

Bio-fabrication of Copper Nanoparticles Using *Acalypha indica*: A Sustainable Approach to Self-Cleaning Textile Finishes

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ABSTRACT

Nanotechnology has revolutionized materials science by enabling precise manipulation of matter at the nanoscale, leading to materials with unique physicochemical properties. Among different nanomaterials, copper nanoparticles (CuNPs) stand out due to their affordability, high electrical and thermal conductivity, catalytic activity, and strong antimicrobial effects. Conventional, physical, and chemical methods for producing these nanoparticles often require high energy consumption, are costly, and can be environmentally harmful. As a sustainable alternative, green synthesis has become increasingly popular. This eco-friendly approach employs biological agents, such as plant extracts, to reduce and stabilize metal ions into nanoparticles.

This study analyzes the green synthesis of CuNPs using *Acalypha indica* leaf extract, a plant that is rich in phytochemicals that act as natural reducing and capping agents. The synthesis process was confirmed through visual observation of color change and further characterized using UV-Vis spectroscopy, FTIR, SEM, XRD, Particle size, and Zeta potential analysis, which validated the formation, morphology, and crystalline structure of CuNPs. The synthesized nanoparticles were subsequently applied to cotton fabrics using dip-dry methods, imparting multifunctional properties.

The finished fabrics demonstrated antibacterial activity, effectively inhibiting microbial growth, along with UV-protective capabilities and self-cleaning behaviour due to enhanced hydrophobicity. These results highlight the potential of eco-friendly CuNPs synthesis in producing functional textiles for healthcare, hospitality, and technical applications. The integration of green nanotechnology with textile finishing not only enhances performance but also aligns with global sustainability goals, offering a viable pathway toward safer and more durable textile innovations.

Keywords: *Acalypha indica*, Copper nanoparticles, Self-cleaning property, Green synthesis.

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1. INTRODUCTION

Nanotechnology is a newly emerging field in science that manipulates matter in the nanoscale range, factoring for outstanding contributions to technological innovation so far, including the development of tailorable nanoscale materials – nanomaterials – evidencing improved features and in numerous applications within the biomedical field (Khan *et al.*, 2018, Mahdavi *et al.*, 2019, Mostafa *et al.*, 2019, Pal *et al.*, 2019). Nanotechnology is one of the essential areas of research in modern sciences, including the manipulation of matter on an atomic, molecular, and supramolecular scale (J. Jenifer, 2012). Nanoparticles have several unique properties due to their specific size, shape, composition, greater surface area to volume ratio, and purity of individual constituents. These properties make them amenable to be used as nano-magnets, in drug/gene delivery systems, water disinfectants, catalysts, quantum dots for electronic devices, and as pollutant remediating agents (Jacob *et al.*, 2017; Khan *et al.*, 2019). Among the distinct nanomaterials developed so far, nanoparticles have attracted a lot of enthusiasm owing to their unique characteristics, particularly the capability of modifying the catalytic, thermal, and mechanical properties and the increased surface-volume ratio.

Green synthesis is a sustainable method presenting a different way of thinking in chemistry intended to eliminate toxic waste, reduce energy consumption, and use ecological solvents (water, ethanol, ethyl acetate, etc). It aims at minimizing generated waste and implementing sustainability. It involves using plant parts to bio-reduce metal ions into their elemental form in the size range of 1-100 nm. Among all the methods used in green synthesis of CuNP (phytological, phycological, mycological, and bacteriological fabrication), the plant-based synthesis emerges as the best choice, since it produces stable NPs, in a quick and effective synthesis (Rehana *et al.*, 2017; Mahdavi *et al.*, 2019). Biological synthesis uses the biological principle of oxidation and reduction by microbial enzymes or plant phytochemicals. It is simple, more efficient, and has a larger performance. Biological synthesis methods are favoured over chemical synthesis methods because of their rising environmental issues. Moreover, the green synthesis method does not require harmful chemicals like reducing and oxidizing agents since it requires only plant extracts. Green synthesis of nanoparticles using plant extracts is one of the cleanest, most biocompatible, non-toxic, and eco-friendly methods for large-scale production of nanoparticles.

