IRSTI 31.15.33

# RECENT ADVANCES IN GREEN SYNTHESIS OF METAL OXIDE NANOPARTICLES USING PLANT EXTRACTS

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**Abstract.**
Green synthesis of metal oxide nanoparticles using plant extracts has emerged as a sustainable and environmentally friendly alternative to conventional chemical and physical synthesis methods. This review comprehensively examines recent advances in plant-mediated biosynthesis of various metal oxide nanoparticles, including zinc oxide, titanium dioxide ($TiO_2$), iron oxide ($Fe_2O_3$/$Fe_3O_4$), copper oxide, and other metal oxides. The mechanisms involving phytochemicals such as flavonoids, terpenoids, alkaloids, phenolic compounds, and saponins as reducing and stabilizing agents are discussed in detail. Characterization techniques including UV-Vis spectroscopy, X-ray diffraction, scanning electron microscopy, transmission electron microscopy, and Fourier-transform infrared spectroscopy are reviewed. Applications of green-synthesized MONPs in environmental remediation, biomedical fields, photocatalysis, antimicrobial activity, and agricultural practices are highlighted. The advantages of plant-based synthesis over microbial and chemical methods, including cost-effectiveness, scalability, and reduced environmental impact, are emphasized. Future perspectives and challenges in standardization, mechanistic understanding, and industrial translation are also addressed.

**Keywords:** Green synthesis, metal oxide nanoparticles, plant extracts, phytochemicals, biosynthesis, environmental remediation, biomedical applications, photocatalysis

## 1. Introduction

Nanotechnology has revolutionized materials science by enabling the manipulation of matter at the nanoscale (1-100 nm), resulting in materials with unique physicochemical properties that differ significantly from their bulk counterparts [1], [2]. Metal oxide nanoparticles have garnered considerable attention due to their versatile applications in catalysis, drug delivery, sensors, energy devices, semiconductors, food technology, agriculture, and medicine [3]. The distinctive properties of MONPs, including high surface area-to-volume ratio, enhanced reactivity, quantum confinement effects, and tunable optical and electronic characteristics, make them indispensable in modern technological applications [3], [4].

Conventional synthesis methods for MONPs, including chemical reduction, sol-gel processes, hydrothermal synthesis, and physical methods such as laser ablation and vapor-phase synthesis, often require toxic chemicals, high energy inputs, and harsh operating conditions [5], [6] . These approaches generate hazardous byproducts, pose environmental risks, and may result in nanoparticles with residual toxicity that limits their biomedical and environmental applications [5], [7]. The growing concern over environmental sustainability and the need for eco-friendly nanomaterials has driven the development of green chemistry approaches for nanoparticle synthesis [1], [8].

Green synthesis using plant extracts represents a paradigm shift in nanomaterial fabrication, offering a sustainable, cost-effective, and biocompatible alternative to traditional methods [1], [9]. Plants serve as abundant, non-toxic, and renewable sources of phytochemicals that can act as both reducing agents and stabilizing agents in nanoparticle synthesis [9], [10]. The biodiversity of plant species provides a vast library of bioactive compounds, including flavonoids, terpenoids, alkaloids, phenolic compounds, saponins, and vitamins, which can mediate the reduction of metal ions to nanoparticles and control their size, shape, and stability [8], [10].

This review provides a comprehensive analysis of recent advances in the green synthesis of metal oxide nanoparticles using plant extracts, covering synthesis mechanisms, characterization techniques, applications, and future perspectives. Special emphasis is placed on understanding the role of phytochemicals in nanoparticle formation and the advantages of plant-based synthesis over other biogenic and chemical methods.

## 2. Principles of Green Synthesis

The concept of green synthesis is rooted in the twelve principles of green chemistry, which emphasize the design of chemical processes that reduce or eliminate the use and generation of hazardous substances [7], [8]. According to Cheviron et al., three general aspects need to be considered in green synthesis: solvent medium, non-toxic reducing agents, and environmentally safe nanoparticle stabilizers [7]. Green synthesis approaches aim to minimize energy consumption, use renewable feedstocks, reduce waste generation, and design safer chemicals and processes [1], [10]. Plants are readily available, inexpensive, and do not require complex culture conditions or specialized equipment [1], [10]. The use of plant extracts eliminates the need for expensive reducing and capping agents typically used in chemical synthesis [5]. Plant-based synthesis uses water or ethanol as solvents, avoiding toxic organic solvents [1]. The process generates minimal hazardous waste and does not require high temperatures or pressures [5]. Plant extracts can be easily scaled up for industrial production, making plant-mediated synthesis suitable for large-scale commercial applications [1], [11]. Nanoparticles synthesized using plant extracts often exhibit enhanced biocompatibility and reduced toxicity, making them suitable for biomedical applications [9], [12]. Plant extracts can reduce metal ions in a much shorter time compared to fungi and bacteria, which require longer incubation periods [8], [12]. Plant extracts serve as both reducing agents and stabilizing agents, eliminating the need for additional capping agents [10].

