifungal traits	*Syzygium aromaticum*	[8]
Terpenoids	Facilitate metal ion reduction and long-term stability *via* hydrophobic capping.	*Annona muricata, Aegle marmelos*	[52]
Ascorbic acid	Potent antioxidant; reduces Zn^{2+} to ZnO while enhancing biocompatibility	*Citrus aurantiifolia, Emblica officinalis*	[53]
Saponins	Act as surfactants; promote nanoparticle dispersion and prevent aggregation	*Sapindus mukorossi, Quillaja saponaria*	[51]
Alkaloids	Reduce and stabilize NPs; interact with Zn^{2+} through nitrogen-containing groups.	*Catharanthus roseus, Tinospora cordifolia*	[54]

through direct reduction of Zn^{2+} ions to metallic zinc. In aqueous media, zinc precursor salts undergo hydrolysis to generate zinc hydroxide intermediates that subsequently undergo dehydration and crystallisation to yield ZnO NPs. Phytochemicals present in plant extracts, particularly flavonoids, phenolic acids, terpenoids and alkaloids, regulate this transformation by acting as chelating agents, nucleation modulators and surface stabilizers, thereby influencing particle size, morphology, crystallinity and colloidal stability.

The process begins with the interaction of Zn^{2+} ions with hydroxyl groups originating from water molecules or plant-derived metabolites, leading to the formation of $Zn(OH)_2$ in solution. Polyphenolic constituents possessing hydroxyl and carbonyl functionalities coordinate with Zn^{2+} ions to generate intermediate metal-organic complexes that govern nucleation and crystal growth kinetics [56-58]. Such complexation moderates the availability of free zinc ions and suppresses rapid precipitation, creating conditions favourable for controlled nanoparticle formation and uniform particle growth.

The resulting $Zn(OH)_2$ species subsequently undergo thermal or spontaneous dehydration, particularly under mild heating conditions commonly used in green synthesis protocols (60-90 ºC), leading to the formation of ZnO nuclei. Continued nucleation followed by crystal growth gives rise to nanoparticle formation. During these stages, phytochemicals present in plant extracts adsorb onto the growing ZnO surfaces through hydroxyl, carbonyl and carboxylate functional groups, providing steric and electrostatic stabilisation that limits agglomeration and regulates crystal growth. These biomolecules act as natural capping agents and facilitate the formation of stable ZnO NPs with controlled size distributions, typically in the range of 10-50 nm [38,59]. Formation of metallic zinc (Zn^0) intermediates is generally not favoured under aqueous green synthesis conditions due to the low reduction potential of Zn^{2+}. The hydrolysis-dehydration pathway responsible for ZnO NPs formation is strongly influenced by the phytochemical composition of the plant extract, which regulates precursor complexation, nucleation behaviour, crystal growth and surface stabilisation. Variations in the metabolite profiles arising from botanical source, extraction method and seasonal conditions may lead to distinct nanoparticle characteristics and biological responses. These features account for the versatility of plant-mediated synthesis and its growing importance as a sustainable alternative to conventional physicochemical routes.

Advanced synthesis and characterisation: Recent developments in ZnO NPs synthesis have emphasised improvements in particle uniformity, yield and functional performance. Microwave-assisted methods enable rapid nanoparticle formation with low energy consumption and narrow size distributions [60]. FTIR serves as an important tool for identifying phytochemical functional groups associated with nanoparticle surfaces during plant-mediated synthesis. The characteristic –OH and C=O stretching vibrations observed at approximately 3400 cm^{-1} and 1630 cm^{-1}, respectively, confirmed the presence of plant polyphenols involved in ZnO NPs capping and stabilisation [61]. UV-Vis spectroscopy typically showed absorption edges between 370 and 380 nm with bandgap energies of 3.1-3.3 eV attributed to nanoscale confinement effects [62].

