Open Horizon Scientific Review

Vol. 03 No.01 2025

Green Synthesis of Metal Nanoparticles for Environmental and Biological Applications

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ABSTRACT

Green synthesis has emerged as a sustainable alternative to physical and chemical routes for producing metal nanoparticles, using plant extracts, microorganisms and algae as natural reducing and capping agents. This article reviews the principles, biological sources, formation mechanisms and parameter control involved in green synthesis, together with the main characterisation techniques used to confirm particle properties. Environmental applications, including dye degradation, water disinfection, heavy metal remediation and pollutant sensing, are discussed alongside biological applications such as antimicrobial, anticancer and drug delivery uses. Catalytic and antimicrobial performance is strongly linked to size, shape and surface coating, which can be tuned through pH, temperature and precursor concentration. Concerns regarding toxicity, reproducibility of biological extracts and scale-up remain the principal barriers to commercial adoption. Future progress will depend on standardised protocols, mechanistic understanding and safe-by-design strategies.

Key words: *green synthesis, metal nanoparticles, plant extracts, antimicrobial activity, environmental remediation*

Introduction:

Nanotechnology deals with materials having at least one dimension between one and one hundred nanometres, where properties differ markedly from those of the bulk material. Metal nanoparticles of silver, gold, zinc, copper, iron and their oxides display unique optical, catalytic, magnetic and antimicrobial behaviour that has made them central to fields as diverse as medicine, electronics, energy and environmental protection. As demand grows, the environmental cost of producing them has come under increasing scrutiny.

Traditional chemical synthesis frequently relies on toxic reducing agents, organic solvents and high energy input, generating hazardous by-products. Green synthesis addresses these concerns by employing biological entities such as plant extracts, bacteria, fungi and algae, whose metabolites reduce metal ions and stabilise the resulting particles in a single, often aqueous, step (Iravani, 2011). The approach is simple, economical and

compatible with the principles of green chemistry.

The aim of this article is to provide a coherent overview of green nanoparticle synthesis and its applications. The discussion is organised around nine thematic outlines covering principles, biological sources, formation mechanisms, control of particle properties, characterisation, environmental and biological applications, and the challenges that must be overcome, followed by an overall summary.

1. Principles of Green Synthesis and Comparison with Conventional Methods

Green synthesis is the production of nanoparticles using biological materials and benign solvents, typically water, under mild conditions and without hazardous reducing or stabilising agents. It is guided by the broader principles of green chemistry, which emphasise waste prevention, safer chemicals, energy efficiency and the use of renewable feedstocks. Conventional physical routes such as laser ablation and evaporation-condensation require high energy input and specialised equipment, while chemical routes often rely on sodium borohydride, hydrazine or organic solvents that leave toxic residues and create disposal problems (Iravani, 2011).

In contrast, green routes use extracts of plants, cultures of bacteria, fungi and algae, or isolated biomolecules to reduce metal ions to their zero-valent form and to cap the resulting particles. The process is usually performed at ambient or slightly elevated temperature and neutral to mildly alkaline pH, which lowers cost and energy demand. Hebbalalu and co-workers highlighted that plant extracts, enzymes, bacteria, biodegradable polymers and microwave assistance all expand the toolbox of sustainable synthesis (Hebbalalu et al., 2013).

The principal advantages of green synthesis are simplicity, scalability, biocompatibility and the ability to produce particles that are already coated with natural stabilisers. These coatings can improve colloidal stability and may confer additional biological activity. However, the complexity of biological extracts also introduces variability, and reproducibility remains a central concern that must be addressed through standardised protocols.

2. Biological Sources and Reducing Agents

Plants are the most widely used biological resource because extracts are easy to prepare, safe to handle and rich in phytochemicals. Polyphenols, flavonoids, terpenoids, alkaloids, proteins, sugars and organic acids act as reductants and capping agents. A classic example is the rapid formation of silver, gold and bimetallic particles using neem

leaf broth, which demonstrated that a simple aqueous extract could control nucleation within minutes (Shankar et al., 2004). Leaves, roots, fruit peels, seeds and flowers have all been explored, and agricultural waste is increasingly valued as a low-cost source.

Microorganisms offer an alternative platform. Bacteria and fungi secrete enzymes such as nitrate reductase and reducing cofactors that convert metal ions to nanoparticles either intracellularly or extracellularly. Fungi are attractive because they produce large quantities of extracellular proteins and are easy to handle in bioreactors, as shown by early work on fungus-mediated silver nanoparticle formation (Mukherjee et al., 2001). Microbial routes are generally slower than plant-based ones and require sterile culture conditions, but they may provide better control over particle morphology.

