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Green Synthesis of Metal Oxide Nanoparticles Using Plant Extracts: Applications in Catalysis and Biomedicine

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ABSTRACT

The green synthesis of metal oxide nanoparticles (MONPs) using plant-based resources has gained significant traction as an environmentally benign, cost-effective, and scalable alternative to traditional chemical and physical methods. This review comprehensively explores the plant-mediated synthesis routes for a variety of MONPs, including CuO, CaO, FeO, PbO, ZnO, and TiO_2, emphasizing the role of phytochemicals as natural reducing, capping, and stabilizing agents. We discuss the physicochemical properties conferred by the green synthesis approach, such as tailored morphology, particle size control, surface functionality, and biocompatibility. Comparative analyses are provided to highlight morphological variations and activity profiles of MONPs derived from different botanical sources. Furthermore, we critically evaluate the emerging applications of these phytogenic nanomaterials in photocatalysis, antimicrobial activity, and biosensing. Special attention is given to the mechanistic insights that govern the functionality of these nanoparticles and their interface with pollutants and pathogens. The review concludes by outlining key research gaps, challenges in large-scale reproducibility, and future opportunities for integrating green-synthesized MONPs in circular nanotechnology frameworks. This work aligns with the growing demand for sustainable materials in coordination chemistry and offers valuable insights into nature-inspired nanomaterial development.

1 | Introduction

Metal oxide nanoparticles (MONPs), characterized by their reduced dimensionality and high surface-to-volume ratio, have emerged as a pivotal class of inorganic nanomaterials due to their versatile physicochemical profiles and structural diversity [1–3]. These nanostructures, typically confined within the 1–100 nm range, comprise metal cations coordinated with oxygen anions and exhibit unique size-dependent properties distinct from their bulk counterparts. The remarkable electrical, magnetic, and optical behaviors of transition metal oxides, in particular, have rendered them indispensable in a variety of frontier technologies, including heterogeneous catalysis, gas sensing, lithium-ion batteries, and environmental remediation [4–6]. The nanoscale regime amplifies interfacial effects and quantum confinement phenomena, contributing to enhanced charge transport, redox activity, and surface reactivity—hallmarks of their functional utility in energy and environmental domains [7, 8]. In parallel, with the expanding functional applications of MONPs, significant efforts have been directed toward the development of greener synthesis routes that circumvent the environmental and health concerns associated with conventional physicochemical methods [9, 10]. Among these sustainable strategies, phytogenic (plant-mediated) synthesis has gained substantial traction owing to its benign reaction conditions and the dual role of plant-derived biomolecules as both reducing and stabilizing agents [11–13]. The phenolic and flavonoid compounds, owing to their hydroxyl and carbonyl functional groups, primarily act as electron donors, facilitating the reduction of metal precursors ($M^{n+} \rightarrow M^0$ or M–O nuclei) through proton-coupled electron transfer. These moieties

also chelate metal ions, thereby regulating controlled nucleation and preventing uncontrolled agglomeration. Terpenoids and other hydrophobic phytochemicals, on the other hand, preferentially adsorb onto high-energy crystal facets, acting as surface-capping agents that modulate anisotropic growth and improve phase stability by lowering surface free energy. This biogenic route capitalizes on the inherent chemical complexity of botanical extracts—rich in flavonoids, alkaloids, terpenoids, and phenolics—to mediate the nucleation and growth of metal oxide nanocrystals under ambient or mildly elevated temperatures [14, 15]. Representative examples include the synthesis of ZnO, CuO, TiO_2, and Fe_2O_3 nanoparticles, wherein particle morphology and surface functionality can be tailored by modulating the botanical species, extraction protocols, and reaction kinetics [16–18]. Notably, plant-mediated MONPs often exhibit superior biocompatibility, surface functionalization, and morphological control compared to those derived from conventional synthesis [19, 20]. These features endow the particles with multifaceted bioactivities, including antimicrobial efficacy, radical scavenging, photocatalytic pollutant degradation, and selective cytotoxicity against tumor cells—broadening their scope in biomedical, environmental, and sensing applications [21–23]. Furthermore, the alignment of this biosynthetic approach with the principles of green chemistry—through minimized reagent toxicity, reduced energy input, and zero-waste pathways—underscores its potential for scalable and sustainable nanomanufacturing [24, 25]. Continued advances in elucidating the mechanistic pathways of bio-reduction, controlling nanoscale architecture, and correlating structure–function relationships will be central to positioning plant-derived MONPs as an innovative platform in coordination chemistry and eco-conscious materials science [26–28].

1.1 | Synthesis of MONPs

The advent of green nanotechnology has provided a sustainable pathway for the synthesis of MONPs, wherein plant-derived extracts serve as multifunctional agents that drive nanoparticle formation under eco-friendly conditions [29, 30]. This bio-inspired strategy aligns closely with the principles of green chemistry, advocating minimal environmental burden through the avoidance of hazardous reagents, the use of renewable resources, and energy-efficient synthetic protocols [30]. Unlike traditional approaches that often require high temperatures, toxic chemicals, and post-synthesis surface modifications, the phytochemical-assisted routes offer a holistic alternative—utilizing naturally occurring bioactives such as phenolics, flavonoids, terpenoids, and alkaloids to simultaneously reduce metal ions and stabilize the resultant nanostructures. These plant-mediated syntheses are typically conducted under mild thermal regimes and aqueous environments, which not only reduce energy input but also eliminate the generation of toxic byproducts. Moreover, the inherent chemical complexity of botanical extracts allows for precise modulation of nanoparticle morphology and surface chemistry, imparting tailored physicochemical properties critical to catalysis, environmental remediation, and biomedical applications. As such, the green synthesis of MONPs stands out as an ecologically sound and economically viable route, with expanding interest in scaling up these processes for advanced material applications [31, 32].

1.2 | Benefits of Green Synthesis

MONP production presents a marked advancement over conventional physical and chemical methodologies, particularly in terms of sustainability, biocompatibility, and environmental stewardship [33]. Traditional routes frequently rely on aggressive reducing agents such as sodium borohydride or hydrazine, and often demand elevated temperatures, inert atmospheres, or high-pressure conditions—factors that collectively increase cost, operational complexity, and ecological burden [34, 35]. Furthermore, the residual toxicity of chemical reagents and by-products can compromise the applicability of conventionally synthesized nanomaterials in biomedical or environmental contexts. In contrast, green synthesis harnesses the innate bio-reducing capacity of plant-derived metabolites—such as polyphenols, flavonoids, terpenoids, and organic acids—to facilitate nanoparticle formation under ambient or near-ambient conditions. This process not only eliminates the need for toxic solvents and harsh reagents but also inherently imparts surface functionalization from phytoconstituents, enhancing the colloidal stability, biocompatibility, and catalytic reactivity of the resulting nanostructures.

Plant-based synthesis is recognized for its simplicity, scalability, and cost-efficiency, with reaction conditions that are typically aqueous, rapid, and adaptable to industrial translation. Additionally, the ability of plant matrices to interact selectively with metal ions, coupled with their natural abundance and regenerative capacity, offers unique advantages in controlling particle size, morphology, and crystallinity. Parameters such as plant species, extract concentration, metal precursor ratio, reaction pH, temperature, and incubation time have been shown to exert a significant influence on nanoparticle formation and function [36, 37]. Plant-mediated synthesis offers a tunable and eco-conscious platform for the generation of functional metal oxide nanomaterials across diverse sectors including catalysis, drug delivery, water purification, and environmental detoxification. phytochemical variability arising from plant source, geographical location, seasonal factors, and extraction protocols can influence nanoparticle synthesis outcomes. Reproducibility is addressed at the laboratory scale by employing standardized extraction conditions, including fixed solvent composition, extraction temperature, duration, and solid-to-liquid ratio, which yielded consistent nanoparticle size, morphology, and crystallinity across multiple synthesis batches. Green synthesis using plant extracts is more amenable to industrial translation than microbe-based routes due to its simplicity, ambient reaction conditions, and avoidance of sterile environments. For large-scale production, the use of phytochemical profiling (e.g., UV–visible (vis), FTIR, and total phenolic content analysis) can be utilized as quality control tools to ensure batch consistency. Additionally, process intensification strategies such as continuous-flow reactors, extract standardization, and controlled precursor feeding can significantly improve reproducibility and scalability.

1.3 | Properties of Plant-Derived MONPs

MONPs synthesized via plant-mediated strategies exhibit a broad spectrum of tunable physicochemical properties that contribute to their growing relevance in advanced materials science. A

defining advantage of these nanostructures lies in their inherent chemical robustness and resistance to oxidative degradation, features that enhance their longevity in environmental remediation and industrial catalysis [38]. Unlike their bulk analogs, green-synthesized MONPs often possess reduced densities and increased surface area-to-volume ratios, promoting superior dispersibility in aqueous and polymeric matrices and elevating their performance in applications such as coatings [39], catalysis, and biomedical delivery systems [40]. Several classes of plant-derived MONPs—such as aluminum oxide (Al_2O_3) [41], copper oxide (CuO) [42], magnesium oxide (MgO) [43], zirconium oxide (ZrO_2) [44], cerium oxide (CeO_2) [45], titanium dioxide (TiO_2) [46], and iron oxide (Fe_2O_3) [47]—have been extensively characterized for their structure-dependent optical, magnetic, electronic, and catalytic behaviors. The final properties of these nanomaterials are closely influenced by their synthesis parameters, particularly those dictated by the choice of plant species, extraction conditions, and post-synthesis processing. Such variables modulate the size, crystallinity, morphology (e.g., spheres, rods, or platelets), and surface reactivity of the particles, enabling bespoke functionalization for target-specific applications. Another notable advantage of phytogenic MONPs is the organic surface passivation imparted by phytochemicals such as flavonoids, tannins, and phenolic acids. These bio-ligands not only act as reducing agents during nanoparticle formation but also remain bound to the surface, conferring enhanced hydrophilicity, colloidal stability, and biocompatibility [48–50]. This intrinsic surface engineering is particularly beneficial in biomedical contexts, where targeted delivery, biosensing, and interaction with cellular systems demand precise control over interfacial properties. As ongoing research continues to mine the phytochemical diversity across medicinal and aromatic plants, the functional scope of plant-derived MONPs is poised to expand considerably, offering eco-conscious alternatives to conventional nanomaterials in diverse sectors ranging from diagnostics to environmental detoxification.

