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Green Synthesis and Characterization of Silver and Copper Nanoparticles

Kavitha B.*, Bindu Kumar M. B., Priya G. and Mamatha B.
Department of Microbiology, Nrupathunga University, Bengaluru, Karnataka, India
bkavinair@gmail.com

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Abstract

The growing incidence of microbial contamination and the rise of antibiotic resistance have accelerated the need for effective and environmental friendly antimicrobial solutions. Silver and copper nanoparticles have emerged as promising candidates in nanomedicine due to their broad-spectrum antimicrobial activity. In this study, these nanoparticles were synthesized using a green approach with medicinal plants (Calotropis gigantea and Leucasaspera) and spices (Piper nigrum, Cinnamomum cassia, and Elettaria cardamomum). This plant-based synthesis method provides a cost-effective and eco-friendly alternative to traditional chemical techniques. The formation of nanoparticles was confirmed through UV–Visible spectroscopy. Silver nanoparticles displayed characteristic surface plasmon resonance peaks between 400–450 nm, while copper nanoparticles showed absorbance peaks in the 500–550 nm range, indicating successful synthesis. The antimicrobial activity of the nanoparticles was assessed using the agar disc diffusion method against bacterial strains (Staphylococcus aureus, Bacillussubtilis, Pseudomonas spp. and Salmonella spp.) and fungal species (Penicillium and Alternaria). Both types of nanoparticles exhibited strong antibacterial effects against all tested bacteria at a concentration of 100 µL. Among the fungi, Penicillium species were highly sensitive to the nanoparticles, whereas Alternaria showed limited susceptibility. Of the plant sources used, Leucas aspera, Calotropis gigantea, Piper nigrum, and Cinnamomum cassiawere particularly effective in promoting nanoparticle synthesis with enhanced antimicrobial activity. Our results demonstrate that plant-mediated synthesis of silver and copper nanoparticles is a sustainable and efficient approach for developing antimicrobial agents, with potential applications in nanomedicine, food safety, and biomedical materials.

Keywords: Silver Nanoparticles, Copper Nanoparticles, Green synthesis, Antimicrobial, *Calotropis gigantean*, *Piper nigrum*.

Introduction

Nanotechnology is one of the fastest-growing fields, with applications across a wide range of industries. It involves reducing larger materials to the nanoscale, producing particles known as nanoparticles (NPs), which typically range in size from 1 to 100 nm. These nanoparticles exhibit unique properties due to their small size, large surface area-to-volume ratio, high reactivity and enhanced capacity for carrying substances[1]. Nanomaterials possess distinct physicochemical characteristics that open up diverse applications and expand research opportunities in nanoscale science. They are widely used in industries such as pharmaceuticals, diagnostics, consumer goods and healthcare. Notable applications include targeted drug delivery systems, inhibition of biofilm formation, biosensors, bioremediation, and electronic devices[2].

Nanoparticles are structurally complex and are typically described as having three layers: The surface layer, which can be functionalized with various molecules such as metal ions, polymers, or emulsifiers; The shell layer, which is chemically and physically distinct from the core; and The core, which forms the central component of the nanoparticle[3].

The optical properties of nanoparticles are strongly influenced by their size, often resulting in different colours due to absorption in the visible region. Additionally, their size, shape, and structure significantly affect their reactivity, stability, and overall performance[4].

Plant-Mediated Nanoparticle Synthesis: Plants are well known for their significant contributions to human health, largely due to their rich content of bioactive compounds such as flavonoids. These compounds exhibit a range of beneficial properties, including antioxidant activity, prevention of coronary heart disease, anticancer effects, anti-HIV activity, antimicrobial potential and roles as chemotaxonomic markers[5,6]. In recent years, there has been growing interest in utilizing plant-derived phytochemicals in nanotechnology. This field, which deals with materials at the nanoscale (10^{-7} to 10^{-9} m), has broad applications in environmental science, bio-nanotechnology, medicine, chemistry, energy, electronics, optics, and optoelectronic devices[7].

Various plant parts—including fruits, leaves, stems, seeds, flowers, roots, bark, rhizomes, and fruit peels—are widely utilized in the synthesis of different types of nanoparticles[8].

