

Green Chemistry in Ayurveda: Plant-Based Synthesis of Therapeutic Nanoparticles

Dr. Anupma Singh

Assistant Professor, Department of Chemistry
DDU Govt. PG College, Sitapur, Uttar Pradesh, India

Abstract

*Green chemistry has emerged as a sustainable and environmentally benign approach to nanoparticle synthesis, replacing toxic chemical reducing agents with plant-derived phytochemicals. In the context of Ayurveda, medicinal plants—long valued for their therapeutic potential—offer a rich source of bioactive molecules capable of acting as reducing, capping, and stabilizing agents for metal and metal-oxide nanoparticles. This review critically examines the chemistry of plant-mediated synthesis of therapeutic nanoparticles, focusing on reaction mechanisms, structure–property relationships, and biomedical relevance. Polyphenols, flavonoids, terpenoids, alkaloids, and reducing sugars from Ayurvedic plants such as *Azadirachta indica*, *Tinospora cordifolia*, *Withania somnifera*, *Phyllanthus emblica*, and *Ocimum sanctum* play dual roles in nanoparticle formation and surface functionalization, leading to controlled size, morphology, and stability. Green-synthesized silver, gold, zinc oxide, copper oxide, and iron oxide nanoparticles exhibit enhanced antimicrobial, anticancer, antioxidant, and wound-healing properties due to their biofunctionalized surfaces. However, challenges remain in reproducibility, scale-up, toxicity assessment, and standardization of plant extracts. This paper integrates the latest fifteen years of research (2010–2025) to present a coherent chemical framework for plant-based nanoparticle synthesis and its translational potential in nanomedicine.*

Keywords: Green chemistry, Ayurveda, silver NP, zinc oxide NP, phytochemical reduction, nanomedicine.

Introduction

Nanotechnology has transformed materials science, medicine, catalysis, and environmental remediation by enabling control over matter at the atomic and molecular scale. However, conventional nanoparticle synthesis often relies on toxic solvents, high temperatures, and hazardous reducing agents such as sodium borohydride and hydrazine, raising environmental and health concerns [1]. Green chemistry provides an alternative paradigm that prioritizes sustainability, minimal waste, and the use of renewable biological resources [2].

Plant-mediated synthesis of nanoparticles—commonly termed “phyto-nanotechnology”—has gained significant attention over the last decade due to its simplicity, cost-effectiveness, and biocompatibility [3]. Ayurvedic medicinal plants, historically used for healing, are chemically rich in secondary metabolites that can act as natural reducing and stabilizing agents. These phytochemicals include phenolic acids, flavonoids, tannins, saponins, alkaloids, and terpenoids, which donate electrons to metal ions, facilitating their reduction to nanoscale particles [4].

From a chemistry standpoint, plant extracts provide a complex reaction medium where multiple biomolecules participate simultaneously in reduction, nucleation, growth, and surface passivation of nanoparticles [5]. Unlike synthetic capping agents such as polyethylene glycol (PEG), plant-derived molecules confer inherent bioactivity to the nanoparticle surface, improving biological interactions and therapeutic potential [6].

Silver (Ag), gold (Au), zinc oxide (ZnO), copper oxide (CuO), and iron oxide (Fe₃O₄) nanoparticles synthesized using Ayurvedic plants have shown strong antimicrobial, antioxidant, anticancer, and anti-inflammatory effects [7]. Their performance depends critically on particle size, shape, crystallinity, and surface chemistry, all of which are influenced by extract composition, pH, temperature, and reaction time [8].

Despite promising advances, plant-based nanoparticle synthesis faces challenges in reproducibility, batch variability, and mechanistic clarity. Standardization of extract preparation, identification of active phytochemicals, and scalable manufacturing remain key research priorities [9]. This review paper presents a chemistry-centered analysis of green synthesis routes,

reaction mechanisms, characterization methods, and biomedical applications of plant-derived nanoparticles, with a focus on Ayurvedic botanical resources.

Principles of Green Chemistry in Nanoparticle Synthesis

Green chemistry is guided by twelve foundational principles that emphasize waste reduction, safer solvents, renewable feedstocks, energy efficiency, and benign by-products [2]. Plant-mediated nanoparticle synthesis aligns closely with these principles by replacing hazardous chemicals with biodegradable biomolecules [10].