1.4 | Plant-Mediated Green Synthesis of CuO

CuO nanoparticles synthesized using medicinal plants have shown promising tribological behavior, characterized by reduced friction and wear resistance—making them suitable for applications in lubricants and mechanical systems. In addition to their mechanical performance, CuO nanostructures are known for their biodegradability and minimal environmental impact, enhancing their appeal for green industrial technologies [51]. In addition to their biological activity, these plant-derived CuO nanoparticles have shown promise in environmental and energy applications. CuO synthesized using *Caesalpinia bonducella* seeds exhibited rice-shaped morphology and served as efficient electrocatalysts in dye-sensitized solar cells (DSSCs), achieving photo-conversion efficiencies of over 3% [52, 53]. *Jatropha podagrica*-mediated nanorods also showed high photocatalytic performance in the degradation of organic dyes under visible light, indicating potential for wastewater remediation [54, 55]. However, despite promising results, challenges remain in controlling particle morphology, understanding reaction mechanisms, and achieving reproducibility across plant sources. Momeni et al. [56] reported the green synthesis of Cu/ZnO nanoparticles using *Euphorbia prolifera* leaf extract, which served as a renewable and nontoxic reducing agent. The synthesized Cu/ZnO nanoparticles were characterized using transmission electron microscopy (TEM), x-ray diffraction (XRD), and energy-dispersive x-ray spectroscopy (EDS). These analyses confirmed the formation of well-defined nanostructures with high catalytic activity, particularly for the degradation of methylene blue (MB) and Congo red (CR) dyes in the presence of $NaBH_4$.

Similarly, Nasrollahzadeh et al. [57] described the biological synthesis of CuO nanoparticles using *Thymus vulgaris L.* leaf extract as both reducing and capping agents, Figure 1. The nanoparticles were extensively characterized by TEM, EDS, Fourier-transform infrared spectroscopy (FT-IR), XRD, thermogravimetric analysis (TGA), and differential thermal analysis (DTA). The green-synthesized CuO nanoparticles demonstrated excellent performance as heterogeneous catalysts for ligand-free N-arylation reactions involving amines and indoles. Jeronsia et al. [58] reported the green synthesis of CuO nanoparticles using *Camellia sinensis* (tea) leaf extract as a natural reducing agent. The synthesized CuO nanoparticles were characterized using transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FT-IR), XRD, and UV–vis spectroscopy. The average crystallite size was determined to be 22.44 nm, and the estimated band gap was 1.54 eV—higher than that of bulk CuO—indicating potential for enhanced optical properties, Figure 2. Furthermore, these CuO nanoparticles exhibited significant cytotoxicity by reducing the viability of MCF-7 (human breast cancer) cells, suggesting their potential in biomedical applications.

Khatami et al. [59] described the green synthesis of copper oxide nanoparticles using tea extracts as a natural reducing agent. Transmission electron microscopy (TEM) revealed that the synthesized CuO nanoparticles had sizes below 80 nm. The biologically produced CuO NPs exhibited strong antifungal activity, inhibiting nearly 90% of *Fusarium solani mycelial* growth. These findings highlight the potential of green-synthesized CuO nanoparticles as effective antifungal agents for agricultural or biomedical applications, Figure 3.

Vidovix et al. [60] employed *Punica granatum* (pomegranate) extract as both a reducing and capping agent in the eco-friendly fabrication of copper oxide (CuO) nanoparticles. The particles formed were spherical, and XRD analysis revealed an average size of 20.33 nm. A colorimetric test using $CuSO_4 \cdot 5H_2O$ demonstrated a shift from blue to green, attributed to surface plasmon resonance of CuO nanoparticles, further confirmed by a UV–vis absorption peak at 269 nm. In a similar approach, Sukumar et al. [61] synthesized CuO nanoparticles utilizing seed extracts of *C. bonducella*. Comprehensive characterization via XRD, SEM, UV–vis, TGA–DTA, and XPS techniques validated the successful formation of nanoparticles. These nanomaterials exhibited antibacterial efficacy against both *Aeromonas* (Gram-negative) and *S. aureus* (Gram-positive) bacterial strains.

Viesi et al. [62] utilized floral extracts from *Stachys lavandulifolia* to biosynthesize CuO nanoparticles. The resulting particles were predominantly spherical with diameters between 15 and 25 nm. Phytoconstituents including flavonoids, alkaloids, cardenolides, and steroids contributed to both stabilization and bio-reduction of Cu^{2+} ions. UV–vis analysis confirmed the presence of nanoparticles through a characteristic surface plasmon peak near 400 nm.

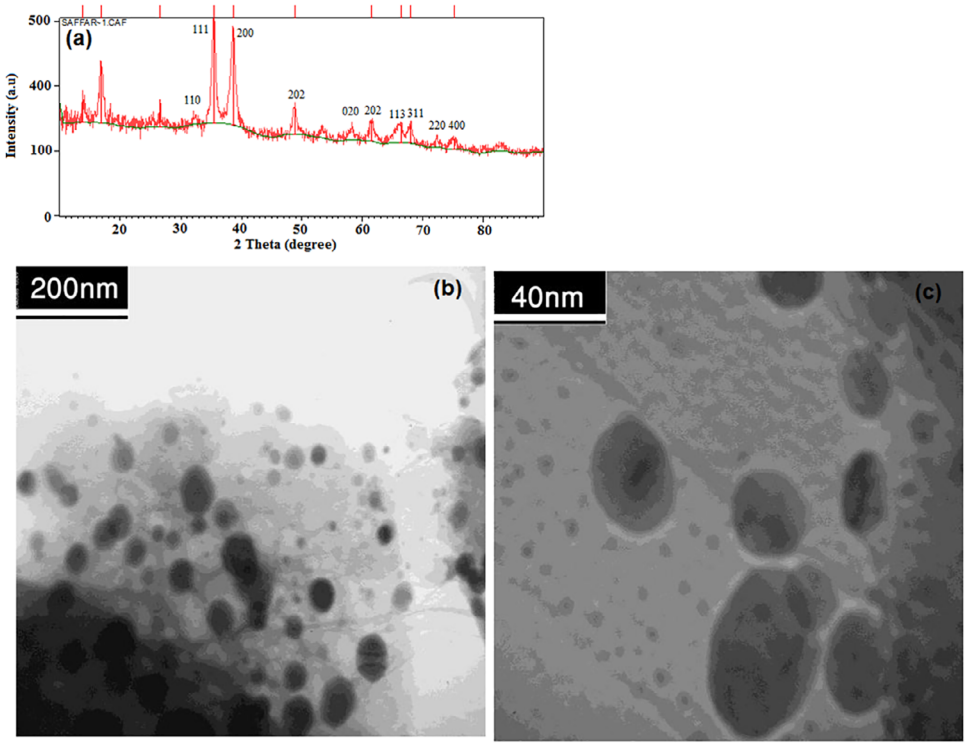

FIGURE 1 | (a) XRD powder pattern of green synthesized CuO NPs by *Thymus vulgaris L.* leaf extract. (b, c) TEM image of the CuO NPs synthesized by *Thymus vulgaris L.* leaf extract. Reproduced with permission from Ref. [57]. Copyright 2016, Elsevier.

Khaldari et al. [63] demonstrated an economical, single-step biosynthetic route for producing CuO nanoparticles using leaf extracts from *Lavandula angustifolia* (lavender) and *C. sinensis* (green tea). Analytical results from XRD, TEM, and FESEM revealed that lavender extract was more effective, producing smaller and more uniform particles with an average size close to 50 nm (Figure 4).

Balakumar et al. [64] explored a green synthesis route for copper oxide nanoparticles using *Citrus limetta* fruit extract. Structural and morphological characterization of the synthesized nanoparticles was carried out using XRD, FT-IR, TEM, and SEM techniques. The CuO nanoparticles demonstrated notable catalytic efficiency, particularly in facilitating high-yield reactions and promoting efficient conversion rates in various catalytic applications [65].

1.5 | Plant-Mediated Green Synthesis of CaO

Osuntokun et al. [66] investigated a green synthesis method for calcium oxide (CaO) nanoparticles using broccoli extract as a bio-reducing agent, specifically leveraging the presence of quercetin and flavonoids. According to the proposed mechanism, the flavonoid compounds first coordinate with calcium salts, reducing them to calcium ions. These ions subsequently react with hydroxide groups within the quercetin structure, leading to the intermediate formation of $Ca(OH)_2$. Upon drying and calcination, CaO nanoparticles are formed. The resulting nanoparticles had sizes ranging from 29 to 38 nm, with particle size inversely related to the volume of broccoli extract used—larger extract volumes produced smaller nanoparticles, Figure 5.

