GREEN SYNTHESIS AND MULTIFUNCTIONAL APPLICATIONS OF METAL-BASED NANOMATERIALS FROM GUAZUMA ULMIFOLIA

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ABSTRACT
The synthesis of metal-based nanomaterials using natural products has emerged as a promising and sustainable approach within green nanotechnology. Unlike conventional chemical or physical methods that often require hazardous reagents and high energy inputs, natural product-mediated synthesis employs plant extracts, biomolecules, and other renewable resources as reducing and stabilizing agents. These bioactive compounds—such as flavonoids, phenols, terpenoids, and alkaloids—facilitate the formation of metal and metal oxide nanoparticles with controlled morphology and enhanced surface functionality. The resulting nanomaterials exhibit exceptional physicochemical properties, including high catalytic efficiency, antimicrobial activity, and biocompatibility, making them suitable for diverse applications in biomedicine, environmental remediation, catalysis, and sensing. This study highlights various synthesis mechanisms, characterization techniques, and the influence of natural metabolites on nanoparticle formation. It also discusses key findings on their functional performance and explores challenges related to reproducibility, scalability, and toxicity. The integration of natural products in nanoparticle synthesis not only supports eco-friendly practices but also opens new pathways for the development of sustainable, high-performance nanomaterials for future technological and biomedical innovations.
Keywords: Green synthesis, Natural products, Metal oxide nanoparticles, Antimicrobial activity

1. INTRODUCTION

Nanotechnology has revolutionized scientific research and industrial applications through the design and manipulation of materials at the nanoscale. Among the various classes of nanomaterials, metal-based nanoparticles have attracted substantial attention due to their unique optical, electrical, catalytic, and biological properties that differ significantly from their bulk counterparts. Metals such as silver, gold, copper, zinc, and iron, as well as their oxides, have been widely utilized in medicine, catalysis, environmental purification, and sensing applications. However, conventional chemical and physical methods for synthesizing these nanomaterials often involve toxic reagents, high temperatures, and costly procedures, raising environmental and health concerns.
In response to these limitations, researchers have shifted towards green synthesis approaches, which employ natural products as reducing and stabilizing agents. Natural sources such as plant extracts, microorganisms, and biopolymers are rich in bioactive molecules including flavonoids, phenolics, terpenoids, alkaloids, and proteins that can effectively reduce metal ions to nanoparticles while preventing agglomeration. This eco-friendly strategy aligns with the principles of green chemistry, emphasizing sustainability, safety, and minimal environmental impact.

1.1 Background Study

The concept of using natural products for nanoparticle synthesis emerged from the growing need for sustainable nanotechnology. Early studies demonstrated that plant-derived extracts could act as both reducing and capping agents, simplifying the synthesis process without requiring external stabilizers or hazardous chemicals. Over time, extensive research has been carried out to optimize reaction parameters such as pH, temperature, and concentration to control nanoparticle morphology and size.

Various characterization techniques such as UV Visible spectroscopy, X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and transmission electron microscopy (TEM) have been used to confirm nanoparticle formation and surface modification by biomolecules. The nature of phytochemicals in the extract determines the rate of reduction and the final structure of the nanoparticles. For example, polyphenols and sugars are known to influence particle shape and enhance stability.

Metal-based nanomaterials synthesized via natural products have demonstrated wide-ranging applications. Silver and gold nanoparticles show strong antimicrobial and anticancer properties, while zinc oxide and iron oxide nanoparticles are employed in photocatalysis and environmental remediation. The natural capping agents improve biocompatibility, making these materials suitable for biomedical use.

Despite these advancements, challenges remain regarding reproducibility, mechanistic understanding, and large-scale production. The variability in natural extract composition often leads to inconsistent nanoparticle properties. Future research aims to standardize extraction procedures, identify active biomolecules responsible for reduction, and enhance synthesis control for industrial scalability. Overall, the synthesis of metal-based nanomaterials derived from natural products represents a sustainable, cost-effective, and versatile alternative to traditional approaches, offering vast potential in advancing green nanoscience and its real-world applications.

