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Green Synthesis of Copper Oxide Nanoparticles Using Pulp and Peel Extracts of *Cucurbita pepo* Followed by Characterization and Comparative Antimicrobial Evaluation

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Abstract

Green synthesis of nanoparticles represents a promising eco-friendly approach, as it utilizes plant extracts as reducing and stabilizing agents without the need for hazardous chemical reagents. This study aims to evaluate the efficiency of green synthesis in producing copper oxide nanoparticles (CuONPs) using two plant-based extracts derived from pumpkin: pulp juice and peel extract. The synthesized samples were characterized using a range of physicochemical techniques, including Fourier-transform infrared spectroscopy (FTIR), ultraviolet–visible spectroscopy (UV-Vis), X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX).

The results confirmed the formation of pure, well-crystallized nanoparticles in the monoclinic phase, with both samples exhibiting similar particle sizes. However, distinct morphological differences were observed: the pulp-derived CuONPs showed a uniform spherical distribution, while the peel-derived ones displayed significant surface agglomeration.

The biological activity of the nanoparticles was assessed against selected bacterial and fungal strains. The pulp-based CuONPs demonstrated selective antibacterial activity against *Staphylococcus aureus*, whereas the peel-based particles exhibited no antimicrobial effect. These findings highlight the critical role of surface properties in governing biological interactions.

Overall, the results support the use of plant extracts as sustainable green agents for the synthesis of multifunctional nanoparticles. Emphasis should be placed on optimizing extract composition to tailor surface characteristics for targeted applications, particularly in photocatalysis and antimicrobial treatments.

Keywords: Green synthesis, Nanoparticles, Copper oxide nanoparticles (CuONPs), Pumpkin, biological activity.

Introduction

The scientific world is undergoing a fundamental transformation in the methods of nanomaterial synthesis, driven by the growing demand for effective and environmentally friendly solutions in medicine, water treatment, and bio-industrial applications. Among nanomaterials, metal oxide nanoparticles—particularly due to their reduced dimensions and increased surface area—exhibit enhanced physicochemical and biological activity compared to their bulk counterparts, making them especially compelling for research and application (AntunesFilho et al., 2023).

Copper oxide nanoparticles (CuO-NPs) stand out among these materials for their multifunctionality and pronounced bioactivity. They exhibit strong antibacterial and antifungal properties, potent free radical scavenging capacity, and anti-inflammatory potential by disrupting intracellular inflammatory signaling pathways in immune cells (Eid et al., 2023; El-Moslamy et al., 2025). These nanoparticles have found use in targeted drug delivery systems, antimicrobial coatings, localized cancer therapies, and bio-contamination control, thereby underscoring the strategic need for sustainable and biocompatible synthesis methods.

However, conventional synthetic routes—which rely heavily on toxic chemical reagents and volatile organic solvents—pose serious environmental hazards and limit medical applicability due to the accumulation of toxic byproducts on the nanoparticle surfaces (Dubey et al., 2024; Njenga, 2023). In response, green synthesis has emerged as a promising alternative that employs naturally derived biomolecules as reducing and stabilizing agents to produce pure, stable nanoparticles without external chemical additives. This approach utilizes plant extracts rich in phenolic compounds, flavonoids, reducing sugars, and organic acids that act dually in reducing metal ions and stabilizing the resulting nanoparticles (Mohsen &Abas, 2024; Montazersaheb et al., 2024).

Within this framework, *Cucurbitapepo* (pumpkin) presents a compelling dual-purpose biological source. Pumpkin pulp juice contains active components such as sugars, amino acids, carotenoids, and natural enzymes that can facilitate the reduction of copper ions and the formation of CuO-NPs under mild conditions. Simultaneously, pumpkin peels—an agricultural waste byproduct—are rich in polyphenols and flavonoids that contribute to nanoparticle stabilization and structural regulation (Savan Donga &Chanda, 2020; Mohsen &Abas, 2024).

Previous studies have shown that plant-mediated nanoparticles demonstrate potent bioactivities, including antimicrobial and antifungal effects, anti-inflammatory action by suppressing nitric oxide (NO) and pro-inflammatory cytokine (TNF-α, IL-6) production, and lower cytotoxicity toward normal cells relative to chemically synthesized counterparts (El-Moslamy et al., 2025; Eid et al., 2023; Njenga, 2023).