Jadhav et al. [67] demonstrated the green synthesis of calcium oxide (CaO) nanoparticles using aqueous leaf extract of *Moringa oleifera*, which served as a reducing, capping, and stabilizing agent. The biosynthesized CaO nanoparticles exhibited antimicrobial activity and were structurally characterized using FTIR, XRD, SEM-EDS, and UV–vis spectroscopy. These analyses confirmed spherical nanoparticle morphology with an average size of approximately 32.07 nm. XRD results suggested that thermal annealing improved crystallinity and promoted the formation of monocrystalline phases. The study highlighted the advantages of the green route in minimizing hazardous chemical usage, reducing costs, and enhancing environmental sustainability. However, it also acknowledged challenges in reproducibility due to the complexity of phytochemical compositions in plant extracts. Expanding on this approach, *Cleome viscosa* leaf extract has been used to convert calcium carbonate from conch shells into CaO nanoparticles exhibiting antioxidant properties and selective cytotoxicity against breast cancer cell lines (MCF-10A and BT-474) [68]. Similarly, CaO nanoparticles synthesized using *Citrullus colocynthis* fruit extract showed strong antibacterial and antioxidant effects, as well as excellent biocompatibility in vitro and in vivo [69]. *Cymbopogon citratus* (lemongrass) extract yielded CaO nanoparticles with photocatalytic and antibacterial activity, while Annona squamosa seed extract was employed to cap CaO nanoparticles with proven antimicrobial, antioxidant, and anti-ulcer properties [70]. Beyond medical applications, plant-mediated CaO nanoparticles have also shown promise in environmental remediation. CaO nanoparticles synthesized from *Coccinia grandis* fruit extract efficiently degraded industrial dyes such as methyl red, methyl orange, and methylene blue under solar irradiation and inhibited microbial pathogens including *E. coli* and *Aspergillus niger* [71]. Similarly, *Brassica oleracea*

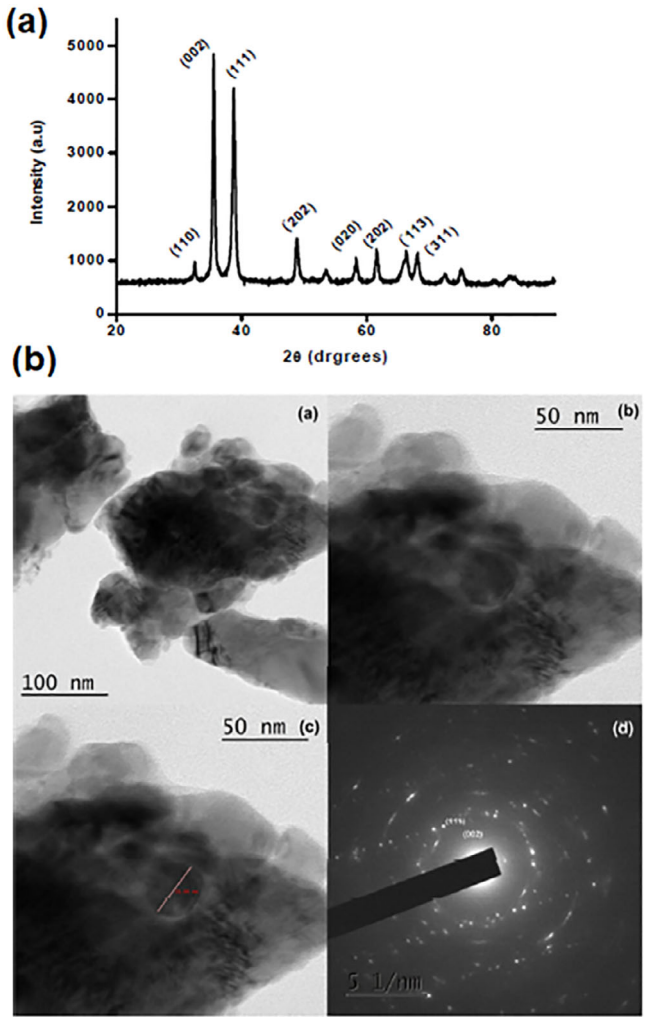

FIGURE 2 | (a) XRD pattern of CuO NPs synthesized using *C. sinensis* leaf extract. (b) TEM images of the CuO NPs synthesized using *C. sinensis* leaf extract. Reproduced with permission from Ref. [58]. Copyright 2019, Elsevier.

(broccoli) extract was used to fabricate CaO nanoparticles capable of degrading bromocresol green dye, reinforcing the catalytic utility of green-synthesized nanomaterials [72]. However, further research is needed to address limitations in scale-up, mechanistic clarity, and variability arising from different phytochemical sources.

1.6 | Plant-Mediated Green Synthesis of FeO

Plant-mediated green synthesis of iron oxide (FeO) nanoparticles has garnered considerable attention for its eco-friendly approach and versatile applications across catalysis, antimicrobial, and environmental remediation fields. Demirezen et al. [73] reported the green synthesis of iron oxide nanoparticles using dried fruit extract from *Ficus carica*. Phytochemicals in the extract acted as reducing agents, facilitating the transformation of iron salts into iron oxide nanoparticles, and concurrently served as stabilizers and capping agents. Characterization was performed using transmission electron microscopy (TEM), UV–vis spectroscopy, Fourier-transform infrared spectroscopy (FTIR), and dynamic light scattering (DLS). The synthesized nanoparticles were spherical, monodisperse, and had diameters below 20 nm. In a related study, Shabbir et al. [74] utilized *Madhuca indica* plant extract to produce iron oxide (FeO) nanoparticles. These biosynthesized nanoparticles demonstrated promising applications in liver disease treatment and drug delivery systems due to their high physicochemical stability, drug-carrying capacity, and ability to encapsulate both hydrophilic and hydrophobic substances. The FeO nanoparticles were characterized using scanning electron microscopy (SEM), FTIR, and UV–vis spectroscopy, which confirmed their nanoscale dimensions and favorable properties. For instance, Ruellia tuberosa leaf extract facilitated the synthesis of hexagonal nanorod FeO, which exhibited robust antibacterial activity against *E. coli*, *K. pneumoniae*, and photocatalytic degradation of crystal violet dye under solar irradiation (~80%) [75]. Similarly, *Amaranthus spinosus* leaf extract produced FeO nanoparticles demonstrating promising physicochemical traits along with significant antioxidant and photocatalytic activity [76]. Furthermore, *Hibiscus rosa-sinensis* (China rose) leaf extract was employed to fabricate stable FeO nanoparticles (~65 nm), which showed strong antioxidant activity based on ABTS and DPPH assays [77]. In addition, *Argemone mexicana*-mediated synthesis yielded ~15 nm FeO nanoparticles with colloidal stability (zeta potential −12 mV) and potent radical scavenging performance (ABTS ~72% and DPPH ~98%) [78]. These phytosynthesized FeO nanoparticles are consistently characterized using UV–vis spectroscopy, FTIR, XRD, SEM/TEM, and DLS to confirm their optical properties, functionalization, crystallinity, and morphology [78]. Many of these nanomaterials exhibit superparamagnetic behavior, which supports facile separation and recyclability. Their multifunctional activity, including microbial inhibition, dye degradation, and radical scavenging, highlights their potential for integrated environmental and biomedical applications.

1.7 | Plant-Mediated Green Synthesis of PbO

Plant-mediated green synthesis of lead oxide (PbO) nanoparticles has attracted attention as an eco-friendly alternative to conventional synthetic routes, exploiting phytochemicals from plant extracts as reducing and capping agents. Khalil et al. [79] reported a green synthesis method for lead oxide (PbO) nanoparticles using leaf extract from *Sageretia thea* as the sole reducing and stabilizing agent, without the need for any additional chemicals beyond the metal precursor, Figure 6. The study demonstrated that these biogenically synthesized PbO nanoparticles exhibited significant bioactivity, particularly against *Leishmania* species. Notably, the antibacterial performance of the PbO nanoparticles was enhanced upon exposure to UV light, indicating photoresponsive behavior. Furthermore, toxicity evaluations showed that the nanoparticles were less damaging to red blood cells compared to macrophages. The PbO nanoparticles also exhibited moderate antioxidant activity and displayed minimal inhibitory effects on key enzymes such as alpha-amylase and protein kinase.

Tailor and Lawal [80] investigated the biosynthesis of lead oxide (PbO) nanoparticles using leaf extracts from *Eucalyptus globulus labill*, Figure 7. In this green synthesis approach, lead acetate [$Pb(CH_3COO)_2$] was utilized as the lead source, and the phytochemicals from the leaf extract served as natural reducing

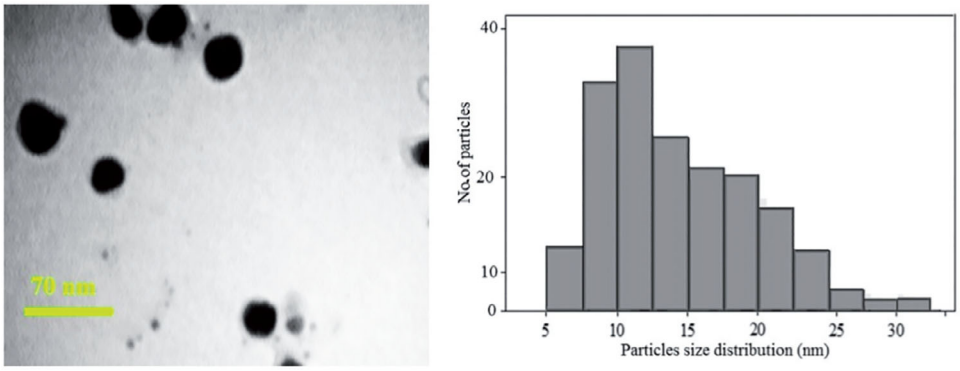

FIGURE 3 | Transmission electron images and histograms of synthesized copper oxide nanoparticles using tea. Reproduced with permission from Ref. [59], Copyright 2017, Elsevier.