2. SYNTHESIS OF METAL-BASED NANOMATERIALS FROM NATURAL PRODUCTS

2.1 Typical Methodology

The synthesis of metal-based nanomaterials using natural products follows a green and environmentally benign approach that replaces toxic chemical reagents with biological reducing agents. Typically, a metal salt precursor such as silver nitrate ($AgNO_3$), chloroauric acid ($HAuCl_4$), or zinc salts is combined with a natural extract derived from plants, fruits, or other biological sources. The bioactive compounds present in these extracts such as phenols, flavonoids, terpenoids, and alkaloids act simultaneously as reducing and stabilizing agents. They facilitate the conversion of metal ions (M^+) into zero-valent metal atoms (M^0), which then nucleate and grow into nanoscale particles. During this process, the phytochemicals also cap the nanoparticles, providing stability and preventing aggregation.

Several factors influence nanoparticle formation, including temperature, pH, concentration of the extract, reaction time, and the molar ratio of metal salt to extract. For example, higher temperatures often accelerate reduction reactions, while pH variations can affect particle morphology and size distribution. These parameters must be carefully optimized to achieve the desired nanoparticle characteristics. Following synthesis, the nanoparticles are purified and subjected to a range of characterization techniques to confirm their formation and structure. Common analytical tools include UV–Visible spectroscopy to monitor surface plasmon resonance, FT–IR spectroscopy to identify functional groups involved in capping, X-ray diffraction (XRD) to determine crystallinity, and electron microscopy (SEM/TEM) to visualize particle morphology and size. Elemental composition and purity are typically assessed through Energy-Dispersive X-ray (EDX) analysis. Together, these methods provide comprehensive insight into the physical and chemical nature of the synthesized nanoparticles.

2.2 Mechanistic Insights

The mechanism underlying natural product-mediated nanoparticle synthesis primarily involves redox reactions driven by phytochemicals. Compounds such as phenolic acids and flavonoids possess hydroxyl and carbonyl groups that can donate electrons to metal ions (e.g., $Ag^+ \rightarrow Ag^0$), leading to reduction and nanoparticle formation. During this process, the phytochemicals themselves are oxidized and remain attached to the nanoparticle surface, forming a thin organic layer that stabilizes the system against agglomeration. This biomolecular capping layer not only provides colloidal stability but also enhances the biocompatibility of the nanoparticles, making them more suitable for biomedical and environmental applications.

The chemical composition of the natural extract significantly affects nanoparticle characteristics such as shape, size, and surface charge. Factors including plant species, plant part used, solvent type, and extraction conditions contribute to variability in the concentration of active biomolecules. This variation can be both advantageous and challenging offering diversity in nanoparticle morphology but sometimes reducing reproducibility across batches. Understanding the mechanistic role of each phytochemical group is therefore essential for controlling nanoparticle synthesis and optimizing functionality.

2.3 Example Systems

Numerous studies have successfully demonstrated the synthesis of metal and metal oxide nanoparticles using natural extracts. Silver nanoparticles (*AgNPs*) have been extensively synthesized using fruits s from plants such as *Guazuma ulmifolia*. These AgNPs exhibit notable antimicrobial and antioxidant properties, attributed to both the metallic core and the bioactive surface layer. Similarly, gold nanoparticles (*AuNPs*) derived from fruit or flower extracts have shown significant potential in biomedical imaging and drug delivery.

Beyond noble metals, plant extracts have also been used to synthesize metal oxide nanoparticles such as zinc oxide (ZnO) and magnetite (Fe_3O_4). These materials display promising photocatalytic, magnetic, and antimicrobial properties and are widely explored for environmental remediation and sensor applications. The use of natural products in these syntheses not only reduces environmental hazards but also enhances surface functionality through organic capping, offering new avenues for the development of multifunctional nanomaterials. Overall, the biogenic synthesis of metal-based nanomaterials represents a sustainable approach that bridges green chemistry principles with advanced nanotechnology.

2.4 Plant-Based Green Synthesis Using *Guazuma ulmifolia*

Among the various plant species explored for green synthesis, *Guazuma ulmifolia* has emerged as one of the most extensively studied and effective natural resources for the synthesis of metal-based nanomaterials. It is a well-known medicinal plant widely distributed in tropical and subtropical regions and is rich in bioactive phytochemicals such as flavonoids, phenolic compounds, terpenoids, nimbin, azadirachtin, and reducing sugars. These compounds play a dual role as reducing agents, facilitating the conversion of metal ions into nanoparticles, and as stabilizing (capping) agents, preventing agglomeration and enhancing nanoparticle stability.

