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Plant-based zinc oxide nanoparticles: Current applications and future trends

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Abstract

Zinc Oxide nanoparticles (ZnO NPs) synthesized by using plant- derived bioactive molecules has emerged as a sustainable and eco- friendly alternative to traditional physicalandchemicalsynthesisprocesses. Plantextractscontainseveralbioactivecompounds or phytochemicals such as flavonoids, alkaloids, terpenoids, phenolics etc. which act as stabilizing and capping agents for ZnO NPs green synthesis that control nanoparticle shape, size distribution and crystallinity. ZnO NPs have antimicrobial, antioxidant anticancer, antifungal, photocatalytic activities. They also used as nano fertilizers in agricultural fields. The green synthesis strategy is highlighted for its eco- friendliness, low toxicity, biocompatibility and cost effectiveness as significant advantages. In comparison with microbes mediated green approach plant-based synthesis provide faster production, less contamination risks. This review addresses utilization of different plant sources (leaves, flowers, fruits, stem, bark etc.), mechanism and factors influencing the synthesis, characterization techniques for biosynthesis of ZnO NPs and their applications in various fields including biomedical, environmental and agricultural fields.

Keywords: Zinc oxide nanoparticles (ZnO NPs), green synthesis, phytochemicals, plant- based synthesis, sustainable nanotechnology

Introduction

Nanotechnology has been a rapidly developing field in recent years, providing a wide range of scientific and industrial applications. Currently, they play a role in everything from environmental restoration and precision medicine to renewable energy and advanced material design [1]. Its applications span multiple sectors, including photocatalysis, water treatment, pharmaceuticals, cosmetics, food safety, aerospace, nanoelectronics, and targeted disease diagnostics [2]. The driving force behind many of these advancements is nanoparticle- engineered materials, which are typically smaller than 100nm and whose properties drastically change at such scales.

Based on their size, morphology, and chemical and physical properties, nanoparticles are typically classified as polymeric, carbon-based, lipid-based, semiconductor and metallic [3]. Metallic nanoparticles have become the focus of intense research owing to their high surface- to-volume ratio and size-dependent characteristics which enhances the catalytic efficiency, unusual optical effects, and significant antimicrobial potential [4]. Zinc, silver, gold, titanium, copper, and iron oxide are among the most studied metals for their applications in sensing, drug delivery, and environmental technologies [5]. Within this category, zinc oxide nanoparticles (ZnO NPs) have been actively studied owing to their eco-friendly and low-cost production properties. ZnO coated nanoparticles exhibit a wide band gap, UV-blocking capability, strong antimicrobial potential and excellent optical and catalytic properties. These characteristics make them highly valuable for use in electronics, pharmaceuticals, cosmetics, environmental remediation, and biomedical devices [6].

Traditionally, ZnO NPs have been produced through physical and chemical synthesis methods such as sol–gel processing, co-precipitation, hydrothermal synthesis, micro emulsion, and laser ablation [7]. These techniques offer excellent control over particle size and morphology but often involve hazardous chemicals, high cost, laborious procedures, time- consuming steps and can generate environmentally harmful waste [8]. The large-scale production of ZnO NPs under these conditions presents significant sustainability challenge. In response to this, researchers have increasingly explored biosynthetic methods. Among them, plant-mediated or phytochemical assisted formation of ZnO NPs has drawn attention because it is cost-effective, fast, and eco-friendly.

Plant sources (leaves, flowers, fruits, stem, bark etc.) have bioactive molecules like flavonoids, terpenoids, alkaloids, phenolics etc., which serve as reducers and stabilizers during nanoparticle formation. These compounds influence critical factors such as particle size, shape distribution, crystallinity, enabling the functional customization of ZnO NPs. Early work on biological synthesis often based on microorganisms, such as bacteria, fungi, algae and yeast. However, microbial systems require strict culture maintenance, risk of contamination, and multi-step purification [9]. Plant-based synthesis avoids these issues and allows for faster and more scalable production. For example, ZnO NPs synthesized from *Cayratia pedata* leaf extracts have shown high purity and strong biomedical potential [10].

Ongoing studies are expanding the plant repertoire, exploring different plant sources such as leaves, flowers, fruits, stems and roots strengthening reaction conditions for higher yields and optimized performance. Phytochemically-ZnO NP synthesis lies at the interconnection of nanotechnology and green chemistry, which offers a sustainable and, portable approach to advanced nanomaterials.