ZnO NPs synthesised using *A. indica* leaf extract and $Zn(NO_3)_2$ as precursor under microwave irradiation at 300 W for 5 min exhibited an average particle size of 15 nm with a polydispersity index (PDI) below 0.2 [63]. The DLS and zeta potential measurements indicated negative surface charges in the range of -15 to -30 mV that contribute to colloidal stability and aqueous dispersibility [64]. Ultrasonication assisted synthesis promotes homogeneous nucleation and improved particle dispersion, yielding spherical nanoparticles with dimensions of 20 ± 3 nm as confirmed by FESEM analysis [65]. However, the electrochemical approaches permit precise control over nanoparticle size through adjustment of current density and facilitate tuning of bandgap properties [66].

In situ XRD enables real-time monitoring of crystallisation behaviour and phase development. XRD patterns consistently exhibit the characteristic (100), (002) and (101) reflections of the wurtzite phase with crystallite sizes of 12-45 nm estimated using Scherrer's equation [66,67]. HR-TEM provides detailed insight into the morphology and crystallographic arrangement of ZnO NPs through visualisation of particle boundaries and lattice planes at the nanoscale. For example, analysis of *O. sanctum*-derived ZnO NPs revealed the characteristic hexagonal wurtzite structure with particle sizes in the range of 15-30 nm [65]. XPS also provides detailed insight into surface chemistry and phytochemical capping interactions

occurring during plant-mediated ZnO NPs synthesis. The characteristic Zn $2p_{3/2}$ and Zn $2p_{1/2}$ peaks observed at 1021.5 eV and 1044.6 eV in *A. vera*-mediated ZnO NPs confirmed the presence of ZnO on the nanoparticle surface [68].

Emerging techniques such as small-angle X-ray scattering (SAXS) and Raman spectroscopy, provide additional insights into particle size distributions and defect states. For example, SAXS analysis of *M. oleifera*-derived ZnO NPs reveals narrow size distributions (PDI < 0.2) [63], while Raman spectra show the characteristic E_2 (high) mode at 437 cm^{-1} and defect-related bands at 580 cm^{-1} [61]. These comprehensive characterisations validate the superior quality of green-synthesised ZnO NPs for targeted applications

Antibacterial performance

Plant-mediated ZnO NPs exhibit antibacterial activity through multiple physico-chemical mechanisms influenced by particle size, morphology, surface area and surface chemistry. Smaller nanoparticles generally display better antibacterial efficacy owing to their higher surface-area-to-volume ratio, which promotes interaction with bacterial membranes and enhances the generation of ROS such as superoxide radicals, hydroxyl radicals and hydrogen peroxide [69]. These reactive species induce oxidative damage to cellular proteins, lipids and nucleic acids. Release of Zn^{2+} ions from the nanoparticle surface further contributes to antibacterial activity through disruption of enzymatic functions and microbial metabolic processes [70].

Phytochemicals adsorbed onto the ZnO NPs surface can further influence antibacterial performance by improving surface stability and modifying surface interactions with bacterial cells. Flavonoids, phenolic acids and terpenoids present in the capping layer may contribute additional antimicrobial effects and strengthen the inclusive antibacterial response [71]. The combined influence of ZnO cores and phytochemical surface coatings highlights the importance of surface chemistry in determining the antibacterial activity.

Gram-negative *vs.* Gram-positive bacteria: Plant-mediated ZnO NPs exhibited broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria through multiple complementary mechanisms (Table-2). The predominant mode of action involved the generation of reactive oxygen species such as superoxide radicals, hydroxyl radicals and hydrogen peroxide, resulting in oxidative stress and DNA fragmentation in *E. coli* [72], lipid peroxidation and membrane damage in *K. pneumoniae* [47] and protein oxidation associated with cytoplasmic leakage in *S. aureus* [73]. Electron microscopy studies further revealed structural damage to the bacterial cell envelopes, characterised by disruption of the peptidoglycan layer in Gram-positive bacteria such as *B. subtilis* [75] and membrane depolarisation and permeabilisation in Gram-negative species including *P. aeruginosa* [74]. Respiratory enzyme inhibition in *S. typhi* [76] and metabolic disruption in *L. monocytogenes* [77] provided additional evidence for the multifaceted antibacterial action of ZnO NPs. It is worth to mention that the differences in the bacterial susceptibility were closely related to variations in cell wall architecture and nanoparticle–cell surface interactions [78].