Algae, including micro- and macroalgae, combine rapid growth with abundant pigments, polysaccharides and proteins that serve as reducing and stabilising agents. Reviews of algae-mediated biosynthesis show that these organisms can generate a broad range of inorganic nanomaterials, including noble metals and metal oxides, and may also be used for bioremediation at the same time (Dahoumane et al., 2017). The choice of biological source therefore depends on target metal, desired particle properties, cost and scale.

3. Mechanisms of Nanoparticle Formation and Capping

The formation of metal nanoparticles from ionic precursors generally proceeds through three overlapping stages. In the activation stage, metal ions are reduced by biomolecules and nucleation of zero-valent atoms begins. In the growth stage, small nuclei merge and adsorb further atoms, a process that can proceed by Ostwald ripening or by direct coalescence. In the termination stage, the particle surface becomes passivated by capping molecules that determine the final shape and prevent further aggregation.

The reducing power of biological extracts arises from several functional groups. Hydroxyl groups of phenolics donate electrons and are oxidised to quinones, aldehyde groups are converted to carboxylic acids, and amine groups in proteins can bind metal surfaces and influence crystal growth. Enzymatic mechanisms, particularly NADH-dependent reductases in microorganisms, transfer electrons directly to metal ions. In many systems a combination of enzymatic and non-enzymatic pathways operates simultaneously (Thakkar et al., 2010).

Capping is equally important. Proteins, polysaccharides and

polyphenols adsorb onto the particle surface through electrostatic and coordination interactions, creating a corona that provides steric and electrostatic repulsion. This corona is largely responsible for the long-term stability seen in many green preparations, and it also controls how nanoparticles interact with cells, pollutants and surfaces in downstream applications.

4. Controlling Size, Shape and Stability

Particle size and shape determine optical, catalytic and biological properties, so reproducible control is a primary objective. Reaction parameters such as pH, temperature, precursor concentration, extract-to-metal ratio and reaction time strongly influence nucleation and growth. Higher pH typically increases the ionisation of functional groups and accelerates reduction, favouring numerous small nuclei and therefore smaller particles, while very low pH can yield larger, aggregated structures.

Temperature affects reaction kinetics. Elevated temperature increases the rate of reduction and nucleation, usually producing smaller and more uniform particles, although excessive heating can denature proteins or degrade active phytochemicals. Precursor concentration has a more complex effect: low concentrations favour small, monodisperse particles, whereas high concentrations promote aggregation and a broader size distribution (Singh et al., 2016).

Shape control, which yields spheres, rods, triangles, prisms or flowers, is more difficult in biological systems but can be achieved by adjusting the type of extract and the presence of anisotropic capping agents. Long-term stability is evaluated through zeta potential and storage studies, with values more negative or positive than about thirty millivolts generally indicating good electrostatic stabilisation. Optimisation approaches based on statistical design of experiments are increasingly used to map the parameter space systematically.

5. Characterization Techniques

Rigorous characterisation is essential to confirm the identity, size, morphology and surface chemistry of green nanoparticles. Ultraviolet-visible spectroscopy is the first and simplest technique, since silver and gold nanoparticles display characteristic surface plasmon resonance bands whose position and width reflect particle size, shape and aggregation state. A colour change of the reaction mixture often provides the earliest visual evidence of formation.

Electron microscopy, including scanning and transmission modes, provides direct images of morphology

and size distribution, while energy-dispersive X-ray analysis confirms elemental composition. X-ray diffraction identifies crystalline phases and allows estimation of crystallite size through the Scherrer equation. Dynamic light scattering reports hydrodynamic diameter and polydispersity in suspension, and zeta potential measurements describe surface charge and colloidal stability.

Fourier-transform infrared spectroscopy is used to identify the functional groups of biomolecules associated with the particle surface, giving insight into which compounds act as reductants and cappers. Thermogravimetric analysis quantifies the organic coating, and X-ray photoelectron spectroscopy can reveal oxidation states. Combining several complementary methods is recommended, because each technique alone provides only a partial view of a complex hybrid material.

6. Environmental Applications: Water Treatment and Dye Degradation

Water contamination by dyes, pesticides, pharmaceuticals and microbial pathogens is a major global concern, and green nanoparticles offer attractive solutions. Textile dyes such as methylene blue, methyl orange and Congo red are persistent and often toxic, and nanoparticle catalysts can degrade them through reduction in the presence of sodium borohydride or through photocatalytic oxidation under light. The large surface area and abundant active sites of nanoparticles accelerate electron transfer between donor and acceptor species.

Silver and gold nanoparticles act as electron relay systems in catalytic reduction, whereas zinc oxide and titanium dioxide particles generate reactive oxygen species under ultraviolet or visible irradiation that mineralise organic molecules. Degradation commonly follows pseudo-first-order kinetics, and rate constants depend on catalyst dosage, pH, dye concentration and light intensity. The conceptual figure below compares typical degradation profiles for different green-synthesised particles.

