GREEN SYNTHESIS OF METAL AND METAL OXIDE NANOPARTICLES USING PLANT EXTRACTS: A REVIEW OF GREEN FABRICATION, CHARACTERIZATION, AND ENVIRONMENTAL APPLICATIONS

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Abstract

Sustainable nanomaterial research is being guided by green synthesis which avoids and replaces hazardous reductants, synthetic stabilizers, organic solvent utilization, and energy consuming procedures of conventional nanoparticle synthesis. This study investigates the plant-extract-mediated synthesis of metal and metal oxide nanoparticles, with an emphasis on phytochemical mechanisms controlling ion reduction, nucleation, growth, capping and colloidal stabilization. Plant matrices that contain phenolics, flavonoids, alkaloids, terpenoids, tannins, proteins, polysaccharides, and organic acids can donate electrons, chelate metal ions, regulate supersaturation and form organic surface coronas on newly formed particles. The review includes information about silver, gold, copper, zinc oxide, iron oxide, titanium dioxide, magnesium oxide, and nickel oxide. The sustainable synthesis routes such as aqueous extraction, one-pot synthesis, microwave-assisted, ultrasonication, solar-assisted processing, and waste-biomass utilization were compared in terms of their reproducibility, safety, scalability, and functional performance. The use of UV-Visible spectroscopy, FTIR, XRD, SEM, TEM, EDX, DLS, zeta potential, BET and thermal analysis as supporting characterization techniques for the confirmation of nanoparticles formation and quality assessment of material will be discussed. The review of emerging uses in antimicrobial materials, environmental cleaning, photocatalysis, biosensing, food packaging, agriculture, wound-healing research, drug-delivery studies, and catalysis must be undertaken cautiously, noting that laboratory results may not reflect clinical or industrial validation. According to the review, plant-mediated synthesis holds promise, but before its routine use in industries a standardized protocol for extraction, assessment of life cycle, toxicity evaluation, and scale-up studies are required.

Keywords: green synthesis; plant extract; metal nanoparticles; metal oxide nanoparticles; phytochemicals; sustainable nanotechnology; biomedical applications

1. Introduction

Nanotechnology has grown rapidly over the years with the discovery of the fact that various nanoscale materials do not just exhibit optical, magnetic, electrical, catalytic and biological properties but these properties are size-dependent. Metal and metal oxide nanoparticles, including Ag, Au, Cu, ZnO, TiO2, Fe3O4, Fe2O3, MgO and NiO, are now being investigated for their use in antimicrobial systems, photocatalysis, degradation of pollutants, biosensing, food packaging, agriculture, biomedical coatings and catalysis related to energy[1,2,3].

Nanoparticles are gaining importance in various biomedical applications like diagnostics, drug delivery and imaging due to their unique physiochemical properties. A nanoparticle is defined as the ultra-fine particle of 1–100 nm and any nanoparticle with a size or dimension of more than 100 nm does not qualify as a nanoparticle.

Although conventional physical and chemical routes are valuable for producing highly controlled nanomaterials, they mostly involve high temperature high pressure, strong reductants, stabilizing polymers and toxic solvents, energy-intensive equipment. Although sodium borohydride reduction (or similar reductions) can produce narrow particle distributions but the reagents needed and post-synthesis waste streams make them less environmentally acceptable. The purity attained through physical methods usually comes at a high cost of instrument and energy use. This has a growth of green synthesis by the sustainable way of nanoparticles synthesis [4, 5].

The green synthesis of nanomaterial involves the integration of green chemistry principles with the engineering of nanomaterials using safer solvents, renewable feedstocks, lower energy conditions, and less hazardous by-products. The formation of nanoparticles can be mediated by plants, bacteria, fungi, algae, enzymes, and agricultural wastes. Plant extracts are especially appealing because they are easy to prepare, don't need sterile microbial culture, and are complex mixtures of biomolecules which can reduce metal ions and stabilize resulting particles[2, 6].

The scientific challenge is that people simplify plant-mediated synthesis too much. A visible alteration in color does not in itself establish a reproducible, safe, and scalable process for nanomaterials. The differences in plant extract species, plant part, season, geography, extractant, temperature, and storage. Phytochemical composition is influenced by these variables and thus it affects nucleation rate, size, morphology, surface charge and stability.

The present review aims to bridge this gap by linking phytochemical mechanism, sustainable synthesis, characterization requirement, emerging applications and limitations within the single review framework based upon the recent literature from 2020-2025.

