Journal of Research and Development
A Multidisciplinary International Level Referred and Double Blind Peer Reviewed, Open Access
ISSN : 2230-9578 | Website: https://jrdrvb.org Volume-18, Issue-3| March-2026

Original Article

# Green Synthesis of Metal Nanoparticles Using Plant-Derived Organic Compounds: Mechanistic Insights, Structural Characterization, and Applications in Catalysis and Antimicrobial Activity

**Dr. Umesh B. Hunagund**
Associate Prof of Chemistry, K.R.C.E. Society's GGD Arts, BMP Commerce and SVS Science College Bailhongal, Dist-Belagavi Affiliated to Rani Channamma University Belagavi
**Email:** umeshhunagund@gmail.com

**Manuscript ID:**
JRD -2026-180330
ISSN: 2230-9578
Volume 18
Issue 3
Pp. 183-189
March- 2026
**Submitted:** 17 Feb. 2026
**Revised:** 27 Feb. 2026
**Accepted:** 12 Mar. 2026
**Published:** 31 Mar. 2026

***Abstract***

*Various plant-derived organic compounds can be used in the green synthesis of the metal nanoparticles with recent interest in producing primary choices over classical chemical and physical methods which are often costly, inefficient, and based on toxic reagents and processes, thus stressful for the environment. This is a long overdue conceptual research paper dealing with phytochemicals like polyphenols, flavonoids, terpenoids, alkaloids as natural reducing and stabilizing agents in the green synthesis of metal nanoparticles emphasizing the reaction mechanisms, structural and functional properties of the product metal nanoparticles. We use a conceptual analytical approach blending ideas from existing literature first to provide a unifying framework for explaining how functional groups found in plant-derived organic molecules enable the reduction of metal ions (e.g., $Ag^{+}$, $Au^{3+}$) to form nanoparticles stabilized through capping interactions with such organic molecules prohibiting aggregation. Abstract Mechanistic insights indicate that hydroxyl- and carbonyl-derived electron donation is essential for the formation of nanoparticles and affects various aspects of nucleation, growth kinetics, and particle morphology. In addition, this paper discusses different characterization techniques such as UV-Visible spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and electron microscopy (SEM/TEM) relevant for size, shape, crystallinity and surface chemistry of the synthesized nanoparticles. Besides exploring structural properties, the work also summarizes different applications of the synthesized nanoparticles in catalysis and antimicrobial activity, proving to be efficient for organic transformations (reduction and oxidation reactions) and acting as membrane disruptors to inhibit bacterial growth. These results indicate green-synthesized nanoparticles are at least as effective as, if not more effective than, conventionally synthesized counterparts in terms of biocompatibility and toxicity. However, variability in the composition of plant extracts and difficulties in the large-scale production of nanoparticles remain key challenges that also require standardization and optimized synthesis protocols. In sum, this work adds to the increasingly important field of sustainable nanotechnology by establishing a theoretical basis that will lead to synthesis of functional materials viable for catalytic, medical, and environmental applications.*

***Keywords:*** *Green synthesis, Metal nanoparticles, Phytochemicals, Organic compounds, Catalysis, Antimicrobial activity*

## Introduction and conceptual background related to the study

Nanoparticles, usually defined as particles with dimensions in the range between 1–100 nm, have attracted much interest in contemporary chemistry due to their unique properties related to their high surface to volume ratio, quantum size effects, improved catalytic activity, and tunable optical, electrical, and magnetic features, which differentiate them significantly from their bulk counterparts and enable their use in a variety of fields including catalysis, drug delivery, environmental remediation, and antimicrobial systems (Klabunde & Richards, 2009), and within the scope of chemistry, metal nanoparticles such as silver (Ag), gold (Au), platinum (Pt), and palladium (Pd) are especially relevant because they can play an important role in the facilitation of the redox reaction, electron transfer processes, and surface-mediated catalysis, making them highly desirable targets in organic synthesis and industrial processes,



**Address for correspondence:**
*Dr. Umesh B. Hunagund, Associate Prof of Chemistry, K.R.C.E. Society's GGD Arts, BMP Commerce and SVS Science College Bailhongal, Dist-Belagavi Affiliated to Rani Channamma University Belagavi*

**How to cite this article:**
*Hunagund, U. B. (2026). Green Synthesis of Metal Nanoparticles Using Plant-Derived Organic Compounds: Mechanistic Insights, Structural Characterization, and Applications in Catalysis and Antimicrobial Activity. Journal of Research & Development, 18(3), 183–189.*
*https://doi.org/10.5281/zenodo.19233326*