This review highlights the emerging significance of plant-based synthesis of zinc oxide nanoparticles as a sustainable and eco-friendly alternative to conventional methods. It focuses on the role of phytocompounds in influencing nanoparticle formation, properties, and functionality. Additionally, this review explores recent advancements, key applications, and future research directions in green ZnO nanoparticle synthesis.

Plant-based ZnO Nanoparticle synthesis

1. Utilization of Different Plant Sources

Biosynthesis of zinc oxide nanoparticles (ZnO NPs) uses diverse plant parts (such as leaves, flowers, fruits, and roots), each offering distinct phytochemical profiles that facilitate nanoparticle formation. Key bioactive molecules including flavonoids, phenolics, terpenoids, alkaloids, saponins, and tannins, - act as reducing agents that convert zinc salts into ZnO and stabilizing/capping agents that control the growth, morphology, and stability of nanoparticles.

1.1 Leaves

Leaves are the most widely studied source for ZnO NP biosynthesis, as they contain abundantphytochemicalswithstrongreducingandstabilizingcapacities. *Raphanus sativus* leaf containing phenols and saponins, facilitated capping and stability extract yielded ZnO NPs with anticancer potential [11], *Azadirachta indica* (Neem) leaves produce triangular shapes with significant antimicrobial activity against *Escherichia coli* and *Bacillus subtilis* [12]. while ZnO combined with moringa extract enhanced crop tolerance under stress [13].

1.2 Flowers

Flowers are also widely studied in the synthesis of ZnO NPs which have high concentrations of anthocyanins, flavonoids, and essential oils, and they serve as efficient electron donors during nanoparticle formation. For example, *Nyctanthes arbor-tristis* flower extracts, which are rich in anthocyanins and phenolic compounds, have successfully produced ZnO NPs with enhanced antifungal activity [14]. *Tagetes erecta* (marigold) and *Clitoria ternatea* (butterfly pea) flowers were also used.

1.3 Fruits and Fruit Peels

Fruit peels, which are often considered waste, are rich in ascorbic acid, citric acid, flavonoids, and polyphenols, making them sustainable and inexpensive precursors. *Wodyetia bifurcata* peels produces ZnO NPs with antimicrobial, antioxidant, anticancer, and wound-healing properties [15]. In addition, peels of *Passiflora foetida* produce zinc oxide nano particles that are used for the catalytic degradation of hazardous organic dyes [16]. Fruits and their waste have broad applications in agriculture, photocatalysis and biomedicine.

1.4 Other Plant sources

Plant parts such as stems, seeds, bark, and roots also provide valuable phytochemicals that are utilized for the biosynthesis of Zinc oxide NPs and have various applications. For example, *Citrullus lanatus* seeds produced NPs that were effective against multi drug-resistant bacteria [17]. *Persicaria lapathifolia* stems produce ZnO NPs with antibacterial and anticancer potential [18]. *Zingiber officinale* root extract is rich in flavonoids and polyphenolic compounds that produce ZnO nanoparticle (30–50 nm), offering an eco-friendly alternative to chemical synthesis methods [19]. The root extract of *Andrographis paniculata* synthesized highly stable ZnO nanoparticles with efficient antioxidant, anticancer and anti-inflammatory properties [20]. The bark extract of *Amphipterygium adstringens* acts as a natural stabilizer and reducing agent that efficiently degrades various environmental pollutants [21].

2. Phytochemicals and their functional roles in ZnO NP synthesis

Plant basedZnOnanoparticlesinvolvesdiversesecondarymetaboliteswhichfacilitate reduction, nucleation, andstabilization ofnanoparticles. Polyphenolsandphenolicacids—such as tannins, gallic acid, and caffeic acid derivatives—serve as electron donors that reduce Zn^{2+} ions to ZnO nuclei, while their hydroxyl groups act as capping agents to maintain nanoparticle stability [22]. Flavonoids like quercetin and kaempferol initiate nucleation under ambient conditions and inhibit aggregation via hydrophobic interactions. Nitrogen-containing alkaloids, including indole derivatives, contribute to redox reactions and interact with particle surfaces, influencing both morphology and dispersion. Terpenoids, saponins, and carbohydrates not only assist in the reduction process but also offer steric stabilization by forming organic coatings [22]. Other bioactive compounds such as ketones, aldehydes, and amide/carboxyl groups also play critical roles. Nanoparticle size and shape depend on extract composition and synthesis conditions, yielding spherical/hexagonal ZnONPs typically between 15–50 nm (~15.8 nm from *E. colona* and 6.5–20.18 nm from cherry extract) [23] and enhance the functional properties of ZnO NPs including antimicrobial, antioxidant and photocatalytic activity. (Table. 1)