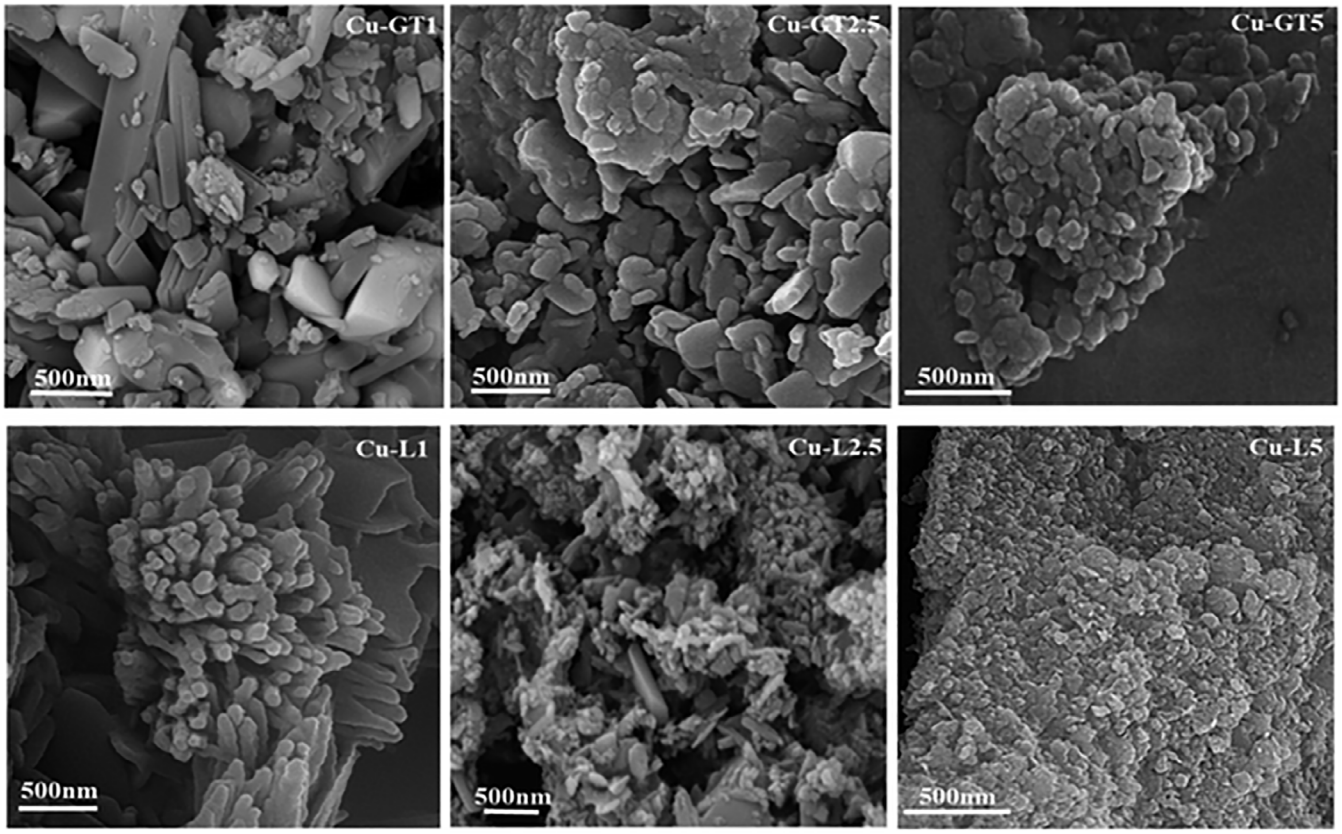

FIGURE 4 | FESEM of CuO nanoparticles synthesized using various amounts of lavender and green tea leaf powders through solid state method. Reproduced with permission from Ref. [63]. Copyright 2021, Elsevier.

and capping agents. The preparation involved mixing the leaf extract and 0.1 M lead acetate in a 1:9 ratio to form a 100 mL reaction mixture in a 250 mL flask. A visible color transition from a faint yellowish-brown to a reddish-colloidal brown indicated the reduction of Pb^{2+} ions and formation of PbO nanoparticles.

Trigonella foenum-graecum (fenugreek) seed extract has been employed to synthesize PbO nanoparticles with tetragonal and orthorhombic phases, averaging around 30 nm in size. These nanoparticles demonstrated approximately 90% photocatalytic efficiency in degrading methylene blue under UVA exposure and exhibited notable cytotoxicity against Huh-7 liver cancer cells, as confirmed by MTT assays [81]. Similarly, *Muntingia calabura* leaf extract was utilized to produce PbO nanoparticles ranging from 35 to 85 nm, as characterized by XRD, SEM, FTIR, and UV–vis spectroscopy. These particles showed strong antifungal activity, particularly against *A. niger* and *Candida glabrata* [82]. In another study, *Ocimum basilicum* seed extracts were used to synthesize spherical PbO nanoparticles (20–30 nm), which possessed a high specific surface area as measured by BET analysis. These nanomaterials degraded approximately 90% of methylene blue within 150 min and displayed low cytotoxicity,

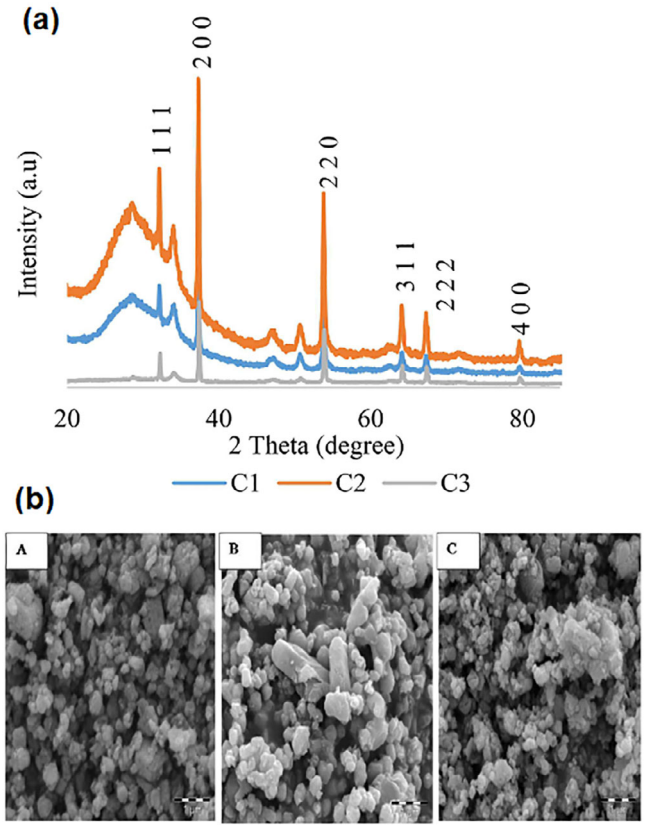

FIGURE 5 | (a) Crisscrossed p-XRD pattern of C1, C2, and C3 of CaO nanoparticles formed from calcination of $Ca(OH)_2$ at 650°C. (b) SEM of (A) C1, (B) C2, and (C) C3. Reproduced with permission from Ref. [66]. Copyright 2018, Wiley.

with an IC_{50} of about 486 μg/mL [83]. Moreover, green tea extract enabled the rapid biosynthesis of PbO nanoparticles exhibiting mixed tetragonal and orthorhombic crystalline phases, which achieved 89% methylene blue degradation under UV light in just 60 min. The photocatalytic performance and morphology of these nanoparticles were found to be dependent on synthesis parameters such as temperature and extract concentration [84].

1.8 | Plant-Mediated Green Synthesis of ZnO

Plant-mediated green synthesis of zinc oxide (ZnO) nanoparticles has gained considerable attention due to its eco-friendly, cost-effective, and scalable nature, leveraging phytochemicals in plant extracts as reducing and stabilizing agents. Naiel et al. [85] discuss the synthesis ZnO nanoparticles using the aqueous extracts of Sea Lavender, *Limonium pruinosum*. Fourier transform infrared spectroscopy (FT-IR), SEM, energy-dispersive x-ray (EDX), and UV–vis spectroscopy were used to characterize the ZnO nanoparticles, Figure 8. These techniques revealed that the ZnO nanoparticles produced had a hexagonal-cubic crystalline structure and an average size of about 41 nm.

Several plant-mediated approaches have been successfully employed for the green synthesis of ZnO nanoparticles, leveraging the bioactive compounds present in various extracts for enhanced functionality. For example, *Pelargonium odoratissimum* leaf extract has been utilized to synthesize ZnO nanoparticles with notable antioxidant, antibacterial, and anti-inflammatory properties. These nanoparticles were thoroughly characterized using UV–vis, FTIR, XRD, TEM, SEM, and dynamic light scattering (DLS) techniques [86]. Similarly, *Solanum nigrum* leaf extract facilitated the formation of quasi-spherical ZnO nanoparticles (20–30 nm) with a wurtzite crystal structure, exhibiting strong antibacterial activity against pathogens such as *S. aureus* and *E. coli* [87]. In another study, *E. hirta* leaf extract yielded ZnO nanoparticles with effective antimicrobial behavior, confirmed through spectroscopic and microscopic analyses [88].

Additional examples include the use of *Azadirachta indica* (neem) for generating ZnO nanoparticles with demonstrated antibacterial and photocatalytic capabilities [89], and *Myristica fragrans* (nutmeg) fruit extract, which produced biocompatible ZnO nanoparticles showing antioxidant and antidiabetic effects [90]. Likewise, ZnO nanoparticles synthesized using *Mesua ferrea* leaf extract (approximately 20 nm in size) showed promising antibacterial and antifungal activities [91]. These biosynthesized ZnO nanoparticles commonly display high crystallinity, stability under UV or visible light, and broad-spectrum bioactivity, making them attractive for both biomedical and environmental applications.