Furthermore, recent investigations have identified additional antibacterial mechanisms that extend beyond oxidative stress and membrane disruption. *Aloe vera*-mediated ZnO NPs with an average size of ~30 nm reduced *P. aeruginosa* biofilm formation by nearly 78% through suppression of the biofilm-associated genes *pelA* and *pslA* [79]. ZnO NPs synthesised using moringa extracts interfered with bacterial energy metabolism by inhibiting ATP synthase activity and key enzymes of the tricarboxylic acid cycle in *E. coli* [80]. Enhanced antibacterial efficacy has also been observed when ZnO NPs are combined with conventional antibiotics, as ZnO NPs in combination with ciprofloxacin reduced the minimum inhibitory concentration against methicillin-resistant *S. aureus* and *E. coli* an effect attributed to improved membrane permeability and intracellular antibiotic uptake [81].

As summarised in Table-3, ZnO NPs with smaller particle sizes, particularly those < 25 nm, frequently exhibit lower MIC values owing to their larger surface-area-to-volume ratio, which promotes closer interaction with bacterial membranes and higher production of reactive oxygen species. Variations in morphology and crystallinity further affect antimicrobial behaviour, since lattice defects within the ZnO structure can serve as active sites for ROS generation [69]. These findings emphasise that synthesis conditions and nanoparticle physico-chemical properties should be considered when comparing antibacterial activity across different studies rather than relying exclusively on MIC values.

Synergy with antibiotics: The combination of ZnO NPs with conventional antibiotics has demonstrated significant synergistic effects in combating biofilm-associated infections [82]. Specifically, co-treatment with ZnO NPs and ciprofloxacin markedly enhanced antibiofilm efficacy against *P. aeruginosa*, a resilient Gram-negative bacterium known for its ability to form complex biofilms and resist antibiotic penetration [83]. Siddiqi *et al.* [82] reported that this combined therapy resulted in an 80% reduction in biofilm biomass, as measured by crystal violet staining, compared with a 50% reduction with ciprofloxacin alone. This enhanced effect is

TABLE-2
ANTIBACTERIAL MECHANISM AND MIC VALUES FOR GREEN-SYNTHESIZED ZnO NANOPARTICLES

Bacterial strain	Gram type	Antibacterial mechanism	MIC (µg/mL)	Ref.
Escherichia coli	Gram-negative	ROS-induced DNA fragmentation and oxidative stress	28	[72]
Staphylococcus aureus	Gram-positive	Cell wall disruption and cytoplasmic leakage	35	[73]
Pseudomonas aeruginosa	Gram-negative	Membrane depolarization and ROS-mediated damage	30	[74]
Bacillus subtilis	Gram-positive	Peptidoglycan layer disruption	25	[75]
Klebsiella pneumoniae	Gram-negative	Lipid peroxidation and oxidative membrane damage	32	[47]
Salmonella typhi	Gram-negative	Respiratory enzyme inhibition	27	[76]
Listeria monocytogenes	Gram-positive	Membrane rupture and metabolic disruption	22	[77]

TABLE-3
COMPARATIVE ANALYSIS OF ANTIBACTERIAL ACTIVITY OF PLANT-MEDIATED ZnO NANOPARTICLES

Plant source	Zn precursor	Particle size (nm)	Morphology	Target bacteria	MIC (μg/mL)	Key factors affecting activity	Ref.
Moringa oleifera	Zinc nitrate	18-25	Spherical	*E. coli*	28	Small particle size increases surface area and ROS generation	[47]
Azadirachta indica	Zinc acetate	15-20	Hexagonal	*S. aureus*	35	Phytochemical capping enhances membrane interaction	[49]
Ocimum sanctum	Zinc nitrate	15-30	Spherical	*E. coli*	30	Uniform dispersion improves bacterial contact	[51]
Syzygium aromaticum	Zinc sulfate	20-40	Rod-like	*P. aeruginosa*	30	ROS generation linked to crystal defects	[8]
Aloe vera	Zinc acetate	25-35	Spherical	*P. aeruginosa*	30	Biofilm disruption *via* ROS production	[79]
Etlingera elatior	Zinc nitrate	20-30	Hexagonal	*S. aureus*	32	Polyphenol capping increases membrane damage	[50]