Accordingly, this study aims to synthesize CuO-NPs using two distinct plant-derived sources from *Cucurbitapepo*: pulp juice and dried peel extract. A comprehensive characterization of the synthesized nanoparticles will be conducted, evaluating their physicochemical properties using advanced analytical techniques: UV–Vis spectroscopy for electronic absorption and formation onset, FTIR for identifying functional stabilizing groups, XRD for crystallographic structure, and SEM for surface morphology and size determination. Moreover, the biological performance of the nanoparticles from both sources will be assessed via antibacterial and antifungal activity assays against pathogenic strains.

This research represents one of the first comprehensive comparative analyses evaluating how different plant extract types (pulp vs. peel) influence the structural and functional attributes of CuO-NPs. It contributes to the development of a cost-effective, safe, and versatile green nano platform, suitable for biomedical and pharmaceutical applications in alignment with the principles of sustainable development and green innovation.

1- Pumpkin (Cucurbitapepo): Botanical Overview and Phytochemical Comparison of Pulp and Peel

Pumpkin (Cucurbitapepo) is an annual herbaceous plant belonging to the Cucurbitaceae family, and its fruits are cultivated extensively worldwide due to their high nutritional value and abundance of bioactive compounds. These include phenolics, flavonoids, carotenoids, terpenoids, peptides, polysaccharides, vitamins, and minerals (Hussain et al., 2022).

Chemical analyses conducted by Sathiya Mala et al. (2016) revealed significant differences in the chemical composition between the fruit peel and pulp of C. pepo, emphasizing the unique nutritional contributions of each part. The pumpkin pulp exhibited a higher moisture content and a remarkably elevated level of beta-carotene (142.38 mg/100 g), a precursor to vitamin A and a potent antioxidant. Additionally, it contained a higher ash content, indicating a richer mineral profile.

In contrast, the peels were found to be an exceptional source of dietary fiber, containing approximately 28.81%, which is nearly double the fiber content observed in the pulp (13.29%). The peels also demonstrated superior concentrations of iron (42.99 mg/100 g) and vitamin C (18.90 mg/100 g). Protein and phosphorus contents were comparable between both parts, though the peels had a slight advantage in phosphorus levels. Notably, both pulp and peel exhibited nearly equivalent concentrations of total phenolic compounds (approximately 5.2 mg GAE/g), underlining their similar antioxidant capacities.

Collectively, these findings suggest that pumpkin peels—commonly discarded as agricultural waste—are, in fact, nutritionally valuable. Their rich composition positions them as promising candidates for incorporation into functional food formulations to enhance nutritional value.

2- Materials and Methods

2-1- Chemicals

All chemicals utilized in this study were of analytical grade, ensuring high purity and consistency in experimental procedures. Anhydrous copper(II) sulfate ($CuSO_4$) and sodium hydroxide (NaOH) were obtained from the *Watania Scientific Products* (WSP)m, Fresh fruits of *Cucurbitapepo* (pumpkin) were handpicked from an orchard located in the eastern region of El Oued province, Algeria. The fruits were thoroughly rinsed with distilled water and processed immediately. Absolute ethanol and double-distilled water (DDW) were supplied by ENPEC and were used throughout all preparation stages.

2-2- Preparation of Plant Extracts

2-2-1- Pulp Juice Extract

Pumpkin pulp was manually separated from the seeds and peel, cut into small fragments, and homogenized using a blender to obtain a fresh juice. The resulting juice was first filtered through muslin cloth, followed by centrifugation to remove residual fibers and particulates. The clarified extract was stored at 4°C until further use.

2-2-2- Peel Extract

Pumpkin peels were chopped into small pieces and left to air dry at ambient temperature for 72 hours. The dried peels were then ground into a fine powder. A total of 10 grams of this powder was boiled in 300 mL of distilled water for 60 minutes. The solution was filtered and centrifuged to obtain a clear extract, which was subsequently stored at 4°C.

2-3- Green Synthesis of CuO Nanoparticles

Copper oxide nanoparticles (CuO-NPs) were synthesized via a green approach by gradually adding 150 mL of each plant extract (either pulp juice or peel extract), separately, into 100 mL of a 0.5 M copper(II) sulfate ($CuSO_4$) solution preheated to 40 °C. The addition was performed dropwise using a burette to ensure controlled mixing. Subsequently, the pH of the reaction mixture was carefully adjusted to 10 by the slow dropwise addition of 2 M sodium hydroxide (NaOH).