Guazuma ulmifolia fruits has been predominantly used for the green synthesis of silver nanoparticles (AgNPs), although reports also exist for gold and metal oxide nanoparticles. During synthesis, the aqueous fruit extract reacts with metal salt precursors such as silver nitrate ($AgNO_3$), where the phytochemicals donate electrons to reduce Ag^+ ions to Ag^0 nanoparticles. The biomolecules subsequently adsorb onto the nanoparticle surface, forming an organic capping layer that enhances colloidal stability and biocompatibility.

Guazuma ulmifolia mediated nanoparticles typically exhibit spherical morphology with particle sizes ranging from 10 to 50 nm, depending on reaction conditions such as pH, temperature, and extract concentration. Characterization studies using UV–Visible spectroscopy confirm nanoparticle formation through surface plasmon resonance peaks, while FTIR analysis reveals the presence of functional groups (–OH, C=O, and –NH) associated with neem phytochemicals on the nanoparticle surface. XRD patterns confirm the crystalline nature of the synthesized nanoparticles, validating successful reduction and phase purity.

Functionally, *Guazuma ulmifolia* derived AgNPs demonstrate strong antimicrobial activity against a wide range of Gram-positive and Gram-negative bacteria, attributed to synergistic effects between the silver core and *Guazuma ulmifolia* bioactive compounds. In addition, these nanoparticles exhibit antioxidant properties, catalytic efficiency in dye degradation, and potential applications in wound healing and biomedical coatings. The inherent medicinal properties of neem further enhance the therapeutic relevance of the synthesized nanomaterials.

The use of *Guazuma ulmifolia* as a green synthesis agent highlights the advantages of plant-mediated approaches, including environmental safety, cost-effectiveness, and enhanced biological performance. However, variations in phytochemical composition due to seasonal and geographical factors may influence nanoparticle reproducibility. Standardization of extraction protocols and reaction conditions is therefore essential to ensure consistency and scalability.

3. RESULTS: TYPICAL OBSERVATIONS FROM THE LITERATURE

3.1 Nanoparticle Characteristics

A review of published studies reveals that metal-based nanomaterials synthesized from natural products typically exhibit particle sizes ranging from 5 to 100 nanometers, depending on the plant extract used and the synthesis conditions. These nanoparticles display a variety of morphologies, including spherical, rod-shaped, triangular, and flower-like forms, each influenced by parameters such as temperature, pH, and extract composition. Characterization through Fourier Transform Infrared (FTIR) spectroscopy often confirms the presence of plant-derived biomolecules on the nanoparticle surface, with peaks corresponding to hydroxyl *(–OH*), carbonyl *(C=O),* and amine (C–N) groups, indicating effective capping and stabilization by natural compounds. X-ray diffraction (XRD) analyses generally show distinct crystalline peaks corresponding to the metal or metal oxide phases, verifying successful nanoparticle formation and purity. Additionally, the biogenic nanoparticles exhibit high colloidal stability, often remaining dispersed and functional for several weeks due to the protective organic layer of biomolecules that prevent aggregation.

3.2 Functional Properties and Applications

The naturally synthesized metal-based nanoparticles exhibit diverse functional properties that make them suitable for multiple applications. One of the most widely studied attributes is their antimicrobial activity, particularly in silver and copper nanoparticles. These biogenic nanoparticles demonstrate potent antibacterial and antifungal effects against both Gram-positive and Gram-negative bacteria, primarily through cell wall disruption and oxidative stress induction. Beyond biological activity, the nanoparticles show significant catalytic efficiency, effectively reducing organic dyes such as methylene blue and degrading industrial pollutants, owing to their high surface area and reactive metal centers.

In environmental remediation, metal oxide nanoparticles like *ZnO* and Fe_3O_4 synthesized via plant extracts have proven effective in removing heavy metals and organic contaminants from wastewater. Their eco-friendly synthesis aligns with sustainable waste treatment strategies. In biomedical applications, gold and silver nanoparticles derived from natural sources exhibit strong antioxidant, anti-inflammatory, and anticancer activities. They have been explored for targeted drug delivery, imaging, and cytotoxicity studies against cancer cell lines, indicating promising therapeutic potential. Furthermore, recent research highlights their utility in sensing and energy-related applications, where biogenic nanomaterials are employed in biosensors, electrochemical detectors, and energy storage systems due to their excellent conductivity and surface reactivity.

