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Eco-Friendly Synthesis of Copper Nanoparticles using Plant Extracts: A Review

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ABSTRACT

Copper nanoparticles (CuNPs) have attracted considerable scientific interest due to their cost-effectiveness, multifunctional properties, and wide-ranging applications in biomedical, environmental, and electronic fields. Conventional synthesis routes, however, commonly rely on hazardous reagents, energy-intensive processes, and generate environmentally harmful by-products. In response, plant-mediated green synthesis has emerged as a sustainable alternative. This review critically examines studies reported between 2011 and 2025, emphasizing the role of plant phytochemicals as natural reducing and capping agents in CuNP formation. Key synthesis parameters, characterization techniques, and application prospects are systematically discussed. Despite significant advancements—particularly in recent years—challenges related to reproducibility, oxidation stability, and large-scale implementation remain unresolved. The review concludes that the development of standardized protocols and scalable green methodologies is essential to advance plant-based CuNP synthesis toward industrial and commercial viability.

1. Introduction

In the first decade of the 2st century, nanotechnology has emerged from its theoretical and metaphorical background to be recognized as a unifying theme for modern materials science, with applications extending from microelectronics and sensing to interdisciplinary medical science, such that there are virtually no disciplines where it does not play a role [1,2]. At the nanoscale, metallic nanoparticles (MNPs) have received great attention due to their peculiar quantum confinement effects, large surface-to-volume ratios, and unique optical, electrical, and catalytic properties, which differ markedly from the corresponding bulk metals [3]. A wide variety of metallic nanomaterials have been developed in recent years, including copper nanoparticles (CuNPs) and copper oxide nanoparticles (CuO NPs), which are increasingly important for industrial, electronic, antimicrobial, and biomedical applications [4-6]. Unlike precious metals such as gold (Au) or silver (Ag), copper offers an attractive economic alternative because it is abundant, inexpensive, and exhibits comparable, and in some contexts even superior, electrical conductivity and antimicrobial efficacy [7-10].

Traditional synthesis of copper nanoparticles (CuNPs) relies on high temperatures, vacuum conditions, and toxic chemicals (e.g., sodium borohydride, hydrazine, DMF, CTAB), resulting in hazardous by-products and environmental risks [11]. In contrast, plant-based (phytosynthesis) methods use bioactive phytochemicals as reducing and capping agents in a simple, scalable "one-pot" process that is energy-efficient and eco-friendly [12-15]. Plant-mediated synthesis avoids toxic reagents, produces biocompatible nanoparticles suitable for biomedical applications, and aligns with green chemistry principles [16,17]. While microbial synthesis offers control but requires aseptic conditions and faces biosecurity concerns [18], plant-based approaches are safer and more industrially viable. Recent research also explores AI-driven optimization for scalability and standardization. Green-synthesized CuNPs show strong catalytic, antimicrobial, antioxidant, and anticancer activities with reduced toxicity and environmental impact compared to conventional methods [19,20]. In this regard, the present paper reviews the recently published literature (2011 - 2025) on the synthesis of plant-based Cu NPs along with the state-of-the-art in describing the advantages, limitations, characterization techniques, and applications of this unique NP synthesis technique.

The formation of copper nanoparticles through the green method involves the reaction of a soluble copper salt ($CuSO_4$, $CuCl_2$, $Cu(NO_3)_2$, $(Cu)_2$, and copper plant aqueous solution) under controlled conditions cite 9 and 10. The formation of the nanoparticles is indicated by a color change of the solution from light blue to reddish brown (Fig. 1).

