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GREEN SYNTHESIS OF LOTUS SEED MEDIATED COPPER NITRATE NANOPARTICLES AND THEIR ACTIVITY: A REVIEW

Arshiya begum K, Keerthana G, Tamil Selvan P and M. I. Niyas Ahamed*

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Abstract

Green synthesis of nanoparticles has emerged as a sustainable and eco-friendly method in nanotechnology. This review focuses on the synthesis of copper nitrate nanoparticles (CuNPs) using lotus seed extract and explores their physicochemical properties, stability, and applications. The lotus seed-mediated synthesis offers a bio-reductive pathway, producing nanoparticles with significant biological activities. These nanoparticles demonstrate potential applications in antimicrobial, antioxidant, and catalytic activities, with reduced toxicity and environmental impact compared to conventional methods.

Keywords: Green synthesis, Lotus seed, Copper nitrate nanoparticles, antimicrobial activity, Catalysis, Nanotechnology.

1 Introduction

Nanotechnology has emerged as a promising field for the development of novel materials with unique properties. Among various nanomaterials, copper nanoparticles (CuNPs) have garnered significant attention due to their excellent electrical, thermal, and antimicrobial properties. However, the conventional methods for synthesizing CuNPs involve the use of toxic chemicals, high energy consumption, and generation of hazardous waste.

Lotus seeds (Nelumbo nucifera) shown in Figure-1 are rich in bioactive compounds such as flavonoids, alkaloids, and saponins, making them ideal reducing and stabilizing agents for nanoparticle synthesis. Copper nitrate, a precursor to CuNPs, is widely used in applications ranging from electronics to biomedicine due to its catalytic and antimicrobial properties. Combining lotus seed extract with copper nitrate enables a greener synthesis route, producing nanoparticles with desirable properties (1-3).

Nanotechnology is rapidly transforming science and industry, offering innovative solutions to longstanding challenges. Among various advancements, the synthesis of nanoparticles has garnered significant attention for its applications in healthcare, environmental remediation, and material sciences.

Figure-1

The transition to eco-friendly and sustainable synthesis methods, termed "green synthesis," aligns with global efforts to minimize environmental impact and reduce

*Corresponding author: email driniyasahamed@shctpt.edu,
Department of Biochemistry, Sacred Heart College (Autonomous),
irupattur - 635 601, Tamilnadu, India,

chemical toxicity.

The use of plant extracts in nanoparticle synthesis is a groundbreaking approach that eliminates the need for hazardous reducing agents. Lotus seeds (Nelumbo nucifera), renowned for their rich phytochemical composition, are particularly promising in green synthesis. Their bioactive compounds—such as alkaloids, flavonoids, and phenolic acids—not only facilitate the reduction of metal ions to nanoparticles but also stabilize the particles, ensuring uniform size and enhanced functionality.

Copper nanoparticles (CuNPs), synthesized from copper nitrate precursors, are of special interest due to their multifaceted applications. Copper's inherent antimicrobial, catalytic, and electrical properties make it a highly versatile material in industries ranging from biomedicine to electronics. Incorporating lotus seed extract in CuNP synthesis not only provides a sustainable method but also enhances the biocompatibility and activity of the nanoparticles.

Moreover, lotus seeds are a renewable resource, widely available in regions with aquatic ecosystems. Their use represents a cost-effective and scalable method for nanoparticle production. This green synthesis pathway is particularly advantageous in developing multifunctional nanoparticles with reduced environmental footprint, supporting advancements in sustainable nanotechnology.

In this review, we examine the mechanisms underlying the green synthesis of copper nitrate nanoparticles using lotus seed extract. We explore the phytochemical interactions, characterize the resulting nanoparticles, and discuss their broad-spectrum activities. These insights highlight the potential for expanding green synthesis techniques and integrating them into commercial and industrial applications (4-8).

Mechanism of Synthesis

The green synthesis of copper nitrate nanoparticles (CuNPs) using lotus seed extract involves multiple interconnected steps driven by the bioactive compounds in the extract. These steps include reduction, nucleation, growth, stabilization, and capping of nanoparticles. Here's a detailed explanation of the mechanism:

Table 1:

Phytochemical Components in Lotus Seed Extract and Their Role in Nanoparticle Synthesis

Phytochemical	Role in Synthesis	Stabilizing Function
Alkaloids	Reducing agent for copper ions	Stabilization of nanoparticles
Flavonoids	Enhance reduction kinetics	Capping agent
Phenolic Compounds	Act as both reducing and stabilizing agents	Prevent agglomeration
Saponins	Facilitate nanoparticle dispersion	Increase solubility

Preparation of Precursor and Extract

- Copper Nitrate Precursor: Copper nitrate [$Cu(NO_3)_2$] serves as the primary source of copper ions (Cu^{2+}). It is dissolved in water to prepare a uniform aqueous solution.
- Lotus Seed Extract: Lotus seeds (Nelumbo nucifera) are processed to obtain an extract rich in phytochemicals. This involves drying, grinding, and boiling in distilled water, followed by filtration to isolate bioactive compounds like flavonoids, alkaloids, and phenolics.