The investigation component present in plant extracts, namely polyol, acts as a chelating and capping agent for the rapid biosynthesis of nanoparticles and stabilizes the formation of metallic nanoparticles. The biological properties of metal nanoparticles have been increasing.

Copper nanoparticles (CuNPs) have recently attracted special attention because of their low-cost and novel optical, mechanical, catalytic, electrical, and thermal conduction properties, which differ from those of their bulk metals (Brust and Kiely 2002). Copper nanoparticles has a variety of distinctive properties such as superior electric and thermal conductivity, photocatalytic behavior, superior plasmonic resonance found unmatched in the fields of electronics, metallurgy, EMI shielding, military equipment, heat sinks, and medical applications (Rana *et al.*, 2020). Numerous varieties of nanoparticles, including magnetic, non-magnetic, and metallic ones, are applied in a wide range of applications such as water purification, electronics, catalysis, solar energy conversion.

Plants are enriched with secondary metabolites (flavonoids, alkaloids, steroids, terpenoids, proteins, sugars, etc) that lead to bio-reduction (nucleation and growth), stabilization, and capping in a single step which helps the process to be more efficient and cost-effective (El-Seedi *et al.*, 2019). Extracts are derived from leaves, bark, stems, roots, and flowers that have been studied extensively for the synthesis of different metal nanoparticles. *Acalypha indica* belongs to the Euphorbiaceae family, which is a common weed. The leaves of *A. indica* have already been evaluated for their wound-healing activity in pets (B.Venkat Rajah *et al.*, 2012). It has cured various diseases like pneumonia, asthma, and rheumatism using Cu nanoparticles obtained from *A. indica* plant leaves. Dried *A. indica* leaves are used to reduce bedsores by placing them on the bed surface, whereas the extract from the plant leaves is mixed with oil or lime and then used to cure many skin diseases. Textile products, especially those made from natural fibers, provide an excellent environment for microorganisms to grow because of their large surface area and ability to retain moisture. Most textile materials currently used in hospitals and hotels are known to cause cross-infection and transmission of diseases caused by microorganisms. There are different physicochemical methods that can be considered to produce antimicrobial fabrics (R. Rajendran *et al.*, 2012; S.R. Sakthivel *et al.*, 2012).

2. MATERIALS AND METHODS

2.1 Preparation of plant extract

Fresh leaves of *A. indica* were collected from in and around Coimbatore, Tamil Nadu, India, and washed twice with tap water followed by multiple washes with double-distilled (DD) water to remove surface dust particles. The cleaned leaves were dried for 15 days and then crushed using a mixer to obtain a fine powder. For the preparation of leaf extract, 10 g of the powdered leaves was dissolved in 100 ml of water and heated in a water bath at 100 °C for 1 hour. The mixture was allowed to cool to room temperature and was filtered using Whatman No. 3 filter

paper. The obtained leaf extract was used as a reducing agent for Cu synthesis without the addition of any other chemicals. Plate 2.1.1 indicates the sample collection, and the preparation of leaf extract.



Plates 2.1.1. Sample collection and Preparation of leaf extracts

2.2 Phytochemical analysis of *A. indica* leaf extract

Standard procedures were employed to analyze the aqueous extract of *A. indica* leaf extract for the presence of various phytochemicals, including flavonoids, alkaloids, proteins, carbohydrates, tannins, saponins, phenols, cardiac glycosides, terpenoids, sterols and quinones:

- Test for alkaloids: Mayer's test: A few drops of Mayer's reagent were added to the plant extract; formation of white precipitate shows a positive result for alkaloids (Senguttuvan *et al.*, 2014).
- Test for flavonoids:
 - Alkaline test: To 5 mL of dilute ammonia, the plant extract was added and shaken well. The aqueous portion is separated, and concentrated H_2SO_4 is added. Formation of yellow color indicates the presence of flavonoids (Wadood *et al.*, 2013).
 - H_2SO_4 test: The extract was added with concentrated H_2SO_4 formation of an orange color indicates the presence of flavonoids.
 - Lead acetate: To 1mL of leaf extract, 1mL of 10% lead acetate was added. Formation of a yellow precipitate indicates the presence of flavonoids (Balamurugan *et al.*, 2019).
- Test for sterols:
 - Liebermann–Burchard test: 2mL of leaf extract, 1mL of conc. Sulfuric acid, 1mL of chloroform was added. The chloroform layer was visible through reddish-blue colour and the acid layer was visible through green fluorescence that represent the presence of sterols (Devmurari, 2010).

