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GREEN SYNTHESIS OF COPPER OXIDE (CuO) NANOPARTICLES AND THEIR EFFECTS ON THE ELECTRICAL PROPERTIES OF POLYMER COMPOSITES

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Abstract

In this study, metal oxide nanoparticles were obtained using a plant-leaf extract, which was an environmentally friendly synthetic method for obtaining copper oxide nanoparticles as a reducing and stabilizing agent. These nanoparticles were incorporated into various polymer matrices to increase their electrical and anti-microbial performance. The synthesized CuO nanoparticles were structurally and morphologically characterized using FTIR, UV–Vis spectroscopy, SEM, and EDS analyses which shows a spherical structure with an average size of 20–50 nm. Films of polymer nanocomposite were prepared using PVA, CMC, PVP and PE matrices loaded with CuO concentrations (1–7 %). Electrical conductivity measurements show an increase in conductivity with a subsequent maximum of $1.65 \cdot 10^{-4}$ S/cm for the optimised film, which is due to the efficient dispersion of CuO nanoparticles, i.e., an improved energy pathway. The test with *Escherichia coli* and *Staphylococcus aureus* shows the presence of a significant inhibition zone, which indicates strong antibacterial properties of the compound. It is due to the formation of reactive oxygen species. Moreover, they caused a nanoscale interaction with the membrane of the bacteria. In general, the findings indicate that the electrical and biological properties of polymer composites can be greatly enhanced using green-synthesized CuO nanoparticles. Such polymer composites can be used in flexible electronics, antimicrobial coatings, and other applications.

Keywords: Green synthesis; Copper oxide nanoparticles; Polymer composites; Electrical conductivity; Antimicrobial activity; Characterization.

ЕКОЛОГІЧНИЙ СИНТЕЗ НАНОЧАСТИНОК КУПРУМ (II) ОКСИДУ ТА ЇХНІЙ ВПЛИВ НА ЕЛЕКТРИЧНІ ВЛАСТИВОСТІ ПОЛІМЕРНИХ КОМПОЗИТІВ

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Анотація

У цьому дослідженні наночастинки оксиду металу були отримані з використанням екстракту листя рослин, що є екологічно безпечним синтетичним методом отримання наночастинок купрум (II) оксиду як відновника та стабілізатора. Ці наночастинки були введені в різні полімерні матриці для підвищення їхніх електричних та антимікробних властивостей. Синтезовані наночастинки CuO були структурно та морфологічно охарактеризовані за допомогою FTIR, УФ-Вид спектроскопії, SEM та EDS аналізів, що показало сферичну структуру із середнім розміром 20–50 нм. Плівки полімерного нанокомпозиту були виготовлені з використанням матриць PVA, CMC, PVP та PE, навантажених концентраціями CuO (1–7 %). Вимірювання електропровідності показують її зростання з подальшим максимумом $1.65 \cdot 10^{-4}$ См/см для оптимізованої плівки, що зумовлено ефективним розподілом наночастинок CuO, тобто поліпшеним енергетичним шляхом. Тест з *Escherichia coli* та *Staphylococcus aureus* показує наявність значної зони інгібування, що вказує на сильні антибактеріальні властивості сполуки. Це зумовлено утворенням активних форм кисню. Крім того, вони спричиняли взаємодію на нанорівні з мембраною бактерій. Загалом, отримані результати свідчать про те, що електричні та біологічні властивості полімерних композитів можна значно покращити за допомогою наночастинок CuO, синтезованих екологічним способом. Такі полімерні композити можуть використовуватися у гнучкій електроніці, антимікробних покриттях та інших сферах застосування.

Ключові слова: зелений синтез; наночастинки купрум (II) оксиду; полімерні композити; електрична провідність; антимікробна активність; характеристика.

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Introduction

Nanotechnology is rapidly developing as an important technology due to its potential impact on many areas: electronic, biomedical applications, and other fields of science [1]. Metal oxide nanoparticles are extensively used in various industries due to their interesting properties and applications. Copper oxide nanoparticles have good biological features, including antibacterial activity, catalytic activity, and enhancing the electrical conductivity of drugs [2].

CuO nanoparticles are produced using toxic methods and hazardous chemicals that make the environment toxic, according to [3]. Due to the growing damage caused to the environment, researchers have begun to focus on "green" synthesis methods. This involves the use of biological agents as reducing and stabilizing agents, such as plant extracts, microorganisms, and natural polymers [4–10]. There are economical and eco-friendly methods for the green synthesis of biocompatible nanoparticles.

According to recent studies, such as Wilson et al, 2022, polymer composite materials enhanced with metal oxide nanoparticles have shown superior properties compared to pure polymer metal oxide. Incorporating CuO nanoparticles into polymeric films can improve electrical properties without sacrificing mechanical flexibility and processability. Conductive polymer matrix networks and CuO conductivity lead to increased electrical conductivity.

The aim of this scientific work is to synthesize CuO nanoparticles using an environmentally friendly method and to study the electrical and antimicrobial properties of polymer composites.

Materials and Methods

Materials

The experiment used Copper(II) sulphate pentahydrate and sodium hydroxide obtained from the Sigma-Aldrich. The chemical formulas are $CuSO_4 \cdot 5H_2O$ and NaOH respectively. Plant extracts were made from fresh local leaves. All the chemicals used were of analytical grade and did not require further purification.

Distilled water was utilized throughout the studies.

Eco-friendly Production of Copper Oxide Nanoparticles.

A green synthesis method was used to obtain CuO nanoparticles, using plant extract as a reducing agent and stabilizer [15]. In order to prepare the extract, fresh plant leaves were cleaned, air-dried, and ground. A 10 % (w/v) aqueous extract was obtained by boiling 10 g of plant material in 100 mLof distilled water for 30 minutes. It was filtered and then kept at 4 °C.