Plants are often preferred over microorganisms such as fungi and bacteria for nanoparticle synthesis, as they eliminate the need for complex procedures involved in maintaining microbial cultures[9]. Plant-mediated synthesis is also advantageous due to its simplicity, lower energy requirements, and reduced risk of biological or chemical contamination. In particular, the production of silver nanoparticles (AgNPs) using plant extracts has gained significant attention because of its eco-friendly nature and strong antibacterial properties. These nanoparticles are typically synthesized through the bioreduction of silver nitrate using plant-derived reducing agents.

Leaf extract of *Hagenia abyssinica* has been used for the successful synthesis of silver AgNPs in a sustainable manner[10]. Similarly, AgNPs derived from the leaves of *Eugenia roxburghii* demonstrated effective inhibition of biofilm-forming bacterial colonies[11]. Furthermore, silver nanoparticles synthesized using aqueous extract of *Allium sativum* showed significant antibacterial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa*[12].

Nanoparticles can be synthesized using a wide range of physical and chemical methods. Common physical techniques for the production of AgNPs include lithography, irradiation, laser ablation, evaporation, and condensation[13-15]. These approaches typically rely on different forms of energy, such as thermal energy in physical vapor deposition, mechanical energy in ball milling, electrical energy in electrical discharge, and light energy in laser ablation[16].

Plant-mediated synthesis has gained considerable attention, as plant extracts can act as both reducing and capping agents. This approach offers advantages over conventional methods such as photochemical, thermal, electrochemical, and chemical reduction techniques[17]. This green synthesis approach offers a sustainable and efficient alternative to conventional chemical methods[18]. However, despite the promising applications of AgNPs, there remains a lack of comprehensive evidence regarding their potential environmental and health impacts. Concerns persist about their short- and long-term toxicity to ecosystems, animals, and humans. Nevertheless, green synthesis of AgNPs continues to attract significant research interest due to its simplicity, cost-effectiveness, and environmentally benign nature, making it a promising alternative to traditional methods[19].

The primary objective of this study is to synthesize silver (Ag) and copper (Cu) nanoparticles using natural plant extracts and to evaluate their potential as antimicrobial agents. This work represents an initial step toward developing a sustainable and eco-friendly approach for nanoparticle synthesis utilizing extracts from *Calotropis gigantea* and *Leucas aspera*, as well as spice extracts from *Piper nigrum*, *Cinnamomum cassia*, and *Elettaria cardamomum*. The synthesized nanoparticles were characterized and subsequently assessed for their biological activities, specifically their antibacterial and antifungal properties.

Materials and Methods

Collection of Samples: Fresh leaves of the herbs *Calotropis gigantea* and *Leucas aspera* were collected from agricultural land near Chintamani, Chikkaballapur, Karnataka, India. The spices *Piper nigrum*, *Cinnamomum cassia*, and *Elettaria cardamomum* were procured from local vendors in Bengaluru, Karnataka, in March 2024. All samples were transported to the laboratory in clean plastic wrapping to prevent contamination.

Processing and Extraction for Nanoparticle Synthesis: The collected leaf samples were thoroughly washed with distilled water and cut into small pieces, while the spice samples were also washed to remove impurities. All samples were then air-dried in a hot air oven and subsequently ground into fine powder. Approximately 1 g of each powdered sample was taken in separate beakers containing 50 mL of distilled water. The mixtures were heated and stirred using a magnetic stirrer at 60–70 °C for 1 hour, followed by filtration. The obtained filtrates were used as reducing agents for the synthesis of nanoparticles.

Synthesis and Purification of Nanoparticles: Silver nitrate ($AgNO_3$) and copper sulfate ($CuSO_4$) solutions (0.1%, 25 mL each) were prepared separately and heated to 70–80°C under constant stirring. Plant extracts were added dropwise as reducing agents, resulting in a colour change indicating nanoparticle formation (brown for AgNPs and green precipitate for CuNPs). The reaction mixtures were cooled and centrifuged at 5000 rpm for 10 minutes. The obtained pellets were washed, dissolved in ethanol, and evaporated to dryness to yield purified nanoparticle powders for further characterization and analysis.

