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Biosynthesis and characterization of copper nanoparticles using ginger extract

Ban Jabbar Aziz Mohammed, Neama Ali Ahmed
Department of Biology, College of Science, Uinversity of Kirkik, Iraq

Abstract
Biosynthesized copper nanoparticles employing ginger extract represent an exciting advance within the field of nanotechnology, integrating the distinctive copper properties with the inherent advantages of ginger delivery. The ginger-mediated synthesis endows the resulting particles with enhanced stability and biofunctionality, signalling wider prospective utility. The present investigation sought to fabricate copper nanoparticles relying explicitly upon ginger extract and to exhaustively characterize the colloidal systems through state-of-the art apparatus. Initial preparation explored copper acetate and copper nitrate as precursors, with ginger being employed in both aqueous and ethanol-toluene -based exactives. Systematic analysis incorporated a battery of diagnostics, including transmission electron microscopy, UV-Vis spectroscopy, Zeta potential, powder X-ray diffraction, and Fourier-transform infrared spectroscopy. Optimal behaviours emerged when copper nitrate was processed within ethanol ginger matrix, displaying a mean particle size of approximately 29 nanometres, exceptionally congruent stability (Zeta potential -57.1 mV) versus copper acetate counterparts reaching dimensions (approximately 245 nanometres, -33.5 mV) and diminished translational stabilization. The collective observations endorse an efficient one-step platform through in situ ginger-derived reducing and stabilizing bio-constituents capable of thermodynamically stabilizing the copper nanodynamics. The research unequivocally delineates that the choice of copper precursor and creative solvent as extraction and dispersant vehicle modulates dimensional, dispersive, and crystallographic dispersivity. The operational parameters thus emerge as decisive levers steering the metallic core properties, reinforcing ginger as a green, intrinsic templating agent.

Keywords: Copper nanoparticles, ginger, biosynyhesis, tem, uv-vis, xrd, ftir

Introduction

Materials research is moving forward at an extraordinary pace, and the science of nanomaterials is no exception. By design, nanostructures have properties that are fundamentally different from those of the same substance at larger scales, which already promises disruptive change across many domains [1]. Within this expanding toolkit, metallic nanoparticles are especially prominent; their tunable size, surface area, and electronic properties open doors in electronics, drug delivery, therapy, catalysis, and environmental remediation [2]. Among the various metal systems, copper nanoparticles (CuNPs) have distinguished themselves through multiple attractive functionalities. Their relativistic ease of synthesis and relatively low cost, combined with excellent thermal, catalytic, and wound-treatment outcomes, establish a singular combination of promise [3]. Conventional routes to nanoparticles, whether bottom-up or top-down, usually employ toxic precursors, intense thermal and athermal processes, and finely engineered equipment that together generate hazardous by-products that compromise wider sustainability goals [4]. Rising awareness of ecological impact, tighter regulatory environments, and societal expectation of sustainable innovation have made reductive, protective, and functionalizing agents of biological origin the techno-economic enabler of “green synthesis.” Employing plant extracts, microbial metabolites, and other biological scaffolds, recent methodologies formulates nanostructures under aqueous, mild, and non-hazardous conditions [5].

Given their abundance of bioactive substances, including flavonoids, polyphenols, vitamins, and carbohydrates, which can lower metal ions and stabilize the resultant nanoparticles, plants are essential in this regard for green manufacturing methods [6]. Several investigations have shown that different plant extracts can form different metal nanoparticles, such as magnesium oxide, gold, platinum, and silver [7].

Because of its many therapeutic benefits, ginger (Zingiber officinale) is a significant medicinal plant with a long history of both traditional and contemporary use. According to research, ginger contains a lot of phenolic chemicals, namely shogaols and gingerols, along with other substances like flavonoids and starches [8]. Ginger extract is a promising option for use as a bioactive agent in the reduction of copper ions and the creation of copper nanoparticles because of these compounds' reducing and antioxidant qualities, especially those of the functional groups they contain (such as hydroxyl and carbonyl groups) [9].

The purpose of this study is to investigate how ginger extract might be used in the production of copper nanoparticles. In addition to researching the physical and chemical characteristics of these particles using cutting-edge characterisation techniques, the main goal will be to create a straightforward, effective, and eco-friendly manufacturing process for copper nanoparticles. Evaluation of the particle's size, shape, stability, and structural characterization will also be a goal of the study. If this project is successful, it will help create a new and sustainable way to make copper nanoparticles, which will lead to new uses for them in a variety of industries, particularly those that need nanomaterials with improved qualities and a small environmental impact.