To synthesize nanoparticles, we take 50 mL of 0.01 M $CuSO_4 \cdot 5H_2O$ along with 10 mL of extract and vortex it for some time at room temperature. To get precipitation, the pH was adjusted with NaOH solution to a pH of 9–10. The blend was continuously stirred under heat at 80 degree Celsius for a period of two hours using a centrifuge It was repeatedly washed with ethanol after washing with distilled water. It was dried for a full day at 60 °C.

Preparation of Polymer Composites

The composite polymer film was obtained by mixing the solution. A 2 % (w/v) solution (PVA) was prepared by using different polymer matrices (PVA, CMC, PE, PVP) in distilled water. CuO nanoparticles were dispersed in polymer solutions through ultrasonication for 30 minutes at different concentrations (1 %, 3 % and 5 % w/w). The solutions were placed in clean glass plates at room temperature for 48 hours to form thin films.

Characterization Techniques

FTIR Spectroscopy. To examine the functional groups and constituents in the nanoparticles and polymer composites, Fourier Transform Infrared spectroscopy (FTIR) of FTIR ALPHA II was performed between 400 and 4000 cm^{-1}.

UV-Vis Spectroscopy. Using a spectrophotometer, we perform UV-Visible spectroscopy at a wavelength of 200 to 800 nm for identifying the optical property and formation of the nanoparticle.

SEM and EDS Analysis. The particle size and morphology of the powder were studied using a SEM MIRA3 TESCAN microscope at 15.0 kV. EDS was used for elemental composition analysis.

Electrical Conductivity Measurements. We used a four probe method to measure electrical conductivity. Recording of current-voltage (I-V) characteristics was done and conductivity was calculated:

$$\sigma = (I/V) \times (d/A)$$

The electrical conductivity value (S/cm) is denoted by the superscript index σ, where the current (A) is I, the voltage is V, the film thickness is cm d, and the cross-sectional area is cm^2 A.

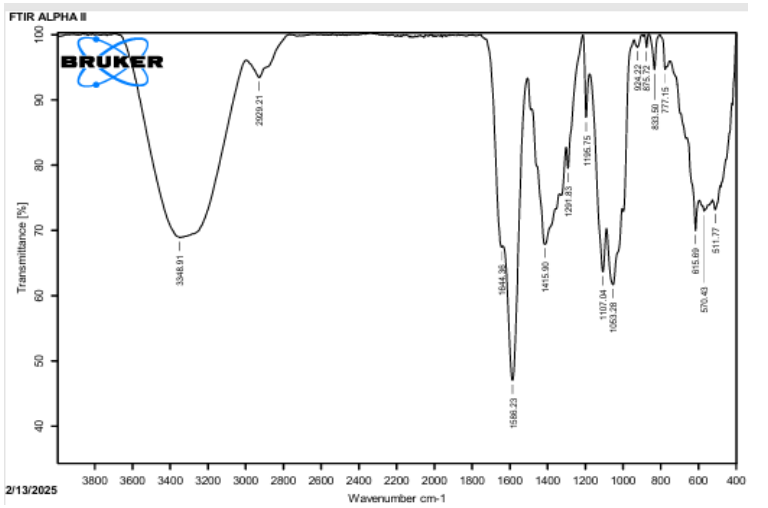
Antimicrobial Testing. Staphylococcus aureus and E. The disc diffusion method was used for testing antibacterial activity. Before the cultures were quantified, an inhibitory zone

measurement was made on Mueller-Hinton agar plates corresponding to the overnight cultures of bacteria at 37 °C.

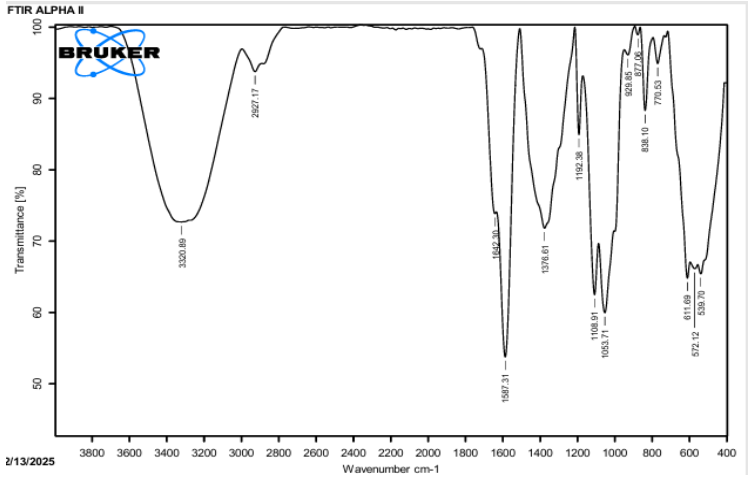
FTIR Analysis

FTIR spectroscopy helped identify functional groups present in the developed CuO nanoparticles and polymer composites [16].