Characterization of Nanoparticles (AgNPs and CuNPs): UV–visible spectroscopy was used to measure the absorbance of nanoparticles in the ultraviolet and visible regions of the electromagnetic spectrum, thereby confirming their formation and quality. For analysis, 0.001g of nanoparticles was dissolved in 5mL of ethanol to obtain a concentration of 1mg/mL. The solution was stirred using a magnetic stirrer for 1 hour to ensure uniform dispersion. The absorbance spectra were recorded over a wavelength range of 350–800nm. The synthesized silver nanoparticles (AgNPs) exhibited a characteristic surface plasmon resonance (SPR) peak in the range of 400–450nm, while copper nanoparticles (CuNPs) showed an absorption peak in the range of 500–550nm, confirming their successful synthesis.

Extraction of Sample (Solvent Extraction): Soxhlet extraction was employed for the preparation of crude extracts from the sample. Approximately 10g of powdered sample was loaded into a pre-weighed thimble and placed inside the Soxhlet apparatus. The extraction was carried out for 7–8 cycles (approximately 2–3 hours) until the solvent in the siphon tube became colourless, indicating complete extraction. Following extraction, the solvent was removed using a rotary evaporator at 65°C under reduced pressure to obtain the crude extract.

The concentrated extract was then stored in a refrigerator at 2–8°C for subsequent phytochemical analysis.

Detection of Proteins (Lowry's Method): The total protein content in the Soxhlet extracts was estimated using Lowry's method. Bovine serum albumin (BSA) was used as the standard, along with alkaline copper reagent and Folin–Ciocalteu (FC) reagent for the preparation of the protein standard curve. Aliquots of the working standard (0.2, 0.4, 0.6, 0.8 and 1.0 mL) were pipetted into labelled test tubes, and the volume in each tube was adjusted to 1 mL with distilled water. A blank containing distilled water instead of the standard was also prepared. To each test tube, 4.5 mL of alkaline copper reagent was added, mixed thoroughly, and allowed to stand at room temperature for 10 minutes. Subsequently, 0.5 mL of FC reagent was added to each tube, mixed well, and incubated at room temperature in the dark for 30 minutes. The absorbance was measured at 660 nm against the blank. A standard calibration curve was constructed by plotting protein concentration on the x-axis and absorbance at 660 nm on the y-axis.

Detection of Carbohydrates (Anthrone Method): Total carbohydrate content was determined using the Anthrone method with glucose as the standard. Aliquots of the working standard (0.2, 0.4, 0.6, 0.8 and 1.0 mL) were transferred into labelled test tubes, and the volume was adjusted to 1 mL using distilled water. A blank containing only distilled water was also prepared. Anthrone reagent was added to all test tubes, mixed thoroughly, and the tubes were placed in a boiling water bath for 10 minutes. After heating, the test tubes were cooled to room temperature. The absorbance was then recorded at 630 nm against the blank. A standard curve was prepared by plotting glucose concentration on the x-axis and absorbance at 630 nm on the y-axis.

Detection of Tannins (Tannic Acid Method): The total tannin content was determined using tannic acid as the standard along with FC reagent and sodium carbonate. Aliquots of the working standard (0.2, 0.4, 0.6, 0.8 and 1.0 mL) were transferred into labeled test tubes, and the volume was adjusted to 1 mL using distilled water. A blank was prepared similarly without the standard. To each test tube, 0.5 mL of FC reagent was added and mixed thoroughly. Subsequently, 1 mL of sodium carbonate solution was added, followed by dilution with distilled water to a final volume of 30 mL. The tubes were incubated in a dark chamber at room temperature for 30 minutes. Absorbance was measured at 700 nm against the blank. A standard curve was constructed by plotting tannic acid concentration on the x-axis and absorbance at 700 nm on the y-axis.

Detection of Total Phenols (Gallic Acid Method): Total phenolic content was estimated using gallic acid as the standard. Aliquots of the working standard (0.2–1.0 mL) were pipetted into labelled test tubes and made up to 1 mL with distilled water. A blank was also prepared. To each tube, 0.5 mL of FC reagent was added, mixed, and allowed to stand for 5 minutes at room temperature. Then, 1 mL of sodium carbonate solution was added, mixed well, and incubated at 23°C for 15 minutes. After incubation, 5 mL of distilled water was added, and absorbance was recorded at 760 nm against the blank. A standard calibration curve was plotted with gallic acid concentration on the x-axis and absorbance at 760 nm on the y-axis.

