

COPPER NANOPARTICLES SYNTHESIZED FROM PHYTOCOMPOUNDS: A COMPREHENSIVE REVIEW**Sushma Prajapati*, Satkar Prasad****RKDF School of Pharmaceutical Sciences, Bhabha University, Bhopal (M.P.)***Corresponding Author's E mail: srashtisahu56@gmail.com

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ABSTRACT

Copper nanoparticles (CuNPs) have emerged as a versatile class of nanomaterials due to their unique physicochemical properties, high surface area, and broad-spectrum biological activities. Traditional chemical and physical methods for synthesizing CuNPs often involve toxic reagents or require high energy inputs, limiting their applicability, particularly in biomedical fields. Phytochemical-mediated synthesis offers a green, cost-effective, and sustainable alternative, using plant-derived compounds such as polyphenols, flavonoids, terpenoids, alkaloids, and proteins as natural reducing and stabilizing agents. This review comprehensively discusses the green synthesis of CuNPs, methods of characterization, biological activities, and potential applications in medicine, agriculture, and industry, while also addressing the challenges and future prospects of this emerging nanotechnology.

Keywords: Copper nanoparticles, phytochemicals, X-ray diffraction, UV-Visible spectroscopy, Green synthesis.

INTRODUCTION

Nanotechnology has transformed scientific research and industrial applications, enabling the manipulation of materials at the molecular and atomic levels to produce nanostructures with unique properties¹. Among metal nanoparticles, copper nanoparticles (CuNPs) have gained significant attention due to their high electrical conductivity, catalytic activity, and antimicrobial properties. However, conventional methods for CuNP synthesis, including chemical reduction, electrochemical deposition, and physical vapor deposition, often involve hazardous chemicals, high temperatures, or pressure conditions, which restrict their use in biomedical and environmentally sensitive applications².

Green synthesis, particularly using plant-based phytochemicals, provides a promising alternative. Plant-derived secondary metabolites such as polyphenols, flavonoids, terpenoids, and alkaloids serve as natural reducing and capping agents. These compounds reduce Cu²⁺ ions to copper nanoparticles while

simultaneously stabilizing them, preventing aggregation, and enhancing their biocompatibility. This eco-friendly approach minimizes environmental hazards, reduces production costs, and produces nanoparticles suitable for biomedical applications ³.

2. Green Synthesis of Copper Nanoparticles Using Phytochemicals

The synthesis of copper nanoparticles using plant extracts involves the utilization of bioactive phytochemicals, which facilitate the reduction of copper salts and control particle formation. Polyphenols and flavonoids, abundant in most plant extracts, play a critical role by donating electrons to copper ions and stabilizing the resulting nanoparticles through hydrogen bonding. Terpenoids and alkaloids contribute to the nucleation process, influencing the size and shape of nanoparticles. Proteins, polysaccharides, and other macromolecules in plant extracts form capping layers around the nanoparticles, preventing aggregation and enhancing colloidal stability⁴.

Typically, the green synthesis process begins with the preparation of a plant extract through boiling, maceration, or solvent extraction. A copper salt precursor, commonly copper sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), is added to the extract under ambient or controlled conditions ⁵.

The reduction of copper ions is often indicated by a visible color change in the solution, such as from blue to brown or green. The nanoparticles are then characterized using analytical techniques including UV-Vis spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and Fourier-transform infrared spectroscopy (FTIR) ⁶.

3. Characterization of Phytochemical-Mediated Copper Nanoparticles

Characterization of CuNPs is essential to confirm their formation, size, morphology, and functional properties. UV-Visible spectroscopy is commonly used to detect the surface plasmon resonance (SPR) peak of copper nanoparticles, typically observed between 560–600 nm, confirming nanoparticle formation. X-ray diffraction (XRD) analysis provides information about the crystalline structure and phase composition, often revealing peaks corresponding to Cu, CuO, and Cu₂O planes. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are used to evaluate morphology and particle size, typically showing spherical or polyhedral shapes with size distributions ranging from 10–50 nm. Fourier-transform infrared spectroscopy (FTIR) identifies the functional groups involved in nanoparticle capping, including hydroxyl groups, carbonyl groups, and amides, which are primarily derived from the phytochemicals present in the plant extract.

These characterization techniques collectively provide insights into the structural and chemical properties of CuNPs, allowing optimization of synthesis conditions and ensuring reproducibility ⁷⁻⁹.

4. Biological Activities of Phytochemical-Mediated Copper Nanoparticles

Copper nanoparticles synthesized using phytochemicals exhibit a range of biological activities, including antimicrobial, antioxidant, anticancer, and wound healing properties.