Quick Response Code:
Website:
https://jrdrvb.org/
DOI:
10.5281/zenodo.19233326

But conventional methods for synthesizing these nanoparticles encompass toxic reducing agents for chemical reduction treatments, like sodium borohydride and hydrazine, as well as physical methods including laser ablation, evaporation-condensation, and high-energy ball milling which have their downsides: environmental toxic by-products, high energy consumption, little biocompatibility of the produced particles, and high operational and maintenance costs lead to none sustainable and green chemistry (Iravani, 2011), and these disadvantages have opened the door for the development of green synthesis methods where the goal is to produce environmentally friendly, low cost, and low energy consumption methods for nanoparticle productions by using naturally occurring raw, plant extractions, growing microorganisms, and biodegradables polymers as green, reducing, positive stabilizing agents (Anastas & Warner, 1998), and plenty of green synthesis methods are based on the usage of simple plant derivatives of organic compounds since they are wide spread and have many other properties, products or derivatives, (natural and synthetic), that can serve to define biological specific functions to bring about biological specificity, and since plant extracts contain a plethora of phytochemicals, containing phenolic and flavonoidal compounds as catechin, flavanone, terpenoids as terpineol, even proteins, carbohydrates, and others all of them interacting with a wide variety of functional groups as –OH, C=O, and others that all can be used to donate electrons and reduce metal ions into their nanostructured forms while acting as capping agents stabilizing the nanoparticle with no need for external chemical stabilizers (Singh et al., 2018), for instance, flavonoids themselves can reduce the silver ions ($Ag^+$) to silver nanoparticles ($Ag^0$) through oxidation of hydroxyl groups and terpenoids can stabilize nanoparticles by hydrophobic interactions or others, and despite the large amount of literature dedicated to plant-mediated synthesis of nanoparticles, gaps of information are present, including the absence of a unique mechanistic path for reduction that explains how different phenols are involved in the reduction of nanoparticles, the variety of size and morphology of the nanoparticles due to the diversity of crude extracts as reducing agents, or insufficient standardization of potentials, leading to non-reproducible and scalable conditions for industrial applications, thus the following conceptual study will analyze, in a purely critical setting, the exact mechanistic drawing out of the pathways inducing green synthesis processes and plant derived organic molecules, identify which, if not all phytochemical properties control, not only the composition, but the characteristics of the nanoparticle obtained, overview existing structural characterization techniques and evaluate their applications in catalytic and antimicrobial activity which in return can, hopefully, further the theoretical foundation existing in this field by systematically delineating sustainable nanoparticle production modes from other biological modes inherent in various old and newly discovered phenolic compounds laying the foundation for guiding future efforts in the pursuit of true sustainable organic chemical synthesis.

**Literature Review**

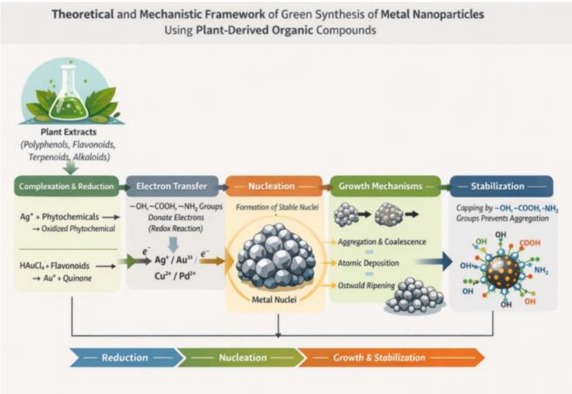
Metal nanoparticles are broadly defined as nanoscale materials with a metallic component, ranging from 1–100 nm, whose small size, large surface-area-to-volume ratio and size-dependent surface reactivity impart unique optical, catalytic, electronic and antimicrobial properties, which are typically described by composition (e.g., silver, gold, platinum, palladium, copper or metal oxides) [1], morphology (e.g., spherical, rod-shape, triangular, cubic or flower-like) [2], method of synthesis (i.e. physical, chemical and biological/green routes) [3] with silver and gold nanoparticles under particular emphasis due to their strong surface plasmon resonance [4], catalytic [5] and broad antimicrobial potential [6]. In this regard, the 12 Principles of Green Chemistry put forward by Anastas and Warner have been proved prevailing in the conceptual basis for green nanoparticle synthesis [7]. Principles such as waste prevention, reduction of hazardous substances, energy efficiency, use of renewable feedstocks, catalysis, and design for intrinsic safety are particularly important because many traditional nanoparticle synthesis methods are based on the use of toxic reducing agents, organic solvents, high-temperature processes and energy intensive physical methods incorporating evaporation–condensation, laser ablation or chemical reduction using borohydride and hydrazine, which creates toxic residues and increase production cost and environmental burden. In this context, plant mediated synthesis is one of the most elaborated green alternatives, and many critical reviews report that plant extracts can act together as a reducing, capping, and stabilizing media which makes possible nanoparticle synthesis under milder conditions and with probable absence of added surfactants or harmful chemical e.g. by Iravani [21] and Singh, Kim, Zhang and Yang [22], various silver, gold, copper, palladium, platinum, zinc oxide, and titanium dioxide nanoparticles were biosynthesized using extract from different parts of plants such as leaves, fruits, bark, roots, and seeds, with the reaction parameters (pH, temperature, concentration, incubation time, and parameter extract-to-metal-salt ratio) reported to strongly affect nucleation, growth, stability, and even monodispersity. Across this literature, a common theme is the reliance upon organic molecules derived from plants, such as polyphenols, flavonoids, terpenoids, alkaloids, tannins, sugars, and proteins, that are capable of donating electrons via their hydroxyl, carbonyl, carboxyl, and amine functionalities to reduce metal ions such as $Ag^+$ or $Au^{3+}$ to their zero-valent state while the same or associated biomolecules adsorb on the nanoparticle surface to prevent aggregation, improve colloidal stability creating a system in which reduction and stabilization all occur in one-pot. Comparative analyses in the review literature typically conclude that green synthesis provides key benefits over conventional synthesis, such as lower toxicity, milder reaction conditions, lower energy requirements, higher biocompatibility and alignment with sustainability targets, but nonetheless highlight key drawbacks, such as irreproducible plant extract profiles from batch to batch, incomplete mechanistic understanding, inability to control geometry/geometry, and issues with reproducibility/crossing the gap between lab and industrial

