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A Review of Phenolic-Mediated Gold Nanoparticle Synthesis Using Hardwickia binata Roxb

Pawar Manjusha Hari

Research Scholar, Department of Chemistry, Malwanchal University, Indore

Dr. Sanjay Chavan

Supervisor, Department of Chemistry, Malwanchal University, Indore

Dr. Pramod Patil

Co- Supervisor, Department of Chemistry, Malwanchal University, Indore

ABSTRACT

The green synthesis of metallic nanoparticles has emerged as a sustainable alternative to conventional physical and chemical routes, owing to its eco-friendly nature, cost-effectiveness, and biocompatibility. Among noble metal nanoparticles, gold nanoparticles (AuNPs) occupy a privileged position because of their distinctive surface plasmon resonance, chemical stability, low cytotoxicity, and versatile applicability in catalysis, biosensing, drug delivery, and antimicrobial therapy. This review critically examines the phenolic-mediated green synthesis of gold nanoparticles using the bark extract of *Hardwickia binata* Roxb., a leguminous hardwood tree native to the Indian subcontinent whose bark is exceptionally rich in polyphenols, flavonoids, tannins, and terpenoids. These phytochemicals function simultaneously as reducing agents that convert tetrachloroauric acid to elemental gold and as capping agents that stabilize the resulting colloidal dispersion. The review synthesizes current understanding of the phenolic reduction mechanism, the influence of reaction parameters such as pH, temperature, precursor concentration, and extract dosage on nanoparticle morphology, and the characterization techniques used to confirm nanoparticle formation. Particular attention is devoted to the role of hydroxyl-bearing aromatic compounds in electron transfer and to the correlation between phytochemical composition and particle size, shape, and stability. The biomedical and catalytic applications of the resulting nanoparticles, including their antioxidant, antibacterial, and anticancer potential, are also discussed. By consolidating the dispersed literature on phenolic-mediated gold nanoparticle biosynthesis and contextualizing the unique potential of *Hardwickia binata* bark, this review identifies the principal knowledge gaps and outlines directions for future research aimed at scalable, reproducible, and application-driven nanoparticle production.

Keywords: Green synthesis; Gold nanoparticles; *Hardwickia binata*; Phenolic compounds; Bark extract; Surface plasmon resonance; Bioreduction



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1. INTRODUCTION

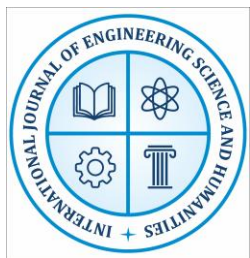
Nanotechnology has transformed materials science over the past two decades by enabling the design and manipulation of matter at the nanoscale, where physical and chemical properties diverge markedly from those of bulk materials. Gold nanoparticles, in particular, have attracted intense scientific interest because of their tunable optical behaviour, large surface-to-volume ratio, and exceptional biocompatibility, which make them suitable for diverse applications spanning catalysis, sensing, imaging, and nanomedicine (Singh et al., 2018). The conventional production of gold nanoparticles relies on physical and chemical methods that frequently involve hazardous reducing agents, toxic solvents, and energy-intensive conditions, raising concerns about environmental safety and biological compatibility. In response, the scientific community has increasingly embraced green synthesis as a benign and economical paradigm for nanoparticle fabrication (Ahmed et al., 2016).

1.1 Significance of Gold Nanoparticles

Gold nanoparticles exhibit a localized surface plasmon resonance that produces an intense absorption band in the visible region, typically between 520 and 560 nanometres depending on particle size, shape, and the surrounding dielectric environment. This optical signature underpins their utility in colorimetric biosensors and diagnostic assays (Khan et al., 2019). Beyond optics, gold nanoparticles display remarkable catalytic activity toward the reduction of organic pollutants and the oxidation of carbon monoxide, while their inertness and ease of surface functionalization enable conjugation with drugs, antibodies, and nucleic acids for targeted therapeutic delivery. The colour of a gold colloid shifts visibly with changes in particle size and inter-particle spacing, a phenomenon exploited for centuries in stained glass and more recently in rapid point-of-care diagnostic strips (Thakkar et al., 2016). Their low intrinsic toxicity compared with other metal nanoparticles further enhances their appeal for in vivo biomedical applications.