2. Conceptual Background of Green Nanoparticle Synthesis.

The synthesis of green nanoparticles is based on the idea that performance of the material should be always pursued with safer chemistry along with the efficiency of resources. Instead of replacing an old reducing agent with a new one, the approach looks at the whole process, from precursor choosing to solvent system, reaction temperature, purifying, drying, waste production and end-of-life behaviour. A pathway that utilize through plant extraction process but depends on scarce biomass, excessive washing, high-temperature calcination of by-products, or unassessed nanotoxicity will not be truly sustainable in a full life-cycle sense[7, 8].

Biological synthesis routes can be microbial, fungal, algal, enzymatic, or plant-mediated.

Microbial synthesis can yield precisely defined biochemistry and extracellular metabolites, requiring nevertheless sterile condition, growth media, culture time, downstream separation and biosafety control. Plant-based synthesis is simpler to accomplish since extracts can be obtained in water or hydroalcoholic mixtures which can be combined with metal precursors under mild conditions. The explanation for the wide observations of plant-mediated synthesis of Ag, Au, Cu, ZnO, TiO2, MgO and iron oxide NPs is the practical simplicity of the technique [1,6].

One of the most important advantages of plant extracts is multifunctionality. A single extract can have everything from phenolic hydroxyl groups, and carbonyl groups to carboxylates and amines. These constituents can form stable complexes with metal ions, donate electrons, control supersaturation, adsorb on particle surfaces and prevent their aggregation. The similar chemical diversity may also introduce functional groups that affect biological interactions, catalytic behavior, adsorption, and film compatibility[4, 9].

Even so, green synthesis should not be considered automatically safer than classical synthesis. The nanoparticle product may still release toxic ions, generate reactive oxygen species, persist in the environment, or interact undesirably with cells. Green synthesis can reduce hazards associated with the manufacturing route, but product safety must still be demonstrated through toxicological, ecotoxicological, and exposure assessments for each biomedical, agricultural, and environmental application[2, 10].

3. Plant Extracts Serving as Reducing, Capping and Stabilizing Agents.

Chemical mechanisms of the plant extract system are coupled and not independent ones.

Phenolic compounds and flavonoids are often emphasized for their ability to oxidize while reducing metal ions due to their hydroxyl groups. Tannins along with some other polyphenolic molecules can chelate metal ions and induce local reaction environments favourable to nucleation. According to Villagrán et al. [6] and Fahim et al. [4], a combination of electron donation, coordination, steric protection, hydrogen bonding, and electrostatic stabilization may be carried out by terpenoids, alkaloids, proteins, amino acids, polysaccharides, and organic acids. Metal nanoparticles are typically synthesized by applying a reduction step where ionic precursors such as Ag + and Au 3+ are reduced to zero-valent atoms that aggregate into nuclei.

After nuclei formation, the growth process competes with the surface passivation process. If the rate of decrease is rapid and abundant capping molecules are present, many small nuclei may form and become stabilized early. An insufficient amount of capping and/or slow reduction leads to the formation of fewer nuclei that grow into larger or more irregular particles. The end result material characteristics are impacted significantly by the aforementioned factors such as concentration of extract, pH, concentration of precursor, temperature, time of reaction, and mixing condition [5, 11] .

Reduction is not the only or dominant process in metal oxide synthesis. The formation of ZnO, TiO_2 , Fe_2O_3 , Fe_3O_4 , MgO, CuO or NiO may take place through hydrolysis, precipitation, dehydration, oxidation or thermal conversion. During calcination, plant metabolites may behave as chelating agents, modifiers of precipitation, structure-directing ligands, and fuel- like organic components. As a result, the mechanisms of formation of oxides must be carefully described and backed up by phase analysis, rather than assuming the same reduction pathway employed for noble metals[9, 12] .

4. Mechanistic Pathways of Nanoparticle Formation

Activation and complexation with metallic ions. The beginning stage is where precursor ions react with functional groups of extract. Metal ions can be aided by substances such as polyphenols, flavonoids, organic acids, proteins and polysaccharides to localize precursors.

At this stage, it helps us understand how the concentration of the extract affects the density of nucleation and the size of the particle. A low concentration of the extract may result in incomplete reduction or aggregation while a higher concentration of the extract may lead to broader size distribution or over-capping [5,6] .

Phytochemicals that are rich in electrons minimize the oxidation state of metals via bioreduction of metal ions. During the synthesis of silver and gold, the color change of the solutions one observes is due to surface plasmon resonance. The use of different phenolic compounds, flavonoids and terpenoids as reducing agents in the synthesis of green silver nanoparticles has been reported. The formation of particles is affected by many reaction parameters such as pH, temperature, precursor concentration, time among others[4,11].