Following pH adjustment, the mixtures were subjected to continuous stirring at a constant temperature of 80 °C for 120 minutes. A distinct color transformation was observed during the reaction: the mixture turned brown in the case of pulp juice and black when peel extract was used—both serving as visual indicators of CuO nanoparticle formation.

After the reaction period, the nanoparticles were isolated by centrifugation at 4010 rpm for 10 minutes. The resulting precipitates were washed thoroughly with distilled water and ethanol to remove residual impurities, then dried in a hot air oven at 60 °C for 24 hours. Finally, the dried precipitates were calcined at 600 °C to obtain black-colored CuO nanoparticles, which were stored for future experimental applications.

2-4- Physicochemical Characterization Techniques

To gain an accurate understanding of the structural and chemical nature of the green-synthesized copper oxide nanoparticles (CuO-NPs), a range of modern analytical techniques—widely cited in the literature—was employed to assess their morphological, spectral, and elemental properties. These characterization methods confirmed the success of the synthesis process and provided insights into the crystallinity, purity, particle size, and elemental composition of the nanoparticles. The characterization was conducted using UV–Vis spectroscopy, FTIR, XRD, SEM, and EDX, in accordance with recent studies on biologically synthesized nanomaterials **(Apriandanu&Yulizar, 2019; Mobarak et al., 2022; Aroob et al., 2023).**

2-4-1- Fourier Transform Infrared Spectroscopy (FTIR)

Infrared spectroscopy (FTIR) is considered a central tool for analyzing functional groups in nanoparticles synthesized using plant extracts, as it reveals the chemical bonds involved in the reduction and stabilization processes. The samples were analyzed using FTIR spectroscopy in the spectral range of 4000–400 cm^{-1} to identify the active functional groups present in the pulp and peel extracts, which contribute to the reduction of copper ions and the stabilization of the nanoparticles.

2-4-2- UV–Visible Spectroscopy

Spectrophotometric analysis was performed using a UV–Vis spectrometer in the range of 200–800 nm to confirm nanoparticle formation. The presence of a Surface Plasmon Resonance (SPR) peak indicated the optical signature typical of CuO-NPs.**(Manjari, G., et al, 2017)**.

2-4-3- X-ray Diffraction (XRD)

XRD was used to determine the crystalline phase and structure of the CuO-NPs. The diffraction patterns revealed the characteristic planes of monoclinic CuO. The average crystallite size was estimated using the Scherrer equation based on the Full Width at Half Maximum (FWHM) of the diffraction peaks.

2-4-4- Scanning Electron Microscopy (SEM)

SEM analysis was conducted to visualize the surface morphology, particle distribution, agglomeration state, and textural features of the nanoparticles. The high-resolution micrographs allowed a direct comparison between nanoparticles synthesized using pulp and peel extracts.

2-4-5- Energy Dispersive X-ray Spectroscopy (EDX)

The elemental composition of the nanoparticles was determined by coupling Scanning Electron Microscopy (SEM) with Energy-Dispersive X-ray Spectroscopy (EDX) analysis. This allowed for the qualitative and descriptive detection of copper (Cu) and oxygen (O) as primary components, along with the identification of any secondary elements originating from the plant extract components or potential impurities.

2-5- Assessment of the Antimicrobial Activity of CuO Nanoparticles

The antimicrobial efficacy of copper oxide nanoparticles (CuO-NPs), biosynthesized using pumpkin pulp and peel extracts, was evaluated using the agar well diffusion method. Three standard microbial strains representing different cell wall structures were selected for the study: Staphylococcus aureus (Gram-positive), Escherichia coli (Gram-negative), and Candida albicans (yeast), Antifungal testing was performed on Sabouraud Dextrose Agar (SDA) supplemented with 2% glucose, while antibacterial activity was assessed using Mueller–Hinton Agar (MHA). Microbial suspensions were prepared from fresh 24-hour cultures and standardized to a concentration of 10^6 CFU/mL. Each agar plate was uniformly inoculated using a sterile cotton swab to ensure even distribution.