Journal of Research and Development
A Multidisciplinary International Level Referred and Double Blind Peer Reviewed, Open Access
ISSN : 2230-9578 | Website: https://jrdrvb.org Volume-18, Issue-3| March-2026

scale and this is the sustainable paradox between ecological brightness and mechanistic inconsistency in the present research gap because although plant-mediated synthesis is so widely reported, there remains a lack of a sufficiently integrated conceptual explanation of the synergy of phytochemical composition, reduction pathways, nanoparticle morphology, and catalytic or antimicrobial performance, across the literature within a defined framework and in a coherent manner.

**Theoretical and Mechanistic Framework**

The coordinated sequence of physical and chemical events that can be described involves metal-ion complexation, phytochemical reduction, nucleation, growth, and surface stabilization, wherein dissolved metal precursors such as $AgNO_3$, $HAuCl_4$, $CuSO_4$, or $PdCl_2$ first interact with reactive biomolecules present in a plant extract, and these biomolecules particularly heteroatom-rich biomolecules—especially phenolic acids, flavonoids, amino acids, proteins, polysaccharides, organic acids, and alkaloids—provide chemically active functional groups such as hydroxyl (−OH), carboxyl (−COOH), and amine ($-NH_2$) that bind metal ions through coordination followed by electron transfer reactions that reduce metal ions to zero-valent atoms, thereby initiating nanoparticle formation; mechanisms include oxidation of hydroxylated aromatic phenolic and flavonoid structures to quinone-like structures while they donate electrons to reduce $Ag^+$ to $Ag^0$ or $Au^{3+}$ to $Au^0$, with the assembly process governed by classical nucleation processes wherein once a certain free energy is achieved cluster stability relies on a critical number of atoms; after reaching the supersaturation point, clusters of neutral atoms then nucleate which involves aggregation of a threshold number of reduced atoms into thermodynamically stable nuclei; classical nucleation theory combined with LaMer-type separation of nucleation and growth would imply that a burst of monomer formation is followed by a growth stage governed by diffusion, surface reaction, and the availability of residual metal precursor; once nuclei are formed further growth models may invoke direct atom addition, coalescence of small clusters, or Ostwald ripening whereby smaller unstable particles dissolve while redepositing on larger ones, leading to an increase in average particle size over time when classical stabilizing effects are avoided, and the final morphology as spherical, triangular, rod-like, cubic or irregular strongly depends on the concentration and structure of phytochemicals, reaction temperature, precursor concentration, pH, and ionic strength because adsorbed biomolecules may selectively bind specific crystallographic faces and modulate anisotropic growth; meanwhile, after nucleus formation the organic molecules with −OH, −COOH, or $-NH_2$ groups undergo aggregation close to the nanoparticle surface, creating a protective corona that ultimately leads to surface stabilization to avoid agglomeration and aggregation of particles beneficial to maintain high dispersion and they may play an essential role in nanoparticle stabilization through hydrogen bonding, electrostatic attraction, coordination bonding, or hydrophobic interactions to lower surface free energy, or the stabilization process in nanoparticles consist of covalent dynamics where the nanoparticle possesses high surface energy and a natural tendency to aggregate without coated species to stabilize and this mechanistic picture can help to explain why nanoparticle formation from plant extracts frequently yields colloidally stable nanoparticles in mild conditions without expensive or toxic surfactants or reductants which represent a ground-breaking advance towards improving the chemical synthesis of nanoparticles and obey the empirical practice from gaining prediction power to design-green nanoparticles through mechanistic standardization which summarizes that the variability in extract composition can alter redox kinetics, nucleation rate, particle size distribution, and catalytic or antimicrobial performance.