1.2 Limitations of Conventional Synthesis

Traditional routes to gold nanoparticles, such as the Turkevich citrate reduction and the Brust-Schiffrin two-phase method, deliver good size control but depend on reagents like sodium borohydride, hydrazine, and organic thiols that are toxic, flammable, or environmentally persistent (Mukherjee et al., 2017). The disposal of chemical by-products, the high energy demand of certain physical approaches, and the residual contamination of nanoparticle surfaces with adsorbed chemical species collectively limit the suitability of these methods for biomedical and food-related applications. These drawbacks have motivated the search for cleaner alternatives that avoid hazardous inputs while retaining control over nanoparticle quality. Physical techniques such as laser ablation, evaporation-condensation, and lithography, although capable of producing highly pure nanoparticles, require sophisticated instrumentation, vacuum systems, and substantial energy, which restrict their accessibility and scalability (Sharma et al.,



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2015). The economic and ecological costs associated with both chemical and physical methods therefore reinforce the case for biologically driven synthesis.

1.3 Green Synthesis as a Sustainable Alternative

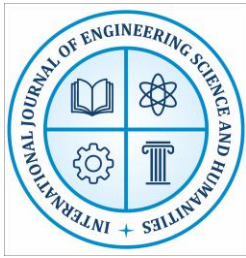
Green synthesis exploits biological entities, including bacteria, fungi, algae, and plant extracts, to mediate the reduction of metal ions and the stabilization of the resulting nanoparticles. Plant-based synthesis is especially attractive because it is rapid, single-step, free of pathogenic risk, and amenable to scale-up (Kumar et al., 2017). Plant extracts contain a complex mixture of biomolecules, notably polyphenols, flavonoids, alkaloids, proteins, and sugars, that perform the dual role of reductant and capping agent. The abundance and renewability of plant feedstocks, combined with the elimination of toxic reagents, position phytosynthesis as a cornerstone of sustainable nanotechnology (Shah et al., 2015). Compared with microbial synthesis, which demands sterile culture maintenance and lengthy incubation, plant-mediated routes are faster, simpler, and free of biosafety concerns associated with handling living cultures (Iravani, 2015). These advantages have driven a rapid proliferation of studies exploring botanical sources ranging from common crops to medicinal trees, with bark, leaf, and fruit extracts each offering distinct phytochemical signatures.

1.4 Role of Phenolic Compounds in Bioreduction

Phenolic compounds are among the most effective phytochemical reductants because their aromatic hydroxyl groups readily donate electrons and protons during the conversion of metal ions to their elemental state. The oxidation of phenolic hydroxyls to quinones supplies the electrons required to reduce auric ions, while the oxidized phenolic species and other functional groups subsequently adsorb onto the nascent nanoparticle surface to prevent aggregation (Patra & Baek, 2017). The reducing capacity of a given extract correlates closely with its total phenolic and flavonoid content, making phenol-rich botanical sources particularly valuable for controlled nanoparticle synthesis. This mechanistic linkage between phenolic chemistry and nanoparticle formation provides the conceptual foundation for the present review. The efficiency of electron transfer depends on the number and position of hydroxyl substituents on the aromatic ring, with ortho-dihydroxy (catechol) and trihydroxy (galloyl) arrangements being especially potent reductants because they stabilize the oxidized intermediate through resonance and chelation. Understanding these structure-activity relationships is essential for predicting which botanical sources will perform best in nanoparticle synthesis.