4.1 Antimicrobial Activity

CuNPs demonstrate broad-spectrum antibacterial and antifungal activities. The antimicrobial mechanism is primarily attributed to the generation of reactive oxygen species (ROS), which induce oxidative stress in microbial cells, leading to protein denaturation, membrane damage, and cell death. Studies have shown that CuNPs synthesized from *Amaranthus tricolor* extract exhibit strong antibacterial activity against *Escherichia coli* and *Streptococcus mutans*, with activity increasing in a dose-dependent manner. Similarly, turmeric-based CuNPs incorporated into carbopol gels demonstrated significant inhibition of bacterial growth in burn wound models, confirming their potential for topical antimicrobial applications ¹⁰.

4.2 Antioxidant Activity

Phytochemical-mediated CuNPs possess antioxidant activity due to the presence of phenolic and flavonoid compounds that can scavenge free radicals. In vitro studies using DPPH and ABTS assays have demonstrated that CuNPs synthesized using plant extracts effectively neutralize reactive oxygen species, thereby reducing oxidative stress. The antioxidant property not only protects cells from damage but also contributes to wound healing by reducing inflammation and promoting tissue repair ¹¹.

4.3 Anticancer Activity

CuNPs have shown promising anticancer effects through mechanisms such as ROS generation, mitochondrial dysfunction, and apoptosis induction in cancer cells. For example, CuNPs synthesized from *Amaranthus tricolor* extract exhibited dose-dependent cytotoxicity against MCF7 breast cancer cells, with IC₅₀ values ranging from 76–84 µg/mL. The incorporation of CuNPs with bioactive phytochemicals enhances cellular uptake and increases therapeutic efficacy, making them potential candidates for targeted cancer therapies ¹².

4.4 Wound Healing and Anti-inflammatory Activity

The application of CuNPs in wound healing has been extensively explored due to their ability to promote collagen synthesis, angiogenesis, and epithelialization. When combined with curcumin or chitosan, CuNPs enhance wound closure, reduce oxidative stress, and inhibit microbial infection ¹³.

5. Applications of Phytochemical-Derived Copper Nanoparticles

Phytochemical-mediated CuNPs have diverse applications across biomedical, agricultural, and industrial sectors. In medicine, they are used for antimicrobial coatings, wound dressings, and anticancer therapies due to their biocompatibility and therapeutic potential. In agriculture, CuNPs serve as nano-fertilizers and antimicrobial sprays, enhancing crop yield and protecting plants from pathogenic infections. In environmental and industrial applications, CuNPs act as catalysts in pollutant degradation, water purification, and chemical reactions. Additionally, their incorporation in food packaging can provide antimicrobial properties, extending the shelf life of perishable goods ¹⁴.

6. Advantages of Phytochemical-Mediated Copper Nanoparticles

Green synthesis of CuNPs using phytochemicals provides several advantages over conventional methods. It is environmentally friendly, avoids hazardous chemicals, and is cost-effective. The natural capping agents derived from plant extracts enhance biocompatibility and reduce cytotoxicity, making these nanoparticles suitable for biomedical applications. Furthermore, phytochemical-mediated CuNPs exhibit multifunctional biological activities, including antimicrobial, antioxidant, anticancer, and wound healing properties, which can be synergistically enhanced by the bioactive compounds in the plant extracts ¹⁵.

7. Challenges and Future Perspectives

Despite the numerous advantages, challenges remain in the green synthesis of CuNPs. Controlling nanoparticle size, shape, and uniformity remains difficult due to the variability in plant extract composition. Stability under physiological conditions is another limitation, as aggregation can reduce efficacy. Additionally, the precise mechanisms of interaction between CuNPs and biological systems are not fully understood, limiting clinical translation ¹⁶.

Future research should focus on optimizing synthesis protocols to achieve reproducible particle characteristics, investigating the mechanistic pathways of CuNP interactions with cells, and developing targeted drug delivery systems. Combining CuNPs with other bioactive phytochemicals or polymers may enhance therapeutic efficacy and stability. Clinical studies are essential to confirm the safety and efficacy of CuNPs for biomedical applications ¹⁷.

Conclusion

Phytochemical-mediated synthesis of copper nanoparticles represents a sustainable and effective approach to generate biocompatible nanomaterials with multifunctional properties. Plant-derived compounds not only facilitate nanoparticle formation but also contribute to their biological activities,

including antimicrobial, antioxidant, anticancer, and wound healing effects. Extensive in vitro and in vivo studies highlight their potential in medicine, agriculture, and industry. With further optimization and mechanistic studies, phytochemical-derived CuNPs hold promise as safe, effective, and versatile nanomaterials for a wide range of applications.

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