Table 1: Plant- based metabolites and their functional role in ZnO NP synthesis

Plant Sources	Key Phytochemicals	Functional Role in NP Synthesis	ZnO NP Characteristics Applications	References
Leaves (*Raphanus sativus, Azadirachta indica, Moringa oleifera*)	Phenolics, flavonoids, tannins, saponins	–OH/phenolic groups reduce $Zn^{2+} \rightarrow$ ZnO; surface capping and stabilization; morphology control	anticancer, antimicrobial, antioxidant, photocatalytic, crop stress tolerance	[11-13]
Flowers (*Nyctanthes arbor-tristis*)	Anthocyanins, flavonoids, phenolics, essential oils	Electron donation for reduction; stabilization by hydroxyl/phenolic groups	ZnO NPs with enhanced antifungal activity	[14]
Fruits & Peels (*Wodyetia bifurcata, Passiflora foetida*)	Flavonoids, polyphenols	Acidic/phenolic groups donate electrons; capping by polyphenols; dispersion via hydrophobic interactions	Antimicrobial, antioxidant, photocatalytic, dye degradation	[15-16]
Seeds (*Citrullus lanatus*)	Alkaloids, phenolics	Electron transfer, surface coordination controlling morphology	effective against multidrug-resistant bacteria	[17]
Stems / Roots / Bark *(Persicaria lapathifolia, Zingiber officinale, Andrographis paniculata, Amphipterygium adstringens*	Flavonoids, phenolics	Steric stabilization via organic shells; morphology regulation	Antibacterial, anticancer, antioxidant, anti-inflammatory, Photocatalytic, pollutant degradation	[18-21]

3. General Synthesis pathway of zinc oxide nanoparticles

Green synthesis of zinc oxide nanoparticles (ZnO NPs) using plant parts such as bark, leaves, stems, fruits, and seeds is eco-friendly, low-cost, and produces contaminant-free nanoparticles [24]. Plant materials were first sterilized with sterile water, then dried and powdered. The powder was boiled in distilled water with stirring to release bioactive compounds, and the extract is filtered to obtain a clear solution [25]. This phytochemical- rich extract, containing phenolics, flavonoids, terpenoids, and alkaloids, is mixed with zinc salts such as zinc nitrate, acetate, sulfate, or chloride [6]. Phytochemicals interact with Zn^{2+}ions through –OH, –COOH, and $–NH_2$ groups to, form complexes that under alkaline conditions hydrolyze into $Zn (OH)_2$. Upon heating or calcinations, $Zn (OH)_2$ dehydrated into ZnO nuclei. Phytochemicals cap and stabilize nanoparticles, regulate their size and morphology, and prevent aggregation [10]. Final drying or calcinations enhances crystallinity and removes organic residues, yielding stable, biofunctionalized ZnO NPs [26]. (Figure. 1)

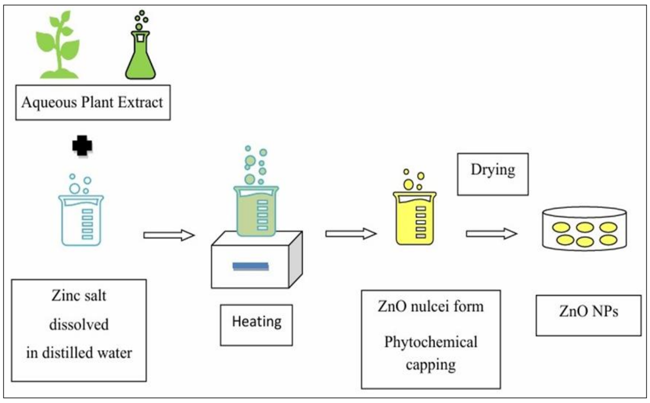

Fig 1: Plant-based ZnO NPs Synthesis [9, 44]

4. Factors influencing nanoparticle formation

pH: Alkaline pH values (typically >7–8) promote the precipitation of $Zn (OH)_2$ and its conversion to ZnO, increasing the number of nucleation sites and producing smaller and more uniform nanoparticles. Neutral or acidic pH conditions decelerate nucleation, yielding larger and aggregated particles [27].