Detection of Flavonoids (Quercetin Method): Flavonoid content was determined using quercetin as the standard, along with sodium nitrite, aluminum chloride, and sodium hydroxide. Aliquots of the working standard (0.2–1.0 mL) were transferred into labeled test tubes and the volume was adjusted to 1 mL with distilled water. A blank was also prepared. To each test tube, 0.5 mL of sodium nitrite was added and mixed, followed by the addition of 1 mL of aluminum chloride. Subsequently, 0.5 mL of sodium hydroxide was added, and the mixture was allowed to stand for 5 minutes at room temperature. Then, 2 mL of distilled water was added to each tube. The absorbance was measured at 510 nm against the blank. A standard curve was prepared by plotting quercetin concentration on the x-axis and absorbance at 510 nm on the y-axis.

Detection of Alkaloids: Alkaloid content was determined using a gravimetric method. About 1 g of powdered sample was mixed with 40 mL of 20% acetic acid and allowed to stand at room temperature for 4 hours. The mixture was then filtered to obtain the filtrate. The filtrate was concentrated on a water bath until the volume was reduced to one-fourth of its original volume. Concentrated ammonia was then added dropwise to the cooled filtrate to precipitate the alkaloids. The precipitate was collected using a pre-weighed filter paper and washed with 9% ammonia solution. The filter paper containing the alkaloids was dried in an oven at 60 °C for 30 minutes, cooled, and reweighed to determine the alkaloid content. The percentage of alkaloids present in the sample is then calculated using the formula:

% of alkaloid = (weight of filter paper with alkaloid (W_2) - weight of empty filter paper (W_1)) / Weight of the sample x 100

Evaluation of Antimicrobial Activity: The synthesized AgNPs and CuNPs derived from *Calotropis gigantea*, *Leucas aspera*, *Piper nigrum*, and *Cinnamomum cassia* were evaluated for their antibacterial and antifungal potential using the agar well diffusion method. The test organisms included bacterial strains *Staphylococcus aureus*, *Pseudomonas* spp., *Salmonella* spp. and *Bacillus subtilis*, as well as fungal strains *Penicillium* and *Alternaria*. Bacterial cultures were spread uniformly on nutrient agar plates, while fungal cultures were inoculated onto Czapek Dox agar plates. Wells were created in the agar using a sterile cork borer. Each well was loaded with 100 µL of nanoparticle suspension. The bacterial plates were incubated at 37°C for 24 hours, and the fungal plates were incubated at 30°C for 72 hours. Following incubation, the antimicrobial activity was determined by measuring the diameter of the zone of inhibition around each well.

Results and Discussion

Green Synthesis of Silver and Copper Nanoparticles: The green synthesis of AgNPs and CuONPs using plant-based reducing agents *Calotropis gigantea*, *Leucas aspera*, *Piper nigrum*, *Cinnamomum cassia* and *Elettaria cardamomum* represents an eco-friendly and sustainable alternative to conventional chemical synthesis methods. This approach eliminates the use of hazardous chemicals, reduces environmental impact, and aligns with the principles of green chemistry[20,21]. The formation of nanoparticles was confirmed through characteristic colour changes- AgNPs was indicated by a visible change in colour from the initial extract to a dark brown solution, while the synthesis of CuONPs was evidenced by a colour shift from blue to green.

Among the plant extracts and spices tested, namely *Calotropis gigantea*, *Leucas aspera*, *Piper nigrum*, and *Cinnamomum cassia*, a colour change to brown along with precipitation was observed, confirming the formation of AgNPs. In contrast, no significant colour change was observed in *Elettaria cardamomum*, indicating the absence of AgNP synthesis in this extract. Similarly, upon the addition of copper sulfate to the plant extracts, *Calotropis gigantea*, *Leucas aspera*, and *Piper nigrum* exhibited a colour change from blue to green, confirming the formation of CuONPs. The observed colour transitions in both silver and copper nanoparticle synthesis are attributed to the excitation of surface plasmon vibrations, which occur due to the reduction of Ag^{+} and Cu^{2+} ions into their respective nanoparticles. These findings are consistent with previous studies, which report that the formation of AgNPs is typically associated with a brown coloration due to SPR, while CuONPs exhibit greenish coloration upon synthesis[20,22]. The role of plant phytochemicals as reducing and stabilizing agents in green synthesis has also been widely documented[21].