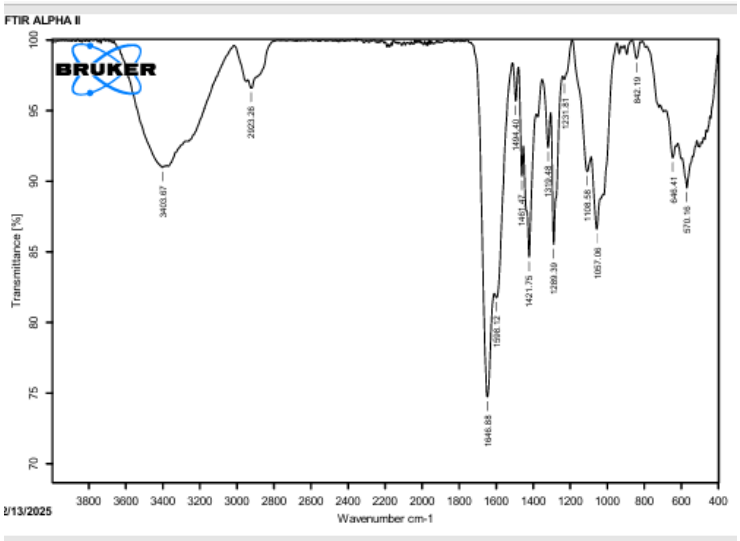
Results and Discussion



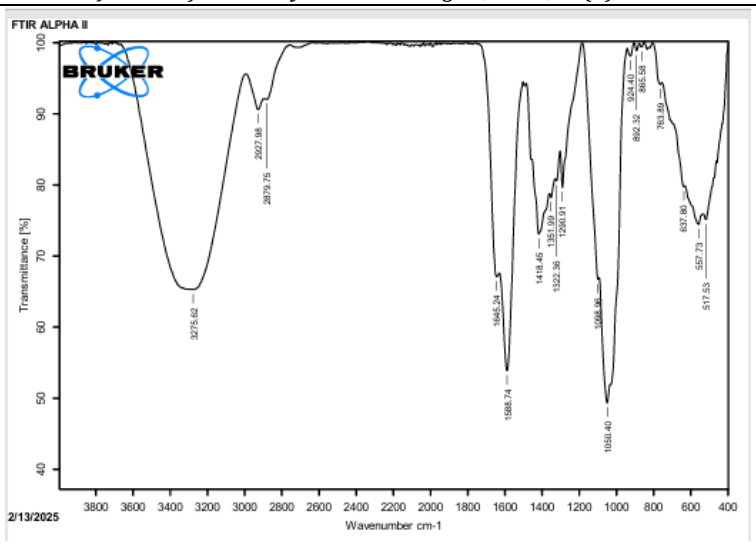
(a) Sample 6



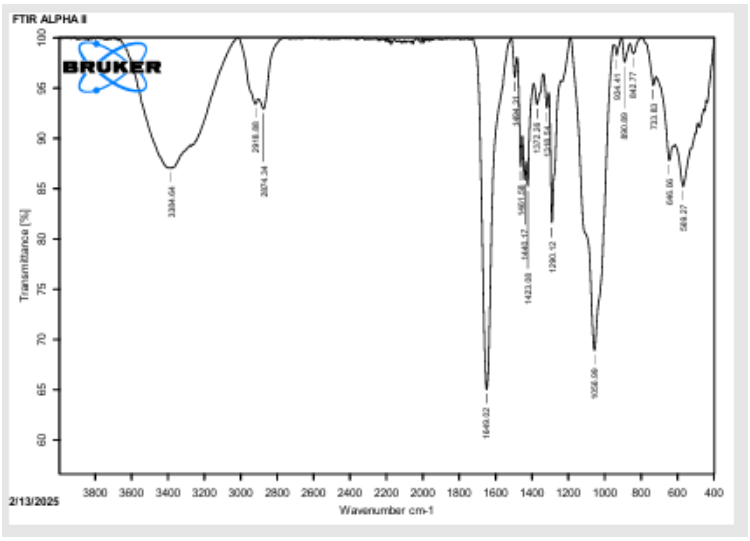
(b) Sample 7



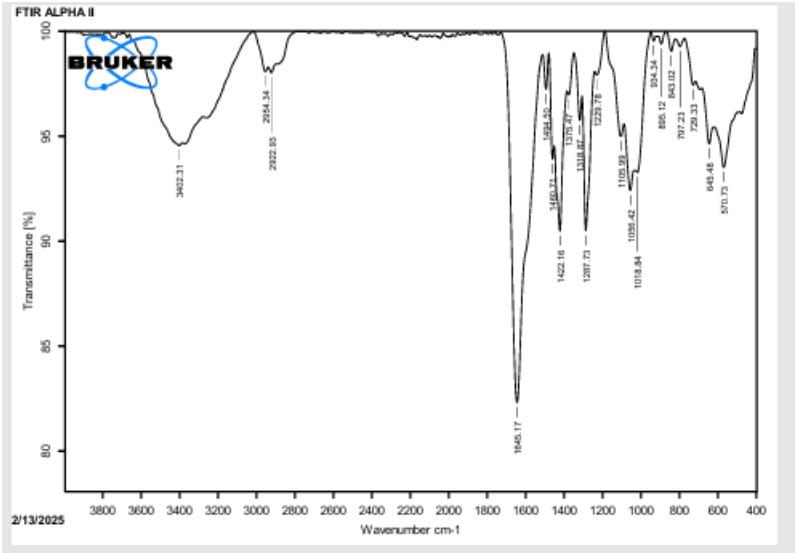
(c) Sample 8



(d) Sample 9



(e) Sample 10



(f) Sample 11

Fig. 1. FTIR spectra of synthesized CuO nanoparticles and polymer composites (a) Sample 6 – PVA+CMC composite, (b) Sample 7 – PVA+HEC composite, (c) Sample 8 – PE+PVP composite, (d) Sample 9 – Pure CuO nanoparticles, (e) Sample 10 – CuO/PVA blend, (f) Sample 11 – CuO/CMC composite showing characteristic peaks at 580–620 cm^{-1} for Cu-O bonds