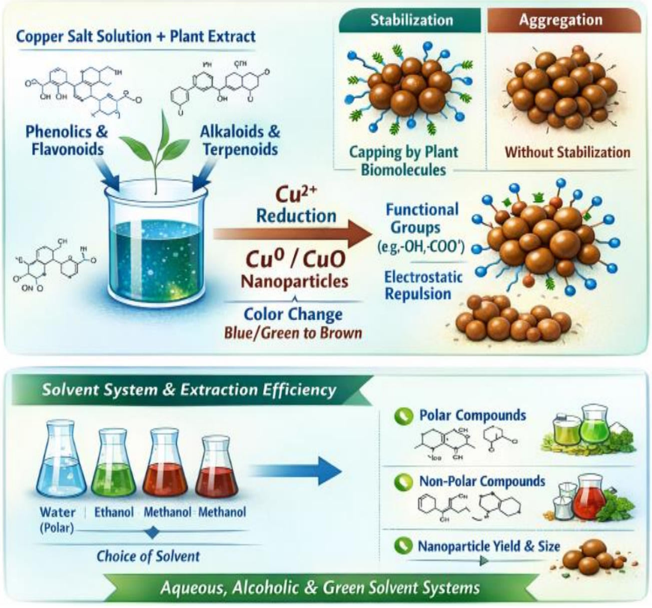

Fig.1 Phytochemical reduction and stabilization mechanism in plant mediated synthesis of copper nanoparticles

The solution characteristics, such as the ratio and composition of the plant extract, as well as the salt solution, and the temperature, and time of reaction, determine the size and number of nanoparticles formed. An alkaline range of (pH 8-10) is optimal for the formation of smaller nanoparticles, as it significantly speeds the reduction of the copper ions and increases the number of particles formed [21-25]. The phytochemicals

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present in the plant extract are sugars, flavonoids and polyphenols; these chemicals are reducing and stabilizing agents, which reduces Cu ions to Cu0 and Cu+ and caps the surface of the nanoparticles [26]. For instance, quercetin facilitates Cu ion reduction by virtue of a keto–enol reaction [27]. A number of different plant sources and agricultural wastes have been utilized, and various plant parts serve as effective bioreagents [28,29].

2. Synthesis of Copper Nanoparticles

Since the reaction conditions affect the properties of the copper nanoparticles, this means nanoparticles can differ in shape and size. Mali et al. reported on the synthesis of ~5 nm CuNPs using *Celastrus paniculatus* leaf extract, which was done at ~80 °C for 3 hours, and the resulting copper nanoparticles had a UV-Vis peak at 269 nm [27]. Likewise, Edsor et al. reported on the synthesis of spherical CuO NPs (10-30 nm) using *Acalypha* and *Ocimum* extracts which were mixed and heated to 40-50 °C [30]. For the copper nanoparticles to be synthesized in a high degree of uniformity, parameters such as pH, extract ratio, and the use of UV-Vis monitoring synthesis need to be optimized [31-33].

Some reaction parameters such as temperature, pH, time, concentration of plant extract, type of precursor and stirring control the nucleation and growth and hence, determine the size, shape, crystallinity and stability of the particles. Proper optimization of these factors helps in obtaining uniform and well-defined nanoparticles and improves the efficiency and scalability of the approach to commercial applications (Fig. 2).

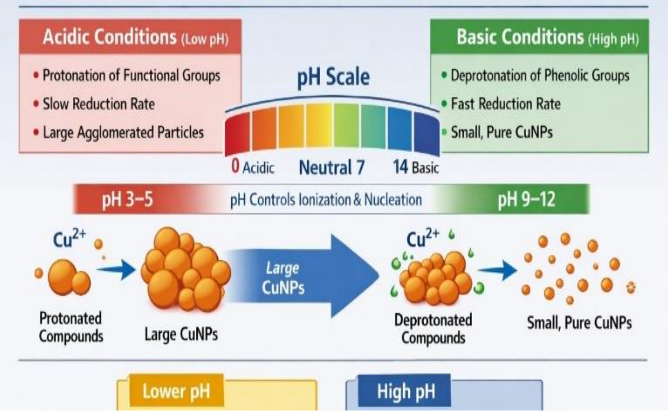

Fig. 2 The critical role of pH in copper nanoparticle synthesis

The Table 1 provide a structured, exhaustive list of the synthesized nanoparticles, categorized by research era to highlight the evolution of the field.