- Test for proteins: Nitric acid test: To 2 mL of leaf extract, a few drops 0.5% of HNO₃ solution were added. The formation of yellow color indicates the presence of proteins (Gul *et al.*, 2017).
- Test for carbohydrates: Molisch's test: A few drops of alcoholic solution of α -naphthol were added to 2 mL of leaf extract and mixed well. Conc. H₂SO₄ was added slowly along the sides of the test tube. Formation of a violet ring indicates the presence of sugars (Mohamed *et al.*, 2010).
Fehling's test: Fehling's reagent (0.5 mL) was added to 2 mL of leaf extract and kept in a boiling water bath for 2min. The presence of carbohydrates is noticed through the formation of red precipitate (Balamurugan *et al.*, 2019).
- Test for saponins: Shaken with water: distilled water (1 ml) was added to 1 mL of leaf extract and shaken well. Formation of foam confirms the presence of saponins (Ahmad *et al.*, 2020).
- Test for cardiac glycosides: Keller-Killani test: To 5mL of leaf extract, add 2mL of glacial acetic acid, a few drops of ferric chloride solution, and 1 mL of conc. H₂SO₄. A brown ring in the interface indicates the presence of cardiac glycosides (Balamurugan *et al.*, 2019).

2.3 Preparation of CuNPs

The percent purity of copper (II) sulfate pentahydrate (CuSO₄·5H₂O) is 98%. The prepared 25 ml of leaf extract was added to 19.36g of 0.01 M copper sulphate pentahydrate solution under magnetic stirring for 1 hour at 60°C, slowly and gradually, the mixture turns from light blue to brownish-black precipitate, and gives an indication of the formation of CuNPs. The obtained brown precipitate solution was then centrifuged for 15 minutes at 10,000 rpm and repeatedly washed with distilled water to remove all the impurities that are present; then, the brownish-black powder was obtained after overnight drying.

2.4 Characterization of CuNPs

To confirm the formation of the Copper nanoparticles, the UV-visible spectrum of the NPs in the range of 200-350nm was determined using a UV-Vis spectrophotometer (DRS Analytek Jena, Germany). Fourier Transform Infrared spectroscopic (FT-IR) (Shimadzu (Miracle 10), Japan) analysis was performed to investigate the functional groups present in the biosynthesized Copper nanoparticles within the range of 4,000–400cm⁻¹. The Zeta sizer SZ-100 (Horriba, Japan), operated at the range of ± 100 mV, was used to determine the particle size and zeta potential (ZP) of the synthesized AI-Cu NPs.

2.5 Functionalization of cotton fabric using AI-CuNPs

Cotton fabric (100%) with a plain weave construction was procured from National Textile Corporation, Murugan Mills, Coimbatore district, Tamil Nadu, India. The properties of the selected cotton fabric were found to be: GSM-96 g/m², warp count 60's, 2 weft count 50's, and thickness 0.23mm. The chosen fabric (10×10) was desized and scoured following the method outlined by Ahmed and Mustafa (2020). Biosynthesized Cu nanoparticles (1%) were dispersed in deionized water and sonicated for 30min. The fabric was dipped into the nanoparticle solution for 30 min. The coated cotton fabric was cured for 3min at 140°C, which ensures strong adhesion and durability of the coating. These techniques provide insights into the characteristics of biosynthesized nanoparticles and their interaction with the fabric surface.