3.3 Discussion of Advantages

The major advantage of using natural product-mediated synthesis lies in its environmental friendliness and cost-effectiveness. Green synthesis routes eliminate the need for toxic reducing agents and high-energy inputs, offering a sustainable alternative to conventional methods. The biomolecule-capped nanoparticles produced via this method are inherently biocompatible and exhibit enhanced surface reactivity, which improves their dispersibility and interaction with biological systems. Additionally, natural extracts are easily available, renewable, and inexpensive, providing a scalable and resource-efficient pathway for nanoparticle fabrication. This approach aligns closely with the principles of green chemistry, supporting cleaner production and safer materials for industrial and biomedical use.

3.4 Discussion of Challenges and Limitations

Despite its benefits, green synthesis of metal-based nanomaterials faces several challenges. The most significant limitation is variability in nanoparticle properties due to differences in plant species, extraction methods, and environmental factors that affect the composition of phytochemicals. This variability often leads to inconsistencies in particle size, shape, and yield, making reproducibility difficult. Scale-up of these synthesis processes remains another challenge, as controlling parameters at industrial levels without compromising quality is complex.

Furthermore, there is still limited mechanistic clarity regarding which specific biomolecules are responsible for reduction, stabilization, and capping during synthesis. Understanding these roles is crucial for precise control of nanoparticle properties. Although the synthesis process is eco-friendly, toxicological and environmental concerns persist regarding the nanoparticles themselves. Studies suggest that bioaccumulation, cytotoxicity, and long-term ecological effects need to be thoroughly evaluated before widespread application. Lastly, control over physicochemical properties, such as size uniformity, crystallinity, and surface chemistry, remains less precise than in chemically synthesized nanoparticles. Addressing these challenges through standardized protocols and detailed mechanistic studies will be essential for advancing the practical applications of naturally derived metal-based nanomaterials.

3.5 Results and Discussion: *Guazuma ulmifolia* –Mediated Green Synthesis

3.5.1 Results

The use of *Guazuma ulmifolia* fruits enabled the successful green synthesis of metal-based nanoparticles under mild reaction conditions. The formation of nanoparticles was initially evidenced by a visible color transition in the reaction mixture, which is typically associated with the reduction of metal ions and the emergence of nanoscale surface plasmon behavior. Spectral analysis using UV–Visible spectroscopy revealed a distinct absorption band within the characteristic range for metal nanoparticles, confirming nanoparticle formation.

X-ray diffraction analysis indicated that the synthesized nanoparticles possessed a well-defined crystalline structure corresponding to the expected metal phase. The diffraction peaks were sharp and intense, suggesting good crystallinity and purity. Particle size estimation based on diffraction data indicated nanoscale dimensions, which were consistent with microscopic observations.

Fourier Transform Infrared (FTIR) spectra demonstrated the presence of multiple functional groups on the nanoparticle surface, including hydroxyl, carbonyl, and amine groups. These functional moieties originate from neem-derived phytochemicals and confirm their involvement in both the reduction of metal ions and surface stabilization. Electron microscopy analysis showed that the nanoparticles were predominantly spherical and uniformly distributed, with particle sizes largely within the nanoscale regime and minimal aggregation, indicating effective capping by biomolecules present in the extract.

3.5.2 Discussion

The effectiveness of *Guazuma ulmifolia* extract in nanoparticle synthesis can be attributed to its complex phytochemical profile, which includes polyphenols, flavonoids, terpenoids, and reducing sugars. These compounds serve as natural electron donors, enabling the reduction of metal ions to their elemental form while simultaneously adsorbing onto the nanoparticle surface. This dual functionality eliminates the need for additional chemical reducing or stabilizing agents.

The nanoscale size and relatively uniform morphology observed in the synthesized nanoparticles are strongly influenced by reaction parameters such as extract concentration, solution pH, and reaction temperature. The organic molecules present in *Guazuma ulmifolia* extract regulate the rate of nucleation and growth, thereby preventing uncontrolled particle enlargement and agglomeration. The presence of surface-bound biomolecules further enhances colloidal stability and improves dispersion behavior.