Nucleation with Growth Once a saturation point is reached, clusters begin to form. The differences in particle size and morphology are primarily due to the frequency of nuclei. The size of the particles is determined by the rate of nucleation and the subsequent growth. Fast Nucleation followed by limited growth will give smaller particles. Slow Nucleation and continued growth will give larger or irregular particles. Heating the mixture may enhance the rate of reduction and crystallization of nanoparticles. However, if the temperature is too high, it will degrade the thermolabile phytochemicals and/or agglomeration may occur[5, 13] .

Capping and colloidal stabilization occur when phytochemicals, proteins, polysaccharides, or other extract constituents adsorb onto the particle surface. This organic corona can provide steric and electrostatic repulsion that limits aggregation and influences hydrodynamic size and surface charge. Consequently, zeta-potential and DLS measurements complement dry-state electron microscopy when assessing dispersion stability[3,4] .

The properties of synthesized material are affected by many factors like the pH of the solution, temperature, concentrations of extracting agent and precursor, reaction time and mixing, solvent system, light and drying after synthesis. Depending on the oxidation temperature, crystallinity, defect chemistry, residual organics, surface area or any of these could change the oxides. Some examples of oxides are ZnO, TiO_2 , Fe_2O_3/Fe_3O_4, MgO,

NiO, etc. Green synthesis should be classed as a well-controlled process rather than mixing an extract with a precursor[2,9] .

5. Types of Nanoparticles Synthesized Using Plant Extracts

Silver nanoparticles: AgNPs are among the most frequently studied plant-mediated nanoparticles. Their surface plasmon resonance, antimicrobial potential, and relative ease of synthesis make them convenient model systems. Silver nitrate is commonly used as the precursor, and formation is generally monitored by a brown colour change and a characteristic UV-Visible absorption band. Antioxidant, antimicrobial, anticancer, and wound-healing applications have been reported, although standardized synthesis and cytotoxicity assessment remain necessary before biomedical translation [4,5,10] .

Gold nanoparticles: AuNPs are valued for their stability, optical properties, catalytic activity, biosensing potential, and biomedical relevance. Leaf extract of Clerodendrum inerme has been used to prepare gold and silver nanoparticles with antimicrobial and antioxidant activity.

However, such claims remain limited to in vitro or material-level evidence unless supported by appropriate biological validation [6, 14] .

Copper and copper oxide nanoparticles: Copper-based nanoparticles are attractive because copper is less costly than noble metals and has antimicrobial, catalytic, optical, and photocatalytic relevance. Plant extracts can reduce copper ions or assist CuO formation, although copper systems can be sensitive to oxidation state, pH, and storage conditions.

Green-synthesized Cu and CuO nanoparticles have been investigated for antibacterial activity, dye degradation, and environmental applications [1,2] .

Zinc oxide nanoparticles: ZnO nanoparticles which has a wide adoption because of their UV absorption, photocatalytic behaviour, antimicrobical behaviour and biomedical research. The process of plant-mediated synthesis of ZnO is commonly carried out with zinc acetate or zincnitrate. Reviews of the recent ZnO report leaves, fruits, seeds, roots and whole plant as source of extract for the role of phenolics, alkaloids, flavonoids, and terpenoids in the reduction and stabilization [9,13] .

Iron oxide nanoparticles: Iron oxides such as magnetite and hematite also have applications in environmental remediation, antimicrobial systems, catalysis, agriculture and magnetic materials. The green synthesis method frequently employs Fe 2+ or Fe 3+ salts along with plant extract, subsequent precipitation or thermal.

According to recent work on plant-extract based iron oxide nanoparticles, although antimicrobial testing and phytochemical involvement is reported, it seems as though proper phase identification is required, as it is not easy to distinguish iron oxide phases without solid XRD, magnetic and spectroscopic data [12, 15] .

Titanium Dioxide Nanoparticles: TiO 2 nanoparticles are essential in photocatalysis, antimicrobial agents, coatings, environmental remediation, and biomedical materials.

Fabrication of TiO 2 using plant mediated take titanium isopropoxide or titanium salts as precursor and calcination for the formation of anatase, rutile, or mixed phases. Recent reviews relate plant biomolecules to synthesis control and discuss applications to the environment and antimicrobials, but warn that toxicity and environmental persistence deserve careful scrutiny [2, 16] .