3. RESULTS AND DISCUSSION

3.1 Phytochemical analysis of *A. indica* extract

The phytochemical analysis of *A. indica* extracts revealed the presence of alkaloids, flavonoids, sterols, proteins, carbohydrates, saponins, cardiac glycosides, and the absence of tannins and quinones (Table 1). Presence of phytochemicals in the extract of *A. indica* might be responsible for reducing and stabilizing the CuNPs (Ahmad *et al.*, 2020). The hydroxyl group present in flavonoids, terpenoids, and alkaloids may cause the reduction reaction to develop coordination with the metal ions. The free amino and carboxylic groups found in proteins might be responsible for the breakdown of metal ions to produce nanoparticles (Patra *et al.*, 2020).

S. No.	Phytochemical tests	<i>C. maderaspatanus</i> extract
1	Alkaloids	
	Mayer's reagent	+
2	Flavonoids	
	Alkaline test	+
	H ₂ SO ₄ test	+
	Lead acetate	+
3	Sterols	
	Liebermann test	+
4	Proteins	
	Nitric acid test	+
5	Carbohydrates	
	Molisch's test	+
	Fehling's test	+
6	Saponins	
	Shaken with water	+
7	Cardiac glycosides	
	Keller-Killani test	+

Table 1. Phytochemical screening of *A. indica* extract, “+” indicates the presence, and “–” indicates the absence of phytochemicals

3.2 Visual observation

The primary detection was performed by visual inspection. The change in the color of the precursor solution from light blue to dark green over time, along with a brownish-black precipitate on the inner surface of the beaker, provides evidence of CuNPs synthesis.

3.3 Characterization of AI-CuNPs

3.3.1 UV-Vis spectral analysis

The UV-Visible spectrum of the CuNPs dispersed in water for a wide range of wavelengths was measured. It is the initial confirmation of CuNPs formation. Figure 1. clearly showed a peak at 220 nm. The spectrum shows that there is a strong absorbance of the UV rays between 200- 350 nm. This represents the presence of nanoparticles in the given sample. The peak formed at 220 nm is due to the surface plasmon resonance of CuNPs. (Rajeshwari *et al.*, 2014; Mulvaney, P. (1996)).

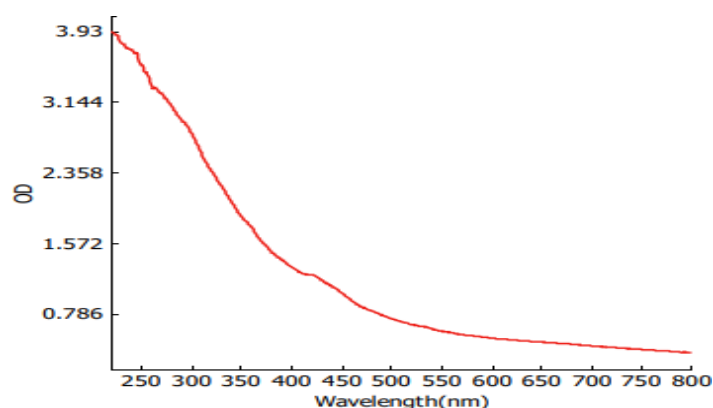


Figure 1. UV-Vis spectral analysis

3.3.2 Fourier- Transform Infrared Spectroscopy

FTIR analysis of the plant source and the CuNPs are shown in Figure 2. The FTIR peaks obtained at 3317.56cm⁻¹ indicates O-H stretch vibrations of carboxylic acids and phenols (Ezhilarasi *et al.*, 2018). The FTIR peaks at 1635.64cm⁻¹ indicates N-H bend, aliphatic amines (C=O stretch) and carboxylic acids (C-H bend, C-N stretch) (Awad *et al.*, 2022). The FTIR peaks at 686.66, 601.79cm⁻¹, 555.50 indicates C-H, the presence of free hydroxyl alcohols, carboxylic groups, phenolic acids and amines s (Chiang *et al.*, 1999). The other peaks around 486.06, 447.49, 424.34cm⁻¹ indicate the presence of metal oxygen (Cu-O). The presence of a functional group present in the leaf extract might be responsible for the bio-reduction of CuNPs.