Nanoparticles also serve as antimicrobial agents for water disinfection. Silver particles disrupt microbial membranes and interfere with respiratory enzymes, making them valuable in filters and coatings. Immobilisation on membranes, sand, cellulose or polymeric supports reduces the risk of release into treated water and enables reuse. Such composite systems are among the most promising routes to decentralised water purification in resource-limited settings.

7. Environmental Remediation of Heavy Metals and Sensing

Heavy metals such as lead, cadmium, mercury, chromium and arsenic persist in soil and water and accumulate in food chains. Iron-based nanoparticles, particularly zero-valent iron synthesised with polyphenol-rich extracts, have attracted attention because they reduce toxic hexavalent chromium to less harmful trivalent chromium and immobilise other metals through adsorption and co-precipitation. The plant-derived coating limits oxidation and aggregation, extending the reactive lifetime of the particles in the subsurface.

Green nanoparticles are also used in sensing. The sensitivity of plasmonic resonance to the local environment allows colorimetric detection of mercury, lead, pesticides and other pollutants at low concentration, using changes that can be seen by eye or measured with simple spectrophotometers. Such sensors are inexpensive and portable, making them suitable for field monitoring where laboratory infrastructure is limited.

In agriculture and soil management, nanoparticles may help to remove pollutants, deliver micronutrients and suppress plant pathogens. Nevertheless, introducing engineered materials into open environments requires careful risk assessment, because their transformation, mobility and effects on soil microbial communities are not fully understood. Safe-by-design approaches and field-scale trials are needed before broad deployment.

8. Biological Applications: Antimicrobial, Anticancer, and Biomedical Uses

The biomedical use of green nanoparticles is led by antimicrobial applications. Silver nanoparticles show broad-spectrum activity against bacteria, fungi and some viruses, acting through membrane damage, release of silver ions, generation of reactive oxygen species and disruption of DNA and protein function (Rai et al., 2009). Plant-extract-mediated silver particles have been shown to inhibit both Gram-positive and Gram-negative bacteria, including drug-resistant strains, which is significant in the face of rising antibiotic resistance (Sharma et al., 2009).

Gold nanoparticles are valued for biocompatibility, ease of surface functionalisation and strong optical properties. They are used in diagnostics, imaging, photothermal therapy and targeted drug delivery, where ligands attached to the surface guide particles to specific cells (Dreaden et al., 2012). Green-synthesised gold particles carry a natural capping layer that can simplify conjugation and, in some cases,

contribute antioxidant or anti-inflammatory activity.

Anticancer activity has been reported for silver, gold, zinc oxide and selenium nanoparticles, which can induce apoptosis through oxidative stress and mitochondrial damage in cancer cell lines. Other applications include wound dressings, dental materials, antioxidant formulations and biosensors. Most of this evidence is derived from in vitro studies, and translation to clinical use requires rigorous in vivo validation, dose optimisation and regulatory evaluation.

9. Toxicity, Scalability, Challenges, and Future Perspectives

Despite their benefits, nanoparticles may produce adverse effects because the same properties that make them useful, such as high reactivity and small size, also allow them to enter cells and generate oxidative stress (Nel et al., 2006). Toxicity depends on size, shape, surface charge, dose, coating and exposure route. Green capping may reduce toxicity in some cases, but this cannot be assumed, and systematic toxicological assessment in relevant organisms is required.

Scalability and reproducibility are the main technical barriers. The chemical composition of biological extracts varies with species, season, geography and extraction method, so identical protocols may yield different products. Standardising extract preparation, identifying the active compounds and developing continuous-flow or bioreactor processes will be essential for industrial production. Life-cycle assessment should accompany development to ensure that the claimed sustainability is real.

Future research should focus on mechanistic understanding of biomolecule-metal interactions, design of multifunctional hybrid nanomaterials, use of agricultural and food waste as feedstock, and integration with membranes and devices. Collaboration among chemists, biologists, engineers and regulators will be required to move green nanoparticles from laboratory demonstrations to safe and effective products.

Summary

Green synthesis offers an environmentally friendly and economical route to metal nanoparticles by replacing hazardous reagents with plant, microbial and algal metabolites that act as both reducing and capping agents. Particle size, shape and stability can be controlled through pH, temperature, precursor concentration and the choice of biological source, and are verified using a combination of spectroscopic, microscopic and diffraction techniques.

The resulting nanoparticles show strong potential in environmental applications such as dye degradation, water disinfection, heavy metal

remediation and pollutant sensing, and in biological applications including antimicrobial, anticancer and drug delivery systems. Challenges remain in reproducibility, scale-up and toxicological safety, which call for standardised extraction methods, long-term in vivo and ecological risk assessments, and life-cycle analysis. Addressing these issues will allow green nanoparticles to progress from promising laboratory results to dependable real-world technologies.

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