



Role of Natural Capping Agents in Green Synthesis of Nanoparticles for Energy Storage and Biomedical Applications

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Abstract

Nanotechnology has become one of the most rapidly advancing scientific fields due to the unique physicochemical properties of materials at the nanoscale. Nanoparticles exhibit enhanced catalytic activity, high surface-to-volume ratio, improved electronic conductivity, and unique optical characteristics that make them highly useful in fields such as energy storage, environmental remediation, and biomedical science. Conventional nanoparticle synthesis methods typically rely on chemical reducing agents and high-energy physical processes. Although these methods allow precise control over particle size and morphology, they often involve toxic chemicals, high energy consumption, and environmentally hazardous by-products.

Green synthesis of nanoparticles has therefore emerged as an environmentally sustainable alternative to traditional synthesis techniques. In plant-mediated nanoparticle synthesis, natural phytochemicals present in plant extracts act simultaneously as reducing, stabilizing, and capping agents. Among these roles, capping agents play a particularly important role in controlling nanoparticle size, morphology, dispersion stability, and surface functionality. Natural compounds such as polyphenols, flavonoids, terpenoids, proteins, and organic acids bind to nanoparticle surfaces and form protective layers that prevent aggregation while introducing reactive functional groups.

These surface-modified nanoparticles exhibit enhanced electrochemical performance and improved biological compatibility. Consequently, plant-capped nanoparticles have been widely investigated for applications in electrochemical energy storage systems such as supercapacitors, lithium-ion batteries, and electrocatalytic devices. In addition, these nanomaterials demonstrate promising biomedical applications including antimicrobial activity, anticancer therapy, drug delivery, and biosensing.

This review discusses the mechanisms of green nanoparticle synthesis and the role of natural capping agents in stabilizing nanostructures. Various plant sources used as capping agents are compared and their influence on nanoparticle properties is analyzed. Applications of plant-capped nanoparticles in energy storage technologies and biomedical systems are reviewed in detail. Characterization techniques such as Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and electron microscopy are discussed to understand nanoparticle structure and surface chemistry. Finally, the challenges and future prospects of plant-mediated nanoparticle synthesis are highlighted.

1. Introduction

Nanotechnology has significantly transformed modern materials science by enabling the development of materials with dimensions between 1 and 100 nm. Materials at this scale exhibit novel physical and chemical properties that differ significantly from those of bulk materials. These unique properties arise mainly from quantum size effects and the extremely high surface-to-volume ratio of nanoparticles.

Nanoparticles are widely used in a variety of applications including catalysis, energy storage, environmental remediation, sensors, and biomedical systems. In energy storage technologies, nanomaterials are used as electrode materials in batteries and supercapacitors because they provide shorter ion diffusion paths and higher active surface area. In biomedical applications, nanoparticles are used for targeted drug delivery, antimicrobial therapy, and diagnostic imaging.

Despite these advantages, traditional nanoparticle synthesis techniques such as chemical reduction, thermal decomposition, and sol-gel synthesis often involve toxic reagents and high energy consumption. These processes may generate hazardous waste and pose risks to both the environment and human health.

To address these limitations, researchers have developed environmentally friendly synthesis methods known as green synthesis approaches. Green synthesis involves the use of biological resources such as plants, microorganisms, and biomolecules to produce nanoparticles under mild conditions.

Plant-mediated synthesis has become particularly popular because plant extracts contain a wide range of bioactive compounds capable of reducing metal ions and stabilizing nanoparticles. Phytochemicals such as flavonoids, polyphenols, alkaloids, proteins, enzymes, and sugars participate in the nanoparticle formation process.

During synthesis, certain biomolecules attach to the nanoparticle surface and act as capping agents. These molecules regulate nanoparticle growth, prevent aggregation, and provide functional groups that influence nanoparticle interactions with the surrounding environment.

Understanding the role of natural capping agents is therefore essential for designing nanomaterials with controlled properties for energy storage and biomedical applications.

2. Graphical Abstract Description

The graphical abstract of this review illustrates the process of plant-mediated nanoparticle synthesis. Plant extracts containing phytochemicals interact with metal salt precursors to reduce metal ions into nanoparticles. During this process, phytochemicals simultaneously adsorb onto nanoparticle surfaces and act as natural capping agents. The capped nanoparticles exhibit enhanced stability and functional properties, enabling applications in energy storage devices and biomedical technologies.

3. Green Synthesis of Nanoparticles

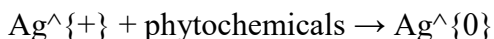
Green synthesis is an eco-friendly approach to nanoparticle production that utilizes biological materials as reducing and stabilizing agents. In plant-mediated synthesis, aqueous extracts of leaves, fruits, roots, or peels are mixed with metal salt solutions such as silver nitrate, chloroauric acid, or zinc nitrate.

The synthesis process generally occurs in three stages:

Reduction of Metal Ions

Phytochemicals present in plant extracts donate electrons to metal ions and reduce them into neutral metal atoms.

Example reaction:



Nucleation

Reduced metal atoms aggregate to form small clusters known as nuclei.

Growth and Stabilization

Additional atoms attach to nuclei to form nanoparticles, while biomolecules adsorb onto the surface and stabilize the particles.

Green synthesis offers several advantages including:

- Eco-friendly synthesis process
- Low energy requirements
- Reduced toxicity
- Biocompatibility
- Cost-effectiveness

These advantages make green synthesis suitable for large-scale nanomaterial production.

4. Role of Natural Capping Agents

Capping agents are molecules that bind to the surface of nanoparticles during synthesis. They play several critical roles in determining nanoparticle characteristics.