1.5 Rationale for Selecting *Hardwickia binata* Bark

Hardwickia binata Roxb., a monotypic leguminous tree of the Fabaceae family commonly known as anjan, is distributed across the dry deciduous forests of peninsular India. Its bark is a recognized repository of tannins, flavonoids, and other polyphenolic constituents, traditionally exploited in tanning and ethnomedicine (Ramesh et al., 2020). The high polyphenol density of



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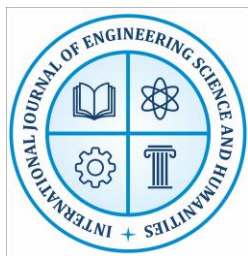
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the bark renders it a promising yet underexplored candidate for the bioreduction of gold ions. Unlike many widely studied plant extracts, *Hardwickia binata* bark combines abundant reducing phytochemicals with regional availability and low commercial value, offering an economical feedstock for green nanoparticle synthesis. This review consolidates the limited but suggestive evidence surrounding this species and situates it within the broader landscape of phenolic-mediated gold nanoparticle biosynthesis.

2. LITERATURE REVIEW

2.1 Plant-Mediated Green Synthesis of Gold Nanoparticles

The plant-mediated synthesis of gold nanoparticles has expanded rapidly, with numerous botanical species demonstrating the capacity to reduce tetrachloroauric acid into stable colloidal gold. Extracts derived from leaves, fruits, seeds, roots, and bark have each been shown to yield nanoparticles whose size and morphology depend on the phytochemical profile of the source material (Singh et al., 2018). Early investigations established that aqueous plant extracts could replace chemical reductants entirely, producing nanoparticles within minutes at ambient or mildly elevated temperatures. Subsequent work demonstrated that the diversity of biomolecules present in plant tissue allows simultaneous reduction and capping in a single reaction vessel, eliminating the need for separate stabilizing agents (Ahmed et al., 2016). Comparative studies across species have revealed that extracts rich in polyphenols and flavonoids consistently generate smaller, more monodisperse particles than those dominated by sugars or proteins, underscoring the central role of phenolic chemistry. Researchers have also documented that bark extracts, owing to their high tannin content, frequently produce nanoparticles with enhanced colloidal stability compared with leaf or fruit extracts, a finding of direct relevance to the selection of *Hardwickia binata* bark as a synthetic feedstock (Nadagouda et al., 2017). Several investigators have further noted that the geographical origin, harvesting season, and drying conditions of plant material influence the concentration of active phytochemicals and, consequently, the reproducibility of nanoparticle synthesis (Vijayaraghavan & Ashokkumar, 2017). The mode of extract preparation, including solvent choice, extraction temperature, and duration, also modulates the yield of reducing biomolecules and thereby the efficiency of the subsequent bioreduction. A recurring theme across the literature is the green credential of these methods: the reactions proceed in aqueous media at near-ambient conditions, generate negligible toxic waste, and require no external stabilizers, thereby aligning with the principles of green chemistry (Dauthal & Mukhopadhyay, 2016). Bark, as a synthetic feedstock, carries the additional advantage of being a by-product of forestry and timber operations, which means its use does not compete with food production or require dedicated cultivation. This positions bark-mediated synthesis as a particularly attractive avenue for waste valorization within a circular-economy framework. Collectively, this body of work confirms that plant-mediated synthesis is a



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robust and generalizable strategy, while highlighting the importance of matching the phytochemical composition of the chosen extract to the desired nanoparticle characteristics.

