REVIEW ARTICLE

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An Analysis of the Green Synthesis of Copper Nanoparticles using Plant Leaf Extracts

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ABSTRACT

Activating research in the field of nanotechnology exists the intense focus on copper nanoparticles or CuNPs because of their numerous applications throughout medicine and catalysis and electronics and environmental clean-up operations. Plant leaf extract-based green synthesis has become an environmentally responsible and cost-efficient method for producing nanoparticles which replaces traditional chemical and physical synthesis techniques. This assessment explores plant leaf extract-based CuNPs synthesis which uses phytochemicals to act as both reduction agents and stability enhancers. The review discusses plant species, extract compositions, reaction conditions while describing how these affect nanoparticle characteristics including size, shape and stability. Biosynthesis mechanisms of CuNPs are determined while analyzing how phenolic compounds and flavonoids together with biomolecules affect nanoparticle formation. The paper examines both the economic and technical limitations of plant-based nanoparticle synthesis methods and evaluates them from a critical standpoint. The evaluation includes modern achievements in green CuNP synthesis and their probable uses in industry. Future research efforts will aim to improve synthesis methods and maximize production outputs and create multifunctional advanced CuNPs with enhanced capabilities. The research presents in-depth findings about plant-generated CuNP methods that promote the development of environmentally friendly nanotechnology applications.

Keywords: Green Synthesis,Copper Nanoparticles, Plant Leave extract, Nano particle preperation.

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INTRODUCTION

The unique physicochemical properties of copper nanoparticles (CuNPs) make them a highly pursued material when considering their wide range of applications in different fields including catalysis. [1,2], medicine [3,4], electronics [5], and environmental remediation [6]. The common methods used for producing Copper Nanoparticles (CuNPs) lead to toxic byproducts while requiring energy-intensive chemicals which create difficult synthetic conditions [7]. The search for environmentally friendly as well as sustainable alternatives has emerged due to this need. Research shows that plant-mediated synthesis using leaf extracts functions as a particularly successful synthesis method. [8]. The reducing and stabilizing properties of phytochemicals in plant extracts form the basis for a cost-efficient eco-friendly pathway to produce CuNPs [5,9]. The review examines the precise methods of green synthesis for CuNP fabrication including key elements which affect their characteristics and processes alongside industrial use potential.

Plant-Mediated Synthesis of CuNPs: The Role of Phytochemicals

Plant leaf extracts by nature can serve as reducing and stabilizing agents during the green production of CuNPs [10]. Phytochemicals, the secondary metabolites produced by plants, are the key players in this process[6,11]. These compounds possess diverse chemical structures and functionalities, many of which exhibit reducing capabilities, enabling the reduction of copper ions (Cu^{2+}) to copper atoms (Cu^0), which then aggregate to form nanoparticles (Barag et al., 2021), [12]. Common phytochemicals involved include flavonoids, terpenoids, tannins, alkaloids, and proteins [3,4]. For example, flavonoids, with their multiple hydroxyl groups, can readily donate electrons to reduce Cu^{2+} ions [13]. Similarly, the presence of phenolic compounds and their hydroxyl groups contribute significantly to the reduction process [12,14]. Furthermore, these phytochemicals also act as capping agents, adsorbing onto the surface of the CuNPs and preventing agglomeration,

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thereby enhancing the stability of the nanoparticles in solution [10]. The specific composition of phytochemicals in a given plant extract significantly influences the size, shape, and stability of the resulting CuNPs [3,12].

Influence of Plant Species and Extract Composition

The choice of plant species is crucial, as the type and concentration of phytochemicals vary significantly across different plants [3,8]. Studies have demonstrated the successful synthesis of CuNPs using extracts from a wide range of plants, including Holoptelea integrifolia[10], Jatropha curcas [8], Murraya koenigii [5], Rumex vesicarius[15], Ocimum gratissimum [16], Terminalia chebula [17], Camelia sinensis [18], Manilkara zapota [19], Malva parviflora [13], Catharanthus roseus[20], Piper nigrum [21], and many others[22]. The extraction method also plays a role, with different solvents (water, methanol, ethanol) potentially yielding extracts with varying phytochemical compositions and consequently influencing the nanoparticle characteristics[23]. This highlights the need for careful selection of both plant species and extraction methods to optimize the synthesis process.