Magnesium Oxide Nanoparticles: In recent years, MgO nanoparticles have attracted interest for their range of antibacterial, photocatalytic and adsorptive applications. The extract-assisted precipitation followed by thermal conversion is a method to prepare plant-mediated MgO, but phase purity and residual carbon, recovery of particles and scaling up needs further studies. According to the literature, MgO has more promise in environmental and antimicrobial research than being considered a more developed product platform [1,2] .

Nickel oxide and other emerging metal oxide nanoparticles: The green synthesis has expanded beyond Ag and ZnO, in which researchers have synthesized NiO, Co 3 O 4 , ZrO 2 , Se, Pd, Pt, and hybrid NPs. Research has been carried out on photocatalytic and cytotoxicity- related studies of NiO made from plant-derived matrices and thus zirconia and selenium systems hold environmental and bio-medical possibilities. In light of Sabouri et al. [17] and Villagrán et al. [6], these new systems need more strict safety evaluation due to considerable differences in ion release,

persistence and exposure risks in comparison to well studied Ag and ZnO.

6. Eco-Friendly Fabrication Methods

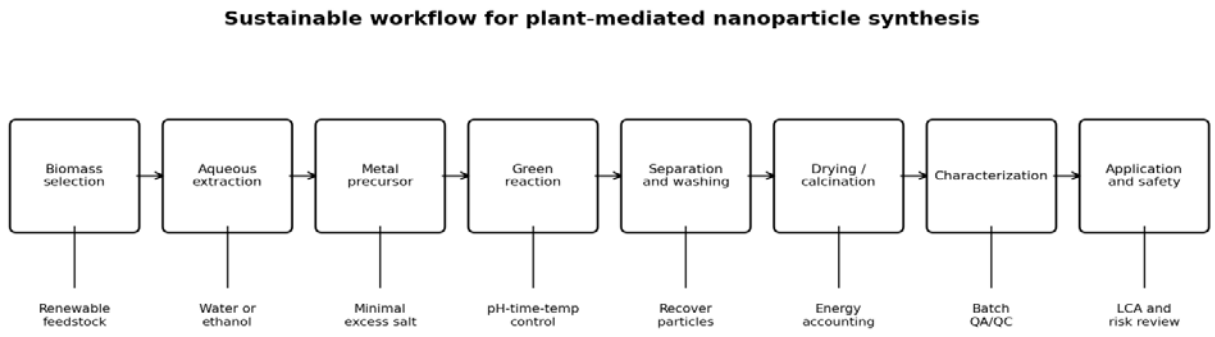
Plant-mediated methods are aqueous extract methods the simplest ones. Plant material that is either fresh or dried is washed, cut or powdered, then extracted in water or hydroalcoholic solvent, filtered and mixed with a metal precursor. The method is appealing because it minimizes the use of organic solvent and can carry out under mild conditions but its reproducibility depends strongly on experiments Characterization and effectiveness of an herbal extract, extraction temperature, extraction time (s), plant to solvent ratio, extract pH, storage conditions[6] .

Synthesis using leaf extract is common due to the ease of availability, metabolically active nature and presence of phenolics, flavonoids, terpenoids, chlorophylls, proteins and carbohydrates in leaf. Waste residuals and valorization in organic synthesis are gaining increasing importance in the area of waste synthesis. Yet, you need to consider whether or not the harvesting will damage the plant and ecosystem. For that reason your best option in terms of sustainability are waste biomass and other plant parts as long as the performance is similar [2,6] .

When properly optimized, microwave-assisted synthesis may lower energy consumption through reduced reaction time and more uniform heating. Ultrasonication may improve mass transfer and nucleation through acoustic cavitation, potentially producing smaller particles and narrower size distributions. Solar-assisted synthesis uses light energy to promote photoreduction and may be suitable for low-resource settings, although irradiation must be controlled. One-pot synthesis combines reduction, nucleation, growth, and capping in a single vessel, reducing solvent use and purification steps, but its parameters require careful control [2,3] .

Yields should not be the only evaluation criterion for sustainability. It should consider factors such as solvent selection, precursor hazard, energy intensity, reaction time, mass efficiency, purification burden, product stability, worker safety, and the waste or fate of liquid waste.

Different sustainability attributes from what their term green will suggest for a plant-extract technique that needs repeated washings with a large volume of solvent or high-temperature calcination [7,8]



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Figure 2. Sustainable workflow of green nanoparticle synthesis. The workflow summarizes key process stages and sustainability checkpoints for plant-extract-mediated synthesis.