While microbial synthesis using bacteria, fungi, and yeast has been extensively studied, plant-mediated synthesis offers several advantages [6], [10]. Microorganisms require specific culture conditions, have slower growth rates, and may produce nanoparticles with lower yields [10]. In contrast, plants can be easily cultivated, harvested, and processed, and their extracts contain a diverse array of phytochemicals that can be tailored for specific nanoparticle synthesis requirements [1], [8]. Additionally, handling and controlling plant material is easier compared to other biological systems [13].

### 2.1 Phytochemicals as Reducing and Stabilizing Agents

The efficiency of plant-mediated synthesis of metal oxide nanoparticles is primarily attributed to the diverse range of phytochemicals naturally present in plant extracts, which function as reducing, stabilizing, and capping agents during nanoparticle formation [14]. These bioactive compounds include flavonoids, terpenoids, alkaloids, phenolic compounds, tannins, saponins, vitamins, proteins, polysaccharides, and various secondary metabolites that collectively facilitate the conversion of metal ions into stable nanoscale materials [15]. Among these constituents, flavonoids are considered particularly important due to their strong electron-donating ability arising from multiple hydroxyl and carbonyl functional groups, which enable efficient reduction of metal ions [16]. In addition to their reducing capacity, flavonoids contribute to nanoparticle stabilization [17] and are known for their antioxidant, antimicrobial, anticancer, antiviral, and hepatoprotective properties, which may enhance the biological functionality of the synthesized nanoparticles [18]. Phenolic compounds and tannins also play a major role in nanoparticle synthesis through electron transfer mechanisms and surface adsorption, thereby preventing particle aggregation and improving colloidal stability [19]. Similarly, terpenoids and alkaloids participate in the bioreduction process and can significantly influence nanoparticle morphology, crystallinity, and surface characteristics [20].

The synergistic interaction of these phytochemicals strongly affects the physicochemical properties, yield, and stability of the synthesized nanoparticles [21]. Saponins contribute to stabilization by modifying surface interactions and dispersion behavior [22], while water-soluble vitamins, coenzymes, amino acids, and other metabolites further support reduction and nucleation processes [23]. The composition and concentration of phytochemicals vary considerably among plant species, extraction methods, plant organs, and environmental conditions, leading to differences in nanoparticle size, shape, and biological activity [24]. Consequently, plant extracts represent highly versatile and environmentally sustainable nanofactories capable of producing nanoparticles with tunable properties suitable for biomedical, catalytic, environmental, and pharmaceutical applications [25]. Figure 1 illustrates the major classes of phytochemicals involved in plant-mediated synthesis of metal oxide nanoparticles and their respective roles in reduction, stabilization, capping, and enhancement of nanoparticle properties.