Optimization of Reaction Conditions

Several reaction parameters significantly influence the final properties of the synthesized CuNPs [12]. These include the concentration of the copper precursor salt (e.g., copper sulfate, copper nitrate, copper acetate), the concentration and volume of the plant extract, the reaction temperature, pH, and reaction time [23,24]. Optimizing these parameters allows for control over the size, shape, and crystallinity of the CuNPs. For example, higher precursor salt concentrations generally lead to larger nanoparticles, while increasing the extract concentration can result in smaller sizes due to increased phytochemical availability for capping and stabilization . Similarly, adjusting the pH can influence the rate of reduction and the stability of the nanoparticles. Reaction temperature also plays a critical role, as higher temperatures may lead to faster reduction but could also promote agglomeration [12]. Therefore, a systematic optimization of these parameters is essential for achieving desired CuNP characteristics.[12,13]

Mechanisms of Green CuNP Synthesis

The green synthesis of CuNPs involves a complex interplay of chemical and biological processes [8,25]. The primary mechanism involves the reduction of Cu^{2+} ions to Cu^0 by phytochemicals acting as electron donors[12,13]. This reduction is facilitated by the presence of reducing groups, such as hydroxyl (-OH) and carbonyl (-C=O) groups in phytochemicals like flavonoids and phenols [12,13]. Once reduced, the copper atoms nucleate and grow into nanoparticles [8]. Simultaneously, phytochemicals adsorb onto the surface of the nanoparticles, acting as capping agents and preventing their aggregation [10]. The specific mechanism can vary depending on the plant extract used and the reaction conditions. However, the overall process involves a combination of redox reactions and surface adsorption, leading to the formation of stable, well-dispersed CuNPs. Further research is needed to fully elucidate the precise mechanisms involved in specific plant-mediated syntheses, particularly considering the complex mixture of phytochemicals in the extracts.

Characterization of Green-Synthesized CuNPs

Various analytical techniques are employed to characterize the green-synthesized CuNPs [4,10]. UV-Vis spectroscopy is commonly used to confirm the formation of CuNPs by detecting the surface plasmon resonance (SPR) band, a characteristic absorption peak at specific wavelengths[9,10,18]. The position and intensity of the SPR band can provide information about the size and shape of the nanoparticles[10]. Fourier Transform Infrared (FTIR) spectroscopy helps identify the functional groups present in the plant extract and on the surface of the CuNPs, providing insights into the capping and stabilization mechanisms [4,10]. X-ray diffraction (XRD) analysis determines the crystalline structure and crystallite size of the CuNPs . Microscopic techniques such as scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide detailed information on the morphology, size distribution, and shape of the nanoparticles [10]. Other techniques like dynamic light scattering (DLS) and zeta potential measurements are used to assess the size distribution and stability of the nanoparticles in solution[9]. The combination of these techniques provides a comprehensive characterization of the green-synthesized CuNPs.

Applications of Green-Synthesized CuNPs

The unique properties of green-synthesized CuNPs, including their size, shape, surface functionalization, and biocompatibility, open up a wide range of potential applications [2,3]. In catalysis, CuNPs exhibit excellent catalytic activity in various organic reactions, offering sustainable and environmentally benign alternatives to traditional catalysts[26,27]. In medicine, their antimicrobial properties make them promising candidates for developing novel antibacterial and antifungal agents [4,7]. Furthermore, CuNPs are being investigated for their potential in drug delivery, imaging, and cancer therapy [3]. In environmental remediation, their ability to degrade dyes and remove heavy metal pollutants has made them attractive materials for wastewater treatment [6]. In addition, CuNPs find applications in electronics due to their high electrical conductivity [1], and in agriculture as plant growth promoters[3]. The versatility and potential of green-synthesized CuNPs highlight their importance in developing sustainable technologies across multiple sectors.

Advantages and Limitations of Plant-Mediated CuNP Synthesis

Plant-mediated synthesis offers several significant advantages over conventional methods [3,8,25]. It is environmentally friendly, avoiding the use of toxic chemicals and reducing waste generation [3]. It is also cost-effective, utilizing readily available and inexpensive plant materials[5,9]. The process is relatively simple and can be carried out at ambient temperatures and pressures, reducing energy consumption [5,9]. Furthermore, the biocompatibility of green-synthesized CuNPs is often enhanced compared to chemically synthesized counterparts, making them suitable for biomedical applications [3 25]. However, there are limitations to consider [8,11]. The reproducibility and scalability of the process can be challenging due to variations in plant extract composition and reaction conditions [11]. The precise control over nanoparticle size and shape can be difficult to achieve, and the potential for batch-to-batch variations exists [8]. Furthermore, thorough characterization of the plant extracts and the final CuNPs is essential to ensure the absence of any potentially toxic compounds [11]. Addressing these limitations is crucial for the wider adoption of plant-mediated CuNP synthesis in industrial settings.