Materials and methods

Materials used

Fresh ginger plant was obtained from local markets in Kirkuk city. Copper (II) acetate salts (Cu $(CH_3COO)_2 \bullet H_2O$) and copper (II) nitrate salts (Cu $(NO_3)_2 \bullet 3H_2O$) were used from Sigma-Aldrich. High purity solvents included deionized water and pure ethanol (98%).

Preparing ginger extracts

Fresh ginger roots were cleaned, cut into thin slices, and then shade-dried for a week. They were then ground to obtain a fine powder. To prepare the aqueous extract, 10 grams of the powder was dissolved in 150 ml of deionized water, and the mixture was heated at 70°C for 30 minutes with continuous stirring. The alcoholic extract was prepared in the same manner, using ethanol instead of water. The extracts were filtered using Whatman No. 1 filter paper and stored in a refrigerator at 4°C until use.

Biosynthesis of copper nanoparticles

Copper salt solutions were prepared at a concentration of 0.01 M in deionized water. To prepare the nanoparticles, 250 ml of the salt solution was mixed with 250 ml of the freshly prepared plant extract at a ratio of 1:1. The mixture was placed on a magnetic thermal stirrer at 70 °C for 15 min with continuous stirring. An immediate color change indicating the formation of nanoparticles was observed, where the copper acetate turned blue-green, while the copper nitrate turned clear green.

After the reaction was completed, the mixture was allowed to cool to room temperature, and the pH was measured and confirmed to be in the range of 8-11. The solution was left for 24 hours to complete the reaction and form the nano-precipitate. Then, the nanoparticles were separated by centrifugation at 10,000 rpm for 15 minutes, and washed three times with deionized water to remove impurities.

Characterization of nanoparticles

Transmission electron microscope (TEM)

The size and shape of the nanoparticles were examined using a Philips CM12 transmission electron microscope at an accelerating voltage of 120 kV. Samples were prepared by diluting the nanoparticle suspension and placing a drop onto a carbon-coated copper grid, and allowed to dry at room temperature before examination.

Ultraviolet-Visible (UV-Vis) Spectroscopy

The absorption spectra of the nanoparticles were measured using a Shimadzu UV-2600 spectrometer in the range of 200-800 nm to identify the characteristic surface plasmon resonance (SPR) peak of copper nanoparticles.

(Zeta Potential) Zeta analysis potential

The zeta potential and size distribution of the nanoparticles were measured using a ZS Nano Zetasizer Malvern to evaluate the colloidal stability and dispersibility in solution.

X-ray diffraction (XRD)

The crystal structure of the nanoparticles was analyzed using a MiniFlex Rigaku 600 instrument at a radiation of (λ Kα Cu Å) = 1.5406 in the angular range 2θ from 10° to 80°.

Infrared (FTIR)

The functional groups present on the surface of the nanoparticles were analyzed using an Elmer Perkin 100 Spectrum in the range 400-4000 cm^{1-} to identify the phytochemicals bound to the particles.

Results

Biosynthesis of CuNPs

When copper nanoparticles (CuNPs) were prepared using copper acetate (Cu $(CH_3COO)_2 \bullet H_2O$), the solution color was observed to turn bluish green, while the use of copper nitrate (Cu $(NO_3)_2 \bullet 3H_2O$) resulted in a clear green color, as shown in Figure 1. This color difference is attributed to several physical and chemical factors related to the nature of the salt used, the effect of the accompanying anions, and the behavior of the nanoscale interaction.

Fig 1: illustrates biosynthsized NPs from: A- Copper nitrate B- Copper acetate.

Transmission electron microscope (TEM) results

TEM examination results showed a clear difference in the size and shape of the nanoparticles depending on the type of salt used, as can be seen in Figure 2. Copper nanoparticles prepared using copper nitrate dissolved in ethanol showed a smaller size with an average of 29 ± 5 nm and a more regular distribution with a spherical to ovoid shape. In contrast, water-soluble copper acetate particles were significantly larger with an average size of 245 ± 35 nm with greater size variation and a tendency to aggregate.