**Above image showing Theoretical and Mechanistic Framework related to the study**

**Methodological Approach**

The method in this work is of non-experimental nature, based on a conceptual and review-type analytical framework that uses a systematic approach to evaluate existing scientific knowledge about plant-mediated nanoparticle synthesis in the domain of organic and nano chemistry, constituted of an integration of secondary data obtained from peer-reviewed journal articles, review papers, and high-impact scientific databases (e.g. Scopus, Web of Science, PubMed and ScienceDirect) selected through a rigorous search strategy aiming to cover broadly and deeply the latest advances related to nanoparticle preparation, characterization, and applications, focusing on studies published in high-impact

Journal of Research and Development
A Multidisciplinary International Level Referred and Double Blind Peer Reviewed, Open Access
ISSN : 2230-9578 | Website: https://jrdrvb.org Volume-18, Issue-3| March-2026

journals on green chemistry, nanotechnology, materials science, and applied organic chemistry and analyzing delivery methods for metal nanoparticles (Ag, Au) and metal oxides synthesized from plant extracts rich in phytochemicals (e.g. silver (Ag), gold (Au), platinum (Pt), copper (Cu), magnesium (Mg) and metal oxides), with the exclusion of non-peer-reviewed and low methodological quality research to reinforce the academic reliability of the integrative approach; the analytical strategy is comparative synthesis and thematic analysis, with a systematic comparison of multiple studies based on several abstraction levels, specifically: type of plant extract used, phytochemical composition, reaction conditions (pH, temperature, time, and concentration), size, morphology, stability, and functional performance of nanoparticles in catalytic and antimicrobial applications, and thematic analysis that facilitates identifying emerging patterns and underlying conceptual themes, including the effect of functional groups on reduction mechanisms, kinetics of nanoparticle formation, and correlations between structural properties and application efficiency, allowing the assimilation of mechanistic knowledge with practical outcomes into a coherent theoretical model; in addition, the study establishes a framework to evaluate efficiency, sustainability, and application potential of green-synthesized nanoparticles, dealing with efficiency in terms of yield, reaction time, particle uniformity, and catalytic performance on organic transformations (oxidation and reduction reactions), sustainability in conjunction with green chemistry principles (renewable feedstocks, non-toxic reagents, minimal energy input, and low environmental impact), and application potential assessed by the effectiveness of inorganic nanoparticles on antimicrobial activity (Gram-positive and Gram-negative bacteria) and catalytic potential (co-manufacturing industry-focused), notably the impact of size, surface chemistry, and stability of nanoparticles on performance outcomes, enabling the identification of both strengths and limitations of plant-mediated synthesis, including issues regarding reproducibility, variability in composition/structure, and difficulties in production scale-up while, at the same time, providing a systematic basis for future experimental validation and technological development within sustainable nanomaterials research.