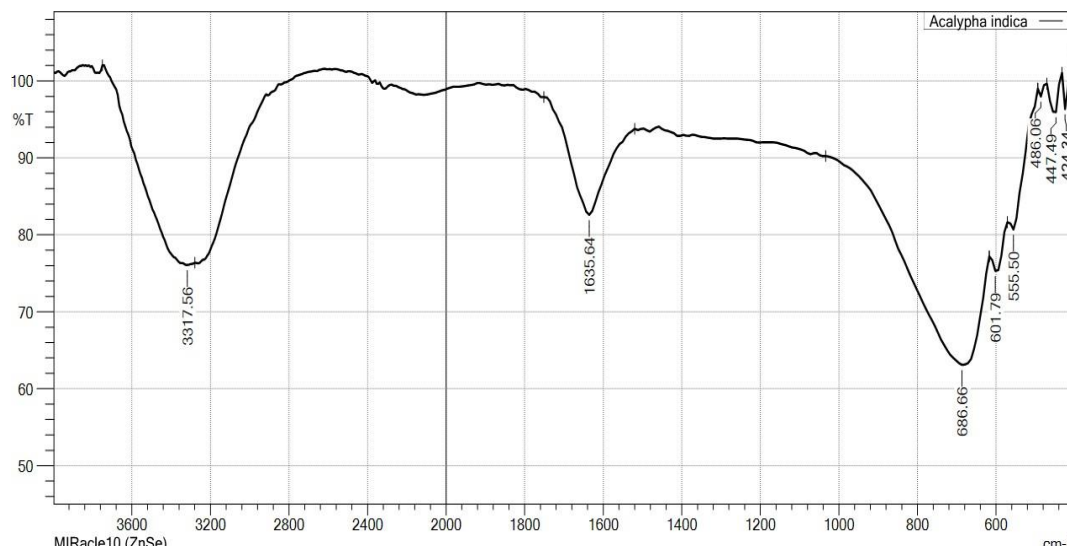


Figure 2. FTIR analysis

3.3.3 Particle size and Zeta potential of Al-CuNPs

The dynamic light scattering (DLS) Zeta sizer was used to measure the average size of the NPs. The Z-average mean diameter (d [nm]) of the *Al-CuNPs* was found to be 9.7nm, with a polydispersity index (PDI) of 0.645 Figure 3a.

The zeta potential value of *Al-CuNPs* was found to be -46.1mV (Figure 3b), indicating weaker electrostatic repulsion, which can lead to a higher tendency for particle aggregation and reduced colloidal stability. In some cases, such as non-aqueous systems, biological environments, or systems where other stabilization mechanisms are in effect (like steric stabilization), a zeta potential of less than -30 mV may still result in adequate stability and functional properties (Garg *et al.*, 2022).