Once the agar surface had dried, wells with a diameter of 6 mm were aseptically punched in the center of the plates and filled with 50 µL of CuO-NP solution at concentrations of 40, 20, 10, and 5 mg/mL. The plates were incubated at 37°C for 24 hours for bacterial strains and 48 hours for the fungal strain.

Antimicrobial activity was determined by measuring the diameter of the inhibition zones surrounding the wells. Zones exceeding 6 mm were considered indicative of significant antimicrobial activity. **(Bonev et al., 2008; Kiehlbauch et al., 2000).**

3- Results and Discussion

3-1- Preliminary Observations of the Reaction

The reaction between the pumpkin extracts (pulp and peel) and copper sulfate solution was accompanied by a distinct color change, which is a conventional visual indicator of nanoparticle formation. The mixture turned brown when using pulp juice and black with the peel extract, suggesting a difference in the reduction rate and the stability of the resulting nanoparticles. This observation is consistent with similar reports on green synthesis, such as that by **(Mobarak et al., 2022).**

In addition to the initial colorimetric changes, calcination of the resulting nanoparticle precipitates at 600°C led to the formation of a stable black powder, which strongly indicates the successful conversion into the crystalline form of copper oxide (CuO). Calcination represents a critical step in nanoparticle production,

as it facilitates the removal of moisture and residual organic compounds from plant-derived molecules and induces a phase transition from an amorphous to a monoclinic crystalline structure.

Previous studies, including those by (Letchumanan et al., 2021) and **(Aroob et al., 2023)**, have confirmed that calcination at temperatures between 500–600°C enhances the crystallinity of biologically synthesized copper oxides and reduces surface aggregation caused by phytochemical residues. This thermal treatment improves both the purity and structural stability of the nanoparticles, thereby enhancing their chemical and biological performance.

3-2- FTIR Spectroscopy Results

The Fourier-transform infrared (FTIR) spectroscopy of copper oxide nanoparticles (CuONPs) synthesized from plant extracts provided essential insights into the chemical interactions involved during the biosynthesis process. As illustrated in **Figure 1,** the FTIR spectra of both samples displayed generally weak and limited absorption peaks, indicating a high degree of purity in both nanoparticle preparations. The spectral similarity between the two samples also suggests the presence of common constituents in both pumpkin extracts.

A weak absorption band observed around 3700 cm^{-1} corresponds to the stretching vibrations of free hydroxyl (–OH) groups, indicating the presence of phenolic and alcoholic compounds in the extracts (Silverstein et al., 2014). These compounds are believed to have contributed to the reduction of Cu^{2+} ions into CuO and to the stabilization of the nanoparticles. Moreover, a distinct absorption peak at approximately 1045 cm^{-1} is attributed to the stretching vibration of the C–O bond found in carboxylic groups and alcohols (Andualem et al., 2020), further confirming the role of organic functional groups in the synthesis mechanism.

Most notably, characteristic peaks were observed in the region between 450 and 600 cm^{-1}, which are clearly associated with Cu–O bond vibrations. This strongly confirms the successful formation of copper oxide nanoparticles through the green synthesis approach (Ethiraj et al., 2012).

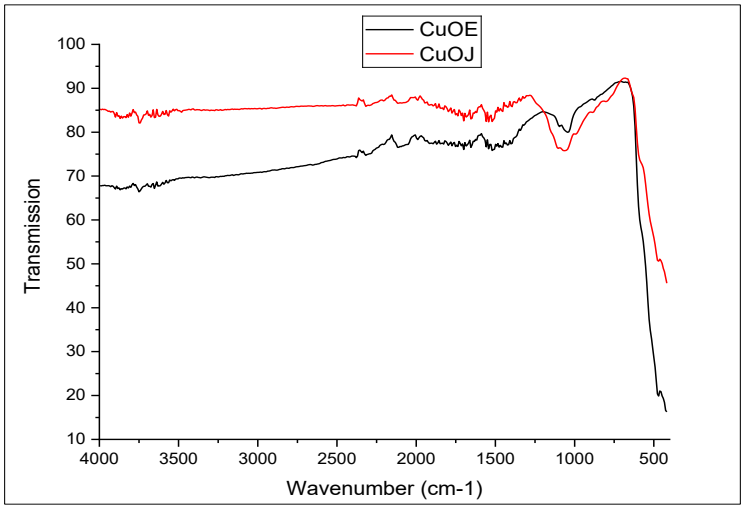


Figure 1: FTIR spectrum of CuONPs prepared with pumpkin pulp juice and prepared with pumpkin peel extract.