**Structural Characterization of Nanoparticles**

The structural characterization of metal nanoparticles synthesized using plant-derived organic compounds is essential for their physicochemical property, stability, and functional performance studies, and therefore this study conceptually combines several methodologies UV–Visible (UV-Vis), Fourier Transform Infrared (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), and Dynamic Light Scattering (DLS) techniques in both characterization approaches to provide a multidimensional assessment of nanoparticle formation (UV-Vis), morphology (SEM/TEM), surface chemistry (FTIR), crystallinity (XRD), and size distribution (DLS) (where UV-Vis spectroscopy is most often characterized as a rapid and primary method for verifying nanoparticle synthesis through recording surface plasmon resonance (SPR) bands resulting from the collective oscillation of conduction electrons on the external nanoparticle surface under the excitation of light, Ag nanoparticles generally have SPR peaks of 400–450 nm and gold nanoparticles 520–550 nm, then minor shifts in these peaks provide information on particle size, aggregation state, and dielectric area; FTIR play a critical role to demonstrate functional groups involved in reduction and stabilization processes, characteristic absorption bands associated with –OH, –COOH, $–NH_2$, and C=O groups were revealed, confirming the interactions of phytochemicals such as polyphenols and proteins with nanoparticle surface, demonstrating phytochemicals role as capping agents that increase the amount of colloidal stability preventing agglomeration; XRD analysis confirmed crystalline nanomaterial rationale over the amorphous aggregate through determining the crystalline structure, phase purity, and average crystallite size of nanoparticles where diffraction peaks are associated with specific lattice planes (face-centered cubic structures (fcc) then Ag and Au nanoparticles), while the Debye–Scherrer equation was applied to estimate crystallite size assigned as a normal value in the nanometer range, SEM and TEM were characterized as high-resolution imaging methods regarding nanoparticle morphology, size, and surface topology (SEM to provide imaging of external visualization and particle aggregation speed and TEM for direct observation of internal structure, lattice fringes, and particle size distribution perfectly at the nanoscale which is often represented in shapes such as spherical, rod-like, triangular or irregular morphologies which related to phytochemical representations and construction conditions; DLS is used to measure the hydrodynamic diameter and size distribution profile of nanoparticles in the colloidal state, providing information regarding particle dispersion, polydispersity index (PDI), and stability in solution which are especially significant for future biological and catalytic systems, often while DLS values are different than the ones from TEM measurements due to solvation layers and surface-bound biomolecules, in short terms, only the integration of all these characterization methods draw a multidimensional interpretation of nanoparticle properties, structural parameters determining catalytic and antimicrobial performance (i.e., optical property; UV-Vis, surface chemistry; FTIR, crystallinity; XRD, morphology; SEM/TEM, and hydrodynamic diameter; DLS), interrelated therefore, this comprehensive characterization is sometimes neglected in green synthetic works in order to ensure reproducibility, improve reaction conditions and suggest necessary relations-structure property relationships that govern catalysis and antimicrobial activity.

**Applications related to the study**

Green protocols for metal nanoparticle synthesis using plant-based organic molecules have numerous applications, particularly in catalysis and biocidal activities, where the unique nanoscale properties such as large surface area, abundance of surface sites, and modified electronic properties compared to bulk metal result in improved catalytic

Journal of Research and Development
A Multidisciplinary International Level Referred and Double Blind Peer Reviewed, Open Access
ISSN : 2230-9578 | Website: https://jrdrvb.org Volume-18, Issue-3| March-2026

performance for example, metal nanoparticles, including silver (Ag), gold (Au), palladium (Pd), and platinum (Pt) prepared by green methods have been shown to be efficient catalysts for various organic reactions, including oxidation reactions (e.g., alcohol oxidation to aldehydes or ketones), reduction reactions (e.g., nitro compounds reduction to amines), and carbon–carbon coupling reactions such as the Suzuki and Heck reactions, with the presence of phytochemical capping agents being particularly noteworthy as they can affect the catalytic performance of these nanoparticles by changing their surface reactivity respectively, and these nanoparticles have been shown to provide high turnover frequency (TOF) and yield, making their behavior at the nanoscale advantageous for green catalytic processes in organic synthesis while their remarkable recyclability and reusability, which permit their recovery through a simple separation technique, such as centrifugation or filtration, and their reuse for several catalytic cycles with minimal loss of activity in many cases, contribute to improving the cost-effectiveness and sustainability of chemical processes although some studies report gradual deactivation during repeated catalytic cycles due to surface fouling or aggregation stressing the necessity of stabilization strategies to ensure long-term catalytic performance; apart from these catalytic applications, the antimicrobial activity of these nanoparticles against a broad spectrum of Gram-positive and Gram-negative and fungi, has been attributed to multimodal synergism encompassing the generation of reactive oxygen species (ROS), such as superoxide radicals and hydroxyl radicals, which result in an oxidative burst in the microbial cells, disruption of the cell membrane through direct interaction with lipid bilayers increased permeability and leakage of intracellular substances, binding of cellular proteins and enzymes functionally inhibiting the biocatalytic activity and interaction with DNA inhibiting replication and transcription, with the capacity of nanoparticles to penetrate microbial cell walls better than conventional antimicrobial agents also contributing to their final activity even at decreased concentrations and the potential bioactive effects of phytochemical residues on nanoparticle surfaces, which may have further contribute to the antimicrobial activity, similarly, while green-synthesized nanoparticles have advantages over conventional antibacterial and antifungal agents, including broad-spectrum activity, reduced probability of resistance development, high stability, lower toxicity when dosed adequately, one of the key disadvantage of green-synthesized nanoparticles is the concern associated with their cytotoxicity and environmental impact, that arise at higher concentrations and need proper dosage optimization and biocompatibility assessment, yet, the unique combination of catalytic efficiency and antimicrobial action between green-synthesized nanoparticles suggests their potential multifunctional nature, which can be exploited in sustainable chemistry, biotechnology, and environmental technologies, although further research will be needed to optimize mechanisms, scalability, and to establish safe application frameworks.