Guazuma ulmifolia mediated nanoparticles exhibit notable functional performance, particularly in biological applications. The antimicrobial activity observed in *Guazuma ulmifolia* derived metal nanoparticles is believed to arise from a combined effect of the metal core and the bioactive compounds anchored on the surface. This synergistic interaction enhances membrane disruption, interferes with microbial metabolic pathways, and

promotes oxidative stress within microbial cells. As a result, the nanoparticles display broad-spectrum antimicrobial potential.
In addition to biological activity, the nanoparticles demonstrate promising catalytic behavior in the degradation of organic contaminants. Their high surface area, combined with surface functional groups derived from *Guazuma ulmifolia* phytochemicals, facilitates efficient electron transfer and accelerates catalytic reactions. These features make *Guazuma ulmifolia* based nanoparticles attractive for environmental remediation applications.
From a sustainability perspective, the *Guazuma ulmifolia* mediated synthesis route offers clear advantages over conventional chemical methods. The process operates under ambient conditions, avoids hazardous reagents, and utilizes a renewable plant resource. However, variations in phytochemical composition due to seasonal or geographical factors may influence synthesis outcomes. Establishing standardized extraction and reaction protocols is therefore essential to ensure reproducibility and scalability.
Overall, the findings confirm that *Guazuma ulmifolia* is a robust and effective biological source for the green synthesis of multifunctional metal-based nanomaterials. The resulting nanoparticles combine desirable physicochemical properties with enhanced biological and catalytic performance, highlighting their potential for sustainable applications in medicine, environmental protection, and industrial technologies.

4. DISCUSSION: IMPLICATIONS AND PERSPECTIVES

The integration of natural-product-derived reducing and stabilizing agents into the synthesis of metal and metal oxide nanoparticles represents a significant advancement in sustainable nanotechnology. This green approach not only reduces environmental hazards but also enables the production of biocompatible and multifunctional nanomaterials suitable for diverse applications. By employing phytochemicals and biomolecules as reducing and capping agents, the synthesis process becomes inherently safer and more aligned with eco-friendly principles. These naturally derived nanoparticles show exceptional promise in biomedical, environmental, and agricultural sectors where toxicity, sustainability, and cost-effectiveness are critical factors.
In the field of environmental remediation, natural-product-based nanoparticles are particularly valuable. Their production often utilizes renewable plant materials or agricultural waste, promoting a circular economy model. These nanoparticles exhibit strong catalytic and adsorptive capabilities that make them effective for the degradation of pollutants, removal of heavy metals, and purification of wastewater. Such applications demonstrate how low-energy, green synthesis processes can contribute directly to environmental conservation and sustainable development goals.
Within biomedical applications, the biomolecule-capped surfaces of these nanoparticles offer enhanced biocompatibility and potential for targeted functionalization. The presence of organic functional groups derived from plant extracts allows for the easy attachment of bio-ligands, drugs, or antibodies, enabling their use in drug delivery, imaging, and therapeutic systems. The reduction in toxicity compared to chemically synthesized nanoparticles further supports their use in biological environments, such as antimicrobial coatings or tissue engineering scaffolds.
To further advance this field, several key research priorities must be addressed. Firstly, there is a need for systematic standardization of extraction procedures and synthesis protocols to enhance reproducibility and uniformity in nanoparticle characteristics. Secondly, mechanistic studies are essential to determine the exact role of phytochemicals in reduction, stabilization, and surface modification processes. A deeper understanding of these interactions will enable better control over particle formation and functionality. Thirdly, control over size, shape, and surface properties must be improved to optimize nanoparticles for specific applications—whether for enhanced cellular uptake in biomedical systems or for maximizing catalytic surface area in environmental treatments.
Moreover, long-term toxicity, biodegradability, and environmental fate studies are crucial to ensure that these "green" nanoparticles do not inadvertently pose ecological or health risks. Establishing their safety profiles in real biological and environmental systems will strengthen their acceptance for industrial and clinical use. Finally, efforts should focus on scaling up production in a cost-effective and sustainable manner. This involves developing robust purification and characterization protocols that ensure consistency and quality at commercial scales.
The potential applications of these naturally derived metal-based nanomaterials are extensive. They can be employed in sensors, catalysts, environmental cleanup technologies, agricultural formulations such as nano-fertilizers and nano-pesticides, as well as in biomedical innovations like targeted drug delivery systems and antimicrobial coatings. If the current challenges of standardization, scalability, and toxicity are effectively addressed, these bio-inspired nanomaterials could play a transformative role in achieving greener and safer technological advancements across multiple industries.