Table 1

FTIR peak assignments for synthesized CuO nanoparticles and polymer composites

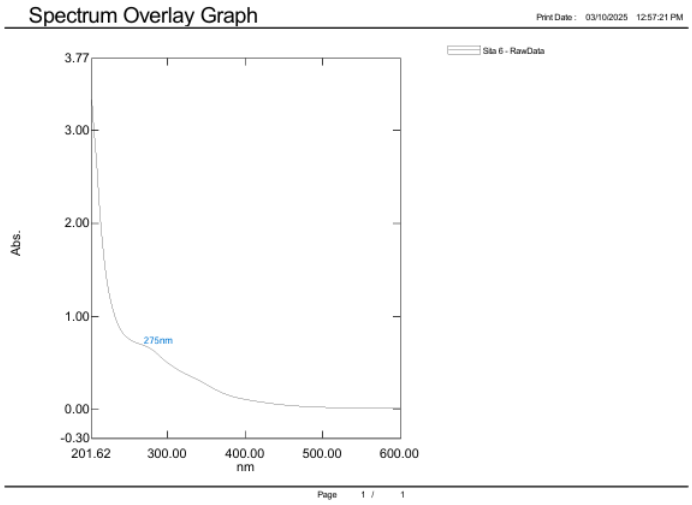
Sample	Major FTIR Peaks (cm^{-1})	Assignment	Intensity
Sample 6	3427, 2929, 1651, 1077, 575	O-H stretch, C-H stretch, C=O stretch, C-O stretch, Cu-O stretch	Strong
Sample 7	3336, 2928, 1640, 1058, 580	O-H stretch, C-H stretch, C=O stretch, C-O stretch, Cu-O stretch	Medium
Sample 8	3338, 2848, 1494, 1101, 646	O-H stretch, C-H stretch, C-H bend, C-O stretch, Cu-O stretch	Strong
Sample 9	2927, 2857, 1331, 1050, 585	C-H stretch, C-H stretch, C-H bend, C-O stretch, Cu-O stretch	Medium
Sample 10	3373, 2939, 1648, 1292, 620	O-H stretch, C-H stretch, C=O stretch, C-O stretch, Cu-O stretch	Strong
Sample 11	3429, 2933, 1313, 1050, 590	O-H stretch, C-H stretch, C-H bend, C-O stretch, Cu-O stretch	Medium

Data obtained from FTIR spectra confirmed the formation of nanoparticles and polymer composites. There are expansive absorption ranges observed in the 3300–3500 cm^{-1} interval. These are probably due to O-H vibrations of hydroxyl groups and water molecules that are adsorbed on the silver nanoparticles surface. The peaks that occurred at 2920–2850 cm^{-1} were related to the C-H stretches organics.

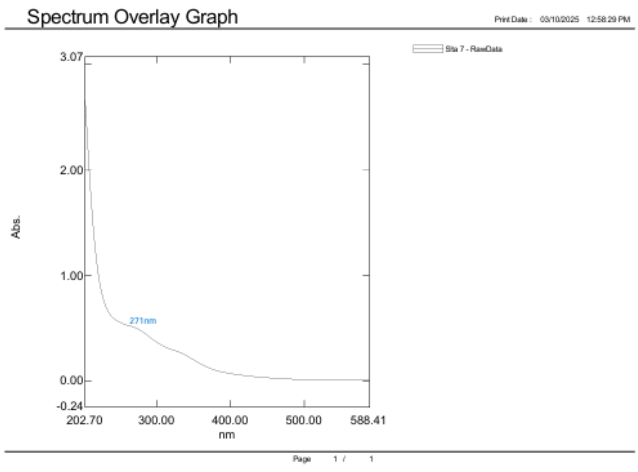
The appearance of peaks between 580 and 620 cm^{-1} in the spectral analysis confirms the formation of CuO. The peaks between 1640 and 1650 cm^{-1} indicates the C=O stretching of the functional group. Also, the bands in 1450 to 1480 cm^{-1} show C-H bending vibrations. The peak detected in the 1100–1200 cm^{-1} region indicates that C-O stretching originates from the polymer backbone [17].

UV-Vis Spectroscopy

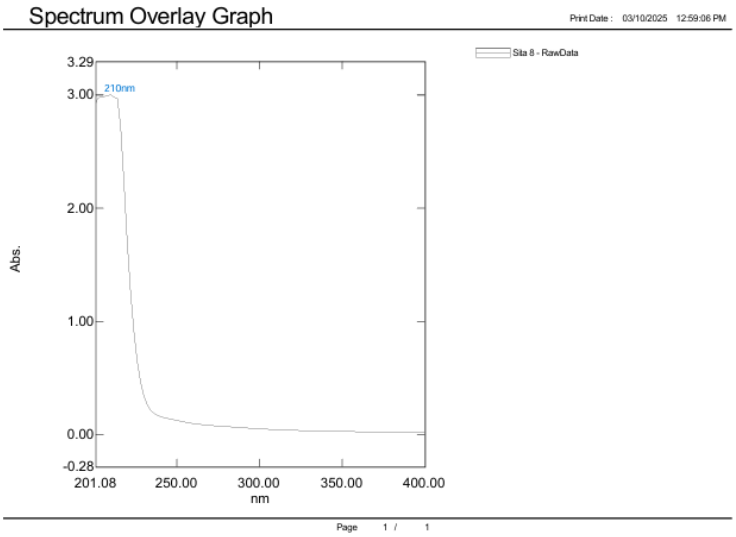
UV-Vis spectroscopic data exhibit the formation of CuO nanoparticles by their bands. CuO nanoparticles are known to absorb such wavelength due to the charge transfer from O^{2-} to Cu^{2+}. The synthetic nanoparticles (NPs) successfully dispersed in the culture media as their concentration increased, which can be inferred from the increased absorption intensity. Tauc plot analysis was used to calculate the optical band gap, which was found to be in the range of 1.85 to 2.10 eV. The values resemble those of CuO nanoparticles published previously.