Table 1 Advanced synthesis and synergistic applications of copper nanoparticles

Plant Source	Part Used	Cu Precursor	Synthesis Conditions	Size/Morphology	Key Application	Ref.
Lonicera japonica (Honeysuckle)	Aqueous Extract	$CuCl_2$ (0.1 M)	Green synthesis; Optimized heating	2–4 nm; Spherical	Highest catalytic efficacy for dye reduction (AB-10B, MB, CR); Cytotoxicity established	[34]
Camellia sinensis + *Ocimum sanctum*	Leaf (Synergistic)	$CuSO_4$ (0.01 M)	Room Temp (~25 °C), 3 hrs stirring	20–50 nm; Spherical; Zeta: -29.5 mV	Synergistic effect yielded higher antibacterial activity than single extracts. Mechanism linked to flavonoid tautomerism	[35]
Camellia sinensis (Green Tea)	Leaf	$Cu(NO_3)_2$	60 °C, 1 hr stirring	20–60 nm; Spherical	High-resolution TEM confirmation of crystalline nature	[36]
Echinochloa pyramidalis	Leaf, Stem, Root	$CuSO_4$	Aqueous extraction	~0.16 nm (crystallite); Pore size ~200 nm	Remediation of Polycyclic Aromatic Hydrocarbons (PAHs) via porous structure.	[37]
Aloe barbadensis (Aloe Vera)	Leaf	$Cu(NO_3)_2$	70–80 °C, pH 10, 4 hrs	15.8 nm; Sago-shaped	Unique "Sago" morphology achieved at high pH; Photocatalytic	[38]
Hagenia abyssinica	Leaf	$Cu(NO_3)_2$	50 °C, 1 hr; 24 hr incubation	10–50 nm; Hexagonal Triangular, cylindrical	Demonstration of shape anisotropy control via plant extract	[39]
Azadirachta indica (Neem)	Leaf	$CuCl_2$	85 °C, pH 6.6	48 nm; Cubical	Detailed optimization of precursor concentration vs. morphology	[40,41]
Krameria sp. (Rhatany)	Root	$CuSO_4$ (0.3 M)	60 °C, pH 11, 3 hrs	40–100 nm (Avg ~6 nm in optimization)	Strong pH dependence observed (no reaction at pH <7)	[42]
Citrus medica (Citron)	Fruit Juice	Not specified	Green synthesis	10–60 nm (Avg 20 nm); Spherical	Utilization of fruit juice rich in ascorbic/ citric acids	[43]
Nerium oleander	Leaf	$CuSO_4$ (1 mM)	Room Temp, 28 hrs	3.5–15.2 nm; Spherical	Broad-spectrum antibacterial activity (Gram +/-)	[44]
Ocimum sanctum (Tulsi)	Leaf	$CuSO_4$ (1 mM)	80 °C boil; Room temp reaction	~77 nm (via XRD); FCC Cubic	FTIR confirmation of terpenoid/alcohol stabilization	[45]
Magnolia kobus	Leaf	$CuSO_4$	95 °C	37–110 nm; Spherical	Antibacterial coating for latex foams; Alternative to AgNPs	[46]
Terminalia arjuna	Bark	$Cu(NO_3)_2$	Microwave Assisted	5–25 nm; Stable dispersions	Introduction of microwave-assisted green synthesis.	[47]
Aloe barbadensis	Leaf		50 °C	5–50 nm; Spherical	Early optimization of optical properties.	[48]

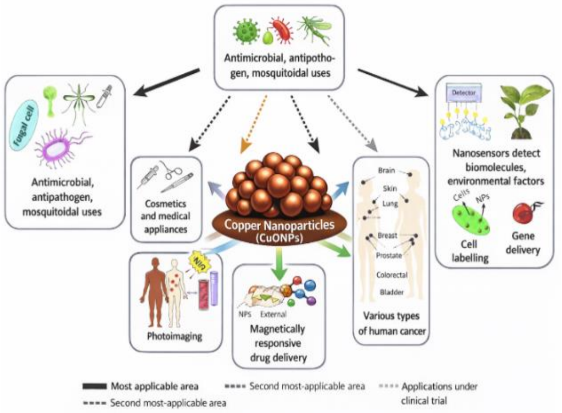

Fig. 3 Application of Copper nanoparticles

3. Characterization

Complementary methods are used to characterize copper nanoparticles. The development of surface plasmon resonance (SPR) at the wavelengths of 300-580 nm in the case of Cu NPs and 300-360 nm in the case of CuO NPs is confirmed by UV-vis spectroscopy.

Amaliyah et al. [49] observed SPR peak at 679 nm to kumquat-derived Cu NP. XRD is used to determine the crystalline phases of Cu, CuO, or Cu_2O, that is evidenced by Hernandez-Guadarrama et al. [50] in the case of Pelargonium-mediated CuO NPs.