The effectiveness of *Leucas aspera*, *Calotropis gigantea*, and *Piper nigrum* in nanoparticle synthesis can be attributed to their rich phytochemical composition, including flavonoids, phenolic compounds, proteins, and reducing sugars. These bioactive compounds act as both reducing and stabilizing agents, facilitating the conversion of metal ions into nanoparticles and preventing their aggregation[20]. In particular, *Piper nigrum* contains bioactive constituents such as piperine, flavonoids, and phenolics, which enhance nanoparticle formation and stability[23].

Characterization of Silver and Copper Nanoparticles (UV–Visible Spectroscopy): UV–visible spectroscopic analysis of the synthesized nanoparticles revealed characteristic absorption peaks corresponding to surface plasmon resonance (SPR). Silver nanoparticles synthesized using *Calotropis gigantea*, *Leucas aspera*, *Piper nigrum*, and *Cinnamomum cassia* exhibited prominent absorption peaks in the range of 400–450nm, confirming their formation. In contrast, *Elettaria cardamomum* did not show any distinct peak in this region, indicating the absence of AgNP synthesis (Figure-1).

Similarly, CuONPs synthesized from *Calotropis gigantea*, *Leucas aspera*, and *Piper nigrum* showed characteristic absorption peaks in the range of 500–550nm (Figure-2). However, no significant peaks were observed for *Cinnamomum cassia* and *Elettaria cardamomum*, suggesting that CuONPs were not formed in these samples.

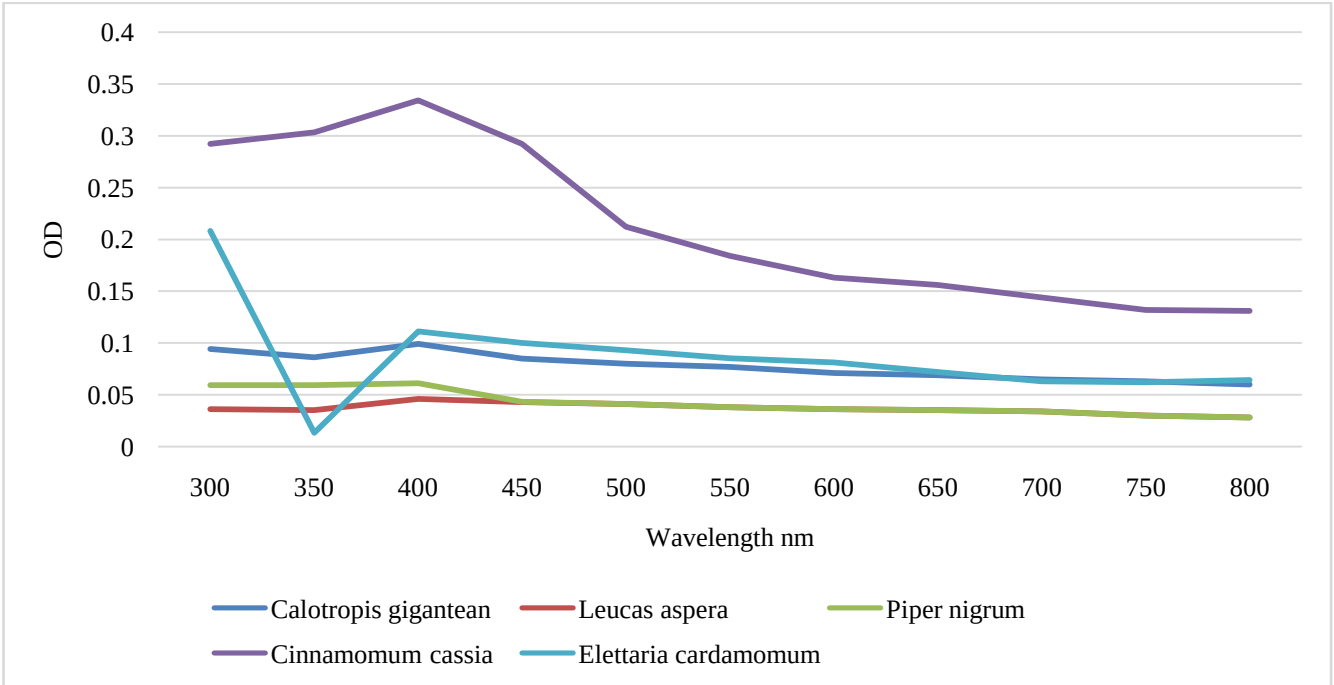


Figure-1: Absorption peak of Silver nanoparticles.