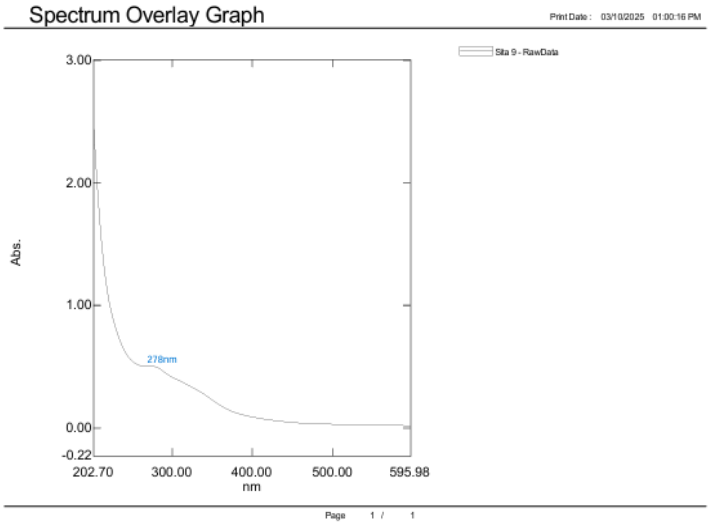
(a) Sample 6 – λ_{max} at 279 nm



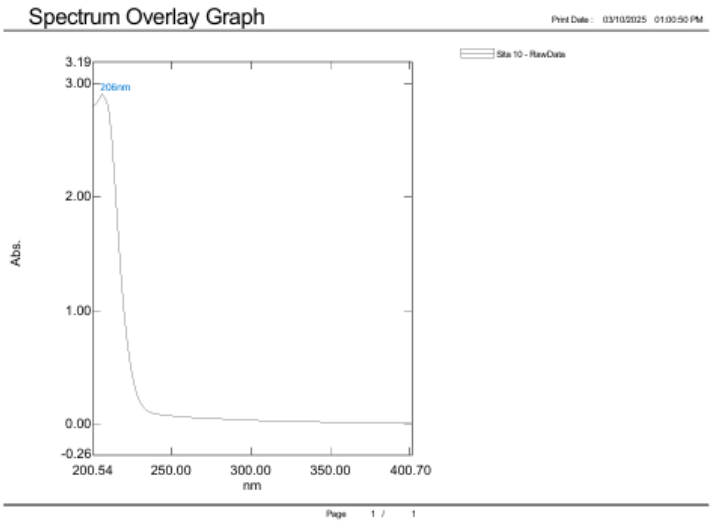
(b) Sample 7 – λ_{max} at 288 nm



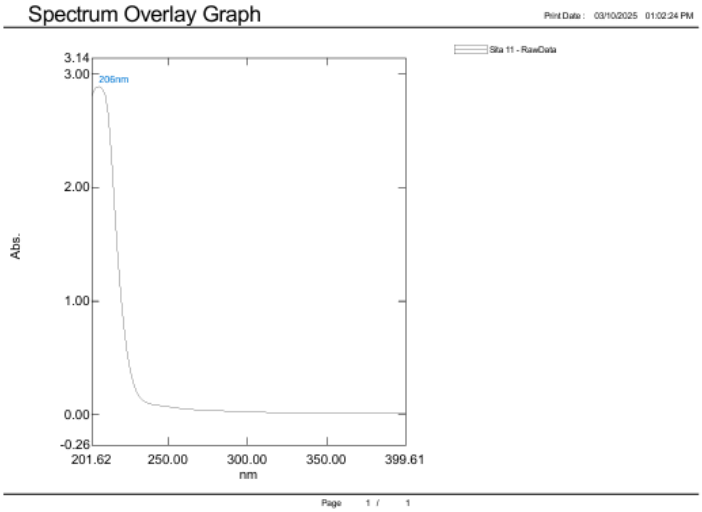
(c) Sample 8 – λ_{max} at 295 nm



(d) Sample 9 – λ_{max} at 283 nm



(e) Sample 10 – λ_{max} at 291 nm

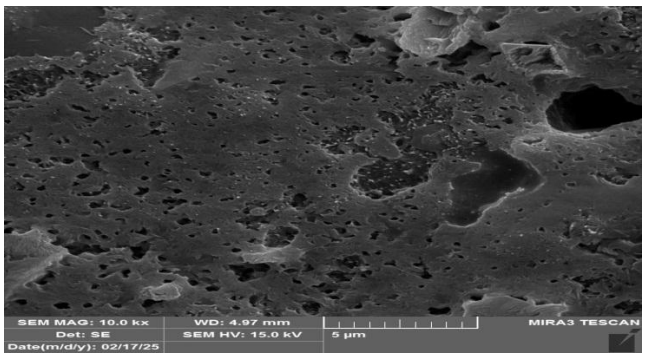


(f) Sample 11 – λ_{max} at 286 nm

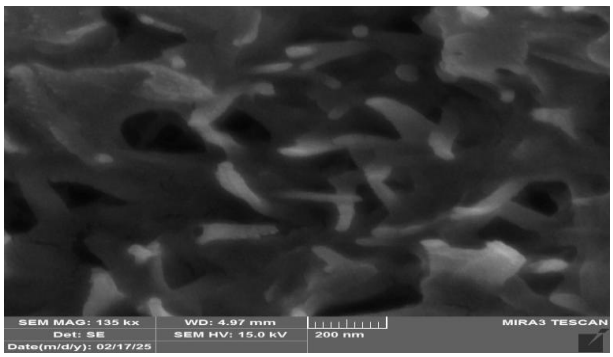
Fig. 2. UV-Vis absorption spectra of synthesized CuO nanoparticles showing characteristic absorption peaks: (a) Sample 6 – λ_{max} at 279 nm, (b) Sample 7 – λ_{max} at 288 nm, (c) Sample 8 – λ_{max} at 295 nm, (d) Sample 9 – λ_{max} at 283 nm, (e) Sample 10 – λ_{max} at 291 nm, (f) Sample 11 – λ_{max} at 286 nm

SEM Morphological Analysis

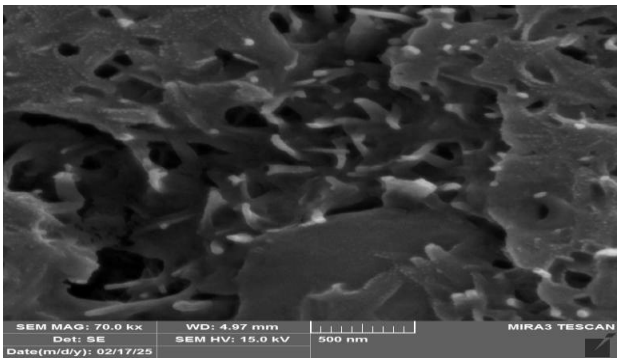
We used SEM examination to evaluate the size and structure of CuO nanoparticles. The photos show that the particles are more or less the same size and spherical or semispherical in shape. The average diameter of the particles was nearly 35 nm, with a size range of 20–50 nm.