Temperature: Elevated temperatures facilitate hydrolysis and dehydration more rapidly, enhancingcrystallinity. However, athighertemperatures (>80 90°Corduringcalcination), the particles grow more slowly and become smaller because of the short reaction response time during synthesis which can degrade the phytochemicals responsible for capping, leading to particle coarsening or agglomeration [6, 22].

Precursor& extract concentration:

The relative amounts of plant extracts and zinc precursors critically influenced the particle formation. Optimal extract concentrations yield abundant nucleation with phytochemical capping and, photocatalytic activity that limits aggregation, producing well-dispersed, size-controlled nanoparticles, as seen in Hibiscus extract yielding uniform 5–12nm ZnO at 8% concentration. Higher concentrations of zinc precursors or plant extracts may yield more nucleation events, often leading to smaller nanoparticle. However, excessively high concentrations of either zinc salt or extract -may promote uncontrolled growth or unstable morphology [27].

5. Characterization techniques for ZnO Nanoparticles

The physical and chemical properties of the plant-based synthesized ZnO nanoparticles were analyzed by using various bioanalytical methods. UV–Vis spectroscopy exhibits characteristic absorption in the UV range (~300–400nm), which confirms the presence of nanoparticles and enables band-gap estimation (3.0–3.5eV) [28]. FT-IR spectra reveal Zn–O stretching along with phytochemical-derived functional groups (e.g., hydroxyl, amine, carbonyl), indicating surface capping and stabilization. XRD patterns identify the wurtzite hexagonal crystalline phase and allow calculate nanoscale crystallite sizes [29]. SEM and TEM imaging detail nanoparticle morphology—frequently hexagonal or rod-shaped, with occasional aggregation, while DLS (and zeta-potential when available) assesses hydro dynamic size and colloidal stability [29].

Applications of Plant-based green synthesized ZnO NPs

Phytochemical-synthesized zinc oxide nanoparticles demonstrate superior biocompatibility, exhibiting antimicrobial, antioxidant, antifungal, and photocatalytic functions, making them eco-friendly agents for agriculture, medicine, and environmental remediation, including applications as sustainable nano fertilizers. (Figure. 2)

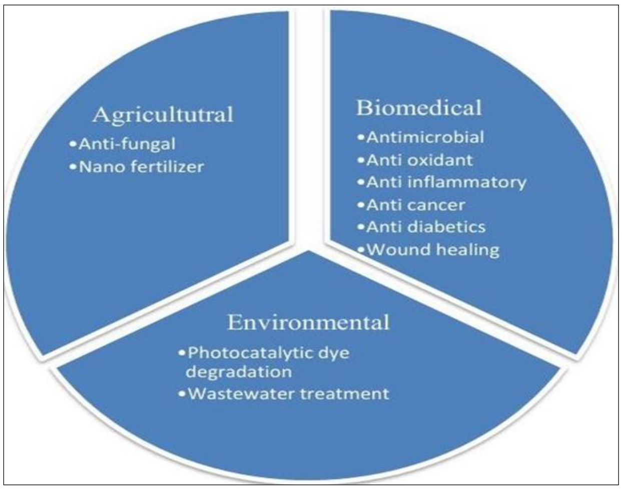

Fig 2: Applications of zinc oxide nanoparticles in various sectors

1. Biomedical Applications

Plant- based ZnO NPs are recognized for their antimicrobial, antioxidant, anticancer, and wound-healing properties. They have broad-spectrum activity against gram-positive and gram-negative bacteria, as well as fungi, while providing an eco-friendly, low-cost alternative to traditional synthesis.

Green synthesis of ZnO NPs from *Ziziphus spina-christi* effectively inhibited *Staphylococcus aureus*, *Escherichia coli*, and *Aspergillus niger*, with inhibition zones upto 36mm [30]. Their antioxidant activities, tested by DPPH and hydrogen peroxide assays, were comparable to that of ascorbic acid. Similarly, *Citrullus lanatus* seed-mediated NPs exhibit antibiotic efficacy against resistant bacteria by disrupting cell membranes [17]. Leaf extracts of *Parthenium hysterophorus* produced spherical to cylindrical NPs (16–45 nm) with strong antibacterial activity [31]. Several studies have emphasized wound -healing applications. *Euphorbia antiquorum* nanoflakes (37 nm) inhibit aquatic pathogens and show potential for eco-friendly infection control [32]. *Clitoria ternatea* - mediated Zn nanoparticles showed spherical morphology, strong antimicrobial activity, low cytotoxicity up to 1 mg/mL, and reduced ROS production, highlighting their potential as eco- friendly therapeutic agents against bacterial infections [33].