The observed absorption peaks are consistent with previously reported studies, where AgNPs typically exhibit SPR bands around 400–450nm and CuONPs around 500–550nm, depending on particle size, shape, and synthesis conditions[20,22,23].

Antimicrobial Activity of Silver and Copper Nanoparticles: Antibacterial Activity: Silver nanoparticles synthesized from *Piper nigrum* and *Leucas aspera* showed strong antibacterial activity, with zones of inhibition ranging from 14–18 mm, indicating significant antimicrobial potential. Copper oxide nanoparticles from the same extracts exhibited moderate to strong activity (10–15 mm), though generally lower than AgNPs (Table-1). Previous studies report that AgNPs exhibit higher antibacterial efficacy due to their ability to disrupt bacterial membranes and release silver ions[22,24]. Moderate antibacterial activity was observed against *Salmonella* spp. and *Bacillus subtilis*, while weaker activity (5–8 mm) was recorded for *Calotropis gigantea*, indicating limited effectiveness. *Cinnamomum cassia* showed minimal or no antibacterial activity, suggesting that its phytochemical composition may not sufficiently support nanoparticle-mediated antimicrobial effects. Furthermore, higher susceptibility was observed in Gram-positive bacteria (*Staphylococcus aureus*) compared to Gram-negative bacteria (*Pseudomonas* spp. and *Salmonella* spp.), which is in agreement with earlier studies attributing this difference to the presence of an outer membrane in Gram-negative bacteria that restricts nanoparticle penetration[24]. The results of this study demonstrate that AgNPs, particularly those synthesized from *Piper nigrum* and *Leucas aspera*, possess significant antibacterial activity, supporting their potential application as antimicrobial agents.