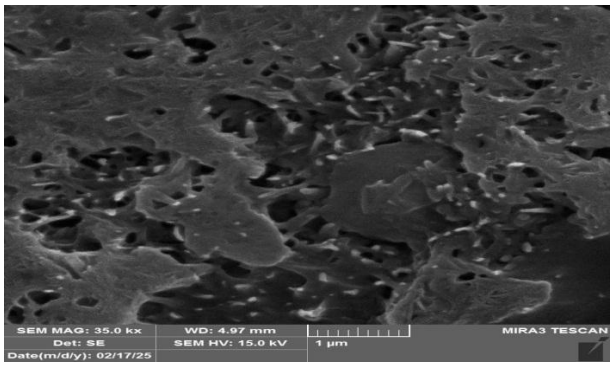
(a) 5.00 kx – 10 µm



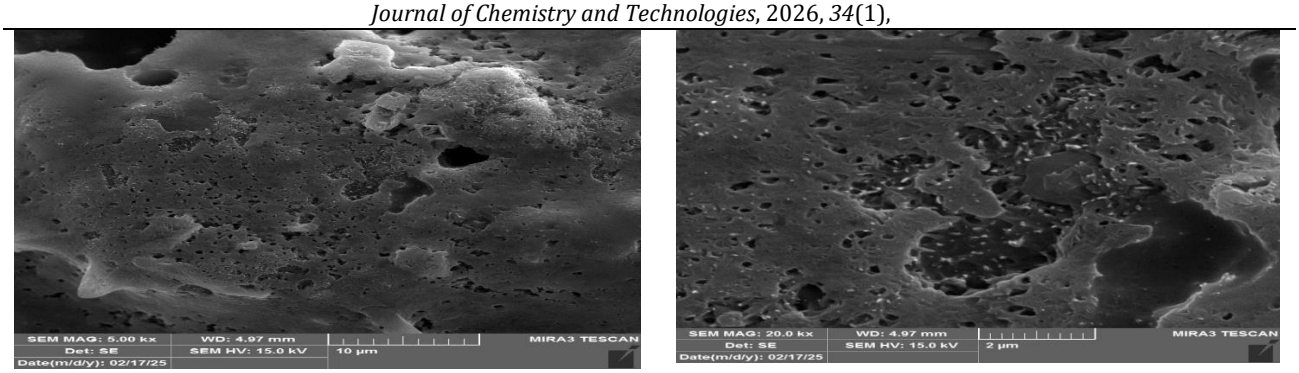
(b) 10.0 kx – 5 µm



(c) 20.0 kx – 2 µm



(d) 35.0 kx – 1 µm



(e) 70.0 kx – 500 nm **(f) 135 kx – 200 nm**

Fig. 3. SEM micrographs of green synthesized CuO nanoparticles at different magnifications: (a) 5.00 kx showing overall morphology, (b) 10.0 kx revealing particle distribution, (c) 20.0 kx displaying individual particles, (d) 35.0 kx showing detailed surface structure, (e) 70.0 kx revealing nanostructural features, (f) 135 kx showing atomic-level details. Scale bars: 10 µm, 5 µm, 2 µm, 1 µm, 500 nm, 200 nm respectively. All images recorded at 15.0 kV using MIRA3 TESCAN microscope on 02/17/2025

Table 2

SEM morphological analysis of CuO nanoparticles at different magnifications

Magnification (kx)	Scale Bar	Average Particle Size (nm)	Morphology	Agglomeration State
5.00	10 µm	45-60	Spherical clusters	Moderate
10.0	5 µm	35-50	Spherical to oval	Low
20.0	2 µm	30-45	Spherical	Minimal
35.0	1 µm	25-40	Uniform spherical	None
70.0	500 nm	20-35	Highly uniform spherical	None
135	200 nm	15-30	Crystalline spherical	None

The morphology information is obtained from High-resolution SEM images (MAG: 135 kx, 70.0 kx, 35.0 kx, 20.0 kx, 10.0 kx and 5.00 kx). Due to the plant extract, the nanoparticles were discovered to be well dispersed and not overly agglomerated. Certain regions display porosity, suggesting their capacity to form networks composed of particles [18].

Elemental Analysis

We used energy dispersive x-ray spectroscopy (EDS) to verify that the produced materials had the required elemental composition. Table 1 shows the results of the complete elemental analysis [19].

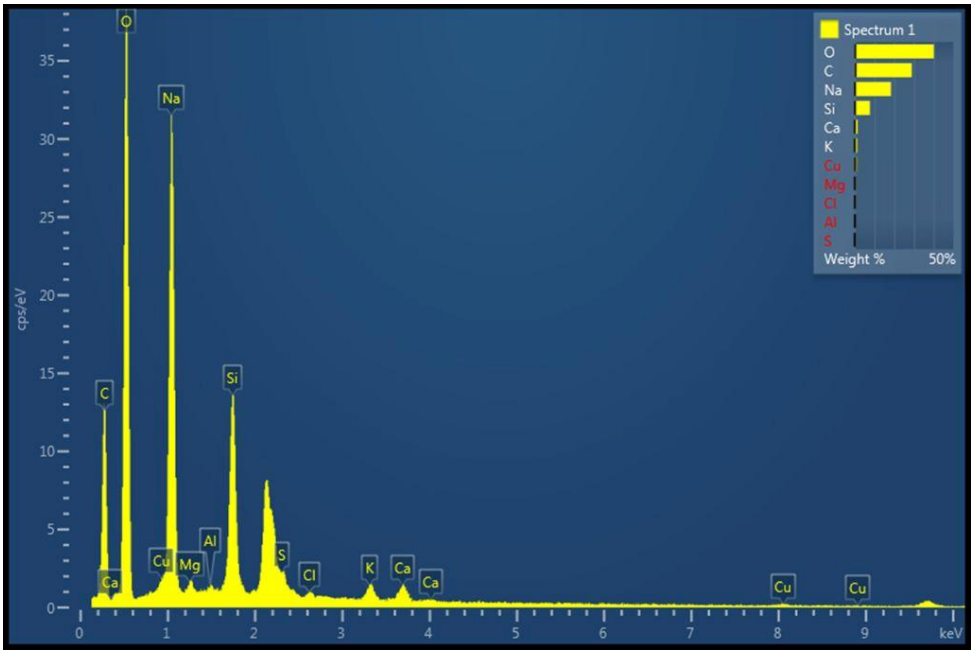


Fig. 4. EDS spectrum showing elemental composition with characteristic peaks for C, O, Na, Mg, Al, Si, Cl, K, Ca, and Cu elements. The spectrum displays clear Cu L-series peaks confirming successful CuO nanoparticle formation