primarily attributed to ZnO NPs' ability to disrupt the extracellular polymeric substances (EPS) matrix, increase bacterial membrane permeability and facilitate intracellular uptake of ciprofloxacin. Moreover, ZnO NPs generate ROS, which further compromise bacterial antioxidant defenses and promote oxidative damage to DNA, proteins and lipids [72]. These mechanisms not only weaken biofilm structure but also sensitise bacteria to antibiotic action. Consequently, the use of ZnO NPs as adjuvants in antibiotic regimens offers a promising strategy to enhance treatment efficacy against multidrug-resistant and biofilm-forming pathogens.

UV protection applications: ZnO NPs are widely used as physical UV filters since they can both absorb and scatter ultraviolet radiation across a broad spectral range. ZnO NPs provide effective protection against both UVA (320-400 nm) and UVB (280-320 nm) radiation due to their wide bandgap (~3.3 eV) and strong optical absorption properties [11]. The UV absorption profile of ZnO extends across the entire UVA region, distinguishing it from TiO_2, which primarily absorbs UVB radiation and part of the UVA-II range. Such characteristics make ZnO particularly attractive for full-spectrum photoprotection [77].

In contrast to organic filters, inorganic materials such as ZnO and TiO_2 possess greater photostability and maintain UV protection for longer periods [11]. Plant-mediated ZnO NPs may offer additional advantages through phytochemical surface coatings that improve nanoparticle stability, suppress photocatalytic radical formation and enhance dispersion within cosmetic formulations, factors that contribute to improved UV-shielding performance [11]. Alternative nanomaterials such as CeO_2 and hybrid nanocomposites have attracted interest for photoprotective applications, although ZnO NPs remain among the most widely used UV-blocking materials due to their broad-spectrum protection, high photostability, relatively low toxicity and regulatory acceptance in cosmetic products across many countries [77].

Toxicity and commercialisation: Toxicological studies indicate that plant-mediated ZnO NPs may exhibit lower toxicity than chemically synthesised counterparts, largely due to phytochemical surface coatings that improve colloidal stability and suppress photocatalytic activity [42,84]. Zebrafish embryo studies conducted according to OECD guideline 236 reported LC_{50} values near 200 μg/mL for *M. oleifera*-derived ZnO NPs, while oxidative stress responses became pronounced only above 150 μg/mL [82]. Topical application studies based on OECD guideline 439 identified minimal dermal irritation for *A. vera*-capped ZnO NPs at doses of 1 mg/cm^2, an effect attributed to antioxidant phytochemicals associated with the nanoparticle surface [77].

Regulatory agencies have approved ZnO NPs for several commercial applications. The U.S. FDA permits their use in sunscreen formulations at concentrations up to 25%, while the European Commission and the Scientific Committee on Consumer Safety recognize their safety for topical cosmetic applications under conditions that limit dermal penetration [85]. The European Food Safety Authority has also evaluated ZnO NPs for antimicrobial food-packaging applications under controlled use conditions [85]. These approvals have facilitated the incorporation of ZnO nanomaterials into commercial products across multiple sectors.

Commercial interest in green-synthesised ZnO NPs continues to expand in cosmetics, biomedicine, pharmaceuticals and food packaging. Plant-derived ZnO NPs have been incorporated into SPF 50+ sunscreen formulations due to their broad spectrum UV protection [86]. Biomedical applications include antimicrobial wound dressings, where curcuma-derived ZnO nanofibers achieved up to 99% reduction of *S. aureus* contamination [87]. Pharmaceutical studies have explored neem-mediated ZnO NPs as pH-responsive carriers for targeted delivery of 5-fluorouracil [88]. Chitosan-ZnO nanocomposite films have attracted attention for active food packaging applications and have extended product shelf life by up to 14 days through antimicrobial action [89].

However, large-scale implementation remains constrained by variability in phytochemical composition associated with plant species, geographical origin and seasonal conditions, factors that influence nanoparticle size, morphology and biological performance. Analytical quality control approaches such as HPLC fingerprinting may improve reproducibility and batch consistency. Production yield remains another challenge since green synthesis protocols often generate concentrations below 200 mg/L, whereas optimised chemical methods may exceed 5 g/L [14].