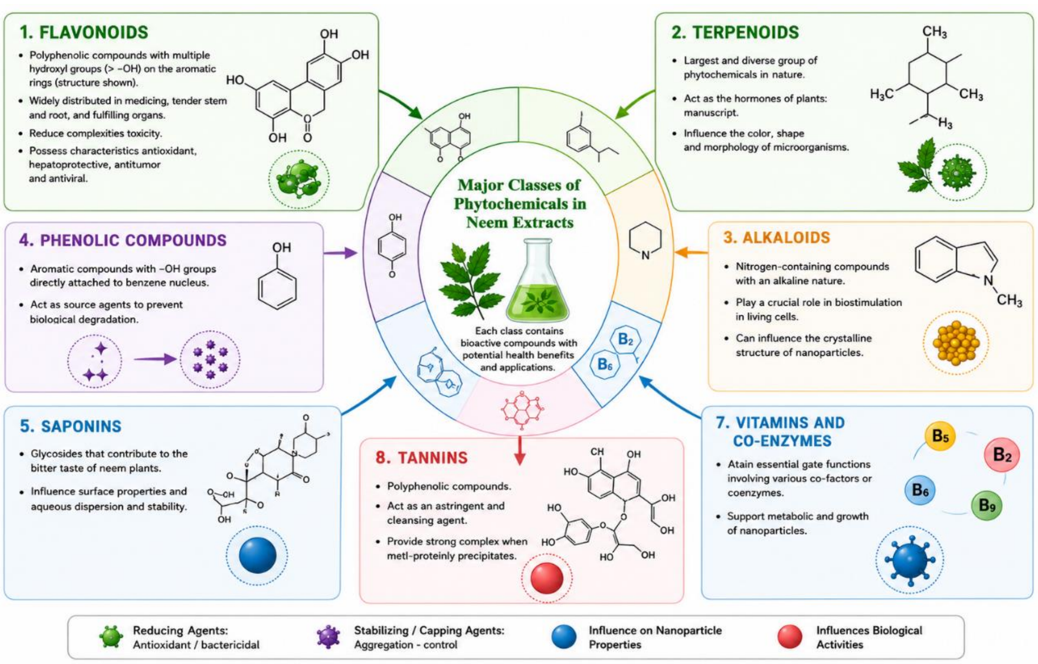


Figure 1 - Major Classes of Phytochemicals Involved in Green Synthesis of Metal Oxide Nanoparticles

### 2.2 Mechanism of Nanoparticle Formation

The green synthesis of nanoparticles using plant extracts is governed by a complex sequence of physicochemical interactions involving the reduction, nucleation, growth, and stabilization of metal species by naturally occurring phytochemicals. Plant-derived biomolecules such as flavonoids, phenolic acids, terpenoids, alkaloids, proteins, polysaccharides, and other secondary metabolites play a central role throughout the synthesis process. Initially, metal ions interact with functional groups present in these compounds through coordination and electrostatic interactions, resulting in the formation of intermediate metal–phytochemical complexes that facilitate the reduction process. Subsequently, reducing agents present in the extract donate electrons to the metal ions, converting them into their reduced metallic or metal oxide forms and initiating the formation of nanoscale nuclei. These nuclei act as active centers for further nanoparticle growth through continuous deposition and aggregation of reduced metal species. As the reaction progresses, biomolecules from the plant extract adsorb onto the nanoparticle surface, functioning simultaneously as stabilizing and capping agents that inhibit excessive aggregation, regulate particle growth, and improve colloidal stability. Consequently, the size, morphology, crystallinity, and dispersion of the synthesized nanoparticles are strongly influenced by the nature and concentration of phytochemicals present in the extract [12], [26] . Figure 2 schematically illustrates the mechanism of plant-mediated synthesis of metal oxide nanoparticles, including phytochemical-assisted reduction of metal ions, nucleation, nanoparticle growth, and stabilization through capping by bioactive compounds.

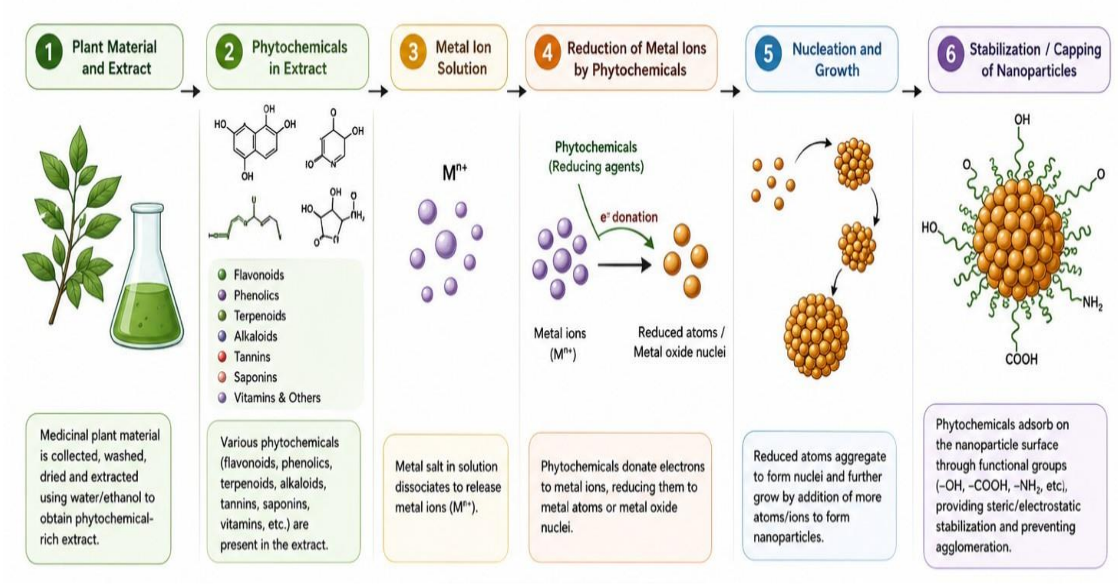


Figure 2 - Mechanism of Green Synthesis of Metal Oxide Nanoparticles Using Plant Extracts.