**Advantages and Limitations**

The environmentally friendly green synthesis of metal nanoparticles using organic compounds of plant origin represents a breakthrough in modern nano chemistry, as it brings nanoparticle production in line with the sustainability principles of modern society and provides numerous advantages, the main one being the environmentally friendly nature of the process-interest in green synthesis is due to the absence or significant reduction in the use of hazardous chemical reducing agents (hydrazine, sodium borohydride) and organic solvents (by replacing them with renewable plant extracts, phytochemicals (polyphenols, flavonoids, terpenoids, alkaloids) are acting as both reducing agents and stabilizing agents), which minimizes environmental pollution, as well as the cost-effectiveness of the method, as plant materials are widely available, inexpensive, and often derived from agricultural waste or cultivated easily, reducing overall costs and making the process economically viable for large-scale applications, especially in developing countries with limited access to expensive reagents and infrastructure; and furthermore, environmental friendliness can be achieved at the expense of the biocompatibility of the nanoparticles synthesized in this way, since the capping by natural biomolecules generally reduces cytotoxicity and increases compatibility with biological systems, which is extremely important for drug delivery, biomedical imaging, and antimicrobial treatment, where low toxicity is necessary, and mild reaction conditions (ambient temperature and pressure), in turn, also increase safety (they are preferable to high-energy physical or chemical methods), and nevertheless, despite all the merits of this method, the green synthesis approach also has a number of significant disadvantages - the variability of the composition of plant extracts remains one of the main problems-the composition of phytochemicals, for example, can vary depending on plant species, geographical location (influence of climatic conditions), season of collection, extraction method, and storage of the extracts, which leads to variability in the size, shape, yield, and functional properties of nanoparticles associated with it, which negatively affects the reproducibility and reliability of the results, and the standardization of extraction and synthesis protocols is absent. There is no universal method that is accepted worldwide for controlling reaction parameters (pH, temperature, extract concentration, reaction time, etc.), which makes it impossible to obtain nanoparticles with the same characteristics in different studies or at an industrial scale, which, in turn, limits scalability and the potential of commercialization, besides, for the industrial adoption of this method, scale-up poses a critical barrier, because processes that have been well established at the lab scale may not scale in an efficient and effective manner to large-scale production due to one or more issues associated with scaling-up such as maintaining uniform mixing, controlling the kinetics of the reaction, ensuring consistent phytochemical activity, preventing aggregation while bulk synthesis, as well as difficulties with downstream processing, purification, and long-term storage stability of nanoparticles, and the limited mechanistic understanding of complex phytochemical interactions and potential inter-

Journal of Research and Development
A Multidisciplinary International Level Referred and Double Blind Peer Reviewed, Open Access
ISSN : 2230-9578 | Website: https://jrdrvb.org Volume-18, Issue-3| March-2026

study variabilities in long-term biological effects point out the need for further research and process optimization, and therefore, while green synthesis has demonstrated to be a green and sustainable alternative to conventional nanoparticle production methods, the breakthroughs and innovations in this area of knowledge are significant and needed and need to well overcome these and many other challenges including the development of standardized protocols, controlled extraction techniques, and scalable production systems should be developed that will ensure consistency, efficiency, and safety.

**Future Research Directions**

Despite have shown a tremendous potential in biomedical applications, the green synthesis of metal nanoparticles (NPs) using phytochemicals faces a number of scientific and technological issues that need to be addressed to move further towards a reliable, applicable and industrial practice by the standardization of synthesis protocols, which is a primary need for all green processes, as the composition of plant extracts is variable depending on plant species, climatic conditions, seasonality and extraction methods, and in search for the controlled pre-treatment methods, as well as reproducible reaction conditions (i.e., pH, temperature, precursor concentration and reaction time), reproducible NP size, morphology and functional properties, the integration of advanced analytical technologies such as high-performance liquid chromatography (HPLC) and mass spectrometry to establish correlations of specific phytochemicals with the reduction efficiency and stabilization mechanisms; besides standardization, the integration of green-synthesized NPs with nanomedicine and drug delivery systems is a very attractive opportunity, where the biocompatibility and low toxicity along with the surface functionalization capabilities of several phytochemicals can be used to design targeted delivery platforms, controlled drug release systems, and theranostic agents by conjugating NPs (e.g., with bioactive ligands, antibodies or polymers) to enhance specificity and therapeutic efficacy as well as exploring the potential to cancer therapy, antimicrobial coatings, and biosensing applications, which calls for an interdisciplinary collaboration among organic chemists, material scientists, and biomedical researchers; in addition, the development of hybrid nanomaterials (e.g., bimetallic NPs (e.g., Ag–Au, Pd–Pt) or composites combining metal NPs with polymers, graphene, or metal oxides) pursuing the improvement of catalytic activity, stability, and multifunctionality to display synergies that improve the performance of organic transformations, environmental remediation, and biomedical applications with enhanced precision of electronic and surface properties through controlled synthesis are a promising direction; further, through the design of continuous flow reactors, scalable bioreactors, and process intensification strategies keep uniform reaction conditions and maintain product quality at larger volumes along with an efficient NP recovery, purification, and stabilization at room temperature and purification from contaminated organic compounds for longer storage, as well as economic feasibility analyses to evaluate the cost, energy consumption, and environmental impact in compared to conventional methodologies, and future studies should also include life cycle assessment (LCA) and sustainability metrics to assess the environmental gains driven by green synthesis while searching for use of agricultural waste and industrial biomass as alternative feedstocks to further boost sustainability, and finally, advancing research in all such directions will be of paramount importance to form a robust, scalable, and application-oriented technology capable to bridge between fundamental chemistry and real-world implementation aiming the green synthesis of nanomaterials.