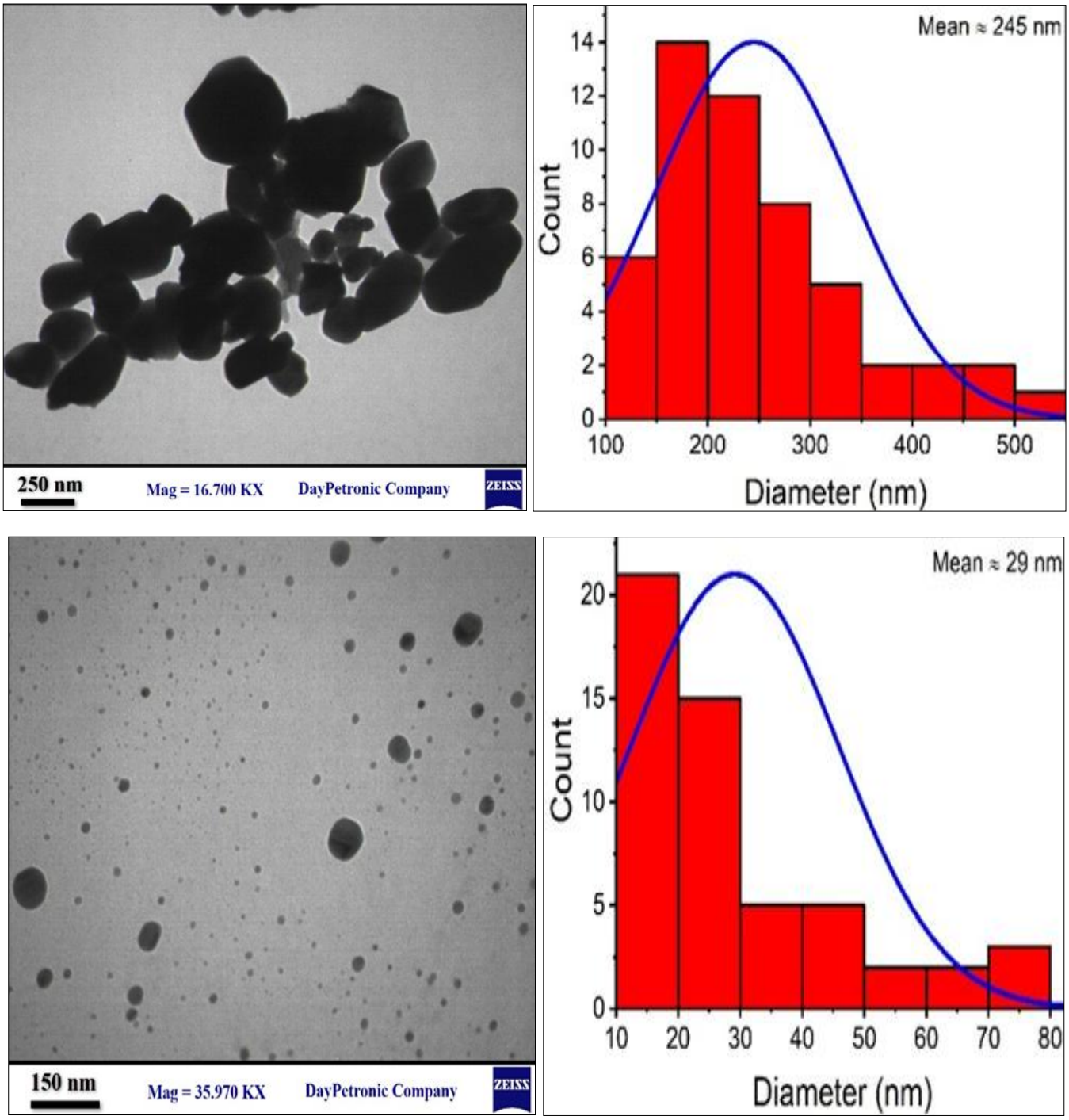

Fig 2: TEM image of copper nanoparticles (Cu NPs) prepared using: A- Copper (II) acetate dissolved in distilled water, B- Copper (II) nitrate dissolved in ethanol.

UV-Vis spectroscopic results

Spectroscopic analysis revealed a distinct surface plasmon resonance (SPR) absorption peak for copper nanoparticles, illustrated in Figure 3 and Table 1. Copper nitrate particles recorded a sharp absorption peak at 575 nm, while copper acetate particles exhibited a broader and less intense peak at 590 nm. This difference reflects differences in particle size and distribution, with smaller and more uniform particles producing sharper peaks and a shift toward shorter wavelengths.