2. Reduction of Copper Ions

- The phytochemicals in lotus seed extract act as natural reducing agents. They donate electrons to Cu^{2+} ions, converting them into elemental copper (Cu^0) atoms.
- Phenolic compounds and flavonoids play a critical role in this reduction process by stabilizing reactive intermediates.

3. Nucleation

- The reduced Cu^0 atoms aggregate to form tiny clusters, initiating the nucleation process.
- This stage is critical, as it determines the number of nanoparticles formed and their size distribution. Rapid nucleation leads to smaller nanoparticles, while slower nucleation results in larger aggregates.

4. Growth of Nanoparticles

- The nascent nuclei grow as more Cu^0 atoms are reduced and deposit on the surface.
- Growth mechanisms are influenced by factors such as temperature, pH, and the concentration of both copper ions and the lotus seed extract.

5. Stabilization

- To prevent agglomeration, the bioactive compounds in the lotus seed extract stabilize the nanoparticles by adhering to their surfaces.
- Flavonoids and alkaloids form a protective layer around the nanoparticles, ensuring colloidal stability and uniform dispersion.

6. Capping and Surface Functionalization

- The functional groups (hydroxyl, carboxyl, etc.) present in the phytochemicals act as capping agents.
- These groups enhance the biocompatibility and reactivity of the nanoparticles, making them suitable for specific applications like catalysis or biomedical use.

Key Factors Affecting the Mechanism

- Concentration of Extract: Higher concentrations provide more reducing agents, leading to smaller and more stable nanoparticles.
- Reaction Temperature: Elevated temperatures accelerate reduction but may lead to particle aggregation if not controlled.
- pH Levels: An optimal pH range ensures efficient reduction and stabilization.
- Reaction Time: Prolonged reaction time enhances growth and stabilization but may result in larger particles.

This green synthesis mechanism demonstrates how nature-derived components can effectively reduce and stabilize nanoparticles. The process is not only environmentally friendly but also produces nanoparticles with enhanced biocompatibility and functionality, suitable for diverse industrial and medical applications (9-13).

Characterization of Nanoparticles

1. UV-Vis Spectroscopy: The surface plasmon resonance (SPR) peaks confirm the formation of CuNPs.
2. Scanning Electron Microscopy (SEM): Reveals spherical morphology and uniform distribution of the nanoparticles.
3. Fourier Transform Infrared Spectroscopy (FTIR): Identifies functional groups in the lotus seed extract responsible for reduction and stabilization.
4. X-ray Diffraction (XRD): Determines the crystalline nature of the synthesized nanoparticles.

Table 2:

Characterization Techniques Used for Copper Nitrate Nanoparticles

Technique	Purpose	Information Obtained
UV-Vis Spectroscopy	Identify formation of CuNPs	Surface plasmon resonance peaks
SEM (Scanning Electron Microscopy)	Determine morphology	Size, shape, surface texture
XRD (X-ray Diffraction)	Determine crystalline structure	Lattice and phase identification
FTIR (Fourier Transform Infrared Spectroscopy)	Identify functional groups in capping agents	Role of phytochemicals
DLS (Dynamic Light Scattering)	Analyze size distribution	Polydispersity index (PDI)

Applications of Lotus Seed-Mediated CuNPs

Lotus seed-mediated CuNPs offer a range of applications across various fields due to their eco-friendly synthesis, enhanced biocompatibility, and functional properties. Below are detailed points on their potential uses:

1. Biomedical Applications

- Antimicrobial Agents: The CuNPs exhibit potent activity against a broad spectrum of microbes, including bacteria, fungi, and viruses, making them suitable for wound dressings and infection control.
- Drug Delivery Systems: Functionalized CuNPs can serve as carriers for targeted drug delivery, enhancing therapeutic efficiency with reduced side effects.
- Biosensors: These nanoparticles can be employed in biosensors for the rapid detection of diseases due to their high surface reactivity and electrical conductivity.
- Cancer Therapy: The nanoparticles' ability to generate reactive oxygen species (ROS) makes them potential candidates for photothermal and photodynamic therapies.