7. Characterization Techniques

Characterisation is the evidentiary backbone of green nanoparticle studies The technique of UV-Visible spectroscopy is used as a rapid confirmation tool for nanoparticles, specifically Ag and Au nanoparticles where plasmon resonance produces absorption bands. Ultraviolet- visible spectroscopy for an oxide like ZnO and TiO_2 is useful in determining optical absorption and band-gap behaviour. However, this technique alone will be incapable of validating phase purity or morphology[3,13] .

FTIR spectroscopy plays a crucial role in identifying the functional groups of the plant metabolites involved in reduction and capping. Shifts or intensity changes in the O-H, C=O, C-

O, N-H, C-N and metal-oxygen bands may indicate that the phytochemicals are still attached to the surface of the nanoparticles. Nevertheless, FTIR proof is indirect; when mechanistic claims are made, it should be conjoined with particle characterization and extract profiling [6,9] .

X-ray diffraction is useful to ascertain crystallinity, phase and approximate crystallite size. It is especially useful for identifying metal nanoparticles, and distinguishing them from oxides or hydroxides, and for identifying phases including anatase/rutile TiO_2 , wurtzite ZnO and magnetite/maghemite/hematite iron oxides and cubic silver.

Reports on green synthesis must not depend only on colour change or SEM images where phase identification is crucial for application [3,12] .

Evidence of morphology and particle size from SEM and TEM The latter can provide higher-resolution information on particle size and shape, while the former is useful for surface morphology and aggregation. The elemental composition by EDX can be confirmed, but crystalline phase and oxidation state cannot be confirmed by EDX. DLS gives a hydrodynamic size in dispersion but can also elucidate aggregation that you can't see dry.

The zeta potential can be utilized to evaluate the colloidal stability and the electrostatic contribution of the capping layer[3,4] .

The surface area of BET surface area analysis is useful when looking for applications such as adsorption, catalysis and photocatalysis. This is because the activity of the system depends on the surface area and porosity. TGA/DSC can measure moisture loss, thermal stability, and remaining organic capping; these measurements can be used when nanoparticles are intended for coatings, catalysis, and thermal processing. When used together, the results tell complementary stories on various other topics such as formation, composition, morphology, phase, surface chemistry, colloidal behaviour, application readiness.

8. Upcoming Uses. Antimicrobial and antifungal effects: The literature on plant-mediated nanoparticles is widely dominated by antimicrobial related research particularly for AgNPs, ZnO, CuO, TiO2, MgO, iron oxides etc. There has been a proposal of mechanism such as membrane permeabilization, ion release, ROS generation, protein dysfunction, DNA interaction, and biofilm inhibition. Notwithstanding, careful interpretation of antimicrobial claims should take into account particle size, concentration, exposure time, microbial strain, test method, controls and comparison with antibiotics or any other chemically synthesized particles[1,5].

Applications in antioxidation and anti-inflammation: The antioxidant behaviour of several green nanoparticles is due to the biogenic capping layers. The efficacy in the clinical setup should not be overblown for anti-inflammatory claims as they are mostly made for in vitro assays or mechanistic markers. It is essential to distinguish the effect of nanoparticles from the effect of free extract residues [4,18] due to the potential contribution of the surface corona to bioactivity.

Potential for Anticancer Activity and Drug Delivery: Various nanoparticles have been studied for their performance in cancer-cell cytotoxicity, apoptosis induction, drug loading, imaging, and controlled delivery, including Ag, Au, ZnO, and iron oxide. Although the studies are useful at the materials and preclinical level, most plant-mediated nanoparticle systems have not gone through a standardized toxicology, pharmacokinetic, biodistribution, or clinical evaluation. The present review thus regards anticancer and drug-delivery leads as emerging research areas instead of proven therapies[10,13] .

Recovery from Injuries and Biomedical Paints: The AgNPs, ZnO, TiO 2 the composite hydrogels, or the polymer coatings are important materials for wound healing. Release and cytocompatibility studies are key because antimicrobial potency is not necessarily tissue-friendly. Green capping may enhance biocompatibility, although this needs to be confirmed through experiments for each formulation[1,4] .

Degradation of pollutants via photocatalysis: The photocatalytic degradation of dyes and organic pollutants is performed using TiO_2, ZnO, CuO, iron oxide, MgO, NiO and doped or hybrid oxides. The synthesized materials may comprise surface defects and residual carbon and/or functionalities from phytochemicals. This has a direct impact on their light harvesting and charge separation abilities. Nonetheless, photocatalytic studies should report catalyst dose, initial contaminant concentration, irradiation source, pH, scavenger tests when

applicable, mineralisation indicators, and reusability [2,16].