3-3- UV-Vis Spectroscopy Results

The UV-Visible spectrum **(Figure 2)** of CuO nanoparticles synthesized using **pumpkin pulp juice (CuOJ)** and **pumpkin peel extract (CuOE)** exhibited absorption peaks at 250 nm and 255 nm, respectively. These peaks are indicative of characteristic electronic transitions for copper oxide nanoparticles, thereby confirming their formation (Manjari, G., et al, 2017). The observed surface plasmon resonance (SPR) resulted from the collective oscillation of electrons on the nanoparticle surface, which is consistent with findings from previous research **(Priya, Manogar, et al. 2023).**

Furthermore, Tauc plots revealed band gap energies of 3.7 eV for the CuOJ sample and 3.6 eV for the CuOE sample. These values align with those reported in prior studies (Abbas, Sara Fadhil, et al. 2024; Kumar, Vinay, et al. 2025), affirming the semiconductor nature of the nanoparticles and indicating quantum confinement effects attributed to their small size. The slight disparity in band gap values further highlights the influence of the plant extract components on the optical properties of the synthesized products.

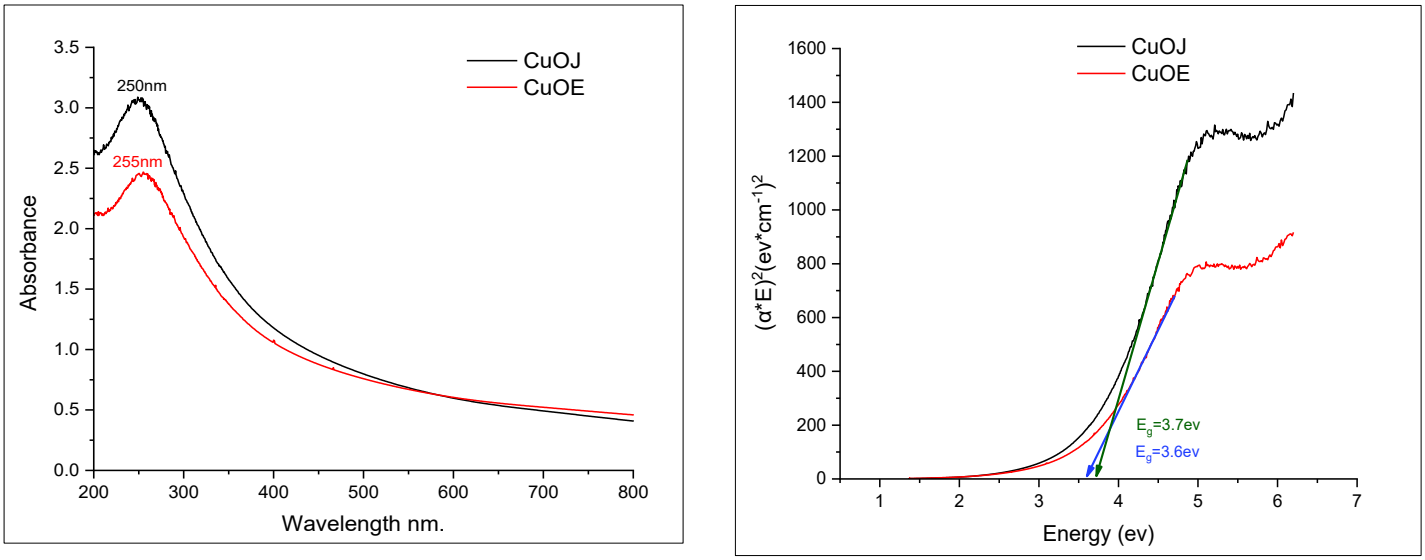


Figure 2: UV-Visible spectrum and energy gap of CuONPs prepared with pumpkin pulp juice and prepared with pumpkin peel extract.