FTIR confirms the capping of phytochemicals using -OH, -C=O and -NH bands Morphology and size (typically 500 nm) are unveiled with SEM and TEM with reported values.

DLS determines the hydrodynamic size and zeta potential (which is normally -15 -28 mV), which denotes colloidal stability. Other methods in correlation with composition and crystallinity include EDS, SAED, XPS, AFM, and SAXS.

4. Applications

The antibacterial and antifungal activity of Cu/CuO NPs is attributed to the release of Cu ions and generation of ROS, which are active against both Gram-positive and Gram-negative bacteria [51]. CuNPs from Plant sources show considerable antifungal activity, with reported MIC >400 µg/mL for CuO NPs, and further activity enhancement is reported for 10–30 nm particles. The phytochemical-capped CuNPs possess antioxidant, anti-inflammatory, and anticancer activities, which are reported to be better than those of the plant extracts alone [52].

The green synthesized Cu/CuO NPs are used as economically viable catalysts for organic reactions and are also reported to be useful in the degradation of dyes, including the removal of methylene blue and Congo Red [53, 54]. Although most of the available literature on the use of the NPs is catalytic and biological, applications in agriculture, sensing, anticancer, and also in printed electronics are also reported (Fig. 3).

5. Benefits and Drawbacks

The use of plants to synthesize Cu NPs is advantageous due to its use of inexpensive, renewable biological material, and the avoidance of toxic chemicals and high energy costs. The approach is also straightforward and provides gram quantities of material reliably and easily, without the need for expensive or complicated instrumentation. The primary capping agent is a plant phytochemical (which will also improve biocompatibility), and the costs of Cu are lower than those of the more noble metals (like Gold and Silver) while providing similar attributes for the conductivity and antimicrobial activity. The variability associated with reproducibility, and extraction of the plant material results in less consistent control of size and morphology of the NPs [55]. Mechanistic and mixed Cu/CuO phases are poorly understood for the optimization of the active phytochemicals The term eco-friendly describes the method, however, due to the use of energy and environmental factors of the released nanoparticles, there are eco-ethical concerns, but the method presents a lower waste profile compared to chemical methods [56].

The use of Green Cu/CuO NPs is viewed as economically viable and environmentally sustainable. The use of Green Cu/CuO NPs in dye degradation and the removal of other pollutants, extends its sustainable potential further [57]. However, the environmental impact and the fate of the materials used should be closely monitored and studied.

6. Conclusion

The area of synthesizing copper and copper oxidized nanoparticles using plant materials is a relatively new and rapidly evolving area of research which is pioneering a new method for producing “green” nanomaterials. The method utilizes simple and pre-existing plant biomaterials to synthesize nanoparticles (NPs) that act as catalysts and possess antimicrobial properties. Plant research has shown that a variety of plant materials can be used to synthesize copper nanoparticles (Cu NPs) of various sizes (usually only a few nanometers to a few tens of nanometers) and that these NPs can be readily incorporated into antimicrobial coatings, and are capable of degrading dyes in waste water, and can be utilized in medical research. NPs also possess antimicrobial properties that can be verified using various spectroscopic and microscopic research techniques. The various plant materials that have been used have been shown to possess antimicrobial properties, as can be verified using various spectroscopic and microscopic research techniques

In spite of these accomplishments, there is a great need for additional research in this area. In order to enhance backward synthesis protocols. The need for standardized protocols for NP lethality and their impact on the environment, especially for their use in the agricultural and medical fields, is evident. The need to explore previously ignored plant materials is also evident as it will help to expand and increase the “green” materials that can be used. It will also be possible to manufacture plant-mediated copper NP hybrids with other nanomaterials and/or polymers in order to obtain new hybrids that can be used for advanced purposes, such as nanocomposites used for energy, sensor, or other advanced type devices.

In plant-based Cu NP synthesis, it cannot be ignored the path it takes toward sustainable approaches to nanotechnology. It not only presents a method that is less harmful to the environment compared to traditional NP synthesis but is also able to provide ancillary bio-active properties to the NPs, due to the use of natural reductants and the non-toxic processes involved. The field has certainly progressed a great deal since 2011, and with a little more innovation and sustained effort, the application of plant-based Cu NP synthesis should be able to address many more problems, particularly in the areas of medicine and environmental remediation.

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