The efficiency and characteristics of green nanoparticle synthesis are also highly dependent on reaction parameters, including pH, temperature, reaction time, metal precursor concentration, and extract composition. Variations in pH can significantly alter the ionization state of phytochemicals and influence reduction kinetics, nucleation rate, and nanoparticle stability. Similarly, temperature affects reaction kinetics and particle crystallization, while the concentration of plant extract determines the availability of reducing and stabilizing compounds [27] . Studies have shown that biopolymers such as lignin may simultaneously function as reducing and stabilizing agents, with their concentration directly affects nanoparticle size distribution and dispersion behavior [28]. In summary, the synergistic interaction between phytochemical constituents and reaction conditions governs the formation mechanism, yield, structural properties, and long-term stability of green-synthesized nanoparticles, making plant-mediated synthesis an environmentally friendly and highly tunable approach for nanomaterial production.

### 2.3 Green Synthesis of Specific Metal Oxide Nanoparticles

*Zinc Oxide Nanoparticles*

Zinc oxide nanoparticles are among the most extensively studied metal oxides due to their diverse applications in antibacterial, antifungal, anticancer, antidiabetic treatments, drug delivery, and agricultural technologies [4], [13]. Green-synthesized ZnO NPs show potent antibacterial effects at very low concentrations compared to chemically synthesized ZnO NPs [13]. Various plant leaf extracts have been used to prepare ZnO NPs, including coriander, crown flower, Copper leaf, China rose, green tea, and aloe leaf broth extract [12]. Other plants include Azadirachta indica, Aloe barbadensis Miller, Moringa oleifera, Artocarpus heterophyllus (jackfruit), and Syzygium cumini [2], [4], [29]. Madan et al. followed a low-temperature solution combustion route, employing Azadirachta indica leaf extract as a template to synthesize multifunctional hexagonal wurtzite-structured ZnO nanoparticles with various morphologies [2]. Ali et al. prepared ZnO nanoparticles using the reducing and capping potential of Aloe barbadensis Miller leaf extract [2]. Vidya et al. demonstrated green synthesis of ZnO NPs utilizing Artocarpus heterophyllus leaf (jackfruit) extract, producing hexagonal wurtzite-like shaped particles with a size of 15–25 nm [4]. The PXRD patterns confirmed the hexagonal phase of ZnO with wurtzite structure. SEM and TEM analysis revealed rectangular flake-like structures for chemical ZnO whereas green ZnO NPs exhibited spherical structures [13]. The crystalline structure of ZnO NPs was confirmed by XRD analysis and Raman investigation [4]. ZnO NPs synthesized using plant extracts have demonstrated significant antibacterial activity against various bacterial strains [2], [29]. Green ZnO NPs exhibited better antibacterial and antifungal activities in addition to superior photocatalytic behavior [13]. The antibacterial studies indicated that ZnONPs had significant antibacterial activity against K. aerogenes and S. aureus, but not against E. coli and P. aeruginosa [2]. ZnO NPs have shown high photodegradation efficiency (>80% in 1 h) against Rose Bengal dye [4].

*Titanium Dioxide Nanoparticles ($TiO_2$ NPs)*

Titanium dioxide nanoparticles are widely used in personal care products, catalysis, and solar cells [30]. Green synthesis methods for $TiO_2$ NPs have been developed to avoid the environmental impacts of conventional synthesis methods [31]. Various plant extracts have been employed for $TiO_2$ NP synthesis, though specific examples in the literature are less extensive compared to ZnO NPs [32]. $TiO_2$ nanoparticles were generally spherically agglomerated in the 10-30 nm range during TEM investigation, and SAED investigation revealed a crystalline form [33].

*Iron Oxide Nanoparticles ($Fe_2O_3$/$Fe_3O_4$ NPs)*

Iron oxide nanoparticles have great potential for water pollution remediation applications due to their ability to efficiently extract pollutants from solutions using a magnetic field. Green synthesis of iron oxide nanorods mediated by polyphenols present in Omani mango tree leaves has been carried out [2]. Researchers successfully applied the as-synthesized material in heavy crude oil viscosity treatment [34].