1.9 | Plant-Mediated Green Synthesis of TiO_2

Plant-based green synthesis of titanium dioxide (TiO_2) nanoparticles has emerged as a sustainable and environmentally conscious alternative to conventional chemical methods, relying on phytochemicals as natural reducing and stabilizing agents. Ashour et al. [92] demonstrated the use of *Morinda citrifolia* leaf extract in the formation of TiO_2 nanoparticles, which were characterized using FTIR, EDX, and XRD. The synthesized particles exhibited a tetragonal rutile phase with an average crystallite size of approximately 10 nm and showed significant antibacterial activity. Several other botanicals have also been employed for TiO_2 nanoparticle synthesis with promising results. For instance, *Trigonella foenum-graecum* (fenugreek) leaf extract has been used to produce anatase-phase TiO_2 nanoparticles (20–90 nm), which displayed robust antimicrobial activity against a broad spectrum of pathogens [93]. Likewise, TiO_2 nanoparticles synthesized using *Psidium guajava* (guava) leaf extract (~33 nm) demonstrated high antioxidant capacity and exceptional antibacterial properties, surpassing conventional antibiotics in disk diffusion assays [94]. In another example, *Jatropha curcas* leaf extract facilitated the synthesis of TiO_2 nanoparticles capable of removing complex pollutants such as chromium and reducing COD in tannery wastewater by approximately 82% under solar irradiation [95]. Further extending the biomedical potential, porous TiO_2 nanostructures synthesized from *Withania somnifera* (ashwagandha) root extract have been shown to disrupt microbial biofilms and exhibit cytotoxic effects against cancer cell lines [96]. Additionally, TiO_2 nanoparticles derived from *Phyllanthus niruri* leaf extract (~20 nm) demonstrated efficient adsorption of dyes like methyl orange, following Langmuir adsorption isotherms under optimized conditions [97]. Collectively, these studies highlight the adaptability of green synthesis approaches in producing TiO_2 nanoparticles with tunable properties suited for diverse

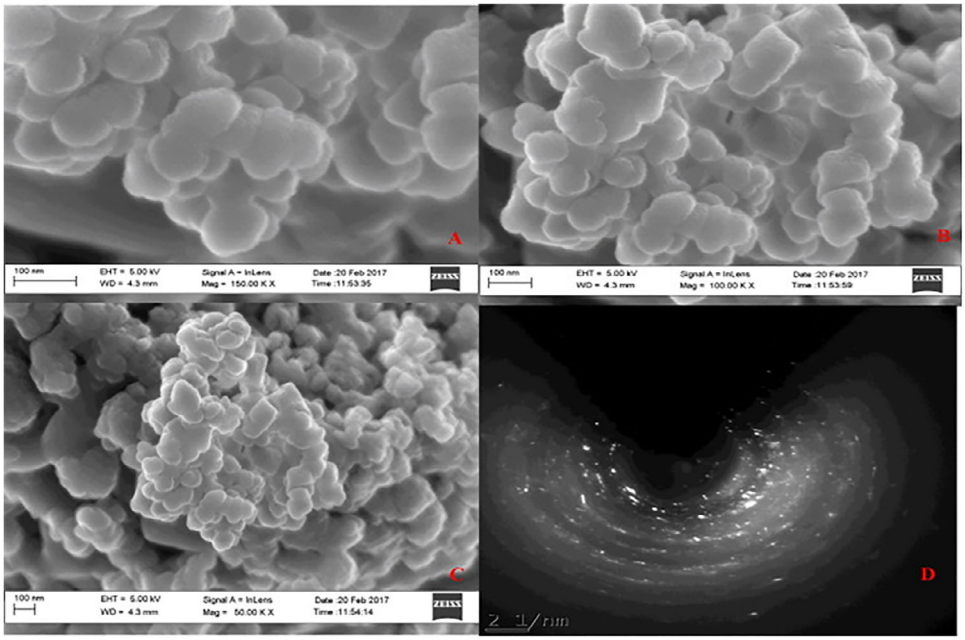

FIGURE 6 | HR-TEM images of biosynthesized lead oxide nanoparticles; (A–D) size distribution and shape. Reproduced with permission from Ref. [79]. Copyright 2020, Elsevier.

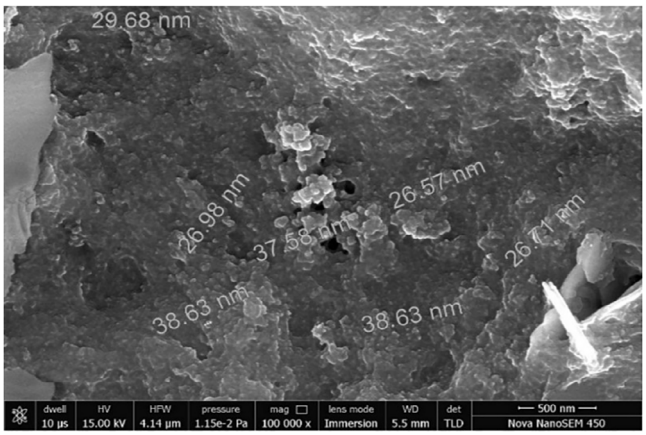

FIGURE 7 | SEM image of PbO-NPs synthesized from *E. globulus* leaf extract. Bar scale—500 nm. Reproduced with permission from Ref. [80]. Copyright 2021, Springer.

applications, including antimicrobial treatments, environmental remediation, and biomedicine.

2 | Comparison of Properties of Plant-Mediated Green Synthesis of MONPs

A comparative analysis of plant-mediated MONPs reveals the significant influence of plant extract composition on nanoparticle morphology, size, and functional behavior. CuO nanoparticles synthesized using *Plectranthus amboinicus* exhibit a distinctive flake- or flower-like morphology with particle sizes ranging from 30 to 40 nm, Table 1, demonstrating potent antibacterial, antioxidant, and photocatalytic properties [12]. In contrast, ZnO nanoparticles show more consistent spherical morphologies across different plant sources. For instance, ZnO NPs derived from *Azadirachta indica* (neem) range from 9.6 to 25.5 nm and have strong antibacterial and photocatalytic dye degradation properties [89]. Similarly, *Pelargonium odoratissimum* yields slightly larger spherical ZnO NPs (20–40 nm), with antioxidant, antibacterial, and anti-inflammatory effects [86]. Interestingly, the synthesis using a combination of *Catharanthus roseus* and *Morinda citrifolia* produces hexagonal ZnO nanoparticles (<50 nm) with potential anticancer activity and biocompatibility [4], indicating that synergistic plant combinations can broaden biomedical applications. Iron oxide (FeO) nanoparticles synthesized using *Amaranthus spinosus* also adopt spherical shapes (15–50 nm) and exhibit multifunctional bioactivity, including antioxidant, antibacterial, and photocatalytic behavior [76]. CaO nanoparticles generated from *Cleome viscosa* are similarly spherical (20–50 nm) and have demonstrated antioxidant and anticancer properties, further expanding the utility of green-synthesized MONPs in therapeutics [68]. Lead oxide (PbO) nanoparticles synthesized from *Trigonella foenum-graecum* exhibit tetragonal or orthorhombic shapes (~30 nm) and are effective in photocatalytic dye degradation while also showing cytotoxic effects, highlighting their dual environmental and biomedical potential [81]. TiO_2 nanoparticles show significant variability in size and application depending on the plant extract. *Trigonella foenum-graecum* leaf-derived TiO_2 NPs exhibit a spherical shape with a size range of 20–90 nm and potent antimicrobial activity [93]. Meanwhile, Psidium guajava yields smaller TiO_2 nanoparticles (~33 nm) with notable antioxidant and antibacterial properties. Overall, this comparative overview demonstrates that while morphology tends to cluster within spherical or near-spherical structures, the particle size and activity profile are highly dependent on the specific plant used. These results underscore the promise of green synthesis routes in tailoring nanomaterials for targeted biomedical, environmental, and catalytic applications.