2.2 Phenolic Compounds as Reducing and Capping Agents

A substantial literature has elucidated the dual function of phenolic compounds in nanoparticle biosynthesis, establishing them as the principal agents responsible for both metal ion reduction and nanoparticle stabilization. Flavonoids such as quercetin, kaempferol, and catechin, along with phenolic acids including gallic and ferulic acid, possess multiple hydroxyl groups whose oxidation furnishes the electrons necessary to convert auric ions to metallic gold (Patra & Baek, 2017). Spectroscopic investigations have repeatedly demonstrated the disappearance or attenuation of hydroxyl-associated infrared bands following synthesis, accompanied by the emergence of carbonyl signatures, providing direct evidence that phenolic hydroxyls are oxidized to quinones during bioreduction (Kumar et al., 2017). The same oxidized and unoxidized phenolic species then chemisorb onto the nanoparticle surface, forming a protective organic corona that imposes steric and electrostatic barriers against aggregation. Studies correlating total phenolic content with nanoparticle yield and stability have consistently found that extracts of higher phenolic concentration generate nanoparticles more rapidly and with narrower size distributions (Shah et al., 2015). Tannins, a class of high-molecular-weight polyphenols abundant in tree bark, are especially effective capping agents because their numerous galloyl and catechol units provide multidentate anchoring to the metal surface. Beyond their reductive and stabilizing roles, phenolic compounds influence the morphology of the resulting nanoparticles through selective adsorption onto specific crystallographic facets, thereby directing anisotropic growth into triangular, hexagonal, or rod-like structures under appropriate conditions (Siddiqi & Husen, 2017). The molecular weight and structural complexity of the phenolic species also matter: low-molecular-weight phenolic acids tend to drive rapid nucleation and small spherical particles, whereas high-molecular-weight tannins favour slower, more controlled growth and superior long-term stability. Researchers employing nuclear magnetic resonance and chromatographic fractionation have begun to deconvolute the contributions of individual phenolic constituents, revealing that synergistic interactions among multiple compounds often outperform any single purified reductant (Rajan et al., 2015). This mechanistic consensus directly supports the hypothesis that the tannin- and flavonoid-rich bark of *Hardwickia binata* can efficiently mediate gold nanoparticle formation while conferring strong colloidal stability.

2.3 Influence of Reaction Parameters on Nanoparticle Properties

The physicochemical properties of biosynthesized gold nanoparticles are governed by a constellation of reaction parameters that researchers have systematically investigated. Solution pH exerts a pronounced effect on nanoparticle size and shape by altering the ionization state of



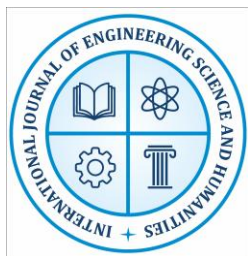
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phenolic hydroxyl groups and thereby modulating their reducing power; alkaline conditions generally accelerate reduction and favour smaller, spherical particles, whereas acidic conditions tend to yield larger or anisotropic structures (Khan et al., 2019). Temperature similarly influences the kinetics of nucleation and growth, with elevated temperatures promoting rapid nucleation that produces smaller particles, while lower temperatures favour slower growth and broader size distributions (Mukherjee et al., 2017). The concentration of the gold precursor and the dosage of plant extract jointly determine the balance between nucleation and particle growth, such that an excess of reducing phytochemicals relative to metal ions tends to generate numerous small nuclei and consequently finer nanoparticles. Reaction time governs the completeness of reduction, with the characteristic plasmon band intensifying and stabilizing as the reaction progresses toward equilibrium (Ramesh et al., 2020). Researchers have demonstrated that judicious optimization of these interdependent variables enables considerable control over nanoparticle morphology, ranging from spheres and triangles to hexagons and rods. In addition to these primary variables, secondary factors such as the stirring rate, light exposure, and the presence of dissolved oxygen have been reported to influence reaction outcomes, with photochemical activation under sunlight accelerating reduction in certain systems (Mittal et al., 2017). The interplay among parameters is frequently nonlinear, so that the optimal value of one variable depends on the settings of the others, which complicates the transfer of conditions from one plant system to another. For this reason, statistical design-of-experiment approaches have gained favour as a means of efficiently navigating the multidimensional parameter space and identifying robust optima. The sensitivity of nanoparticle characteristics to reaction conditions implies that synthesis using *Hardwickia binata* bark would likewise require careful parameter optimization to achieve reproducible and application-specific outcomes.