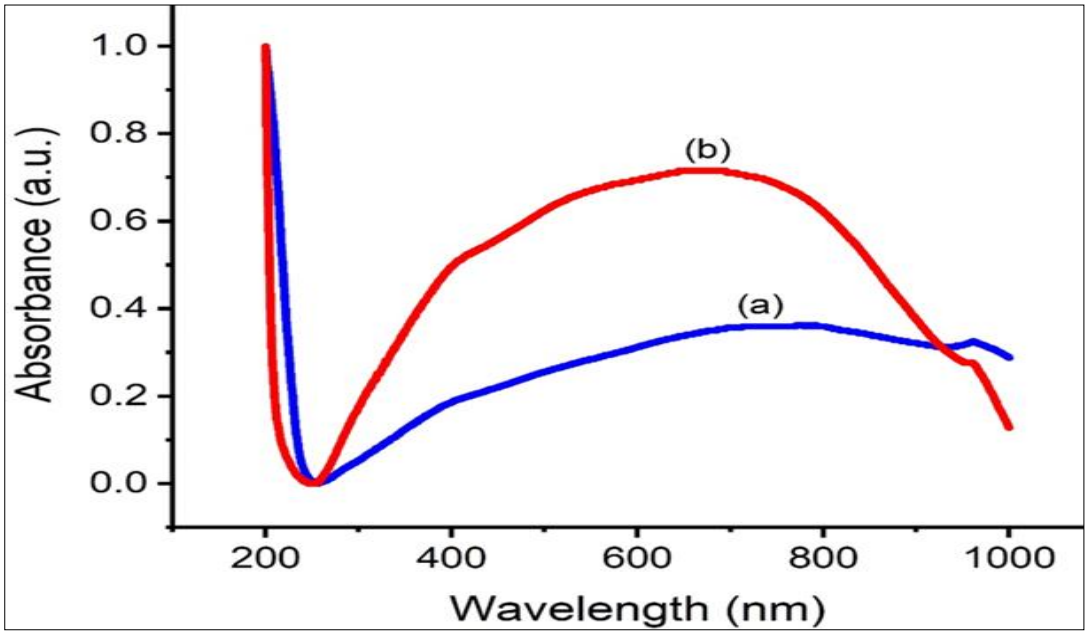

Fig 3: Absorption spectrum of copper nanoparticles (Cu NPs) prepared using: A- Copper (II) acetate dissolved in distilled water, B- Copper (II) nitrate dissolved in ethanol.

Zeta potential analysis results

Copper nitrate particles showed higher colloidal stability at a zeta potential of -57.1 ± 3.2 mV, indicating high stability in solution and resistance to aggregation. In contrast, copper acetate particles recorded a lower zeta potential of -33.5 ± 2.8 mV, indicating lower stability and greater potential for aggregation over time. Figure 4 and Table 1, show the results of zeta potential analysis.