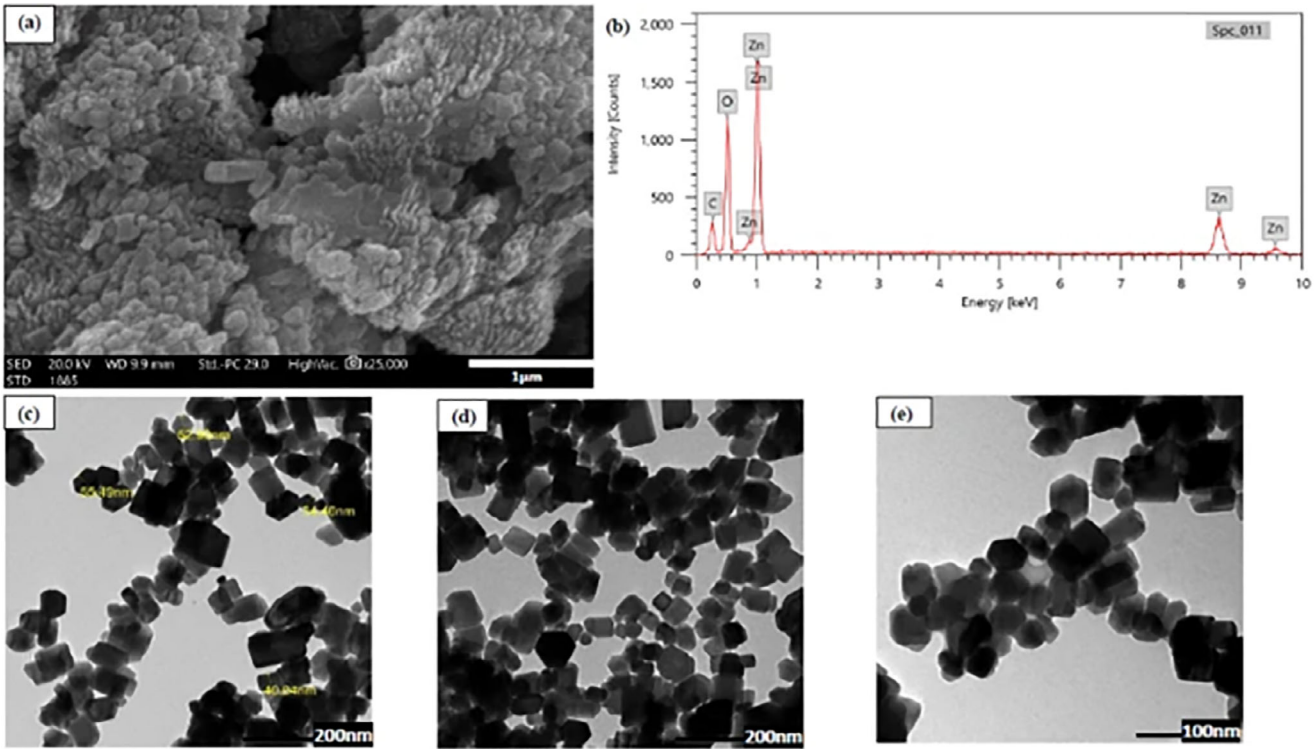

FIGURE 8 | (a) SEM; (b) EDX; (c–e) TEM images of the phyto-synthesized ZnO. Reproduced with permission from Ref. [85]. Copyright 2022, Nature.

TABLE 1 | Comparative size and properties of MONPs synthesized using different plant extracts.

Metal oxide	Plant source	Morphology/Size	Key activities
CuO [12]	*Plectranthus amboinicus*	Flake/flower-like (~30–40 nm)	Antibacterial and antioxidant, photocatalysis
ZnO [4, 89]	*Azadirachta indica* (neem)	Spherical (9.6–25.5 nm)	Antibacterial and photocatalytic degradation of dyes
	Pelargonium odoratissimum	Spherical (~20–40 nm)	Antioxidant, antibacterial, and anti-inflammatory
	Catharanthus roseus and *Morinda Citrifolia*	Hexagonal NPs (~<50 nm)	Anticancer potential and biocompatibility
FeO [76]	*Amaranthus spinosus*	Spherical (~15–50 nm)	Antioxidant, photocatalytic, and antibacterial
CaO [68]	*Cleome viscosa*	Spherical (~20–50 nm)	Antioxidant and anticancer
PbO [81]	*Trigonella foenum-graecum*	~30 nm (tetragonal/orthorhombic)	Photocatalytic dye degradation and cytotoxicity
TiO_2 [93]	*Trigonella foenum-graecum* leaf	Spherical (~20–90 nm, anatase)	Antimicrobial activity
	Psidium guajava leaf	~33 nm	Antioxidant and antibacterial

The various literature presented on nanometal oxides are applicable in environmental catalysis and water remediation. An example is nano iron oxide which is applicable in the removal of heavy metals and dyes from wastewater. These nanoparticles are also applicable biomedically as they have shown antibacterial and antiviral properties. The nanometal oxides' photocatalytic properties have enhanced their application in energy production, too, such as the use of cerium oxide nanoparticles to convert CO_2 into fuel precursors [98].

3 | Applications of MONPs Synthesized From Plant Source

Plant-synthesized MONPs have demonstrated remarkable versatility across environmental, biomedical, and industrial domains. One of the most extensively studied systems is plant-mediated ZnO nanoparticles, which exhibit strong photocatalytic degradation of organic dyes and broad-spectrum antibacterial efficacy, making them promising agents for wastewater remediation and

antimicrobial formulations [99, 100]. Beyond ZnO, other green-synthesized MONPs—such as CuO, TiO_2, Fe_2O_3, and MgO—have shown exceptional catalytic properties, antioxidant activity, and selective cytotoxicity, applicable in pollutant remediation, sensor platforms, and healthcare materials [101, 102]. Plant-mediated synthesis of MONPs often results in nanostructures enriched with surface-associated phytochemicals, which enhance their compatibility with biological systems, improve colloidal stability, and provide functional groups suitable for biomedical applications such as wound care, drug transport, and biosensing [103–104]. These environmentally benign nanoparticles have also demonstrated potential in sensor development due to their adjustable optical and electronic features, facilitating the precise detection of environmental contaminants or biomolecules. In the area of environmental cleanup, green-synthesized MONPs function effectively as photocatalysts under solar or visible light, aiding in the breakdown of harmful dyes and pharmaceutical residues in water with reduced ecological impact. In summary, plant-derived MONPs offer a sustainable and versatile platform with significant utility in antimicrobial therapy, photocatalysis, diagnostics, and environmental remediation. Their green production pathways and customizable properties position them as promising materials for sustainable innovation in materials science and nanotechnology [104].

3.1 | Photocatalytic Applications of MONPs Derived From Plant Source

MONPs synthesized through plant-assisted green methods have shown strong potential for use in photocatalytic water purification, especially for breaking down persistent organic contaminants such as synthetic dyes and pharmaceutical residues. For instance, CuO–ZnO composite nanoparticles produced with *Verbascum sinaiticum* leaf extract demonstrated an impressive methylene blue degradation rate constant of 0.017 min^{-1}, markedly higher than that of standalone ZnO nanoparticles (~0.0027 min^{-1}). This enhanced performance was attributed to improved visible-light absorption and suppressed electron–hole recombination rates [105]. Likewise, CuO–ZnO nanohybrids synthesized using *Melissa officinalis L.* leaf extract rapidly decomposed pollutants like 4-nitrophenol and Rhodamine B under ambient conditions, underscoring the critical role of plant-derived biomolecules in tuning the structural features and catalytic efficiency of these nanocomposites [106]. Investigations into ZnO nanoparticles synthesized using *Ambrosia ambrosioides* extract have demonstrated their strong ability to photodegrade a variety of organic dye contaminants—including methylene blue and methyl orange—under solar irradiation, showcasing the practical potential of sunlight-activated, biogenically synthesized MONPs for scalable water treatment systems [107]. Comparable outcomes have been documented TiO_2 nanoparticles derived from plant extracts, which also exhibited efficient dye degradation and broad-spectrum antibacterial effects, suggesting that such green-synthesized oxides possess versatile applications across different material systems [107, 108]. Extending beyond dye remediation, plant-based synthesis of nickel oxide (NiO) and copper–nickel oxide (Cu–NiO) nanocomposites using *Phytolacca dodecandra* leaves resulted in notable degradation efficiencies—up to 97.8% for methylene blue—as well as significant antioxidant activity [107, 108]. Collectively, these studies underscore the dual environmental and functional advantages of plant-derived MONPs, where surface-functionalizing phytochemicals contribute to improved nanoparticle dispersion, reactivity, and sustainable performance in aqueous pollution control.

3.2 | Biological and Antimicrobial Applications of Plant-Mediated MONPs

MONPs synthesized through eco-friendly plant-mediated methods have consistently demonstrated strong antimicrobial activity against a range of bacterial and fungal pathogens, including strains resistant to conventional antibiotics. For instance, biosynthesized ZnO and CuO nanoparticles using *Mentha pulegium* extract showed clear zones of inhibition—up to approximately 21 mm—against resistant strains of *E. coli* and *S. aureus* [109, 110]. The superior activity of CuO was attributed to its smaller particle size and enhanced reactive oxygen species (ROS) generation. Similarly, Co-doped ZnO nanoparticles prepared with *Platycladus orientalis* leaf extract exhibited enhanced antimicrobial effects over undoped ZnO, likely due to increased surface defects and synergistic bio-ligand doping. Another example includes ZnO nanoparticles derived from *Calpurnia aurea*, which effectively combined antimicrobial properties with visible-light photocatalytic dye degradation [111, 112]. These plant-synthesized MONPs operate via multiple antimicrobial mechanisms, including membrane disruption through ROS, metal ion release, and interference with cellular biomolecules such as DNA and proteins. The phytochemical surface functionalization from plant extracts improves dispersion, enhances bioavailability, and may reduce cytotoxicity, offering a distinct advantage over traditional antimicrobial agents that typically target a single mode of action [113]. Moreover, by adjusting the plant species and synthesis parameters, the morphology, size, and surface characteristics of MONPs can be finely tuned, enabling tailored applications across medical, packaging, and environmental sectors. Overall, the integration of antimicrobial activity with green synthesis underscores their value in sustainable nanotechnology and real-world biomedical and environmental interventions.

MONPs have proven to be promising materials for biosensor development due to their adaptable optical, electronic, and surface characteristics. In particular, green-synthesized ZnO nanoparticles have shown great potential for enzyme-based biosensors. For instance, ZnO nanoparticles fabricated using *Cayratia pedata* leaf extract were effectively used to immobilize glucose oxidase, resulting in a biosensor capable of detecting glucose with approximately 60% retained enzyme activity—indicating good biocompatibility and functional stability of the nanomaterial [114]. Additionally, various phytogenic MONPs such as ZnO, TiO_2, and their composites exhibit favorable properties like high electron mobility, wide bandgaps, and abundant surface defects, which enhance signal sensitivity and transduction in biosensing applications. A recent review [115] emphasized the importance of phytochemical coatings on these nanoparticles, which not only stabilize the particles but also serve as active binding platforms, thereby improving analyte recognition and lowering detection thresholds [116]. These biogenic nanostructures are especially valuable for their eco-friendly synthesis, biofunctional interfaces, and compatibility with scalable, low-cost

manufacturing processes. Collectively, these features position plant-derived MONPs as sustainable and high-performing candidates for biosensor technologies across medical diagnostics, food safety, and environmental monitoring sectors.