*Copper Oxide Nanoparticles*

Copper oxide nanoparticles have been synthesized using various plant extracts and have shown promising applications in catalysis and antimicrobial activity. Thakur et al. developed technology for manufacturing barium ferrite nanoparticles from Acorus calamus rhizome extract and examined their antifungal activity against pathogenic fungi affecting multiple plant species [10]. Madhukara et al. produced zinc ferrite nanoparticles from Limonia acidissima using the green synthesis method, and the resulting nanoparticles demonstrated excellent photodegradation of Evans blue and methylene blue when exposed to visible light [10]. Table 1 summarizes representative examples of plant-mediated synthesis of metal oxide nanoparticles and their major applications reported in recent studies. Various plant extracts rich in phytochemicals such as flavonoids, phenolics, terpenoids, and alkaloids have been successfully utilized as reducing and stabilizing agents for the synthesis of nanoparticles including ZnO, $TiO_2$, CuO, $Fe_3O_4$, and $CeO_2$. The synthesized nanoparticles exhibit diverse physicochemical properties and demonstrate promising applications in biomedical, environmental, catalytic, agricultural, and sensing fields. The data presented in Table 1 highlight the versatility, eco-friendliness, and functional potential of green-synthesized metal oxide nanoparticles for advanced technological and biomedical applications.

Table 1 - Plant-Mediated Synthesis of Metal Oxide Nanoparticles and Their Applications

| Plant Source | Nanoparticle | Major Phytochemicals | Particle Size | Main Application |
|---|---|---|---|---|
| Artemisia annua | ZnO | Flavonoids, phenolics | 20–50 nm | Antibacterial |
| Moringa oleifera | CuO | Terpenoids, tannins | 15–40 nm | Photocatalysis |
| Azadirachta indica | $Fe_3O_4$ | Alkaloids, flavonoids | 10–30 nm | Drug delivery |
| Camellia sinensis | $TiO_2$ | Polyphenols | 25–60 nm | Dye degradation |

## 3. Characterization Techniques

Comprehensive characterization of green-synthesized metal oxide nanoparticles is essential to understand their physicochemical properties and correlate them with their applications [33], [35]. The following techniques are commonly employed:

*UV-Visible Spectroscopy*

UV-Vis spectroscopy is the primary technique used for the characterization of nanoparticles, providing information about particle aggregation and optical properties [35]. It is employed to analyze the dimensions and configurations of nanoparticles in a water-based solution [33]. Typically, wavelengths in the range of 300 to 800 nm are utilized to characterize nanoparticles with sizes ranging from approximately 2-100 nm [33]. Previous research findings have shown that the absorption of wavelengths of 200-800 nm was suitable for classifying nanoparticles with a size range of 2-100 nm [36].

*X-Ray Diffraction*

X-ray diffraction is a valuable technique for gaining insights into the structural aspects, size, and phase composition of metallic nanoparticles [33]. By directing X-rays at nanomaterials, the diffraction pattern that results can be compared to reference patterns to determine structural features [33]. XRD provides information about the different phases of a crystalline material and provides nanoparticle dimensions [35]. It can analyze the atomic structures of materials, and the qualitative and quantitative composition of materials can be determined with this technology [36]. Crystalline nanoparticle size and structure were identified and verified by XRD analysis [36] . To analyze the particle dimensions of nanoparticles from XRD data, the Debye-Scherrer formula is applied by measuring the width of the Bragg reflection peak [36], [37].

*Scanning Electron Microscopy*

Scanning electron microscopy analyzes the surface morphology of nanoparticles through the use of a focused electron beam [35], [38]. It offers fine-grained visuals of the size, shape, texture, and dispersion of the nanoparticle [38]. SEM can be used to characterize nanoparticle distribution, morphology, size, and form of synthesized nanoparticles [36]. The SEM study measured changes in morphological structure both before and after treatment [36]. According to earlier research, observable changes in cell shape and the presence of nanoparticle perforations in the cell wall are used as indicators of the antibacterial activity of nanoparticles

[36]. Energy dispersive X-ray spectroscopy, which is connected to the SEM equipment, is another method for obtaining information on elemental composition [38].

*Transmission Electron Microscopy*

Transmission electron microscopy is the most efficient and widely used technique for the characterization of nanoparticles [35] . TEM images provide insights into the size and aggregation of nanoparticles, and single nanoparticles can be studied by TEM while SEM cannot resolve them [35]. TEM is typically used to describe the morphology and size of nanoparticles [33]. Additionally, the distribution of nanoparticles in a material TEM can reveal [38]. Green-synthesized carbon nanotubes were entirely wrapped in polyaniline layers for TEM and SEM examination [33].

*Fourier-Transform Infrared Spectroscopy*

FTIR spectra reveal the functional groups present on the nanoparticle surface during its synthesis [35]. This technique is crucial for identifying the phytochemicals responsible for reduction and stabilization of nanoparticles [37]. FTIR is one of the most frequent methods used to explore the structural characteristics of nanomaterials, along with XRD, energy dispersive X-ray, XPS, and Zeta size analysis [37].