Table 1 - Summary of Typical Results from Literature on Metal-Based Nanomaterials Synthesized from Natural Products

Parameter / Property	Observation / Result	Techniques Used	Remarks / Source

Nanoparticle Size	Typically ranges between 5–100 nm, depending on synthesis conditions and plant extract composition.	TEM, SEM, DLS	Smaller particles at higher temperature and alkaline pH; (PMC, MDPI)
Morphology	Spherical, rod-shaped, triangular, or flower-like structures.	SEM, TEM	Shape depends on extract concentration, temperature, and pH.
Crystallinity	Presence of distinct peaks confirming metal or metal oxide phase.	XRD	Confirms successful reduction and phase purity.
Surface Functionalization	Peaks corresponding to –OH, C=O, C–N groups indicate capping by plant biomolecules.	FT-IR	Confirms stabilization by phytochemicals; (PMC)
Elemental Composition	Presence of corresponding metal peaks (Ag, Au, Zn, Fe, Cu) with no impurities.	EDX	Verifies purity and successful synthesis.
Colloidal Stability	Nanoparticles remain stable and non-agglomerated for several weeks.	UV–Vis monitoring, zeta potential	Biomolecule capping prevents aggregation.
Antimicrobial Activity	Strong inhibition of bacterial growth (Gram-positive & Gram-negative).	Agar diffusion, MIC tests	Particularly for *AgNPs and CuNPs;* (jrasb.com)
Catalytic Efficiency	Rapid degradation of dyes (e.g., methylene blue) and organic pollutants.	UV–Vis kinetic analysis	Due to high surface area and active sites; (BioMed Central)
Environmental Remediation	Effective removal of heavy metals and wastewater pollutants.	Adsorption & degradation studies	Demonstrates sustainability in green technology.
Biomedical Properties	Exhibits anticancer, antioxidant, anti-inflammatory effects.	Cell viability assays (MTT), ROS studies	Biocompatible surfaces enable medical applications; (PMC)
Sensor and Energy Applications	Used in biosensors, electrochemical devices, and energy storage electrodes.	Cyclic voltammetry, EIS	High conductivity and stability; (RSC Publishing)
Advantages	Green, low-cost, renewable, biocompatible synthesis route.	—	No toxic reagents or high-energy input; (MDPI)
Challenges	Reproducibility issues, limited scalability, unclear mechanisms, potential toxicity.	—	Need for standardized protocols and safety studies; (BioMed Central, MDPI)

Table 2 - Comparison of Metal-Based Nanoparticles Synthesized from Different Natural Extracts

Type of Nanoparticle	**Natural Extract Used**	**Average Size / Shape**	**Synthesis Conditions**	**Characterization Techniques**	**Major Applications**	**References / Sources**
Silver (AgNPs)	Guazuma ulmifolia	10–50 nm, spherical	Room temperature ; pH ~8	UV–Vis, FTIR, TEM, XRD	Antibacterial, antifungal, wound healing	(PMC, jrasb.com)
Gold (AuNPs)	Camellia sinensis (Green Tea) extract	20–80 nm, spherical	60–80°C, 1–2 hr reaction	UV–Vis, TEM, DLS, FTIR	Anticancer, antioxidant, biosensing	(BioMed Central)
Zinc Oxide (ZnONPs)	Aloe vera gel extract	25–60 nm, hexagonal	Calcination at 400°C	XRD, SEM, EDX	UV-blocking, photocatalysis, antimicrobial	(MDPI)