Kumaran et al. [117] carried out a comprehensive evaluation of the biological potential of ZnO/MgO nanocomposite derived from *Kalanchoe bhidei* that exhibited remarkable efficacy as a free radical scavenger. The antioxidant capacity, quantified through the DPPH radical scavenging assay, revealed an IC_{50} value of 54.28 μg/mL which was higher than ascorbic acid value of 42.15 μg/mL thereby, representing a significant enhancement over the performance of pristine ZnO or MgO nanoparticles. This heightened activity is characterized by a clear dose-response relationship, where radical inhibition progressed from 28.4% at 20 μg/mL to a peak of 82.1% at 100 μg/mL. The superior performance of the nanocomposite was attributed to a synergistic interface between the Zn and MgO matrices, coupled with the presence of bioactive "capping agents" from the *K. bhidei* extract. Specifically, residual phenolic and flavonoid compounds on the surface of the 25.14 nm spherical particles facilitated efficient electron transfer to neutralize reactive oxygen species. Beyond its antioxidant potential, the material demonstrated a favorable safety profile and multifunctionality; it exhibited a high threshold for hemolytic activity IC_{50} value of > 200 μg/mL, suggesting biocompatibility with human erythrocytes, and showcased potent thrombolytic properties with 74.12% clot lysis. Collectively, these findings position the *K. bhidei*-mediated ZnO/MgO nanocomposite as a promising, nontoxic candidate for integrated biomedical and pharmacological applications. In a study exploring sustainable biomedical solutions, Papitha et al. [118] studied green-synthesized ZnO/TiO_2 and CuO/TiO_2 nanocomposites—mediated by *Parkia timoriana* bark extract that demonstrated potent biological properties tailored for managing oxidative stress and metabolic disorders. The ZnO/TiO_2 variant possessed superior antioxidant capacity, achieving a maximum free radical scavenging rate of 84.07%, compared to 72.76% for the CuO/TiO_2 composite. The antidiabetic potential of these nanomaterials was further validated through enzyme inhibition assays, where both composites exhibited significant efficacy. In the alpha-glucosidase inhibition test, the ZnO/TiO_2 nanocomposite proved most effective with an IC_{50} value of 25.69 μg/mL, outperforming the CuO/TiO_2 composite which recorded an IC_{50} value of 30.80 μg/mL. Conversely, in the alpha-amylase assay, the CuO/TiO_2 composite showed slightly higher potency with an IC_{50} value of 72.12 μg/mL, compared to 75.95 μg/mL for the ZnO-based counterpart. These results suggest that the plant-mediated synthesis not only ensures an eco-friendly production route but also imparts specific therapeutic advantages, positioning these nanocomposites as viable, biocompatible candidates for future pharmacological applications in treating diabetes and related oxidative damage.

Arunagiri et al. [119] investigated Au-ZnO nanocomposites—mediated by an ethanolic extract of *Pavetta indica* which revealed superior biological efficacy compared to their pristine counterparts. A critical highlight of the research was the potent anticancer activity observed against the A549 human lung cancer cell line. The nanocomposite achieved a remarkable IC_{50} value of 56.22 ± 1.6 μg/mL, which proved significantly more effective than the individual ZnO nanoparticles value of 67.76 ± 2.1 μg/mL or the raw plant extract 80.46 ± 2.4 μg/mL. This enhanced cytotoxicity was due to the synergistic effect of the au-Zn heterojunction, which promoted the intracellular generation of reactive oxygen species (ROS), leading to mitochondrial dysfunction and programmed cell death in malignant cells. Beyond oncology, the Au-ZnO nanocomposites showcased a multifaceted biological profile, characterized by substantial antioxidant capacity and potent thrombolytic activity, facilitating significant blood clot dissolution. Safety evaluations via hemolytic assays confirmed that the material maintained low toxicity toward human red blood cells, reinforcing its biocompatibility for systemic applications. Furthermore, the material served as an exceptional photocatalyst, degrading 81.96% of Methylene Blue dye under light irradiation within 90 min. The study concluded that the secondary metabolites from *P. indica* not only served as efficient reducing agents but also functioned as bioactive caps that improved the stability and pharmacological reach of the nanocomposites, making them viable candidates for both wastewater treatment and advanced nanomedicine.

Hadkar et al. [120] explored the synergistic effects of metal doping on therapeutic efficacy, CuO and zinc-doped copper oxide (Zn-CuO) nanoparticles biogenically synthesized using the leaf extract of *Calophyllum apetalum*. The Zn-doped CuO nanoparticles exhibited superior cytotoxicity against the A549 lung cancer cell line, outperforming both the pristine CuO nanoparticles and the crude plant extract due to the smaller particle size and altered electronic properties of the doped structures, which facilitate more efficient cellular uptake and the generation of reactive oxygen species (ROS), leading to apoptotic cell death. The high concentration of phenols 218.6 ± 4.16 mg GAE/g and flavonoids 256.5± 3.13 mg QE/g within the *C. apetalum* extract served as efficient reducing and capping agents, imparting a bioactive coating that enhanced the nanoparticles' stability and biocompatibility. Furthermore, the material served as a potent photocatalyst, achieving high degradation efficiencies of organic dyes under light irradiation.

Similarly, Arunagiri, et al. [121] developed ZnO/C nanocomposites using *Anodendron parviflorum*. The study compared pristine ZnO nanoparticles (M–ZnO) with carbon-incorporated nanocomposites (B–ZnO/C and O–ZnO/C), finding that the blue LED-mediated B–ZnO/C nanocomposite exhibited the most potent anticancer activity. Specifically, it achieved remarkably low IC_{50} value values of 23.6 ± 2 μg/mL against A549 lung cancer cells and 28.1 ±1.3 μg/mL against HeLa cervical cancer cells, significantly outperforming the pristine M–ZnO nanoparticles. Furthermore, the integration of natural carbon was found to be a decisive factor in improving the materials' antioxidant and safety profiles. Both B–ZnO/C and O–ZnO/C nanocomposites displayed superior radical scavenging capabilities compared to pure ZnO, likely due to the presence of residual phenolic compounds and flavonoids from the *A. parviflorum* extract acting as active capping agents. Crucially, hemolytic assays and brine shrimp lethality tests confirmed that these carbon-doped structures possess higher biocompatibility and lower systemic toxicity than traditional MONPs. These findings suggest that LED-assisted green synthesis is a highly effective, energy-efficient route for producing spherical, carbon-templated ZnO nanomaterials 14.8–24.5 nm that are uniquely suited for dual-action antioxidant and oncological therapies.

The same author also synthesized MgO NPs using the leaf extract of the endangered medicinal plant *Hildegardia populifolia* with an average crystallite size of 19.8 nm, characterized by a bioactive coating of natural phenols and flavonoids that facilitate stabilization [122]. These biogenic MgO NPs exhibited exceptional antioxidant potential, achieving an 88.25% DPPH scavenging rate, alongside a robust anti-inflammatory response with a 94.15% inhibition of protein denaturation. Furthermore, the nanoparticles displayed significant antibacterial efficacy against both Gram-positive and Gram-negative pathogens, specifically *S. aureus* and *E. coli*, with inhibition zones reaching up to 15 mm. The Hp-MgO NPs functioned as a high-performance photocatalyst, facilitating the 92.4% degradation of MB dye under UV light irradiation within 120 min. The environmental safety of the synthesis and remediation process was further validated through phytotoxicity assays on *Vigna radiata* seeds; the results confirmed that the photocatalytically treated water was nontoxic, allowing for normal seed germination and seedling growth. These findings position *H. populifolia*-mediated MgO NPs as a promising, eco-friendly material for dual-purpose applications in targeted nanomedicine and sustainable wastewater management.

The author also investigated MgO NPs via a green route using *Scutia myrtina* extract and highlighted the material's potent anticancer efficacy against the A549 lung cancer cell line, yielding a significant IC_{50} value of 44.9 ± 0.2 μg/mL [123]. This cytotoxic performance was complemented by a robust anti-inflammatory response, where the nanoparticles achieved 95.8% ± 0.9% inhibition of protein denaturation. The high concentration of phenolic and flavonoid metabolites from the *S. myrtina* extract not only facilitated the reduction of magnesium precursors into stable, spherical nanoparticles (approx. 15.8 nm) with radical scavenging rates reaching up to 87.68% in DPPH assays. The MgO nanoparticles showcased unique anti-helminthic activity, proving effective against parasitic models with IC_{50} value of 33.41 mg/mL for paralysis and 24.32 mg/mL for death time. The study further emphasized the environmental safety of these biogenic materials; while the NPs acted as an efficient photocatalyst—degrading 85.32% of Reactive Black 5 (RB5) dye—subsequent phytotoxicity evaluations on *Vigna radiata* seeds confirmed that the resulting byproducts were entirely nontoxic. These findings position *S. myrtina*-mediated MgO NPs as highly biocompatible and versatile agents capable of bridging the gap between advanced antiparasitic treatment, oncology, and sustainable environmental remediation. Hadkar et al. [124] investigated Ag_3PO_4/SnO nanocomposites synthesized via a green route mediated by *Miliusa sericea* leaf extract with significant anticancer potential, particularly against the MCF-7 breast cancer cell line, which yielded a potent IC_{50} value value of 42.76 μg/mL, while a slightly higher IC_{50} value of 61.33 μg/mL was recorded against HeLa cervical cancer cells. The nanocomposites also demonstrated robust antioxidant properties, characterized by strong radical scavenging and metal chelating activities, likely enhanced by the bioactive phenolic and flavonoid capping from the *M. sericea* extract. Beyond clinical applications, the nanocomposite proved to be an exceptional photocatalyst, achieving an 88.13% degradation of RhB dye under light irradiation.