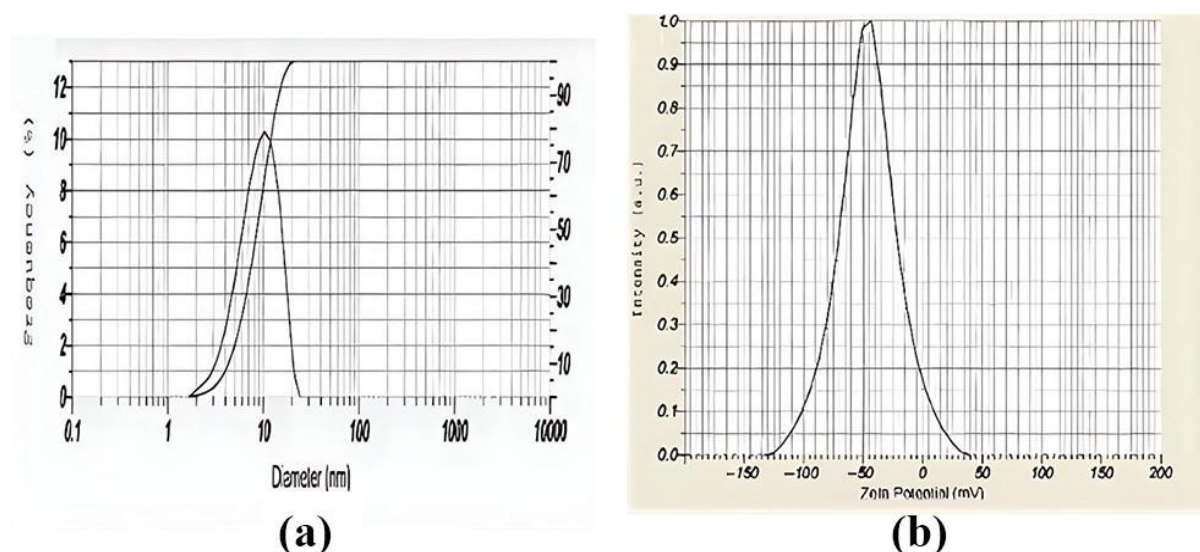


Figure 3. (a) Particle size of *Al-CuNPs* (b) zeta potential of *Al-CuNPs*

3.4 Self-cleaning property of AI-CuNPs-coated fabric

The effectiveness of Cu coated cotton fabrics for self- cleaning properties was assessed by measuring the degree of coffee-stained removal. The fabric samples were demonstrated through K/S values, which represent the characteristics of colour absorption (K) and colour scattering (S) of both exposed and unexposed areas of the samples, which were measured after 6h, 12h, 18h, and 24h of sunlight exposure. It is measured by calculating the percentage decrease in the K/S value of the exposed sample compared to the unexposed sample. In Figure 4, it is seen that the reduction in color of the coffee-stained coated fabric sample is zero at 0 h and after 24 h of sunlight exposure, it increased to 46%. This effect may occur because, when exposed to light, titanium nanoparticles generate reactive oxygen species (ROS), which break down organic contaminants and stains on the fabric (Frida *et al.*, 2024). This observation is consistent with earlier research on green-synthesized titanium nanoparticles coated cotton fabric, which demonstrated a 44% reduction after 12 h (Butola *et al.*, 2018).

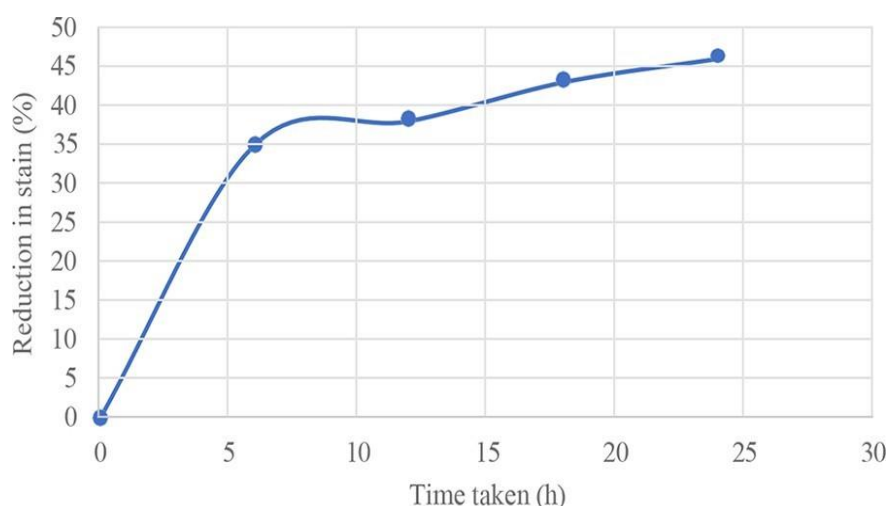


Figure 4. Self-cleaning property of AI-CuNPs-coated fabric

4. CONCLUSION

Synthesizing of nanoparticles using green method leads to safety for environmental sustainability. The plant extract *A.indica* helps in synthesizing copper nanoparticles in an eco-friendly and sustainable manner where characterization techniques employed to analyse the confirmation of AI-CuNPs. This study illustrated that the fabric coated with AI-CuNPs has versatile characteristics encompassing self -cleaning activities. These methods helps in promoting sustainable textile industry.

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