Treatment of wastewater and removal of heavy metals: The use of green nanoparticles as adsorbents, catalysts and reductive material for heavy metal removal and organic pollutant transformation. Iron-based nanoparticles, ZnO, TiO_2, MgO and hybrid systems are of particular interest. Environmental release must take into consideration aggregation, dissolution, and regeneration, ecotoxicity as well as recovery from treated water [2,12].

Nanotechnology and Plant Disease Control in Agriculture: Nanoparticles are being investigated as antimicrobial agents against plant pathogens, nanofertilizers, pesticide carriers and growth promoters. Due to the potential impact of nanoparticles on soil microorganisms, seed germination, plant metabolism and food-chain exposure, agricultural applications require dose-response studies and environmental-risk assessment [2, 19].

Applications related to food packaging and sensing: Nanoparticles can be incorporated into films and coatings to provide antimicrobial activity, antioxidant protection, ethylene response, or sensing functions. AgNPs and ZnO are common in packaging research, whereas Au and Ag nanostructures are widely investigated for optical and electrochemical sensing.

Migration, ingestion safety, regulatory approval, and recycling must be evaluated before practical use [2,3].

Energy storage and catalytic applications: Nanoparticles mediated by plants have various functions related to electrocatalysis, photocatalysis, sensing of hydrogen peroxide, supercapacitors, and catalysts for biomass conversion. This properties are beneficial for application in various technologies and manufacturing. Nonetheless, performance must be benchmarked against conventional materials in compliance with standardized electrochemical or catalytic metrics before claiming practical superiority [2,3].

9. Comparative Analysis

The comparative synthesis literature shows strong material diversity, but also uneven reporting. Many papers provide particle size and biological activity without fully reporting extract composition, yield, zeta potential, storage stability, toxicity, or life-cycle metrics. The following tables therefore summarize selected 2020-2025 studies and recent reviews as evidence of scope rather than as a claim of direct comparability across methods. Values are intentionally not fabricated; where a condition or limitation is not consistently reported in the cited source, the table states the issue as a reporting or standardization limitation.

Table 2. Plant-mediated synthesis of metal nanoparticles from selected 2020-2025 studies

Study/reference	Plant source	Extract part used	Nanoparticle synthesized	Synthesis condition	Characterization techniques	Major application	Key finding	Limitation
Vanlalveni et al. [5]	Multiple medicinal plants	Leaves, fruits, seeds and other parts	Ag	Review of plant-extract reduction routes	UV-Vis, FTIR, XRD, SEM/TEM, EDX	Antimicrobial activity	Plant extracts can reduce and cap AgNPs with broad antimicrobial potential	Heterogeneous methods limit direct comparison
Khan et al. [14]	Clerodendrum inerme	Leaf	Ag and Au	Aqueous plant extract-mediated synthesis	UV-Vis, FTIR, XRD, TEM/SEM, EDX	Antimicrobial and antioxidant studies	Leaf metabolites acted as reducing/capping agents	Application evidence remained laboratory-scale
Salayová et al. [11]	Various medicinal plants	Plant extracts	Ag	Comparative extract-mediated route	UV-Vis, TEM/SEM, XRD, FTIR	Antibacterial efficacy	Plant source affected morphology and antibacterial outcome	Extract chemistry not fully standardized
Jabir et al. [18]	Annona muricata	Plant extract	Ag	Plant-mediated AgNP synthesis	UV-Vis, FTIR, XRD, microscopy	Cancer-cell and inflammatory-pathway research	Reported apoptosis-related and inflammasome-related activity in models	Not clinical evidence; safety translation required

Pechyen et al. [3]	Various plants	Multiple extract sources	Ag, Au and other metals	Review of green synthesis routes	UV-Vis, FTIR, XRD, SEM/TEM, DLS, EDX	Biosensing and material applications	Green synthesis supports biosensing platforms	Need stronger performance benchmarking
Lithi et al. [1]	Leaves, barks, roots and other tissues	Multiple plant tissues	Ag, Cu, Au	Plant-extract-mediated green synthesis	Spectroscopic and microscopic methods	Antimicrobial materials	Summarized metal nanoparticle antimicrobial mechanisms	Scale-up and standardization remain obstacles

Table 3. Plant-mediated synthesis of metal oxide nanoparticles from selected 2020-2025 studies