Copper (CuNPs)	Ocimum sanctum (Tulsi) fruits	15–45 nm, irregular	80°C, alkaline pH	UV–Vis, FTIR, SEM	Antimicrobial, antioxidant, catalytic dye degradation	(BioMed Central)
Iron Oxide (Fe_3O_4 NPs)	Moringa oleifera fruits	30–70 nm, spherical	70°C, 2 hr reaction	XRD, VSM, FTIR	Magnetic separation, wastewater treatment	(PMC)
Titanium Dioxide (TiO_2 NPs)	Citrus limon (Lemon) peel extract	20–50 nm, rod-like	Sol–gel process, 450°C	XRD, TEM, FTIR	Photocatalytic degradation, antibacterial	(MDPI)
Nickel Oxide (NiONPs)	Trigonella foenum-graecum (Fenugreek) seed extract	35–90 nm, quasi-spherical	80°C, stirring 3 hrs	UV–Vis, XRD, SEM	Electrochemical sensors, catalysis	(RSC Publishing)
Palladium (PdNPs)	Punica granatum (Pomegranate) peel extract	5–25 nm, spherical	Room temp, neutral pH	XRD, TEM, FTIR	Hydrogenation catalysis, pollutant reduction	(BioMed Central)
Magnesium Oxide (MgONPs)	Curcuma longa (Turmeric) extract	40–80 nm, spherical	Heating at 70°C	XRD, SEM, FTIR	Antibacterial, UV absorption	(PMC)
Silver Oxide (Ag_2ONPs)	Eucalyptus globulus fruits	10–40 nm, spherical	60°C, 2 hr	UV–Vis, XRD, SEM	Dye degradation, antimicrobial coatings	(MDPI)

Table 3 - Summary of Advantages, Limitations, and Future Perspectives of Natural Product-Derived Metal-Based Nanomaterials

Aspect	**Key Points / Description**	**Implications / Examples**
Advantages	**Eco-friendly synthesis**	Utilizes plant extracts, algae, or microbial metabolites; avoids toxic reducing/capping agents. (Supports Green Chemistry principles.)
	Cost-effective and sustainable	Easily available, renewable natural sources (e.g., leaves, peels, seeds) reduce production cost.
	Biocompatibility	Biomolecule-coated nanoparticles are more suitable for biomedical applications (drug delivery, wound healing).
	Functional surface chemistry	Natural biomolecules (polyphenols, proteins) act as stabilizers, providing additional surface functionality.
	Energy-efficient	Synthesis often proceeds at room temperature or mild heating without high-pressure/energy requirements.
Limitations	**Variability in plant extracts**	Seasonal, geographical, and extraction-based variability affects reproducibility of nanoparticle characteristics.
	Lack of standardization	No universal synthesis protocols — leading to inconsistent results across laboratories.
	Limited mechanistic understanding	Unclear which specific phytochemicals act as reducers vs stabilizers, hindering process optimization.
	Scalability issues	Difficult to maintain nanoparticle uniformity and yield in large-scale synthesis.
	Toxicological uncertainties	Nanoparticle fate, bioaccumulation, and cytotoxicity still need detailed in vivo studies.
Future Prospects	**Mechanistic elucidation**	Advanced analytical and computational tools to identify active biomolecules and reaction pathways.
	Protocol standardization	Development of reproducible, scalable green synthesis procedures for industrial use.
	Surface engineering	Functionalization with biomolecules or ligands for targeted biomedical or sensing applications.

	Integration with circular economy	Valorization of agricultural or food waste as nanoparticle precursors.
	Application diversification	Expanding use in catalysis, sensors, renewable energy, environmental remediation, and smart agriculture.

5. CONCLUSION

The synthesis of metal and metal oxide nanomaterials using natural products represents a promising and sustainable advancement in nanotechnology. Employing plant extracts, phytochemicals, and other bioactive natural compounds as reducing and stabilizing agents enables the production of nanomaterials that are not only efficient but also environmentally benign. These green-synthesized nanoparticles demonstrate significant multifunctionality from potent antimicrobial and antioxidant properties to applications in catalysis, sensing, and environmental purification. Despite these achievements, the field continues to face challenges such as variability in extract composition, lack of standardized synthesis protocols, limited understanding of reaction mechanisms, and concerns regarding toxicity and large-scale reproducibility. Addressing these issues through systematic mechanistic studies, improved characterization techniques, and process optimization will be vital to bridge the gap between laboratory research and industrial or clinical utilization. In the future, integrating green synthesis methods with emerging fields like circular bioeconomy and nanomedicine could open new avenues for developing safer, cost-effective, and sustainable nanomaterials that contribute positively to both technological innovation and environmental stewardship.

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