

Green Synthesis of Copper Oxide Nanoparticles Using Plant Extracts and Their Applications: A Comprehensive Review

Dr. Sajid F. Shaikh, Dr. Gurumit Wadhava, Swapnali Patil, Parshuram Mane

Department of Chemistry, Anjuman Islam Janjira, Degree College of Science, Murud-Janjira Raigad, Maharashtra

Department of Chemistry, Veer Wajekar Arts, Commerce & Science College, Phunde-Uran Raigad, Maharashtra

sajidoshaikh@gmail.com

Abstract: *Green synthesis of copper oxide nanoparticles (CuO NPs) using plant extracts has gained significant attention as an environmentally benign alternative to conventional physical and chemical methods. Plant-derived phytochemicals such as flavonoids, phenolics, and terpenoids play a crucial role in reducing and stabilizing metal ions into nanoparticles. This review provides a comprehensive overview of synthesis mechanisms, influencing parameters, and characterization techniques. Recent study highlight improved photocatalytic degradation efficiency, antimicrobial activity, and biomedical applications. Furthermore, challenges and future perspectives toward industrial-scale production and commercialization are discussed*

Keywords: *Copper oxide nanoparticles; Green synthesis; Plant extracts; Phytochemicals; Nanotechnology; Photocatalysis; Antimicrobial activity.*

I. INTRODUCTION

Nanotechnology has emerged as one of the most rapidly advancing fields of modern science, enabling the design and development of materials at the nanoscale (1–100 nm) with unique physicochemical properties. Green nanotechnology, in particular, has gained significant attention due to its emphasis on sustainable and environmentally benign approaches for synthesizing nanomaterials. This multidisciplinary domain integrates principles from physics, chemistry, biology, medicine, and materials science to develop innovative solutions for technological and societal challenges.

Nanoparticles (NPs) serve as the fundamental building blocks of nanotechnology. Various types of nanoparticles have been synthesized, including those composed of gold, silver, zinc, titanium, copper, and iron. Among these, copper nanoparticles (Cu NPs) and copper oxide nanoparticles (CuO NPs) have attracted considerable interest due to their cost-effectiveness, natural abundance, and versatile applications in nanoscience and nanomedicine. Copper (atomic number 29) is a soft, malleable, and ductile metal with excellent electrical and thermal conductivity. [1,2, 11-15]

Compared to noble metal nanoparticles such as gold (Au), silver (Ag), and platinum (Pt), copper-based nanoparticles are significantly more economical, making them suitable for large-scale industrial applications. Additionally, copper and its composites exhibit strong biocidal properties, which have led to their widespread use in healthcare, antimicrobial coatings, and agricultural pesticides. [2] Conventional methods for synthesizing Cu nanoparticles, including chemical reduction, sol-gel, and hydrothermal techniques, often involve toxic chemicals, hazardous reducing agents, and organic solvents. These methods pose environmental and health risks due to the generation of toxic byproducts and high energy requirements. The presence of residual toxic substances in nanoparticles further limits their biomedical applicability.

To overcome these limitations, green synthesis approaches have been developed as sustainable alternatives. Inspired by the early conceptualization of nanotechnology by Richard Feynman, researchers have increasingly focused on plant-



mediated synthesis methods. These methods utilize plant extracts as natural reducing and stabilizing agents, eliminating the need for hazardous chemicals and complex procedures. [3,4]