**Conclusion**

This conceptual study synthesizes theory, mechanism, applications and present the viewpoint on the emerging green sustainable nanotechnology field that the plant-mediated synthesis is eco-friendly and scientifically sound alternative to conventional physical and chemical methods of metallic nanoparticle experiments and key findings are type of metallic nanoparticle reported to be green synthesized as well as its configurational characterizations from UV–Vis, FTIR, XRD, SEM/TEM, and DLS techniques that show the crystalline and stable form of these bio-organized nanoparticles and their applicability in catalysis towards oxidation, reduction, and coupling reaction as well as their antimicrobial activity via ROS generation mechanism, membrane disruption, and interaction with microbial biomolecules, respectively confirming their beneficial multifunctionality; importantly this study emphasizing increased importance of green synthesis in the sustainable chemistry framework that focus on minimizing environmental impact, reducing hazards, utilizing renewable feedstock, and promoting energy efficiency to avoid material-based dismiss within the global context of environment depletion, public health, and natural resources sustainability problems and especially in growing industrial demands for nanomaterial synthesis in lower environmental and health risk through green synthesis pathway where the significant challenges must be addressed may include variability of plant extract composition, reproducible synthesis methodologies, and scaling up production and the implications of this research must be potential in developing methodologies to better alacrity reproducible synthesis methods, integration of green nanoparticles within advance applications such as nanomedicine, targeted drug delivery, and smart catalytic systems, design of hybrid and multifunctional materials, and establishment of an efficient and scalable production systems while incorporating life cycle assessment and sustainability metrics to quantify the environmental contribution of plant-mediated synthesis; and finally, while the characteristic potential of plant-mediated synthesized metal nanoparticles have shown considerable scientific and practical potential their full realization will depend on continuous inter-disciplined research with process optimization and industrial adaptation, making it a cornerstone of the toward future sustainable nanoscience and green chemistry advances.

Journal of Research and Development
A Multidisciplinary International Level Referred and Double Blind Peer Reviewed, Open Access
ISSN : 2230-9578 | Website: https://jrdrvb.org Volume-18, Issue-3| March-2026