*Dynamic Light Scattering*

Dynamic light scattering measures the size distribution of suspended nanoparticles by analyzing the light scattering resulting from the Brownian motion of the particles [38]. This approach provides information regarding hydrodynamic size and polydispersity, which is very helpful when researching nanoparticles in colloidal fluids [38].

*Morphological and Elemental Characterization*

The size, shape, and spatial distribution of nanoparticles are primarily assessed through electron microscopy [39]. SEM provides detailed topographical images of the surface features, texture, and degree of agglomeration [36], [38]. When coupled with Energy Dispersive X-ray spectroscopy, it allows for the quantitative and qualitative determination of elemental composition, ensuring that the target metal oxide is the dominant phase and identifying any residual biological elements (such as C, N, or O from the extract) that contribute to the capping layer [40], [41] . TEM is critical for high-resolution imaging of individual nanoparticles, enabling the observation of their internal lattice structure and precise shape (e.g., spherical, hexagonal, or rod-like) [35], [42]. Furthermore, Selected Area Electron Diffraction patterns obtained during TEM analysis provide independent verification of the crystalline or polycrystalline nature of the particles, often showing bright concentric rings that correspond to specific lattice planes [33].

*Physical Stability and Surface Area*

DLS measures the hydrodynamic size of the particles in a colloidal suspension, which is often larger than the "core" size measured by TEM due to the presence of the solvated capping layer [38], [43]. The Zeta potential indicates the surface charge and serves as a predictor of colloidal stability; high absolute values (typically > ±30 mV) suggest strong electrostatic repulsion, preventing sedimentation and aggregation [38], [43]. Brunauer-Emmett-Teller (BET) measurements are used to determine the specific surface area and pore size distribution [6]. For metal oxides used in catalysis or environmental remediation, a high SSA is critical, as it provides a greater number of active sites for adsorption or redox reactions [44], [45]. Other characterization techniques include X-ray photoelectron spectroscopy, which is commonly used to establish the actual elemental ratio and bonding type of the elements in nanoparticle materials [46], and atomic absorption spectroscopy [47].

*Plant Extract Parameters*

Different plants comprise varying concentration levels of phytochemicals, which affect nanoparticlesynthesis [8], [12]. The composition of the plant leaf extract is an important factor in nanoparticle synthesis [8]. The concentration of phytochemicals in the plant leaf extract plays a significant role in nanoparticle production [12]. Higher concentrations generally lead to faster reduction and smaller particle sizes[48]. The method of extract preparation (e.g., boiling, maceration, solvent extraction) affects the types and concentrations of phytochemicals extracted [49].

*Reaction Conditions*

The concentration of the metal precursor influences nanoparticle size, yield, and morphology [8], [12]. Higher concentrations may lead to larger particles or aggregation [50]. The pH of the reaction medium significantly affects nanoparticle formation [10], [12]. The mechanism of nanoparticle production using lignin notably depends on pH, with lignin concentration affecting the size and dispersion of silver nanoparticles [10]. Reaction temperature affects the kinetics of nanoparticle formation and can influence particle size and crystallinity [8], [12]. The duration of the reaction affects nanoparticle size and yield [8]. Plant extracts can reduce metal ions in a much shorter time compared to fungi and bacteria [8], [12]. The method of mixing (stirring, sonication, etc.) can affect nanoparticle uniformity and size distribution.

### 3.1 Applications of Green-Synthesized Metal Oxide Nanoparticles

*Environmental Remediation*

Green-synthesized metal oxide nanoparticles have shown pivotal roles in several environmental applications such as nano-adsorbents, nano-membranes, photocatalysts, and disinfection of microbial wastewater [2], [5].

Bio-synthesized metal oxide nanoparticles have triggered huge global research interest owing to their advantageous properties and various environmental remediation and water treatment applications [3]. They offer significant advantages in various industries, attributable to their heightened physicochemical, optical, mechanical, and electronic attributes [3]. Environmentally friendly nanoparticles are widely used to treat environmental pollutants, including the removal of heavy metals [5]. Green-synthesized MONPs are used for photocatalytic degradation of organic pollutants [5]. ZnO NPs have shown high photodegradation efficiency (>80% in 1 h) against Rose Bengal dye [4]. The photocatalytic efficiency of 98% for Acid Red 88 dye degradation was recorded for ZnO NPs [29]. The synthesized Cu/ZnO composite nanomaterial exhibited excellent catalytic activity in degrading methylene blue and congo red dyes in their aqueous solutions in the presence of $NaBH_4$ [2]. Zinc ferrite nanoparticles demonstrated excellent photodegradation of Evans blue and methylene blue when exposed to visible light [10].