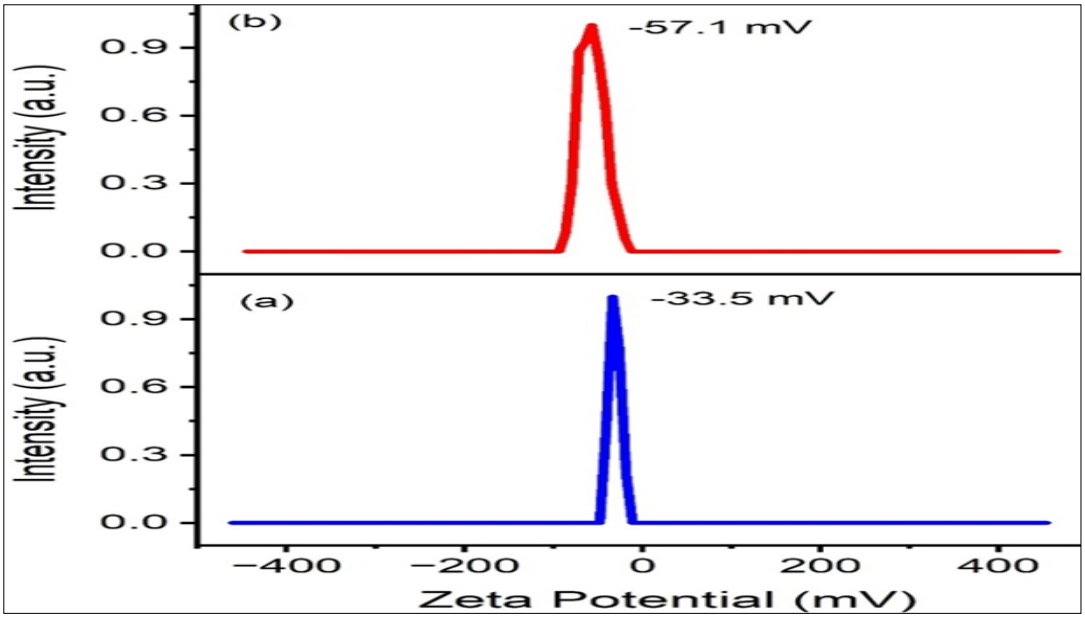

Fig 4: Zeta potential of copper nanoparticles (Cu NPs) prepared using: A- Copper (II) acetate dissolved in distilled water, B- Copper (II) nitrate dissolved in ethanol.

Table 1: Summary of the properties of the prepared nanoparticles.

Particle type	Average volume (nm)	Zeta potential (mV)	SPR Peak	Colloidal Stability (nm)
Copper nitrate-ethanol	5 ± 29	3.2 ± 57.1	575	High
Copper acetate-water	35 ± 245	2.8 ± 33.5	590	Medium

X-ray diffraction (XRD) results

XRD analysis showed the presence of sharp and strong diffraction peaks, confirming the crystalline nature of the prepared nanoparticles, as presented in Figure 5. Characteristic peaks were recorded at angles of 2θ = 43.3°, 50.4°, and 74.1°, which correspond to the (111), (200), and (220) crystal planes of the face-centered cubic (FCC) structure of copper. The copper nitrate particles showed sharper peaks, indicating higher crystallinity compared to the copper acetate particles.

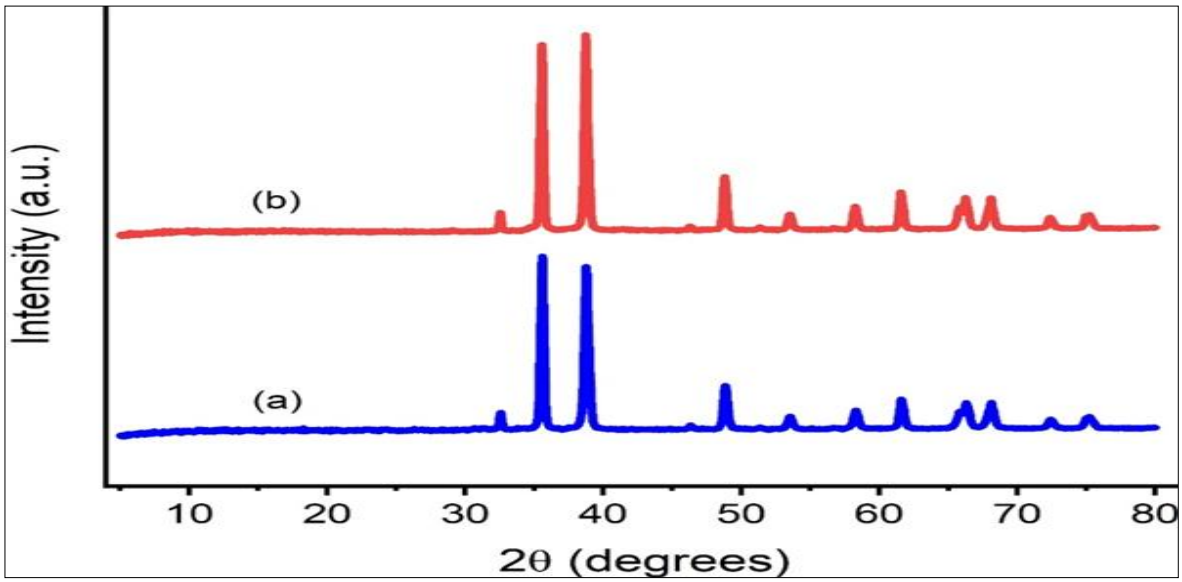

Fig 5: X-ray diffraction (XRD) pattern of copper nanoparticles (Cu NPs) prepared using: A- Copper (II) acetate dissolved in distilled water, B- Copper (II) nitrate dissolved in ethanol.

FTIR results

FTIR analysis revealed the presence of various functional groups on the surface of the nanoparticles derived from ginger extract. For copper acetate nanoparticles, absorption peaks were observed at 1138, 1049, and 956 cm^{1-}, associated with C-O-C extension of esters, C-OH extension of polyphenols, and metal-oxygen bonds, respectively. Copper nitrate particles showed peaks at 2030, 1412, 1147, 1012, and 878 cm^{1-} associated with N=C=O groups, nitrate ions, and CO bonds resulting from active plant compounds. As shown in Figure 6.