Table 3:

Potential Applications of Copper Nanoparticles Synthesized from Lotus Seed Extract

Application Field	Specific Use	Key Properties
Biomedical	Antimicrobial coatings, drug delivery	Biocompatibility, low toxicity
Catalysis	Organic synthesis, pollutant degradation	High catalytic activity
Environmental Remediation	Water purification, pollutant degradation	Eco-friendly, reusability
Agriculture	Pest control formulations	Targeted action, biodegradable

2. Environmental Applications

- Water Purification: CuNPs synthesized via lotus seed extract can degrade organic pollutants and remove heavy metals, offering a sustainable solution for wastewater treatment.
- Antifouling Coatings: Applied to marine and industrial surfaces, these nanoparticles prevent microbial and biofilm growth.
- Air Pollution Control: CuNPs can catalyze the breakdown of harmful gases like CO and NOx, contributing to air quality improvement.

3. Agricultural Applications

- Pesticides and Fertilizers: CuNPs can act as nano-pesticides to combat plant pathogens and as fertilizers to supply micronutrients.
- Soil Enrichment: The nanoparticles enhance soil quality and microbial activity, promoting sustainable agriculture.
- Seed Treatment: Treating seeds with CuNPs boosts germination rates and enhances crop resistance to environmental stressors.

4. Industrial Applications

- Catalysis: The high catalytic activity of CuNPs is used in organic transformations, pollutant degradation, and fuel cell reactions.
- Electronics: CuNPs are utilized in the development of conductive inks and coatings for printed electronics.
- Energy Storage: Their ability to enhance electron transfer efficiency makes them suitable for use in batteries and supercapacitors.
- Textile Industry: The nanoparticles are used to impart antimicrobial and antifouling properties to fabrics.

5. Cosmetic Applications

- Skincare Products: The antioxidant properties of CuNPs make them ideal for anti-aging and skin-repair formulations.
- Sunscreens: CuNPs can be incorporated into sunscreens for UV protection and as an antimicrobial additive.

6. Food Industry

- Food Packaging: CuNPs can enhance the shelf life of food by preventing microbial contamination in packaging materials.
- Food Preservation: Their antimicrobial properties are applied in coatings to extend the freshness of perishable goods.

- Nutritional Supplements: Copper is an essential trace element, and CuNPs can be used to fortify foods or beverages.

7. Renewable Energy Applications

- Photocatalysis: CuNPs derived from lotus seeds can facilitate hydrogen production and solar energy harvesting.
- Fuel Cells: Their role in catalyzing reactions improves the efficiency and sustainability of fuel cells.

8. Material Science

- Nanocomposites: CuNPs are embedded in polymer matrices to improve material strength and durability.
- Anti-corrosive Coatings: These nanoparticles protect metals from oxidative damage, increasing their lifespan in harsh environments.

9. Biomedical Diagnostics

- Imaging Agents: CuNPs are used in bio-imaging due to their optical properties and ability to bind to specific biological targets.
- Diagnostic Kits: Functionalized CuNPs improve the sensitivity of diagnostic assays for detecting biomolecules and pathogens.

These diverse applications highlight the potential of lotus seed-mediated CuNPs in contributing to sustainable and innovative solutions across industries (14-18).

Challenges in Green Synthesis

Green synthesis, while environmentally friendly and sustainable, faces several challenges that limit its widespread adoption and industrial scalability. Here are detailed points addressing these challenges:

1. Standardization of Procedures

- Variability in Extract Composition: The phytochemical content in plant extracts can vary based on factors such as species, growth conditions, harvest time, and extraction methods, leading to inconsistent results.
- Lack of Protocol Uniformity: Differences in synthesis methods (e.g., temperature, pH, and reaction time) make it difficult to standardize the production process across different research groups or industries.

2. Control Over Nanoparticle Properties

- Size and Shape Control: Achieving uniform nanoparticle size and morphology remains a significant challenge due to the complex interaction of bioactive compounds during synthesis.
- Polydispersity Issues: Green synthesis often results in nanoparticles with a broad size distribution, which can limit their specific applications (19-22).

3. Scalability

- Laboratory to Industrial Scale: Scaling up green synthesis methods for commercial production is difficult due to the complex and sensitive reaction conditions.
- Cost Constraints: Although raw materials like plant extracts are inexpensive, scaling up may require large quantities of biomass, increasing operational costs.