2.4 Characterization Techniques and Biomedical Applications

The confirmation and characterization of biosynthesized gold nanoparticles rely on a suite of complementary analytical techniques that the literature has standardized. Ultraviolet-visible spectroscopy provides the first indication of nanoparticle formation through the appearance of the surface plasmon resonance band, whose position and width report on particle size and dispersity (Singh et al., 2018). Fourier-transform infrared spectroscopy identifies the functional groups responsible for reduction and capping, frequently implicating phenolic, hydroxyl, and carbonyl moieties in the stabilization process. Transmission and scanning electron microscopy reveal nanoparticle size and morphology, while dynamic light scattering and zeta potential measurements quantify hydrodynamic size and colloidal stability, and X-ray diffraction confirms the crystalline metallic gold structure (Khan et al., 2019). On the application front, biosynthesized gold nanoparticles have demonstrated significant antioxidant activity attributable to the phenolic corona, alongside antibacterial efficacy against both Gram-positive and Gram-



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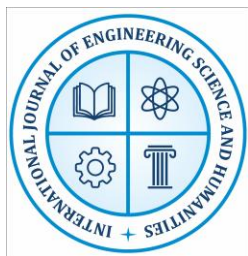
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negative pathogens through membrane disruption and reactive oxygen species generation (Patra & Baek, 2017). Anticancer investigations have reported selective cytotoxicity toward tumour cell lines, while catalytic studies have established the effectiveness of these nanoparticles in degrading organic dyes and reducing nitroaromatic pollutants (Nadagouda et al., 2017). Their utility extends to biosensing, where the plasmonic response enables sensitive colorimetric detection of analytes ranging from heavy metal ions to biomolecular markers, and to bioimaging, where their strong light scattering and biocompatibility support contrast enhancement (Yadav et al., 2016). Energy-dispersive X-ray spectroscopy further verifies the elemental gold composition, while thermogravimetric analysis quantifies the organic capping layer surrounding the metallic core (Zhang et al., 2020). The mechanisms underlying the biological activity of these nanoparticles have also received attention: their antibacterial action is attributed to a combination of direct membrane interaction, interference with electron transport, and the catalytic generation of reactive oxygen species, while their anticancer effects are linked to the induction of apoptosis and the disruption of cellular redox homeostasis (Hussain et al., 2016). The phenolic corona inherited from the plant extract contributes additional antioxidant and therapeutic value, distinguishing green-synthesized nanoparticles from their chemically produced counterparts. The convergence of robust characterization methodology and demonstrated functional utility provides a strong precedent for anticipating that gold nanoparticles synthesized from *Hardwickia binata* bark would exhibit comparable structural quality and biomedical promise.

Table 1. Major phenolic phytochemicals reported in plant bark extracts and their roles in gold nanoparticle synthesis.

Phytochemical Class	Representative Compounds	Functional Role in Synthesis
Flavonoids	Quercetin, kaempferol, catechin	Electron donation for reduction of auric ions; surface capping
Phenolic acids	Gallic acid, ferulic acid, caffeic acid	Rapid reduction via hydroxyl oxidation to quinones
Tannins	Hydrolysable and condensed tannins	Multidentate capping for enhanced colloidal stability
Terpenoids	Triterpenes, diterpenes	Secondary stabilization and steric protection

Table 2. Effect of key reaction parameters on the properties of green-synthesized gold nanoparticles.



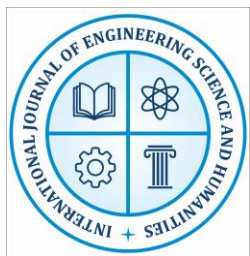
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Parameter	Effect on Reaction	Effect on Nanoparticle Properties
pH	Alters ionization of phenolic hydroxyls and reducing power	Alkaline pH favours small spherical particles; acidic pH yields larger or anisotropic forms
Temperature	Governs nucleation and growth kinetics	Higher temperature gives smaller, more uniform particles
Precursor concentration	Sets the supply of auric ions for reduction	Excess precursor promotes growth and larger particles
Extract dosage	Determines availability of reducing phytochemicals	Higher dosage yields numerous nuclei and finer particles
Reaction time	Controls completeness of reduction	Longer time intensifies and stabilizes the plasmon band