**References**


1. Ahmed, S., Ahmad, M., Swami, B. L., & Ikram, S. (2016). A review on plants extracts mediated synthesis of silver nanoparticles. Journal of Advanced Research, 7(1), 17–28. https://doi.org/10.1016/j.jare.2015.02.007
2. Anastas, P. T., & Warner, J. C. (1998). Green chemistry: Theory and practice. Oxford University Press.
3. Astruc, D., Lu, F., & Aranzaes, J. R. (2005). Nanoparticles as recyclable catalysts. Angewandte Chemie International Edition, 44(48), 7852–7872. https://doi.org/10.1002/anie.200500766
4. Baruwati, B., Varma, R. S., & Polshettiwar, V. (2009). Green synthesis of silver nanoparticles. Green Chemistry, 11(7), 926–930.
5. Berne, B. J., & Pecora, R. (2000). Dynamic light scattering: With applications to chemistry, biology, and physics. Dover Publications.
6. Cullity, B. D., & Stock, S. R. (2014). Elements of X-ray diffraction (3rd ed.). Pearson.
7. Dahl, J. A., Maddux, B. L. S., & Hutchison, J. E. (2007). Toward greener nanosynthesis. Chemical Reviews, 107(6), 2228–2269. https://doi.org/10.1021/cr050943k
8. Dhand, C., Dwivedi, N., Loh, X. J., Ying, A. N. J., Verma, N. K., Beuerman, R. W., Lakshminarayanan, R., & Ramakrishna, S. (2015). Methods and strategies for nanoparticle synthesis. RSC Advances, 5, 105003–105037.
9. Henglein, A. (1989). Small-particle research: Physicochemical properties of colloidal metals. Chemical Reviews, 89(8), 1861–1873.
10. Huang, J., Li, Q., Sun, D., Lu, Y., Su, Y., Yang, X., Wang, H., Wang, Y., Shao, W., He, N., Hong, J., & Chen, C. (2007). Biosynthesis of nanoparticles using plant extracts. Nanotechnology, 18(10), 105104.
11. Iravani, S. (2011). Green synthesis of metal nanoparticles using plants. Green Chemistry, 13(10), 2638–2650. https://doi.org/10.1039/C1GC15386B
12. Iravani, S., Varma, R. S., & Green, M. (2020). Plant-mediated synthesis of nanoparticles. ACS Sustainable Chemistry & Engineering, 8(15), 5391–5402.
13. Kelly, K. L., Coronado, E., Zhao, L. L., & Schatz, G. C. (2003). Optical properties of nanoparticles. The Journal of Physical Chemistry B, 107(3), 668–677.
14. Kharissova, O. V., Dias, H. V. R., Kharisov, B. I., Pérez, B. O., & Pérez, V. M. J. (2013). Greener synthesis of nanoparticles. TrAC Trends in Analytical Chemistry, 46, 1–34.
15. Kharissova, O. V., Kharisov, B. I., Olvera, M. V., & Méndez, Y. P. (2019). Green synthesis using plants. Green Chemistry Letters and Reviews, 12(3), 271–302.
16. Klabunde, K. J., & Richards, R. M. (2009). Nanoscale materials in chemistry (2nd ed.). Wiley.
17. Kuppusamy, P., Yusoff, M. M., Maniam, G. P., & Govindan, N. (2016). Biosynthesis of nanoparticles using plant derivatives. Saudi Pharmaceutical Journal, 24(4), 473–484.
18. LaMer, V. K., & Dinegar, R. H. (1950). Mechanism of nanoparticle formation. Journal of the American Chemical Society, 72(11), 4847–4854.
19. Makarov, V. V., Love, A. J., Sinitsyna, O. V., et al. (2014). Green nanotechnologies. Acta Naturae, 6(1), 35–44.
20. Marambio-Jones, C., & Hoek, E. M. V. (2010). Antibacterial effects of nanoparticles. Journal of Nanoparticle Research, 12(5), 1531–1551.
21. Mittal,A.K.,Chisti,Y.,& Banerjee,U.C.(2013).Synthesis using plant extracts.BiotechnologyAdvances,31(2),346–356.
22. Murphy, C. J., Sau, T. K., Gole, A. M., et al. (2005). Anisotropic nanoparticles. The Journal of Physical Chemistry B, 109(29), 13857–13870.
23. Narayanan, K. B., & Sakthivel, N. (2010). Biological synthesis of nanoparticles. Advances in Colloid and Interface Science, 156(1–2), 1–13.
24. Polshettiwar, V., Varma, R. S., & Fihri, A. (2010). Nano catalysts for green chemistry. Chemical Society Reviews, 39(5), 1615–1625.
25. Rai,M., Yadav, A.,& Gade,A.(2009). Silver nanoparticles as antimicrobials. Biotechnology Advances, 7(1), 76–83.
26. Raveendran, P., Fu, J., & Wallen, S. L. (2003). Green synthesis of nanoparticles. Journal of the American Chemical Society, 125(46), 13940–13941.
27. Shankar, S. S., Rai, A., Ahmad, A., & Sastry, M. (2004). Neem-mediated nanoparticle synthesis. Journal of Colloid and Interface Science, 275(2), 496–502.
28. Sharma, V. K., Yngard, R. A., & Lin, Y. (2009). Green synthesis and antimicrobial activity. Advances in Colloid and Interface Science, 145(1–2), 83–96.
29. Singh, P., Kim, Y. J., Zhang, D., & Yang, D. C. (2018). Biological synthesis of nanoparticles. Trends in Biotechnology, 36(6), 562–575.
30. Stuart, B. (2004). Infrared spectroscopy: Fundamentals and applications. Wiley.
31. Thanh, N. T. K., Maclean, N., & Mahiddine, S. (2014). Mechanisms of nanoparticle formation. Chemical Reviews, 114(15), 7610–7630.
32. Zhang, X. F., Liu, Z. G., Shen, W., & Gurunathan, S. (2016). Applications of nanoparticles. International Journal of Molecular Sciences, 17(9), 1534.