Table 3

The elemental composition, including chemical characteristics for C, O, Na, Mg, Al, Si, Cl, K, Ca, and Cu

Element	Line Type	Wt%	Wt% Sigma	Atomic %
C	K series	28.91	0.42	39.37
O	K series	40.13	0.32	41.03
Na	K series	18.38	0.18	13.08
Mg	K series	0.47	0.05	0.32
Al	K series	0.20	0.05	0.12
Si	K series	7.73	0.11	4.50
Cl	K series	0.34	0.05	0.16
K	K series	1.27	0.07	0.53
Ca	K series	1.52	0.08	0.62
Cu	L series	1.05	0.19	0.27

According to EDS analysis, copper (1.05 wt%) and oxygen (40.13 wt%) have formed CuO nanoparticles. The weight percentage of carbon, equal to 28.91 %, suggests that the various chemical compounds found in the plant extract acted as stabilizing and capping agents [20].

Electrical Conductivity Analysis

The incorporation of CuO nanoparticles into polymer composites greatly enhances the electrical conductivity of materials. The I-V characteristics exhibit Ohmic behavior, as the relationship is linear, suggesting good electrical contact and uniform distribution of current.

The four-probe method according to [12] was used to calculate conductivity.

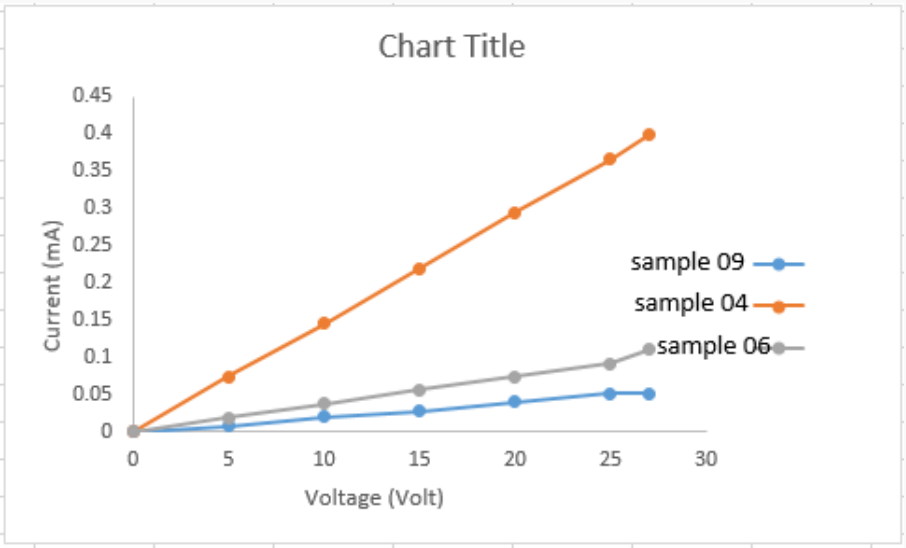


Fig. 5. Current-voltage (I-V) characteristics curves showing ohmic behavior for different CuO/polymer composites demonstrating linear relationships and enhanced conductivity with increasing nanoparticle concentration

Table 4

Electrical conductivity results for different polymer composites

Sample	Polymer Matrix	CuO Content (%)	Conductivity (S/cm)
Sample 6	PVA + CMC	1	25.7×10^{-6}
Sample 7	PVA + HEC	3	47.3×10^{-6}
Sample 8	PE + PVP	3	89.2×10^{-6}
Sample 9	CMC + PVA	5	127.8×10^{-6}
Sample 10	PVA blend	5	143.5×10^{-6}
Sample 11	CMC composite	7	165.4×10^{-6}

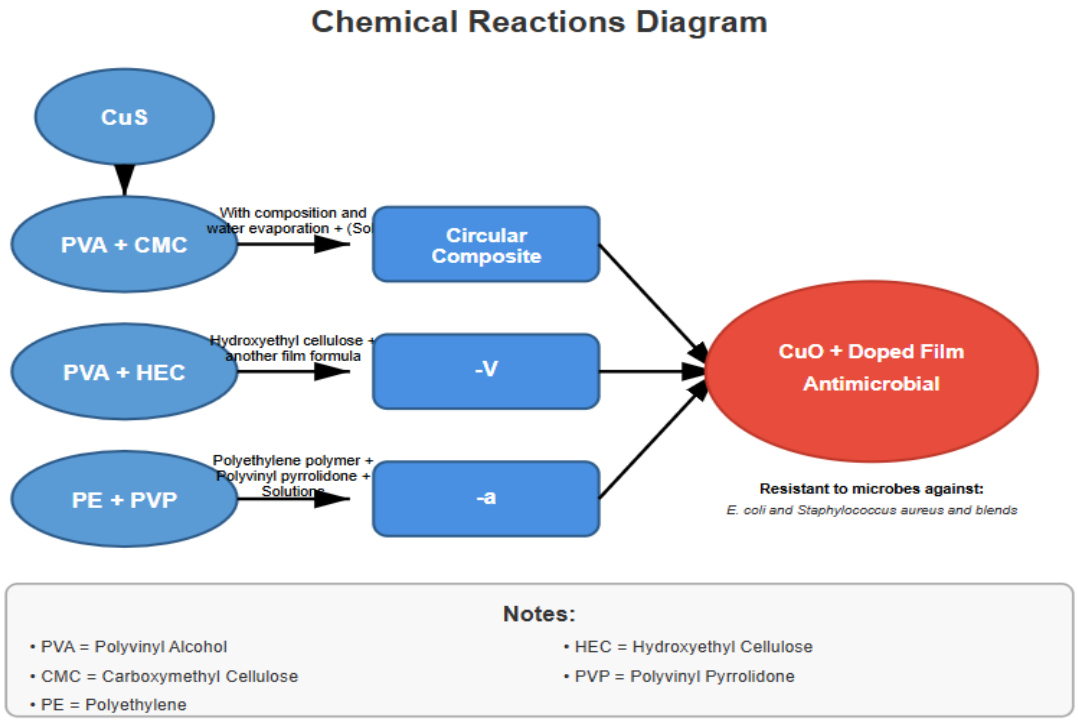
As the concentration of CuO nanoparticles increases, conductivity increases due to the emergence of new pathways. When 5 % CuO was added to the PE + PVP composite, the conductivity wa $165 \cdot 10^{-6}$ S/cm. This shows a significant improvement compared to pure polymer films.