3. CONCLUSION

This review has synthesized the current understanding of phenolic-mediated green synthesis of gold nanoparticles and articulated the distinctive promise of *Hardwickia binata* Roxb. bark extract as a reducing and stabilizing agent. The accumulated literature establishes unambiguously that phenolic compounds, particularly flavonoids, phenolic acids, and tannins, serve as the principal drivers of bioreduction, donating electrons through the oxidation of aromatic hydroxyl groups while simultaneously forming a protective organic corona that confers colloidal stability. The tannin- and flavonoid-rich composition of *Hardwickia binata* bark positions it as an exceptionally suitable yet underutilized feedstock for this purpose, combining abundant reducing phytochemicals with regional availability and low commercial cost. Evidence drawn from related botanical systems indicates that careful optimization of reaction parameters, including pH, temperature, precursor concentration, extract dosage, and reaction time, permits substantial control over nanoparticle size, shape, and stability. The standardized characterization toolkit comprising ultraviolet-visible spectroscopy, infrared spectroscopy, electron microscopy, dynamic light scattering, and X-ray diffraction provides reliable means of confirming nanoparticle formation and quality, while the documented antioxidant, antibacterial, anticancer, and catalytic activities of green-synthesized gold nanoparticles establish a strong functional rationale for pursuing this synthesis. Taken together, the convergence of mechanistic insight, phytochemical suitability, and demonstrated application potential supports the conclusion that *Hardwickia binata* bark extract represents a viable and sustainable platform for the production of



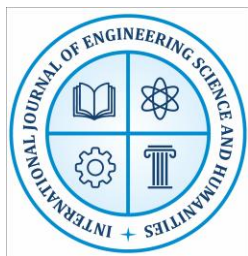
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functional gold nanoparticles, meriting dedicated experimental investigation. The integration of an inexpensive, polyphenol-dense, and regionally abundant feedstock with a single-step aqueous synthesis protocol embodies the aspirations of green nanotechnology, and the realization of this potential could contribute meaningfully to both the valorization of an underutilized forest resource and the advancement of environmentally responsible nanomaterial production.

4. FUTURE WORK

Although the theoretical case for using *Hardwickia binata* bark extract in gold nanoparticle synthesis is compelling, several research priorities must be addressed to translate this potential into validated practice. First, systematic phytochemical profiling of the bark using high-performance liquid chromatography and mass spectrometry is required to quantify the specific phenolic constituents responsible for bioreduction and to correlate their abundance with nanoparticle yield and quality. Second, comprehensive parameter optimization studies should map the influence of pH, temperature, precursor and extract concentration, and reaction time on nanoparticle morphology, employing response-surface or other statistical design methodologies to identify optimal synthesis conditions. Third, rigorous characterization across multiple complementary techniques is needed to establish the size distribution, crystallinity, surface chemistry, and long-term colloidal stability of the resulting nanoparticles. Fourth, the biological and catalytic functionality of the nanoparticles should be evaluated through standardized assays of antioxidant capacity, antimicrobial efficacy against clinically relevant pathogens, cytotoxicity toward both cancerous and normal cell lines, and catalytic performance in pollutant degradation. Fifth, attention should be directed toward reproducibility, batch-to-batch consistency, and scalability, since seasonal and geographical variation in bark phytochemistry may affect synthesis outcomes. Finally, comparative life-cycle and toxicity assessments would help confirm that the proposed green route delivers genuine environmental and economic advantages over conventional methods. Addressing these directions would consolidate *Hardwickia binata* bark extract as a reproducible, scalable, and application-ready feedstock for sustainable nanotechnology. Interdisciplinary collaboration among phytochemists, materials scientists, and biomedical researchers will be indispensable to this endeavour, as will the establishment of standardized reporting protocols that document extract composition and reaction conditions in sufficient detail to permit independent replication. Such concerted effort would not only validate the specific promise of this species but also enrich the broader methodological foundation of phenolic-mediated nanoparticle biosynthesis.



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