Study/reference	Plant source	Extract part used	Nanoparticle synthesized	Synthesis condition	Characterization techniques	Major application	Key finding	Limitation
Al-darwesh et al. [9]	Multiple plants	Leaves, seeds, fruits, roots and whole plants	ZnO	Review of plant extract-mediated ZnO routes	UV-Vis, FTIR, XRD, SEM/TEM, DLS	Biomedical applications	Phytochemicals influence ZnO formation and surface chemistry	Biomedical claims require deeper validation
Naiel et al. [13]	Sea lavender (Limonium pruinosum)	Plant extract	ZnO	Green extract-assisted preparation	UV-Vis, FTIR, XRD, SEM/TEM, EDX	Antimicrobial, antioxidant and anti-skin-cancer studies	Reported bioactivity in laboratory models	Findings require broader safety and translation studies
Elkhateeb et al. [12]	Garlic and pomegranate	Plant extracts	Iron oxide	Biosynthesis using plant extracts	UV-Vis, FTIR, XRD, TEM/SEM, EDX	Antibacterial activity	Plant extracts assisted iron oxide formation and testing	Phase and performance control need standardization
Aslam et al. [16]	Plant-based biomolecules	Plant biomolecular sources	TiO2	Review of plant-based TiO2 green synthesis	XRD, FTIR, SEM/TEM, UV-Vis	Environmental and antimicrobial uses	Plant biomolecules support TiO2 formation routes	Calcination and phase control affect sustainability
Sabouri et al. [17]	Salvia hispanica	Seed extract	NiO	Seed-extract-mediated synthesis	UV-Vis, FTIR, XRD, SEM/TEM	Photocatalytic and cytotoxicity studies	NiO produced by green route showed functional potential	Toxicity and scalability need further evidence
Lithi et al. [1]	Leaves, barks, roots and other tissues	Multiple plant tissues	ZnO, MgO, Co3O4, TiO2	Review of plant-extract-mediated synthesis	Spectroscopy, diffraction and microscopy	Antimicrobial activity	Metal oxides showed antimicrobial promise	Comparability limited by inconsistent protocols

10. Advantages of Plant-Mediated Green Synthesis

Plant-mediated synthesis when done under designed conditions has many advantages. It minimizes dependence on strong reducing agents and stabilizers, promotes the use of renewable feedstocks, and can utilize water as a dominant solvent. The organic capping layer can enhance dispersion or introduce functional groups beneficial for downstream applications [2,6] and it can reduce the reaction severity and preparation ease compared to microbial cultures.

Another crucial benefit is cost-effectiveness. Many plant materials are found in abundance locally and agricultural residues (peels, leaves, husks, or seed waste) may be converted to value-added feedstocks of nanomaterials. This connects green synthesis with circular economy thinking particularly if waste biomass will be used instead of edible or ecologically- sensitive parts of plants. Despite this benefit, extraction, purification and drying may use excessive energy or solvent such that the benefit is lost [2,7] .

It is often suggested that green nanoparticles have biocompatibility due to plant-derived biomolecules in the surface layer. It can help to reduce aggregation and improve interaction with polymers, gels, membranes, and coatings. It is important to show biocompatibility; it isn't assumed. Research by Arshad et al. [10] and Fahim et al. [4] suggests that, for biomedical and food-contact applications, the benefits of plant capping may only be acceptable if a range of impacts is controlled.

Another benefit is functional diversity. Plant extracts contain multiple functional groups or organic constituents that can offer reducing, stabilizing, and surface functionalization in a single step, unlike single-molecule reducing agents. This complexity can be advantageous for antimicrobial, catalytic, sensing and adsorptive applications, but it must be weighed against the issue of reproducibility.

11. Limitations and Challenges

The chemical structure of bioactive ingredients is variable Extracts from a similar species may differ due to differences in location, season, plant age, method of extraction and storage.

Synthesis reports have a limited ability to reproduce or compare without extract profiling. When authors give size control or biological activity to a broad class of compounds such as flavonoids, and do not quantify the extract or name the active constituents, this is especially serious [6,9] .

Another limitation is partial control over particle size and morphology. When reduction, nucleation, and capping are not well synchronized in green routes, polydisperse or agglomerated particles may be produced. This has an impact on the toxic nature, activities, behaviour, filtration, and catalytic behaviour of antimicrobials. It is essential to standardize pH, precursor concentration, extract concentration, mixing, temperature, reaction time, and purification [4,5] .

Scalability remains a challenge for many systems. Reactions performed at litre or kilogram scale do not necessarily behave as they do in laboratory mixtures containing only a few millilitres of extract because heat transfer, mixing, oxygen exposure, purification, drying, and batch-to-batch consistency change with scale. Industrial deployment also requires specifications for particle-size distribution, residual organics, microbial contamination, heavy metals in biomass, and long-term stability [2] .