*Biomedical Applications*

Metal oxide nanoparticles have found their inevitable place in the field of nanotechnology due to their versatile applications in drug delivery, sensors, and medicine [6], [11]. ZnO NPs have extraordinary antibacterial properties due to their expanded specific surface area, as the reduced particle size leads to enhanced surface reactivity [13]. Green-synthesized ZnO NPs show potent antibacterial effects at very low concentrations [13]. Green ZnO NPs demonstrated antibacterial activity against Pseudomonas aeruginosa, Klebsiella oxytoca, and Escherichia coli [29]. The antibacterial activity of ZnO NPs was investigated against three bacterial strains: E. coli, Salmonella paratyphi, and Staphylococcus aureus [10]. The percentage of inhibition of mycelial growth was observed during antifungal testing of ZnO NPs [29]. ZnO NPs have diverse applications in fields such as anticancer treatments [10]. Flavonoids have anticancer properties, which can be transferred to synthesized nanoparticles [9]. Metal oxide nanoparticles are used in drug delivery applications [7], [11]. Zinc oxide nanoparticles derived from Ficus microcarpa leaf extracts exhibited high

larvicidal efficacy against mosquitoes and demonstrated antibacterial properties [10]. Green synthesis metals and their oxide nanoparticles show therapeutic efficiency in periodontitis [12].

*Photocatalytic Applications*

When excited by light with an energy greater than the bandgap of ZnO, electrons from the valence band are excited to the conduction band to form photogenerated electrons in the CB and photogenerated holes in the VB. These photogenerated electrons and holes migrate to the surface of ZnO to react with $H_2O$ and $O_2$ to generate $O_2$ •− and •OH radicals, which oxidize organic substances [51]. ZnO NPs are an effective futuristic water purification material [52]. ZnO NPs can exhibit photo-oxidizing and photocatalytic effects on chemical and biological species [51]. Green ZnO NPs exhibited superior photocatalytic behavior [29]. Methylene Blue decolorization under sunlight was examined to determine the photocatalytic activity of the generated ZnO NPs, which completed in 90 min, ZnO NPs were used to generate hydrogen via photocatalysis [4]. The development of this field has progressed from simple exploratory studies involving plant extracts toward highly optimized, multifunctional, and application-oriented nanomaterials. Significant improvements in synthesis control, nanoparticle stability, characterization techniques, and large-scale production have enabled the expansion of green-synthesized nanoparticles into biomedical, environmental, catalytic, agricultural, and energy-related applications. Recent trends further emphasize sustainable nanotechnology, multifunctional nanoparticle systems, and the integration of artificial intelligence and smart technologies for process optimization and advanced material design, indicating the growing scientific and technological importance of green nanomaterials in future research and industrial applications. Figure 3 presents the overall evolution of green nanotechnology and highlights the major advances achieved in plant-mediated synthesis of metal oxide nanoparticles over the past decades.

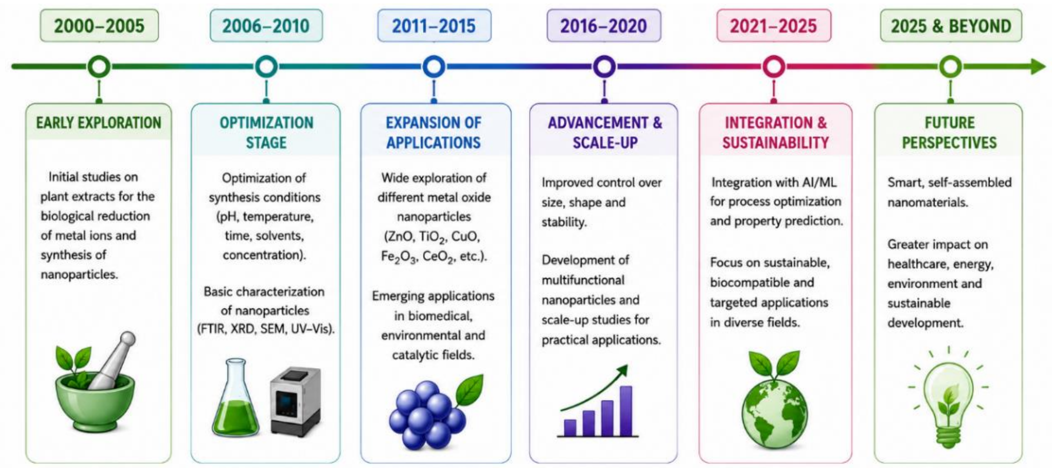


Figure 3 - Evolution and Development Trends of Green Nanotechnology in Plant-Mediated Metal Oxide Nanoparticle Synthesis