Green synthesis using plant extracts offers several advantages, including simplicity, cost-effectiveness, scalability, and environmental compatibility. Unlike microbial synthesis, which requires stringent culture conditions, plant-based synthesis is straightforward and does not require aseptic conditions. The phytochemicals present in plant extracts—such as flavonoids, phenolics, alkaloids, terpenoids, and proteins—play a crucial role in the reduction of metal ions and stabilization of nanoparticles. [5, 16-17] This bottom-up approach involves redox reactions under mild conditions, often at room temperature and atmospheric pressure, using water as a solvent. Such conditions make the process energy-efficient and suitable for large-scale applications. Furthermore, green synthesized nanoparticles exhibit enhanced biocompatibility, making them suitable for medical and pharmaceutical applications. [4,6] Among various plant species, *Murraya koenigii* (curry leaf plant), belonging to the Rutaceae family, has emerged as a promising candidate for nanoparticle synthesis due to its rich phytochemical composition and medicinal properties. Traditionally, *M. koenigii* has been used in Ayurveda for treating various ailments, including wound healing and infections. The plant contains a diverse range of bioactive compounds such as carbazole alkaloids, flavonoids, phenolics, quinones, terpenoids, carotenoids, and vitamins. [7] These phytochemicals not only facilitate the reduction of metal ions into nanoparticles but also act as capping agents, enhancing the stability and functionality of the synthesized nanoparticles. The complex mixture of phenols, quinones, and organic acids in *M. koenigii* extract enables efficient conversion of metal ions into nanostructured materials. [8] Recent studies have demonstrated the successful biosynthesis of various nanoparticles using *M. koenigii* extract, including silver (Ag), zinc oxide (ZnO), iron oxide (Fe₃O₄), and copper-based nanoparticles. These nanoparticles have shown promising applications in antimicrobial activity, catalysis, biomedical applications, and hydrogen production. Furthermore, advanced nanomaterials such as Co-doped NiO have also been synthesized using *M. koenigii*, highlighting its versatility in green nanotechnology. [9] Given the increasing demand for sustainable nanomaterials, the green synthesis of copper-based nanoparticles using plant extracts represents a promising and rapidly evolving area of research. This review focuses on the synthesis, characterization, and applications of CuO nanoparticles derived from plant sources, with particular emphasis on *Murraya koenigii*. [10]

II. GREEN SYNTHESIS OF CUO NANOPARTICLES

Principle of Green Synthesis: Green synthesis involves the reduction of Cu²⁺ ions into CuO nanoparticles using plant-derived biomolecules. These biomolecules act as:

- Reducing agents
- Stabilizing/capping agents

Phytochemicals such as flavonoids and phenolics donate electrons to reduce copper ions and stabilize nanoparticles.

Mechanism of Formation: The mechanism generally involves:

1. Chelation of Cu²⁺ ions with phytochemicals
2. Reduction to Cu atoms
3. Oxidation to CuO nanoparticles
4. Stabilization via capping agents

Plant extracts enable rapid synthesis under mild conditions, often at room temperature.

General Synthetic Procedure:

- Preparation of plant extract (leaves, peel, seeds)
- Mixing with copper salt solution (CuSO₄, Cu(NO₃)₂)
- Adjustment of pH and temperature
- Formation indicated by color change
- Purification via centrifugation and drying

Factors Affecting Green Synthesis:

Key parameters influencing nanoparticle formation include:



- pH: Neutral to alkaline pH favors stability
- Temperature: Higher temperature accelerates reaction
- Extract concentration: Controls particle size and morphology
- Precursor type and concentration: Affects crystallinity and yield

Optimization of these parameters is crucial for controlled synthesis.

Characterization Techniques:

CuO nanoparticles are characterized using:

UV-Visible Spectroscopy: Confirms nanoparticle formation through characteristic absorption peaks.

FTIR Analysis: Identifies functional groups responsible for reduction and stabilization.

XRD Analysis: Determines crystalline structure and phase purity.

SEM and TEM: Provide morphology, size, and shape of nanoparticles.

EDX Analysis: Confirms elemental composition.

These techniques confirm nanoparticle formation, size distribution, and stability.

III. APPLICATIONS OF CUO NANOPARTICLES

Catalytic Applications: CuO nanoparticles are widely used as catalysts in reduction and oxidation reactions. They show excellent performance in the reduction of nitrophenols and organic pollutants.

Photocatalytic Applications: CuO nanoparticles exhibit strong photocatalytic activity for degradation of dyes such as methylene blue, Congo red, and rhodamine B. Recent studies report degradation efficiencies up to 99%.

Antimicrobial Activity: CuO nanoparticles exhibit antibacterial activity against Gram-positive and Gram-negative bacteria due to ROS generation and membrane damage.

Biomedical Applications: Applications include drug delivery, anticancer activity, biosensors, and wound healing.

Environmental Applications: CuO nanoparticles are used for wastewater treatment, heavy metal removal, and degradation of toxic pollutants.

Industrial Applications: Applications include sensors, catalysts, electronics, and energy storage devices.

IV. CONCLUSION

Green synthesis of CuO nanoparticles using plant extracts offers a sustainable and efficient route for nanomaterial production. The integration of phytochemistry with nanotechnology enables the development of multifunctional nanoparticles with applications in catalysis, environmental remediation, and medicine. Continued research and technological advancements will facilitate large-scale adoption of this eco-friendly approach.

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