Toxicity and biosafety are two major concerns. The ions release, reactive oxygen species generated, metal and metal oxide nanoparticles persistence in tissues or in soil, biological barrier crossing, as well as non-target organism disruption. While the green synthesis may reduce some hazards from the reagents, it cannot eliminate any risks specific to the nanoparticles. The unnecessary release of biomedical, agricultural, or environmental products must undergo systematic cytotoxicity, hemolysis, genotoxicity, immunotoxicity, ecotoxicity and life-cycle studies [1,10] .

In the end, many application studies are unrealistic. A high concentration of nanoparticles may be used for antimicrobial studies, model dyes may be used instead of complex waste water for photocatalytic studies, and packaging studies may not measure migration under regulatory food simulants. The aforementioned gaps clarify the factors behind green nanoparticles showing promising laboratory literature and less evolved validated industrial products.

12. Future Prospects and Research Gaps

Future investigations should begin with standardized plant-extract protocols. In your studies, please specify the plant identification, plant part used, drying method, extraction solvent, extraction temperature, and extraction ratio and extract pH and total phenolic/flavonoid content where possible and storage conditions. The researchers would be able to relate extract chemistry of the metabolites by using metabolomic or chromatographic profiling to the nucleation, surface chemistry as well as bioactivity of nanoparticles [6].

Research aimed at understanding mechanisms must go beyond mere color alteration and FTIR analysis. Various techniques such as Time resolved UV-Visible spectroscopy, in-situ pH and conductivity monitoring, XPS, Raman spectroscopy, LC-MS/GC-MS extract profiling, zeta-potential evolution, small angle scattering, and kinetic modeling show how the phytochemicals present in the extract reduce, cap and stabilize the particles.

The transformation pathway strongly depends on hydrolysis, precipitation, dehydration, and calcination in case of oxides [3,9].

Research work on scale-up should focus on continuous-flow synthesis, controlled mixing, extract standardization, membrane separation, solvent recycling, and low-energy drying. It should be included early in process development, not after. A plant-mediated route that uses abundantly available waste biomass, water extraction, ambient conditions, and recoverable particles may be environmentally performing while another route that requires scarce plant material and high-temperature processing may be less so [2,7].

We need to pay attention to toxicity and regulation. Researchers must not confuse material discovery with in vitro screening, preclinical validation, and clinical or industrial translation.

Evidence on dose, route of exposure, protein corona, immune response, biodistribution, clearance and long-term safety needed for biomedical studies. Fate, transport dissolution, transformation, recovery, and non-target organism studies are necessary for environmental applications [1,10].

AI and machine learning tools can be useful in optimizing the green synthesis process, through the modeling of relationships, involving plant species, phytochemical profile, precursor, pH, temperature, time and nanoparticulate properties. Nevertheless, such models require curated datasets with consistent descriptors and negative results. In future work, open, standardized datasets and reproducible reporting templates should be promoted. Hybrid nanoparticles, doped oxides, magnetic composites, and plant-waste-derived nanocomposites are all important future developments when devised with clear sustainability and safety metrics.

13. Final Thoughts.

The green synthesis using plant-extracts has developed into an important branch for sustainable nanomaterials. The method applies renewable biomolecules for the synthesis of metal and metal oxide nanoparticles. These biomolecules can reduce metal ions, control nucleation, cap growing surfaces, and stabilize colloids. Recent evidence shows widespread feasibility across several metals and oxides such as Ag, Au, Cu, ZnO, Fe oxides, TiO2, MgO, NiO, and others. The core scientific value of the approach is not only the avoidance of dangerous reductants but the creation, via chemical composition, of phytochemically functionalized surfaces for a wide range of application (antimicrobial, catalytic, environmental, agricultural, sensing, packaging, biomedical) possible importance.

At the same time, the field must not make overgeneralized claims. The term green has maintained its meaning only if solvent safety, energy accounting, waste reduction, reproducible processing, toxicity testing and life-cycle thinking. Plant extracts exhibit a chemical richness that varies according to the plant source. This variation may facilitate a multifunctional synthesis, but at the same time, it obstructs standardization. Consequently, studies of publication quality should report extract preparation, synthesis parameters, characterization data, controls, and application conditions in detail.

The future of plant-mediated nanoparticles relies on movement beyond descriptive synthesis reports to mechanisms and data-rich and scalable protocols. Characterization of phytochemicals in a standardized manner for a better understanding of the mechanism over time, validated toxicity assessment, realistic

application testings, selection of feedstocks ensuring circular-economy should be required. To further make green synthesis using plant extracts more efficient towards producing safe, sustainable and multifunctional nanomaterials.

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