### 3.2 Challenges and Limitations

Despite the numerous advantages of green synthesis of metal oxide nanoparticles using plant extracts, several challenges and limitations need to be addressed:

*Mechanistic Understanding*

The definite role of phytochemicals in nanoparticle synthesis has not been fully determined [53]. Although the feasibility of controlling the size and shape of nanoparticles by variation in reaction conditions has been demonstrated in many studies, the actual mechanism by which plant constituents contribute to the synthetic process remains fully unknown [1]. More research is needed to elucidate the precise molecular mechanisms involved in nanoparticle formation.

*Standardization and Reproducibility*

Specific conditions should be considered for the preparation of nanoparticles from different plant species [38]. Variations in plant composition due to seasonal, geographical, and environmental factors can lead to batch-to-batch variability in nanoparticle synthesis [54]. Standardization of protocols is essential for reproducible results.

*Yield and Scalability*

While plant-mediated synthesis is considered scalable, achieving high yields with consistent quality remains a challenge [7], [12]. The mass production of atomically precise nanoparticles requires highly reactive substances and/or energy-consuming procedures, which are not considered environmentally friendly [7]. Optimization of synthesis parameters is needed for industrial-scale production.

*Purification and Separation*

Separation of nanoparticles from plant extracts and purification to remove residual phytochemicals can be challenging [1], [55]. Efficient purification methods need to be developed to ensure nanoparticle purity for specific applications.

*Characterization of Phytochemical-Nanoparticle Interactions*

Understanding the interactions between phytochemicals and nanoparticle surfaces is crucial for controlling nanoparticle properties [56],[10]. Advanced characterization techniques are needed to study these interactions at the molecular level.

*Toxicity Assessment*

While green-synthesized nanoparticles are generally considered less toxic, comprehensive toxicity assessment is necessary for biomedical and environmental applications [3], [5]. Long-term environmental and health impacts need to be studied.

## 4. Conclusion

Green synthesis of metal oxide nanoparticles using plant extracts has emerged as a sustainable and environmentally friendly alternative to conventional chemical and physical synthesis methods. The use of plant extracts as precipitating agents for the preparation of metal oxides eliminates the use of hazardous chemicals. Phytochemicals, which are active substances obtained from plants, serve as reducing and stabilizing agents in the ecologically benign manufacturing of nanoparticles. This review comprehensively examines recent advances in the green synthesis of various metal oxide nanoparticles, including ZnO, $TiO_2$, $Fe_2O_3$, CuO, and others, using diverse plant extracts. The mechanisms involving phytochemicals such as flavonoids, terpenoids, alkaloids, phenolic compounds, and saponins have been discussed in detail. Characterization techniques including UV-Vis spectroscopy, XRD, SEM, TEM, and FTIR have been reviewed.

The applications of green-synthesized MONPs in environmental remediation, biomedical fields, photocatalysis, antimicrobial activity, agricultural practices, energy, food, and sensing applications have been highlighted. Green-synthesized nanoparticles often exhibit enhanced biocompatibility, reduced toxicity, and superior performance compared to chemically synthesized nanoparticles. Plant-mediated synthesis offers numerous advantages including cost-effectiveness, scalability, environmental friendliness, and biocompatibility. However, challenges related to mechanistic understanding, standardization, yield, purification, and toxicity assessment need to be addressed for wider adoption and industrial translation.

Future research should focus on elucidating precise mechanisms, standardizing protocols, developing hybrid nanoparticles, exploring novel applications, contributing to the circular bioeconomy, employing computational modeling, facilitating industrial translation, and developing regulatory frameworks. With continued research and development, green synthesis using plant extracts has the potential to revolutionize the production of metal oxide nanoparticles and contribute to sustainable nanotechnology.

**Acknowledgments**

The research undertaken was made possible by the equal scientific involvement of all the authors concerned.

**Author Contributions**

Conceptualization: Nurzhan Chinibayeva, Formal analysis: Aibat Ibraimov, Investigation: Aibat Ibraimov, Methodology and Supervision: Nurzhan Chinibayeva, Writing – original draft: Nurzhan Chinibayeva, Writing – review & editing: Nurzhan Chinibayeva.

**Funding:** Not applicable.

**Conflict of interest:** The authors declare no conflict of interest.

**Data availability statement:** The data presented in this study may be obtained on request from the corresponding author.

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