In conventional chemical reduction, metal salts such as silver nitrate (AgNO_3) or chloroauric acid (HAuCl_4) are reduced using strong chemical agents that generate toxic residues. In contrast, plant extracts provide a self-contained reaction system where reducing agents (phenolics, flavonoids, sugars) and stabilizers (proteins, polysaccharides) are inherently present [11].

The core green chemistry advantages include:

1. Renewable resources: Ayurvedic plants are abundant and biodegradable.
2. Mild reaction conditions: Reactions often occur at room temperature and neutral pH.
3. No toxic by-products: Water is typically used as the solvent.
4. One-pot synthesis: Reduction and stabilization occur simultaneously [12].

The fundamental chemical steps in green synthesis involve:

- Reduction: Electron transfer from phytochemicals to metal ions (e.g., $\text{Ag}^+ \rightarrow \text{Ag}^0$).
- Nucleation: Formation of small metallic clusters.
- Growth: Controlled aggregation into nanoscale particles.
- Capping: Adsorption of biomolecules on particle surfaces to prevent agglomeration [13].

Plant extracts from *Azadirachta indica* (neem), *Ocimum sanctum* (tulsi), *Tinospora cordifolia* (giloy), and *Phyllanthus emblica* (amla) have been widely used as reducing agents due to their high phenolic content [14]. The presence of hydroxyl ($-\text{OH}$), carbonyl ($\text{C}=\text{O}$), and amine ($-\text{NH}_2$) groups enhances metal ion binding and reduction efficiency [15].

Thus, green synthesis not only produces nanoparticles but also embeds them with biofunctional coatings that improve stability, dispersibility, and biological compatibility—key features for therapeutic applications.

Phytochemical-Mediated Nanoparticle Synthesis

The success of plant-mediated nanoparticle synthesis depends fundamentally on the chemical composition of the extract. Major phytochemical classes involved in nanoparticle formation include:

- *Phenolics and Flavonoids*

Phenolic compounds such as gallic acid, quercetin, catechin, and rutin act as strong reducing agents due to their electron-donating hydroxyl groups [4]. These molecules reduce Ag^+ to Ag^0 while simultaneously binding to nanoparticle surfaces via coordination bonds, thereby stabilizing them sterically and electrostatically [16].

- *Terpenoids and Alkaloids*

Terpenoids such as withanolides from *Withania somnifera* contribute to nanoparticle nucleation by complexing with metal ions. Alkaloids, due to their nitrogen atoms, enhance metal binding and influence particle morphology [17].

- *Proteins and Polysaccharides*

Proteins in plant extracts adsorb onto nanoparticle surfaces, preventing aggregation through steric hindrance. Polysaccharides such as pectin and cellulose derivatives act as natural capping agents, improving colloidal stability in aqueous media [18].

Case Studies in Ayurvedic Plants

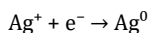
Neem (*Azadirachta indica*) – Neem leaf extract has been extensively used to synthesize silver nanoparticles with strong antimicrobial properties. Azadirachtin and related limonoids play key roles in reduction and stabilization [19]. Amla (*Phyllanthus emblica*) – Amla is rich in vitamin C, tannins, and polyphenols, which efficiently reduce gold ions to form stable AuNPs with antioxidant and anticancer activity [20]. Tulsi (*Ocimum sanctum*) – Tulsi extract yields ZnO nanoparticles with photocatalytic and antibacterial properties, attributed to eugenol and rosmarinic acid [21]. Giloy (*Tinospora cordifolia*) – Giloy-mediated iron oxide nanoparticles show magnetic properties useful in drug delivery and imaging, due to biomolecular surface functionalization [22]. The chemistry of plant-based synthesis is thus governed by redox reactions, coordination chemistry, and intermolecular interactions that determine nanoparticle size, shape, and stability.

Chemical Mechanisms of Green Nanoparticle Formation

The mechanistic understanding of plant-mediated nanoparticle synthesis involves three interlinked processes: reduction, nucleation, and growth.

- *Redox Chemistry*

Metal salts such as AgNO_3 dissociate in aqueous solution to release Ag^+ ions. Phenolic compounds donate electrons via oxidation of their hydroxyl groups, reducing Ag^+ to Ag^0 :



Simultaneously, phenols are oxidized to quinones, which remain adsorbed on the nanoparticle surface [23].