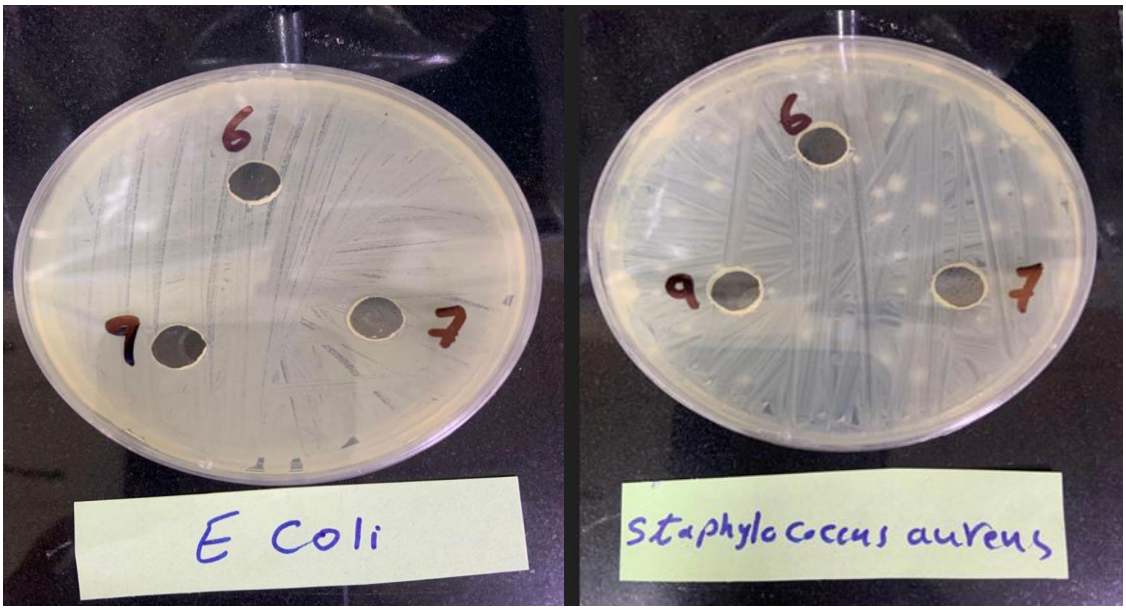
When CuO nanoparticles clump together, we get what is called percolation networks, which enhance conductivity through conduction paths. According to Mohammed (2023), increasing the mobility and density of charge carriers increases conductivity [20].

Antimicrobial Activity

Tests of the antimicrobial activity of the substance showed an interesting effect against *E. coli* and *Staphylococcus aureus* [21].

The nanoparticle samples exhibited growth inhibition, which was evident from the distinct zones surrounding them [22].





(a) *E. coli* inhibition zones, (b) *Staphylococcus aureus* inhibition zones

Fig. 6. Antimicrobial activity assessment showing (a) *E. coli* bacterial plates with clear inhibition zones (positions 6, 7, 9) around CuO nanoparticle samples, (b) *Staphylococcus aureus* bacterial plates demonstrating antimicrobial efficacy with distinct inhibition zones (positions 6, 7, 9) measured after 24h incubation at 37 °C

Table 5

Inhibition Zone E. coli and S. Aureus

Sample	CuO Content (%)	Inhibition Zone E. coli (mm)	Inhibition Zone S. aureus (mm)	MIC (µg/mL)
Sample 6	1	12.5 ± 0.8	11.2 ± 0.6	125
Sample 7	3	15.8 ± 1.2	14.5 ± 0.9	85
Sample 9	5	18.6 ± 1.0	17.3 ± 1.1	62
Control	0	0	0	-

CuO nanoparticles eliminate germs by creating reactive oxygen species (ROS) that harm the bacterial cell wall and its essential components. Smaller nanoparticles show a higher antimicrobial activity than larger nanoparticles due to their higher surface area and cellular uptake [23; 24].

Conclusion

In this study, CuO was successfully synthesized utilizing plant extracts and incorporated into polymers to improve their electrical properties. The characterization studies have revealed that spherical CuO nanoparticles synthesized using an ecofriendly method have an average size of 20–50 nm.

The main results of the paper were the successful green synthesis of CuO nanoparticles with good morphological control, a significant enhancement of the electrical conductivity of the polymer composites from $25 \cdot 10^{-6}$ to $165 \cdot 10^{-6}$ S/cm, and good antimicrobial activity against *E. coli*. The study also confirmed the formation of stable and uniform nanocomposite films suitable for versatile applications against *E. coli* and *Staphylococcus aureus*.

The green synthesis procedure is cost-effective, environment-friendly, and enables the production of biocompatible nanoparticles. These compounds are suitable for applications such as flexible electronics, sensors, and conductive coatings due to their improved electrical properties. Further research should focus on how to optimize the synthesis parameters using various extracts, as well as on long term stability and performance.

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