Plant-based ZnO nanoparticles (ZnO NPs) exhibit promising anticancer activities by inducing oxidative stress, mitochondrial dysfunction, and apoptosis in cancer cells, while sparing normal cells. Their ability to selectively produce reactive oxygen species (ROS) in tumor microenvironments makes them effective candidates for targeted cancer therapies. For instance, ZnO NPs synthesized using *Solanum nigrum* leaf extract showed dose-dependent cytotoxicity against HeLa cervical cancer cells by up regulating p53, caspase-3, and-9, and down regulating β-catenin, confirming apoptosis as the primary mechanism [34]. Similarly, *Hyssopus officinalis*-derived Zn ONPs significantly reduced the viability of MDA-MB-231 breast cancer cells, suppressed angiogenesis via VEGF/VEGFR down regulation, and modulated inflammatory cytokines [35].

Overall, plant-extract-mediated ZnO NPs have multifunctional biomedical applications in infection control, antioxidant therapy, wound healing, and cancer treatment. However, excessive exposure may increase toxicity risks, highlighting the need for careful optimization and safe integration in clinical and industrial applications.

2. Environmental Applications

Plant- based of ZnO nanoparticles (NPs) used for environmental cleanup. These biomolecules act as reducers and stabilizers, which enhance the physicochemical stability and environmentally benign synthesis of biogenic ZnO NPs.

2.1 Photocatalytic Degradation and water purification

Plant based green-synthesized zinc oxide nanoparticles (ZnO NPs) have photocatalytic ability to degrade organic pollutants. Upon UV or visible light irradiation, ZnO NPs generate reactive oxygen species (ROS), including hydroxyl radicals and superoxide anions that oxidize toxic compounds into non-toxic molecules, which enables both pollutant removal and microbial inhibition. For example, ZnO NPs synthesized using *Quercus robur* leaf extract achieved74% dye degradation efficiency [36]. Similarly, ZnO NPs produced from *Sesbania grandiflora* extracts have been applied to seafood effluent treatment to confirm their environmental potential [37]. *Allium sativum* NARC-G1garlic extract mediated ZnO NPs efficiently degraded RB-5dye under sunlight, aided by phytochemical-rich surfaces that enhanced ROS production [38]. ZnO NPs synthesized from *Aronia melanocarpa* fruit achieve 95.5% methylene blue degradation within 120min under UV radiation and, have strong antioxidant and antibacterial activities [39].

Other plants have also yielded multifunctional catalysts. ZnO NPs derived from *Ocimum basilicum* (basil) and *Olea africana* (African olive) leaves successfully degraded both cationic and anionic dyes, with olive-based NPs performing better because of their lower band gap energy and suppressed electron-hole recombination [25]. *Asparagus racemosus* root extract produced 21–29 nm ZnO NPs, achieving 98% methylene blue degradation and antibacterial effects against *E. coli* and *S. aureus* [40]. Further reports have highlighted a broader range of applications.

Plant-mediated ZnO nano catalysts combine eco-friendly fabrication with multifunctional performance in terms of pollutant degradation, adsorption, and reduction. Their applications extend beyond wastewater remediation to dye-sensitized solar cells, catalysis, and biomass valorization. Studies have also emphasized doping and nanostructure tuning to enhance efficiency and, provide sustainable alternatives to conventional pollutant treatment technologies.

3. Agricultural Applications

Plant-based ZnO NPs also have applications in agricultural sectors for their antifungal activities and used as nano-fertilizers. For example, ZnO-NPs synthesized from olive leaf extract showed a small particle size, effectively inhibiting *Xanthomonas oryzae* and its virulence factors, suggesting their use as biocontrol agents in rice [41].