Size Control

Capping molecules attach to specific crystal faces and regulate nanoparticle growth, resulting in uniform particle sizes.

Prevention of Aggregation

Nanoparticles possess high surface energy and tend to aggregate. Capping agents form protective layers that provide steric or electrostatic repulsion between particles.

Surface Functionalization

Surface-bound biomolecules introduce functional groups such as hydroxyl and carboxyl groups that enable chemical reactions and biological interactions.

Stability Enhancement

Capping agents improve nanoparticle stability in solution and protect them from oxidation or degradation.

5. Phytochemicals Responsible for Capping

Several types of phytochemicals present in plant extracts contribute to nanoparticle stabilization.

Polyphenols

Polyphenols are strong antioxidants that reduce metal ions and stabilize nanoparticles through hydroxyl groups.

Flavonoids

Flavonoids participate in electron transfer reactions and bind to nanoparticle surfaces.

Proteins

Proteins provide steric stabilization by forming protective layers around nanoparticles.

Organic Acids

Organic acids such as citric acid provide electrostatic stabilization through negatively charged carboxyl groups.

Polysaccharides

Polysaccharides improve nanoparticle dispersion and biocompatibility.

6. Plant Sources Used as Natural Capping Agents

Various plant extracts have been used in green nanoparticle synthesis.

Plant Source	Major Phytochemicals	Nanoparticles	Applications
Neem	Terpenoids, flavonoids	Ag, Au	Antimicrobial
Turmeric	Curcumin	Au, Ag	Anticancer
Ginger	Gingerols	ZnO	Antioxidant
Garlic	Sulfur compounds	Ag	Antibacterial

Lemon	Citric acid	Au	Catalysis
Orange peel	Pectin	Fe ₃ O ₄	Energy storage
Papaya	Phenolic acids	Ag	Drug delivery
Chilli	Capsaicin	ZnO	Antimicrobial
Green tea	Catechins	Ag	Antioxidant
Aloe vera	Polysaccharides	Au	Biomedical
Tulsi	Eugenol	Ag	Antibacterial
Moringa	Phenolics	Fe ₃ O ₄	Catalysis

Different phytochemical compositions influence nanoparticle size, shape, and stability.

7. Mechanism of Capping

Natural biomolecules bind to nanoparticle surfaces through functional groups such as:

- Hydroxyl (–OH)
- Carboxyl (–COOH)
- Amine (–NH₂)
- Carbonyl (C=O)

These interactions produce:

- Steric stabilization
- Electrostatic stabilization
- Surface functionalization

The result is a stable nanoparticle suspension with enhanced functional properties.

8. Energy Storage Applications

Nanomaterials synthesized using plant extracts have demonstrated significant potential in electrochemical energy storage devices.

Supercapacitors

Metal oxide nanoparticles such as MnO_2 , NiO , and Fe_3O_4 synthesized through green methods provide high surface area and improved conductivity.

Lithium-Ion Batteries

Nanoparticles improve electrode stability and enhance charge transport in battery systems.

Electrocatalysis

Surface functional groups introduced by capping agents enhance catalytic activity in fuel cells and hydrogen evolution reactions.

9. Supercapacitor Performance Comparison

Nanomaterial	Plant Extract	Specific Capacitance (F/g)
MnO_2	Lemon extract	320
NiO	Neem extract	410
Fe_3O_4	Orange peel extract	280
ZnO	Ginger extract	210
CuO	Aloe vera extract	260
Co_3O_4	Green tea extract	340

These values indicate that plant-capped nanoparticles exhibit high electrochemical performance due to improved conductivity and surface area.

10. Biomedical Applications

Plant-capped nanoparticles exhibit excellent biomedical potential.

Antimicrobial Activity

Silver nanoparticles synthesized using plant extracts show strong antibacterial effects against pathogens such as *E. coli* and *S. aureus*.

Anticancer Applications

Certain phytochemicals enhance nanoparticle anticancer activity by inducing oxidative stress and apoptosis in cancer cells.

Drug Delivery

Surface-functionalized nanoparticles enable controlled drug release and targeted delivery.

Biosensing

Nanoparticles are used in biosensors for detecting glucose, DNA, and disease biomarkers.

11. Characterization Techniques

FTIR (Fourier Transform Infrared Spectroscopy)

Wavenumber (cm ⁻¹)	Functional Group	Role
~3400	O–H stretching	Polyphenol reduction
~2920	C–H stretching	Organic compounds
~1650	C=O stretching	Flavonoid binding
~1540	N–H bending	Protein stabilization
~1400	COO ⁻ stretching	Carboxylic acid interaction
~1100	C–O stretching	Phenolic compounds

XRD

XRD identifies crystalline phases and determines nanoparticle size.

SEM

SEM provides information about nanoparticle morphology.

TEM

TEM reveals particle size distribution and internal structure.

12. Challenges and Future Perspectives

Despite its advantages, green nanoparticle synthesis faces several challenges:

- Variability in plant extract composition
- Limited control over nanoparticle size
- Difficulty in large-scale production
- Lack of standardized protocols

Future research should focus on identifying specific biomolecules responsible for nanoparticle stabilization and developing scalable green synthesis methods.

13. Conclusion

Natural capping agents derived from plant extracts play a crucial role in the green synthesis of nanoparticles. These biomolecules regulate nanoparticle growth, prevent aggregation, and enhance surface functionality. As a result, plant-capped nanoparticles demonstrate improved performance in energy storage systems and biomedical applications.

Green nanotechnology therefore represents a promising approach for developing sustainable nanomaterials for future technological advancements.

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