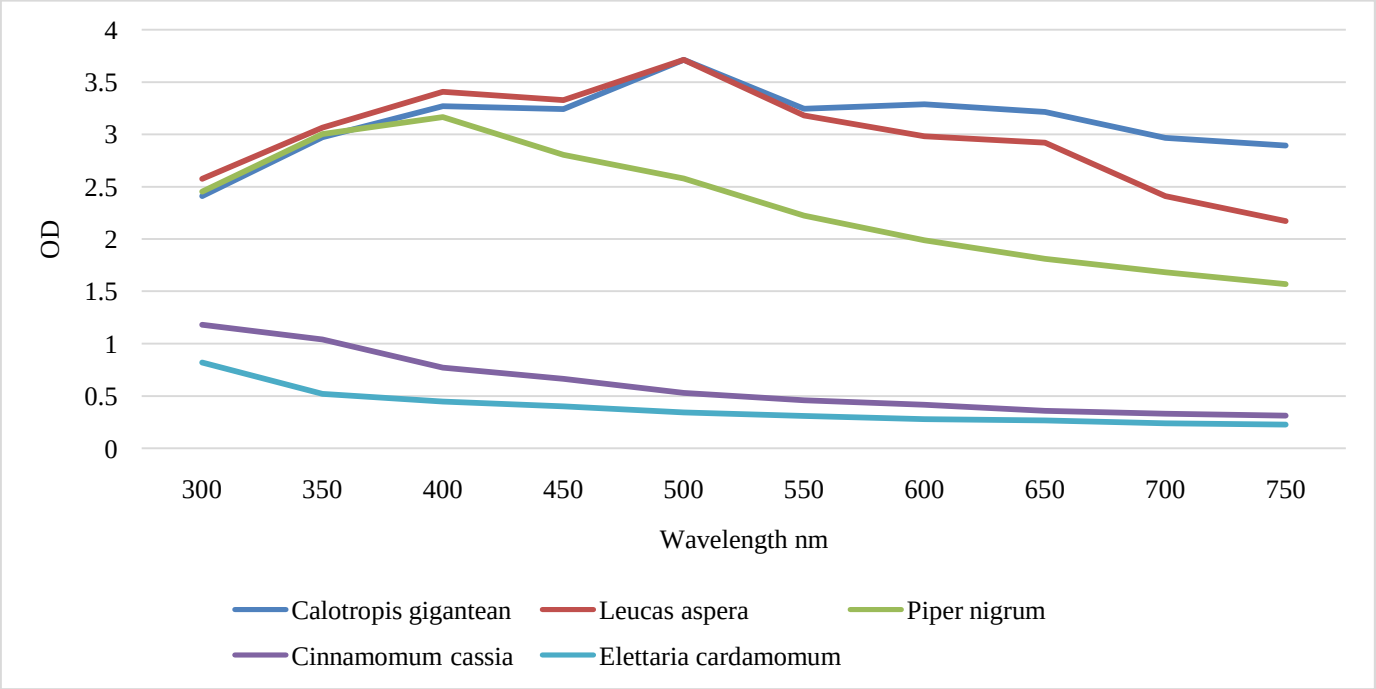


Figure-2: Absorption peak of copper nanoparticles.

Table-1: Antibacterial activity of AgNPs and CuONPs.

Zone of Inhibition(mm)								
Extracts	Staphylococcus aureus		Pseudomonas spp		Salmonella spp		Bacillus subtilis	
	AgNPs	CuONPs	AgNPs	CuONPs	AgNPs	CuONPs	AgNPs	CuONPs
Calotropis gigantean	7	6	7	5	7	7	8	8
Leucas aspera	17	14	8	7	12	10	12	12
Piper nigrum	18	15	8	8	14	13	12	11
Cinnamomum cassia	8		-		-		-	

Antifungal Activity: Silver nanoparticles synthesized from *Calotropis gigantea*, *Leucas aspera*, and *Piper nigrum* showed strong antifungal activity against *Penicillium*, with zones of inhibition ranging from 15–18mm (Table-2). Similarly, CuONPs from these extracts also exhibited moderate to strong inhibition (14–15mm). Among them, *Calotropis gigantean* AgNPs showed the highest activity (18mm), indicating significant antifungal potential. These findings are in agreement with previous studies demonstrating the effectiveness of metal nanoparticles against fungal pathogens due to their ability to disrupt cell membranes and interfere with cellular metabolism[25,26]. In contrast, very low or negligible activity was observed against *Alternaria*. Most extracts showed either no inhibition or minimal zones (0–1mm), indicating that *Alternaria* is relatively resistant to both AgNPs and CuONPs. This reduced susceptibility may be due to differences in fungal cell wall composition and defence mechanisms, which limit nanoparticle penetration[27]. *Cinnamomum cassia* did not exhibit any antifungal activity against either fungal strain, suggesting that it was ineffective in nanoparticle-mediated antifungal action under the tested conditions. The results are supported by previous findings that silver nanoparticles are more potent antifungal agents due to their higher reactivity and ion release[21].

The study confirms that green-synthesized AgNPs and CuONPs possess significant antimicrobial properties. AgNPs, particularly those synthesized from *Piper nigrum* and *Leucas aspera*, demonstrated strong antibacterial and antifungal activity. The findings highlight the potential application of these nanoparticles in medicine, agriculture, and environmental management as effective antimicrobial agents.

Evaluation of Phytochemicals: The phytochemical profiling of *Calotropis gigantea*, *Leucas aspera*, *Piper nigrum*, *Cinnamomum cassia* and *Elettaria cardamomum* revealed notable variation in the distribution of major bioactive compounds, including proteins, carbohydrates, phenols, flavonoids, tannins, and alkaloids. Among these, proteins and alkaloids were found to be the most abundant phytochemicals across the extracts, whereas phenols and flavonoids were present in comparatively lower concentrations (Figure-3). *Leucas aspera* and *Piper nigrum* exhibited relatively higher levels of proteins and alkaloids along with moderate tannin content, indicating a rich phytochemical composition.

Table-2: Antifungal activity of AgNPs and CuONPs.