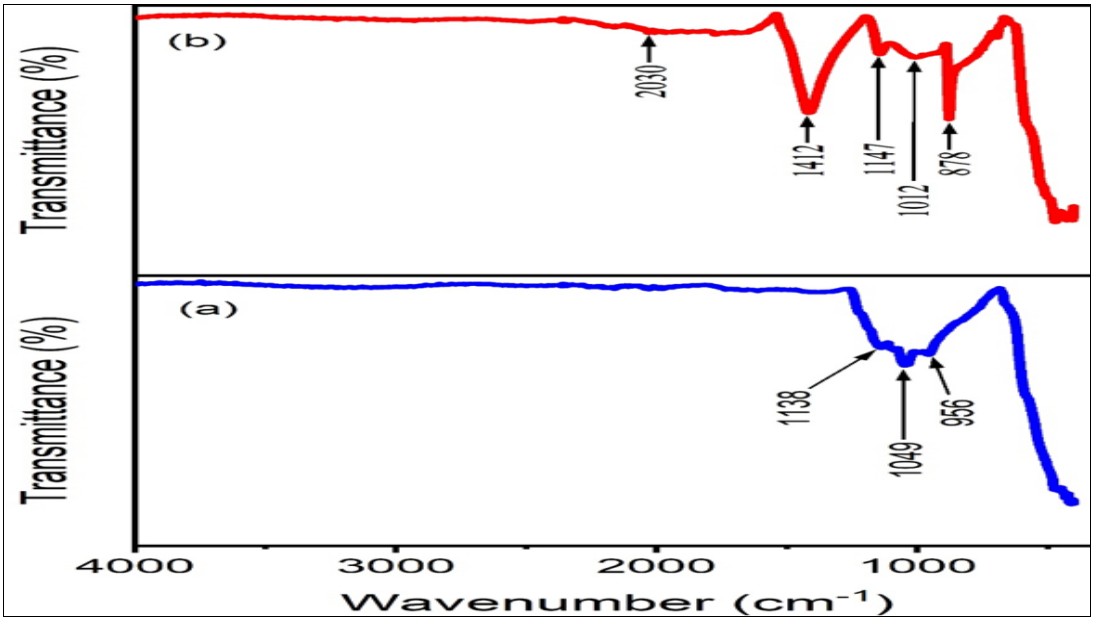

Fig 6: Fourier transform infrared analysis of copper nanoparticles prepared using: A- copper (II) acetate dissolved in divalent water and B- copper (II) nitrate dissolved in ethanol.

Discussion

The results of this study confirm the success of the biosynthesis of copper nanoparticles using ginger extract, with the achievement of distinct nanoscale properties. This success is attributed to the chemical richness of ginger extract in active compounds such as gingerol and shogaol, which act as natural reducing and stabilizing agents, which is consistent with the studies of [10, 11].

The clear difference in the properties of the nanoparticles between the two prepared types reflects the effect of the nature of the salt used and the solvent on the synthesis process. The superiority of copper nitrate particles in terms of small size (~29 nm) and high colloidal stability (-57.1 mV) can be explained by several factors. First, the nitrate ion ($^{-}NO_3$) is less complex and more soluble than the acetate ion, which facilitates the reduction process. Second, ethanol as a solvent provides a more homogeneous environment for the reaction compared to water, leading to better control of the nanogrowth process and the formation of more uniform particles.

These results are consistent with the study by Huang *et al.* (2017), which showed that the type of conjugated anion directly affects the size of the formed nanoparticles, with nitrate producing smaller particles compared to acetate.

FTIR analysis results also support this interpretation, as the spectra revealed the presence of different compounds on the surface of the particles depending on the type of salt, which affects their physical and biological properties.

Conclusion

Biosynthesizing copper nanoparticles using ginger extract offers a promising and potentially beneficial route in nanotechnology. This study successfully demonstrated that the method of ginger extract and copper salt used significantly impacts the resulting copper nanoparticles' characteristics. Specifically, the use of copper nitrate dissolved in ethanol yielded smaller, more stable nanoparticles compared to copper acetate. These findings highlight the critical role of precursor choice and solvent in green synthesis, suggesting that careful optimization can lead to engineered nanoparticles with tailored properties for diverse applications, such as antimicrobial agents, catalysts, or drug delivery systems.

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