4. Limited Understanding of Mechanisms

- Reaction Pathways: The exact mechanisms of nanoparticle reduction and stabilization by plant extracts are not fully understood, leading to challenges in optimizing the process.
- Phytochemical Roles: While many bioactive compounds are involved, identifying which specific molecules act as reducers, stabilizers, or capping agents is challenging.

5. Stability and Shelf Life

- Colloidal Stability: Nanoparticles synthesized via green methods may face aggregation or precipitation over time due to insufficient stabilization.
- Short Shelf Life: These nanoparticles often require additional processing to ensure long-term stability, which can add to production costs and complexity.

6. Limited Applicability

- Industrial Limitations: Green-synthesized nanoparticles may lack the robustness needed for certain industrial applications, such as extreme temperature or pressure conditions.
- Surface Functionalization: The natural capping agents from plant extracts might limit further surface modifications, which are often required for specific applications.

7. Environmental and Ethical Concerns

- Extraction Process: While green synthesis avoids harmful chemicals, the extraction of plant-based materials may involve solvents or processes that are not entirely eco-friendly.
- Sustainability Issues: Overharvesting of certain plants for nanoparticle synthesis can lead to ecological imbalances and depletion of natural resources.

8. Analytical Challenges

- Characterization Complexity: Green-synthesized nanoparticles often have complex surface chemistries due to capping agents, making their characterization and reproducibility more challenging.
- Detection of Impurities: The presence of organic residues or other impurities from plant extracts can interfere with the characterization process.

9. Regulatory and Quality Assurance

- Regulatory Barriers: Many countries lack clear regulatory frameworks for green-synthesized nanoparticles, which delays their commercial adoption.
- Quality Control: Ensuring batch-to-batch consistency in green synthesis is more difficult than in chemical or physical synthesis methods.

10. Competing Synthetic Methods

- Comparison with Traditional Methods: Chemical and physical methods, while less eco-friendly, are often more reliable, faster, and scalable, posing competition to green synthesis approaches.

Addressing these challenges requires multidisciplinary efforts, including advancements in biotechnology, process engineering, and regulatory science. By overcoming these hurdles, green synthesis can become a mainstream, sustainable approach to nanoparticle production across industries (23-35).

Table 4:

Benefits and Challenges of Lotus Seed-Mediated Green Synthesis

Category	Benefits	Challenges
Environmental Sustainability	Eliminates toxic chemicals	Optimization of reproducibility
Cost Efficiency	Inexpensive raw materials	Scaling up for industrial production
Biocompatibility	Safer for biomedical applications	Stability in extreme conditions
Efficiency	Produces highly active nanoparticles	Control over particle size

Conclusion

The green synthesis of copper nitrate nanoparticles using lotus seed extract represents a sustainable approach to nanotechnology. The bio-reductive properties of lotus seed compounds not only simplify the synthesis process but also impart biocompatibility to the nanoparticles. These CuNPs hold immense potential in diverse applications, from medicine to environmental science. Future research should focus on optimizing synthesis protocols, scaling up production, and exploring advanced applications.

The green synthesis of copper nitrate nanoparticles (CuNPs) using lotus seed extract exemplifies an innovative approach in sustainable nanotechnology. By leveraging the bioactive compounds present in lotus seeds, this method eliminates the need for hazardous chemicals, making it an eco-friendly alternative to traditional synthesis processes. The simplicity, cost-effectiveness, and biocompatibility of this method hold immense promise for industrial scalability and real-world applications.

The multifaceted potential of these nanoparticles spans a wide range of industries. In the biomedical field, CuNPs synthesized via lotus seed extract exhibit potent antimicrobial and antioxidant properties, making them ideal candidates for drug delivery systems and therapeutic agents. In environmental science, their catalytic efficiency offers solutions for pollution remediation and wastewater treatment. Furthermore, their potential in electronics and energy storage aligns with the growing demand for sustainable materials in advanced technologies.

Despite these advantages, challenges remain. Optimizing synthesis parameters to achieve consistent nanoparticle size and morphology is critical for application-specific performance. Moreover, expanding the understanding of their long-term stability and toxicity is essential to ensure safety and efficacy in diverse applications. Future research should focus on enhancing the scalability of the synthesis process and exploring synergistic effects when combining lotus seed-mediated CuNPs with other materials.

In conclusion, the integration of green chemistry principles in nanoparticle synthesis not only reduces environmental impact but also enhances the functionality of the resulting materials. Lotus seed-mediated CuNP synthesis represents a harmonious blend of traditional knowledge and modern technology, paving the way for sustainable advancements in nanotechnology. This approach serves as a model for further exploration of plant-based nanoparticle synthesis and their transformative impact across various scientific disciplines.

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