3.1 Antifungal Performance

Biogenic ZnO -NPs exhibit broad fungicidal activities. *Scadoxus multiflorus*-based nanoparticles (~31 nm) inhibited *Aspergillus flavus* and *A. niger* [42], whereas *Eucalyptus globulus*-derived NPs suppressed apple orchard fungal pathogens [43]. Mycosynthesized ZnO- NPs from *Trichoderma harzianum* inhibited *Alternaria brassicae* by 91.5% at 200 µg/mL, outperforming fungicide (mancozeb). Microscopic observations have revealed spore deformation, reactive oxygen species (ROS) production, and membrane damage in fungal cells [44]. *Cinnamomum camphora* extract-based NPs suppress *Alternaria alternata* in tomatoes via ROS generation, membrane damage, and leakage of proteins and nucleic acids [45]. *Polyalthia longifolia*-synthesized ZnO-NPs (~27.5 nm) showed strong toxicity toward *Fusarium oxysporum f. sp. ciceris*, the chickpea wilt [46]. Similarly, *Parthenium hysterophorus*-derived ZnO-NPs (27±5 to 84±2 nm) displayed strong antifungal activity against *Aspergillus* species [47].

3.2 Nano-Fertilizer Potential

ZnO-NPs improved nutrient use efficiency through seed priming, foliar spraying, and soil application. A field study on rice revealed that foliar application of ZnO-NPs (~31nm) at ~40ppm combined with conventional $ZnSO_4$ enhanced the grain yield and uptake of nitrogen, potassium, and zinc—outperforming standard treatments [48]. In chickpea and other crops, low-dose ZnO-NP exposure (e.g., 1.5 ppm) improved biomass, reduced oxidative damage (e.g., malondialdehyde content), and increased tolerance to abiotic stresses [50]. In peanuts, 25 nm ZnO-NPs at 1000 ppm boosted seed germination, vigor, root development, and plant growth, were highlighting their function as colloidal fertilizers [49]. In grapes and mulberry, foliar doses (100–200ppm) markedly improved yield-related traits, biochemical quality (sugars, phenolics, vitamin C, TSS), and nutrient content (P, K, Zn, N)—notably outpacing conventional zinc sources [50].

Overall, phytogenic ZnO-NPs acted as antifungal agents and nano-fertilizers, promoting sustainable agriculture. (Table. 2).

Table 2: Different plant extracts for Zinc oxide nanoparticle synthesis and their applications

Plant Extract	NP Characteristics	Applications	Properties	Reference
Ziziphus spina-christi	Inhibition zones up to 36 mm	Antimicrobial	Strong activity against *S. aureus*, *E. coli*, *A. niger*; antioxidant comparable to ascorbic acid	[30]
Citrullus lanatus (seed)	Membrane-disruptive NPs	Antimicrobial	Effective against resistant bacteria	[16]
Parthenium hysterophorus (leaf)	16–45 nm, spherical–cylindrical	Antimicrobial	High antibacterial effect	[31]
Euphorbia antiquorum	Nanoflakes ~37 nm	Wound-healing	Inhibited aquatic pathogens; infection control	[32]
Clitoria ternatea	Spherical, low cytotoxicity	Antimicrobial	Reduced ROS; eco-friendly therapeutic agent	[33]
Solanum nigrum	Leaf extract NPs	Anticancer	Cytotoxic to HeLa cells via p53/caspase-3/-9	[34]
Hyssopus officinalis	–	Anticancer	Reduced MDA-MB-231 cell viability, suppressed angiogenesis	[35]
Quercus robur (leaf)	–	Photocatalysis	74% dye degradation; antimicrobial	[36]
Allium sativum (garlic)	NARC G1	Photocatalysis	Efficient RB-5 dye degradation	[38]
Aronia melanocarpa	–	Photocatalysis	95.5% MB degradation; antioxidant, antibacterial	[39]
Asparagus racemosus	21–29 nm	Photocatalysis	98% MB degradation; antibacterial	[40]
Scadoxus multiflorus	~31 nm	Antifungal	Inhibited *A. flavus* and *A. niger*	[42]
Eucalyptus globules	–	Antifungal	Suppressed apple pathogens	[43]
Trichoderma harzianum	Myco-synthesized	Antifungal	91.5% inhibition of *A. brassicae*; stronger than fungicide	[44]
Cinnamomum camphora	–	Antifungal	Controlled *A. alternata* in tomatoes	[45]
Polyalthia longifolia	~27.5 nm	Antifungal	Active against *F. oxysporum* (chickpea wilt)	[46]
Oryza sativa (rice, olive leaf NPs as biocontrol)	Small size	Agriculture (biocontrol)	Controlled *Xanthomonas oryzae*	[41]
Cicer arietinum (chickpea)	1.5 ppm	Nano-fertilizer	Improved biomass, stress tolerance	[49]
Arachis hypogaea (peanut)	25 nm, 1000 ppm	Nano-fertilizer	Boosted germination, vigor, growth	[50]
Vitis vinifera (grape) &*Morus alba* (mulberry)	100–200 ppm foliar	Nano-fertilizer	Enhanced yield, sugar, phenolics, vit. C	[49]