The same authors also reported Ag_3PO_4-ZnO nanocomposites using the leaf extract of *Mundulea sericea* [125]. The research characterized these mesoporous nanocomposites as a combination of rod-shaped ZnO and spherical $Ag_3PO_4$with an average crystallite size of 37.77 nm and a narrow bandgap of 2.35 eV. These biogenic NCs demonstrated potent antioxidant activity, reaching an 87.04% DPPH scavenging rate, and exhibited notable anticancer potential by significantly reducing the viability of MCF-7 breast cancer cells (46.61% reduction). The material's biocompatibility was further validated through a hemolysis assay, which showed minimal RBC toxicity 4.50 ±0.13% making it a safe candidate for potential clinical applications. Beyond their medicinal promise, the Ag_3PO_4-ZnO NCs proved to be exceptional photocatalysts, facilitating over 94% degradation of MB dye in complex river water environments under visible light. Sishu et al. [126] developed Au NPs via a green, eco-friendly route using the aqueous leaf extract of *Anamirta cocculus*. The resulting nanoparticles were primarily spherical with a remarkably small size range of 7–10 nm, exhibiting high stability and crystalline structure. Biological evaluations revealed exceptional antioxidant potential, with low IC_{50} values of 22.82± 1.8 μg/mL for DPPH scavenging and 20.82 ± 0.8 μg/mL for iron chelating assays. The therapeutic profile of the *A. cocculus*-mediated Au NPs extended significantly into metabolic and cardiovascular health. The nanoparticles demonstrated potent antidiabetic activity by inhibiting key enzymes, specifically alpha-amylase 79.54%, alpha-glucosidase 83.14%, and DPP-IV 81.20%, suggesting a multi-pathway approach to managing hyperglycemia. Furthermore, the study highlighted robust anti-inflammatory 81.12% and thrombolytic effects, alongside excellent hemocompatibility. The minimal toxicity observed toward red blood cells confirms the high biocompatibility of these biogenic nanoparticles, positioning them as safe and versatile candidates for the treatment of inflammatory diseases and cardiovascular disorders. The same authors also studied Ag-CuO nanocomposites biogenically synthesized using the root extract of *Cichorium intybus* [127]. The resulting spherical nanocomposites, with an average crystallite size of 14.2 nm, displayed exceptional biological multifunctionality due to the natural phenols and flavonoids from the chicory root acting as stabilizing agents. The material exhibited a potent anticancer effect against the A549 human lung cancer cell line, yielding an IC_{50} value of 42.18 ± 0.4 μg/mL. This cytotoxic performance was complemented by a significantly boosted antioxidant potential, which achieved a low IC_{50} of 22.14 μg/mL in DPPH radical scavenging assays, as well as a robust anti-inflammatory response characterized by a 93.12% inhibition of protein denaturation. Beyond their therapeutic utility, the Ag-CuO NCs served as a robust photocatalyst for environmental remediation, achieving a 94.15% degradation of Norfloxacin—a common antibiotic pollutant—under sunlight irradiation within 120 min. The efficiency of this process is attributed to the surface plasmon resonance of silver and the narrowed bandgap of the composite, which facilitates the generation of reactive oxygen species. Crucially, phytotoxicity evaluations using *Vigna radiata* seeds confirmed that the photocatalytic process rendered the antibiotic-contaminated water entirely safe, supporting healthy germination and root development. These findings highlight the potential of *C. intybus*-mediated Ag-CuO NCs as a versatile, eco-friendly platform for both targeted oncology and advanced wastewater treatment. Bhargava et al. [128] synthesized Ag-MgO by *Moringa concanensis* extract. The research demonstrated that the integration of silver into the MgO lattice significantly enhanced the material's pharmacological profile compared to its undoped counterpart. These Ag-MgO NPs exhibited superior

TABLE 2 | The comparative table of biological properties of MNOPS.

Nanomaterials	Plant source	Size (nm)	IC_{50}/inhibition%	Environmental efficiency
ZnO/MgO [117]	*Kalanchoe bhidei*	25.14	54.28 ug/mL (DPPH); 74.12% clot lysis	N/A
ZnO/TiO_2 [118]	*Parkia timoriana*	—	25.69 ug/mL alpha-glucosidase	N/A
CuO/TiO_2 [118]	*Parkia timoriana*	—	72.12 ug/mL alpha-amylase	N/A
Au-ZnO [119]	*Pavetta indica*	—	56.22 ug/mL (A549 cancer)	81.96% (MB dye)
Zn-CuO [120]	*Calophyllum apetalum*	—	Enhanced cytotoxicity (A549 cancer)	High degradation
B–ZnO/C [121]	*Anodendron parviflorum*	14.8–24.5	23.6 ug/mL (A549 cancer)	N/A
MgO [122]	*Hildegardia populifolia*	19.8	94.15% anti-inflammatory	92.4% (MB dye)
MgO [123]	*Scutia myrtina*	15.8	44.9 ug/mL (A549 cancer)	85.32% (RB5 dye)
Ag_3PO_4/SnO [124]	*Miliusa sericea*	N/A	42.76 ug/mL (MCF-7 cancer)	88.13% (RhB dye)
Ag_3PO_4-ZnO [125]	*Mundulea sericea*	37.77	46.61% inhibition (MCF-7 cancer)	94% (MB dye)
Au [126]	*Anamirta cocculus*	7–10	83.14% inhibition (alpha-glucosidase)	N/A
Ag-CuO [127]	*Cichorium intybus*	14.2	22.14 ug/mL (DPPH)	94.15% (norfloxacin)
Ag-MgO [128]	*Moringa concanensis*	N/A	10.78 mg/mL (DPPH)	MIC: 0.625 mg/mL

antioxidant activity with an IC_{50} value of 10.78 mg/mL and an improved antidiabetic effect, achieving a 48.0% inhibition of the alpha-amylase enzyme at a concentration of 0.25 mg/mL. This synergistic effect is attributed to the increased surface area and modified electronic properties resulting from the Ag-doping, which facilitate more effective interaction with biological targets. The antimicrobial efficacy of the nanoparticles was also notably bolstered, with the minimum inhibitory concentration (MIC) against *E. coli* being reduced to 0.625 mg/mL, a fourfold increase in potency over pure MgO (Table 2).

Recent literature collectively reveals a decisive shift toward biogenic, multicomponent nanomaterials that exploit the synergistic interplay between metallic heterojunctions and plant-derived metabolites. Studies by Kumaran et al. [117] and Arunagiri et al. [119] demonstrate that integrating multiple oxide or metal phases—such as ZnO/MgO and Au–ZnO—consistently yields superior biological performance compared to their pristine counterparts. This enhanced functionality is primarily attributed to two interdependent mechanisms: (i) heterojunction formation, which promotes efficient charge separation and electron transfer, and (ii) the development of a bioactive surface corona enriched with phenolics and flavonoids. These phytochemical capping agents not only stabilize nanoparticles by suppressing agglomeration but also impart intrinsic therapeutic functionality, as evidenced by the 74.12% clot-lysis efficiency reported for the *K. bhidei*-derived composite. Beyond antioxidant and anticancer applications, these nanocomposites exhibit remarkable versatility in metabolic regulation and environmental remediation. Papitha et al. [118] and Sishu et al. [126] reported outstanding antidiabetic activity for ZnO/TiO_2 and Au nanoparticles, respectively. Notably, the ZnO/TiO_2 system achieved potent α-glucosidase inhibition, while biogenic Au nanoparticles demonstrated a multi-pathway antihyperglycemic mechanism with enzyme inhibition efficiencies reaching 83.14%. In parallel, investigations by Hadkar et al. [120, 125] and Arunagiri et al. [122, 123] established these materials as high-performance photocatalysts, with Ag_3PO_4–ZnO and Ag–CuO nanocomposites enabling over 94% degradation of persistent organic pollutants such as methylene blue and norfloxacin under light irradiation. Importantly, the environmental compatibility of these remediation strategies was validated through phytotoxicity assessments using *Vigna radiata*, which confirmed that treated water supported normal seed germination and growth. Collectively, these findings position green-synthesized nanocomposites as a sustainable, multifunctional, and biologically optimized platform that bridges the divide between advanced nanomedicine and environmentally responsible remediation technologies.

4 | Conclusion and Future Prospects

Plant-mediated synthesis of MONPs represents a transformative approach in nanomaterials research, offering a sustainable, cost-effective, and eco-friendly alternative to conventional chemical and physical methods. These MONPs have demonstrated significant potential across a broad range of applications—including antimicrobial agents, photocatalysts, biosensors, and biomedical tools—thanks to their unique physicochemical properties, such as high surface area, tunable morphology, and surface functionalization. Research has shown that varying the plant species, extraction conditions, and synthesis parameters can tailor the nanoparticles' properties for specific applications, enabling multifunctional behavior and improved efficacy. Looking forward, there is a strong need to deepen mechanistic understanding of phytochemical interactions during nanoparticle formation and to standardize protocols for reproducibility and scalability. Integrating high-throughput screening, machine learning, and computational modeling could accelerate the opti-

mization of plant-nanoparticle systems. Furthermore, regulatory frameworks, toxicological profiling, and lifecycle assessments must be developed to support safe commercialization and environmental deployment. Future research should also explore hybrid nanocomposites and smart nanoformulations using green-synthesized MONPs for next-generation diagnostics, targeted drug delivery, food packaging, and environmental remediation. Overall, the convergence of green chemistry, nanotechnology, and biotechnology through plant-based nanoparticle synthesis paves the way for sustainable innovation in diverse scientific and industrial domains.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article, as no new data were created or analyzed in this study.

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