Recent Advancements and Future Perspectives

Significant progress has been made in optimizing the green synthesis of CuNPs [12]. Researchers are exploring innovative strategies to enhance the reproducibility and scalability of the process, including the use of standardized plant extracts and the development of automated synthesis systems [11]. The focus is also on improving the control over nanoparticle size, shape, and surface functionalization through precise manipulation of reaction parameters [12]. Furthermore, research is underway to explore the potential of combining green synthesis with other techniques, such as surface modification and encapsulation, to enhance the properties and applications of the CuNPs [14]. Future research should prioritize the development of standardized protocols and scalable production methods to facilitate the transition of this technology from the laboratory to industrial settings[11]. A deeper understanding of the underlying mechanisms and the influence of various factors on CuNP properties is also crucial for further advancements. The exploration of novel plant species with unique phytochemical profiles could lead to the discovery of even more efficient and sustainable synthesis routes[8].

Table 1: Summarizes the successful application of green synthesis procedures on preparation of Nano Particles

Plant Extract used	*Process Details*	*Characterization techniques*	*Observations*	*Ref*
Aerva javanica leaf extract	Synthesis using Aerva javanica leaf extract;	XRD, FTIR, SEM	Crystalline CuO-NPs with an average crystal size of 15 nm and spherical morphology in the 15-23 nm range; exhibited broad-spectrum antimicrobial activity.	28
Oldenlandia corymbosa L. leaf extract	Synthesis using Oldenlandia corymbosa leaf extract; precursor: $Cu(NO_3)_2$ solution; sol-gel method.	UV-Vis DRS, FTIR, PSA, SEM-EDX, TEM, XRD	Characterizations confirmed the formation of CuO NPs.	29
Dicliptera Roxburghiana extract	Synthesis using Dicliptera Roxburghiana extract; photocatalytic activity against methylene blue degradation studied.	XRD, FT-IR, UV-Vis	Spherical Cu-NPs (58 nm size); photocatalytic activity against methylene blue under sunlight.	30
Gloriosa superba L. extract	Synthesis using Gloriosa superba extract; solution combustion synthesis.	XRD, UV-Vis, SEM, TEM	Monoclinic CuO NPs; significant antibacterial activity against Gram-negative and Gram-positive bacteria.	31
Moringa oleifera leaf extract	Synthesis using hydroalcoholic extract; assessment of antioxidant and antimicrobial activities.	UV-Vis, FTIR, HRTEM, SEM, XRD	Amorphous CuNPs (35.8-49.2 nm); considerable antioxidant and antimicrobial activities.	14
Mitragyna parvifolia plant bark extract	Synthesis using Mitragyna parvifolia bark extract	UV-Vis, FT-IR, XRD, SEM, TEM, antimicrobial activity testing	Spherical CuNPs; high antimicrobial activity against Escherichia coli and Bacillus subtilis.	32
Muntingia calabura leaf extract	Synthesis using Muntingia calabura extract; production of CuO nanorods.	SEM, TEM, FTIR, XRD, XPS, Raman spectroscopy	Distinct, homogeneous CuO nanorods (23 nm thickness, 79 nm length); flavonoids and polyphenols act as capping agents.	33
Acanthospermum hispidum L. extract	Synthesis using Acanthospermum hispidum extract; assessment of antimicrobial, antimalarial, and antimycobacterial activities.	FTIR, FESEM, TEM, EDX, Photoluminescence	Monoclinic CuO-NPs; robust antimicrobial, antimalarial, and antimycobacterial activity.	34