Advantages of Plant-based ZnO Nanoparticle Synthesis

Plant-based Zinc oxide nanoparticles represent a sustainable and, low-cost production alternative to traditional chemical and physical techniques. Sol–gel and hydrothermal routes usually require high temperatures, high pressures, or toxic solvents, whereas plant-based synthesis relies on renewable and, biodegradable extracts, thereby lowering energy demands and environmental risks [21]. Plant-based chemicals, such as flavonoids, polyphenols, and terpenoids serve as both reducing and stabilizing agents, ensuring nanoparticle formation while preventing aggregation. Stable, monodisperse, and biocompatible ZnO NPs are formed, which are safer for several biomedical applications than their chemically synthesized counterparts that may retain toxic residues [27]. Microbial and fungal-mediated synthesis is also eco-friendly, but requires strict aseptic conditions, expensive growth media, and careful strain selection. Moreover, owing to genetic variations, microorganisms may lose nanoparticle producing ability, which limits their reproducibility [8]. The selection between microbial and plant-mediated synthesis depends on the particular application, desired nanoparticle properties, and several other considerations. Researchers and industrialists must evaluate their benefits and drawbacks according to their needs and limitations [27]. In addition, plant extracts help achieve better control over nano particle size, uniformity, and shape, and provide a capping effect that prevents aggregation, yielding more stable and mono disperse ZnO nanoparticles in comparison to many other traditional approaches.

Challenges and Future Perspectives

Beyond the advantages of plant- based ZnO nanoparticle synthesis, there are several challenges that affect the widespread adoption of this process. One major issue is the variability in composition of plant extract, which is influenced by the species, growing conditions, and extraction methods. These inconsistencies affect the nanoparticle shape, size, and surface properties that compromise reproducibility and standardization, and are particularly critical in biomedical applications. Additionally, the analytical techniques used for nanoparticle characterization vary across studies, making it complicated for analysis of the results and validate the processes. Although lab- scale green synthesis is cost-effective and eco-friendly, scaling up to large scale production is still challenging. Maintaining consistency in the extract quality, reaction kinetics, and nanoparticle uniformity at larger volumes is more difficult. Hybrid processes, such as combining plant extracts with microwave or hydrothermal methods, may improve control over particle morphology and yield through better temperature and pressure regulation. Future strategies should focus on utilizing agricultural waste as raw materialtoenhancethefunctionality ofZnONPswhilecontributingtocirculareconomicgoals. The plant- based synthesized ZnO NPs also exhibit strong potential for use in photocatalysis, drug delivery, biosensing, and antimicrobial coatings. However, advancements in clinical and commercial applications require rigorous characterization, safety assessments, and scalable standardized production protocols.

Conclusion

Plant-derived metabolites used for the zinc oxide nanoparticles (ZnO NPs) synthesis provide an eco-friendly and cost-effective alternative to conventional synthetic methods. Phytochemicals such as flavonoids, terpenoids, alkaloids, and polyphenols employ a green approach to control particle formation while reducing the environmental impact. A wide range of plant sources, -including leaves, flowers, fruits, peels, seeds, bark, stems, and roots, influence nanoparticle size, shape, and functionality. These green synthesized ZnO NPs exhibit significant potential in biomedical applications including antimicrobial, antioxidant, anticancer, and wound-healing applications, environmental applications, such as photocatalytic pollutant degradation and water purification, as well as antifungal and nano-fertilizer potential in agricultural applications. Agricultural residues and plant waste streams further enhance the sustainability of this approach. Despite these advantages, challenges endure the standardization of protocols, understanding reaction mechanisms, and scaling up production without compromising quality. Advancing interdisciplinary research in plant biochemistry, materials science, and nanotechnology is crucial to fully exploit the potential of plant-based ZnO NPs for sustainable nanotechnology.

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