Environmental exposure of ZnO NPs may lead to dissolution and subsequent release of Zn^{2+} ions into aquatic and terrestrial ecosystems, with potential effects on microbial

communities and algae [90]. Long-term ecological assessments and life-cycle studies remain limited despite evidence that phytochemical surface coatings may reduce environmental toxicity. Progress in toxicological evaluation, environmental risk assessment and internationally harmonised safety guidelines such as ISO/TR 10993-22:2023 will be important for the responsible development of ZnO nanomaterials [91]. The successful commercialisation of plant-mediated nanomaterials will depend on coordinated progress in nanotechnology, toxicological assessment, materials engineering and regulatory oversight.

Future perspectives: Artificial intelligence (AI) and machine learning (ML) are emerging as valuable tools for optimising plant-mediated ZnO NPs synthesis by identifying complex relationships between synthesis parameters and nanoparticle properties. Conventional optimisation of precursor concentration, pH, temperature and reaction time often relies on the empirical approaches, which are labour-intensive and difficult to reproduce. ML models such as artificial neural networks, convolutional neural networks and genetic algorithms can analyze multidimensional datasets to predict nanoparticle size, morphology and functional characteristics with improved efficiency. ANN-based approaches have been employed to identify optimal synthesis conditions for plant-mediated ZnO NPs [92], while CNN models have enabled real-time analysis of UV-Vis spectra during nanoparticle formation to maintain consistent optical properties [14].

However, the predictive capability of these model's remains constrained by limited experimental datasets, inconsistent reporting of synthesis parameters and insufficient experimental validation of model outputs. Plant-mediated synthesis introduces additional complexity due to variations in phytochemical composition, extract concentration and seasonal changes in metabolite profiles, factors that can reduce the transferability of AI predictions across different plant systems [93]. Despite these limitations, AI-assisted approaches have shown potential in the design of hybrid nanocomposites and multi-functional nanomaterials [93]. Deep learning models have been used to optimise metal compositions in ZnO-based hybrid nanoparticles for improved antibacterial and antibiofilm performance [94], while computational analysis of metal–phytochemical interactions has guided the development of ZnO–CeO_2 heterostructures with enhanced antioxidant properties [95].

Moreover, future progress in AI-assisted green nanotechnology will depend on the development of standardised datasets, integration of high-throughput experimentation with ML workflows and rigorous validation of predictive models [71]. The convergence of artificial intelligence, automated synthesis platforms and advanced characterisation techniques has the potential to improve the reproducibility, scalability and precision of plant-mediated nanoparticle synthesis [96].

Conclusions

Plant-mediated synthesis of ZnO NPs using tropical plants offers a sustainable alternative to conventional chemical routes. Phytochemicals such as flavonoids, phenolic acids and terpenoids regulate nanoparticle formation by acting as chelating, capping and stabilizing agents, yielding ZnO NPs with controlled physicochemical properties and enhanced biological performance. The resulting nanoparticles exhibit strong antibacterial activity against multidrug-resistant pathogens through ROS generation, membrane damage and biofilm inhibition, with reported MIC values ranging from 22 to 40 µg/mL. Broad-spectrum UV protection arising from efficient absorption and scattering of UV radiation has further expanded their utility in cosmetic and dermatological formulations.

Large-scale implementation remains constrained by variability in phytochemical composition, limitations in production yield and the absence of harmonised regulatory standards. Progress in AI-assisted process optimisation, development of hybrid nanocomposites and comprehensive toxicological evaluation may improve reproducibility, scalability and safety assessment. The available evidence positions plant-mediated ZnO NPs as promising materials for applications spanning biomedicine, environmental remediation, food packaging and personal care products. This review highlights the potential of green ZnO nanotechnology as an interface between sustainable chemistry and functional nanomaterials while emphasising the importance of multidisciplinary research for future technological advancement.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language and no data, results or scientific conclusions were generated by AI. All analyses, interpretations and conclusions are the authors' own. The authors reviewed and edited the content and take full responsibility for the published work.

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