Cissus quadrangularis and Piper betle extracts	Synthesis using extracts of Cissus quadrangularis and Piper betle; assessment of antibacterial effects.	FTIR, XRD, SEM, TEM	Orthorhombic CuO NPs (32 nm average crystallite size); irregular spherical morphology; antibacterial activity.	35
Lantana camara extract	Comparison of insecticidal activity of Lantana camara extract and synthesized CuNPs against Anopheles multicolor.	UV-Vis, TEM	Biosynthesized spherical CuNPs (11-17.8 nm); higher insecticidal activity of CuNPs compared to plant extract.	36
Duranta erecta fruit extract	Synthesis using Duranta erecta fruit extract; catalytic activity for azo dye reduction.	UV-Vis, FTIR, XRD, EDX, FESEM	Outstanding catalytic activity for methyl orange and congo red reduction in the presence of NaBH4.	37
Jatropha curcas leaf extract	Synthesis using Jatropha curcas leaf extract; study of optical properties, CT-DNA binding, and photocatalytic activity.	XRD, FT-IR, SEM, TEM, UV-Vis spectrophotometry	CuNPs (10-12 nm); SPR peaks at 266 and 337 nm; photocatalytic activity against methylene blue; CT-DNA binding.	8
Hagenia abyssinica leaf extract	Synthesis using Hagenia abyssinica leaf extract; investigation of antimicrobial properties.	UV-Vis, UV-DRS, FT-IR, XRD, SEM, EDXA, TEM, HRTEM, SAED	CuNPs with mixed spherical, hexagonal, triangular, cylindrical, and irregularly shaped particles (34.76 nm average size); good antibacterial activity.	38
Brassica oleracea var. italic extract	Synthesis using Brassica oleracea var. italic extract; antifungal application.	UV-Vis, FTIR, FESEM, EDAX, XRD	Highest antifungal activity against Aspergillus niger and Candida albicans.	39
Cochlospermum gossypium extract	Hydrothermal synthesis using activated carboxymethyl gum from Cochlospermum gossypium; assessment of antibacterial and antifungal activity.	UV-Vis, FTIR, TEM, XRD	Face-centered cubic structure; good antibacterial and antifungal activity.	40
Catha edulis leaf extract	Synthesis using Catha edulis leaf extract; assessment of antibacterial activity.	XRD, SEM-EDS, TEM, UV-Vis, FTIR	Spherical CuO NPs; high zone of inhibition against various bacteria.	41
Pterospermum acerifolium leaf extract	Synthesis using Pterospermum acerifolium extract; comparative toxicity study with engineered CuO NPs against Daphnia magna.	UV-Vis, FE-SEM, EDX, FTIR, XPS, DLS	Oval-shaped CuO NPs; more stable than engineered NPs; lower EC50 value against Daphnia magna.	42
Aloe barbedensis, Azadirachta indica, Coriandrum sativum extracts	Synthesis of AgNPs and CuNPs using extracts from three plants; application as adsorbents for naphthalene decontamination.	FTIR, UV-Vis	AgNPs and CuNPs showed high efficiency in naphthalene removal from contaminated water.	43
Cynomorium coccineum extract	Synthesis using Cynomorium coccineum extract; sorption of methylene blue dye.	FT-IR, SEM, EDX, XRD, TG	Crystalline CuNPs (14.2 nm average crystallite size); chemisorption process involved in methylene blue adsorption.	44
Parthenium hysterophorus extract	Synthesis using Parthenium hysterophorus extract; assessment of antimicrobial, antioxidant, and cytotoxic activities.	UV-Vis, antimicrobial and antioxidant activity testing, cell viability assay	CuNPs showed greater antimicrobial and antioxidant activity than methanolic leaf extract; good cell viability.	45
Carica papaya peel extract	Synthesis using Carica papaya peel extract; photocatalytic degradation of palm oil mill effluent (POME).	Various analytical methods including XRD, SEM, FTIR, UV-Vis.	Spherical CuO NPs (85-140 nm); 66% degradation of POME after 3 h UV irradiation; reduced phytotoxicity after photodegradation	46
Asparagus adscendens Roxb. extract	Synthesis using Asparagus adscendens extract; assessment of antimicrobial activities.	UV-Vis, FTIR, HRTEM	Crystalline CuNPs; significant zone of inhibition against various pathogenic bacteria.	47

CONCLUSION

Green synthesis of CuNPs using plant leaf extracts offers a compelling alternative to conventional methods, providing a sustainable, cost-effective, and environmentally friendly route to producing these valuable nanomaterials[3,25]. The process leverages the reducing and stabilizing capabilities of phytochemicals present in plant extracts, offering a relatively simple and versatile approach [10]. While challenges related to reproducibility and scalability remain [11], significant advancements are being made to address these limitations[12]. The unique properties of green-synthesized CuNPs and their wide-ranging applications across catalysis, medicine, electronics, and environmental remediation highlight their importance in developing greener nanotechnology approaches [2,3]. Continued research into the optimization of synthesis parameters, the exploration of novel plant sources, and the development of scalable production methods will be crucial for realizing the full potential of this promising technology. The integration of green synthesis into industrial processes promises a more sustainable future for nanomaterial production.

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