- *Nucleation and Growth*

Once reduced atoms accumulate, they form small clusters that serve as nuclei. These nuclei grow by further atom deposition until a stable nanoparticle size is reached.

Reaction parameters such as pH, temperature, and extract concentration critically influence this process [24].

- *Surface Capping and Stabilization*

Proteins, polysaccharides, and polyphenols bind to the nanoparticle surface through electrostatic and hydrogen bonding interactions. This prevents aggregation and controls particle morphology [25].

- *Role of pH and Temperature*

Higher pH accelerates reduction by increasing electron availability from deprotonated phenolic groups. Elevated temperatures enhance reaction kinetics but may also lead to larger particle sizes due to rapid nucleation [26].

- *Size Control and Shape Tuning*

Spherical nanoparticles are most common, but rods, cubes, and triangles can be produced by adjusting extract composition and reaction conditions. Shape strongly influences optical, catalytic, and biological properties [27].

Thus, green synthesis is governed by classical principles of redox chemistry, coordination interactions, and colloidal stability—making it a fundamentally chemical process rooted in plant biochemistry.

Types of Nanoparticles and Biomedical Applications

Plant-derived AgNPs exhibit broad-spectrum antibacterial activity against *E. coli*, *S. aureus*, and *Pseudomonas* species. The mechanism involves membrane disruption, ROS generation, and DNA damage [28]. Green-synthesized AuNPs are used in cancer therapy, drug delivery, and biosensing. Their biocompatible phytochemical coating improves cellular uptake and reduces toxicity [29]. ZnO nanoparticles synthesized using tulsi and neem extracts show photocatalytic activity for wastewater treatment and antimicrobial effects in biomedical coatings [30]. Biogenic iron oxide nanoparticles are used in magnetic resonance imaging (MRI), targeted drug delivery, and hyperthermia therapy due to their magnetic properties [31]. CuO nanoparticles synthesized from plant extracts exhibit strong antifungal and catalytic properties, making them useful in agriculture and medicine [32]. Overall, plant-mediated nanoparticles offer multifunctional therapeutic potential due to their bioactive surface chemistry.

Characterization Techniques

To ensure reproducibility and quality, green nanoparticles are characterized using advanced analytical tools:

- UV-Visible Spectroscopy: Confirms nanoparticle formation via surface plasmon resonance (SPR) peaks.
- Transmission Electron Microscopy (TEM): Determines particle size and morphology.
- Scanning Electron Microscopy (SEM): Visualizes surface structure.

- X-ray Diffraction (XRD): Confirms crystallinity.
- Fourier Transform Infrared Spectroscopy (FTIR): Identifies functional groups involved in capping.
- Dynamic Light Scattering (DLS): Measures particle size distribution and zeta potential [33].

These techniques establish a robust chemical profile necessary for biomedical translation.

Challenges, Toxicity and Safety

Despite advantages, plant-mediated nanoparticle synthesis faces several limitations:

- Batch variability: Different plant harvests yield different phytochemical profiles [34].
- Reproducibility: Lack of standardized extraction protocols affects consistency.
- Toxicity concerns: Nanoparticles may induce oxidative stress at high doses [35].
- Scale-up issues: Industrial production requires controlled reactors and purification steps [36].

Toxicological studies indicate that surface chemistry, size, and concentration determine biological safety. Proper functionalization and dose optimization are essential for clinical use [37].

Future Directions

Future research should focus on:

- Standardizing plant extract composition through chromatographic profiling.
- Identifying key active phytochemicals responsible for reduction.
- Developing scalable bioreactor systems.
- Integrating computational modeling to predict nanoparticle behavior.
- Conducting clinical trials for therapeutic validation [38].

Plant-based synthesis of therapeutic nanoparticles represents a powerful convergence of green chemistry and traditional Ayurvedic knowledge. By harnessing the reducing power of phytochemicals, researchers can produce biocompatible, stable, and multifunctional nanomaterials without toxic reagents. Silver, gold, zinc oxide, copper oxide, and iron oxide nanoparticles synthesized using Ayurvedic plants demonstrate significant biomedical potential in antimicrobial therapy, cancer treatment, imaging, and environmental remediation. However, challenges in reproducibility, toxicity assessment, and industrial scalability must be addressed through rigorous standardization and mechanistic research. Green nanotechnology thus offers a sustainable pathway toward next-generation nanomedicine rooted in chemistry and nature.

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