Zone of Inhibition(mm)				
Extracts	Penicillium		Alternaria	
	AgNPs	CuONPs	AgNPs	CuONPs
Calotropis gigantean	18	15	1	1
Leucas aspera	15	14	-	1
Piper nigrum	16	14	-	-
Cinnamomum cassia	-	-	-	-

This balanced presence of biomolecules is known to facilitate both the reduction and stabilization of metal ions during nanoparticle synthesis[20]. In contrast, *Calotropis gigantea* showed moderate phytochemical levels, correlating with its comparatively lower efficiency in nanoparticle synthesis and antimicrobial activity. Interestingly, *Elettaria cardamomum* demonstrated a significantly higher protein content but relatively low levels of other phytochemicals. Despite this, it did not show effective nanoparticle formation, suggesting that proteins alone may not be sufficient for nanoparticle synthesis.

The synergistic role of multiple phytochemicals, particularly polyphenols and reducing sugars, is critical in the bioreduction process[21]. *Cinnamomum cassia* displayed moderate tannin levels but lower overall phytochemical diversity, which may explain its limited contribution to nanoparticle synthesis and biological activity. Tannins and other phenolic compounds are known to act as reducing agents; however, their effectiveness depends on their concentration and interaction with other biomolecules[22].

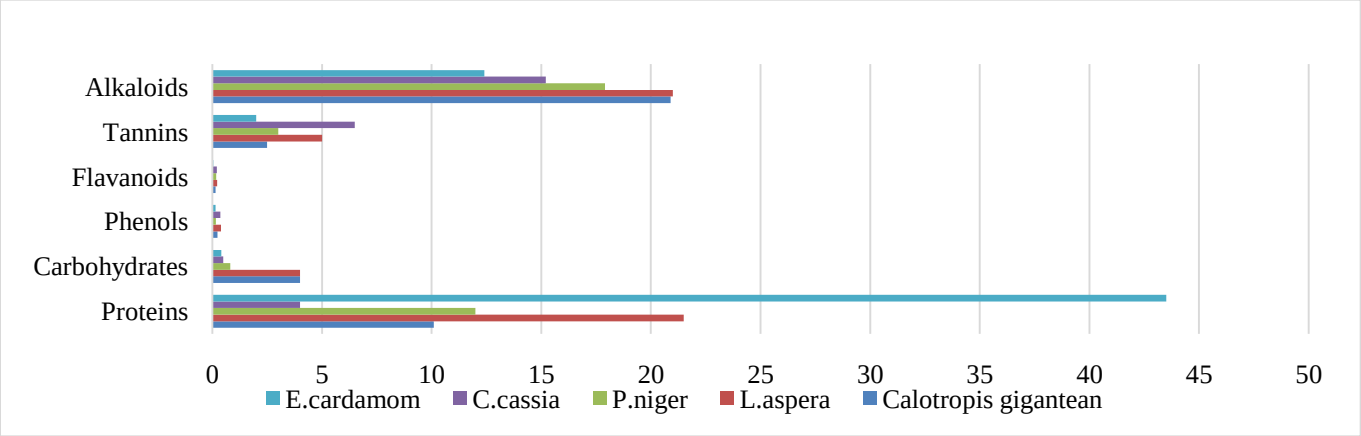


Figure-3: Evaluation of phytochemicals.

Our results suggest that nanoparticle synthesis efficiency is strongly influenced by the combined presence of phytochemicals, particularly proteins, alkaloids, and polyphenols. Extracts with a balanced phytochemical profile, such as *Leucas aspera* and *Piper nigrum*, demonstrated better performance in nanoparticle formation and antimicrobial activity. These findings are consistent with previous studies highlighting the importance of plant-derived biomolecules in green nanotechnology[25,21].

Conclusion

Compared to conventional chemical synthesis methods, plant-mediated nanoparticle synthesis offers several advantages, including cost-effectiveness, biocompatibility, and reduced toxicity. Chemical methods often involve hazardous reagents and generate toxic by-products, posing risks to human health and the environment. In contrast, green synthesis utilizes naturally available plant materials, making the process safer and more sustainable. Overall, our study demonstrates that plant-mediated synthesis of AgNPs and CuNPs is an efficient and environmentally benign approach. The synthesized nanoparticles exhibit promising antibacterial and antifungal properties, suggesting their potential applications in medicine, agriculture (as biopesticides and growth enhancers), and environmental management. Thus, green nanotechnology using plant extracts is emerging as a significant area of research with wide-ranging future applications.

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