3-4- X-ray Diffraction (XRD) Analysis

The X-ray diffraction (XRD) **Figure 3** patterns of copper oxide nanoparticles (CuONPs) synthesized via green methods using pumpkin pulp juice (CuOJ) and pumpkin peel extract (CuOE) revealed a clear match for both samples with the standard JCPDS card no. 041-0254**(Geyer, A.,et al.1989)**, confirming the formation of highly crystalline **monoclinic CuO**.

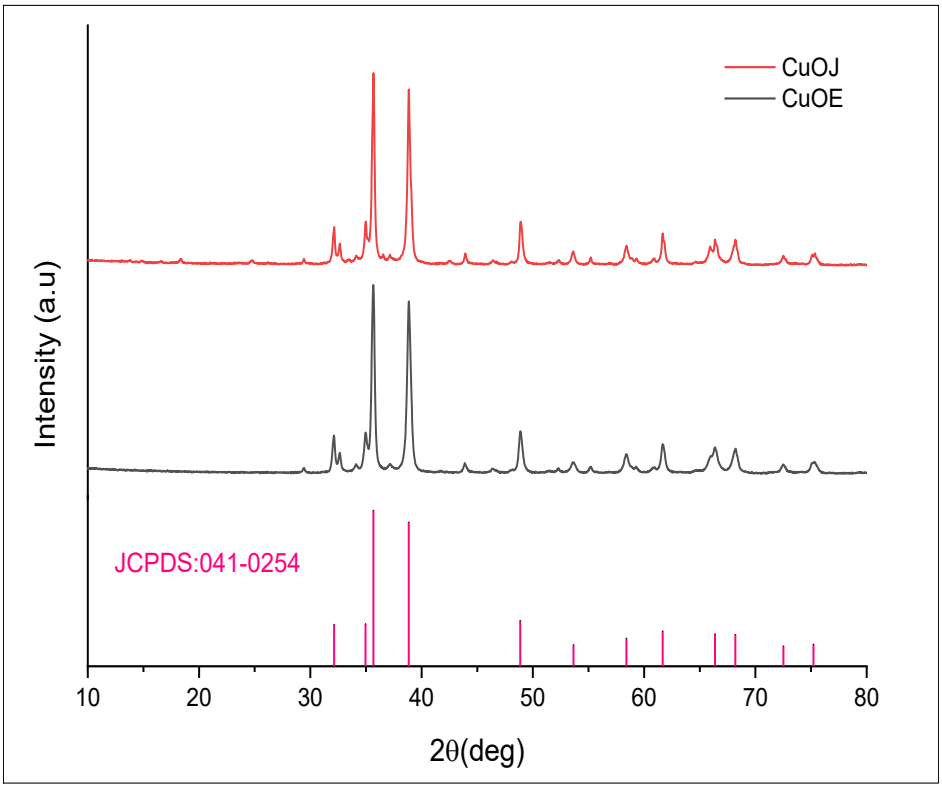
Distinct diffraction peaks were observed at the following 2θ angles:

32.13°, 34.96°, 35.66°, 38.84°, 48.86°, 53.64°, 58.40°, 61.66°, 66.37°, 68.19°, 72.51°, and 75.21°, which correspond to the crystallographic planes:

(110), (002), (-111), (200), (-202), (020), (202), (-113), (-311), (220), (311), and (-222), respectively.

The repeated occurrence of these characteristic peaks confirms the well-defined crystalline nature of CuO. Moreover, the peak intensities and their sharpness indicate good crystallinity and nanoscale structure. Notably, the (-111) plane showed slight intensity variation between the two samples, suggesting minor differences in crystal growth rate, likely due to variations in the phytochemical composition of the respective extracts.

The average crystallite size was calculated using the Scherrer equation, based on the full width at half maximum (FWHM) of selected peaks. For example, the FWHM was approximately **0.2303°** for the (110) plane at 32.13°, and **0.1535°** for the (002) plane at 34.96°. The resulting crystallite sizes ranged from **19 nm to 54 nm**, with an overall average size of approximately **29.60 nm**. These findings confirm the successful synthesis of highly crystalline CuONPs with nanoscale dimensions, making them suitable for various industrial and biomedical applications.



Pos. [°2Th.]	h k l	FWHM Left [°2Th.]
32.1388	1 1 0	0.2303
34.9646	0 0 2	0.1535
35.6684	-1 1 1	0.2814
38.8412	2 0 0	0.3070
48.8665	-2 0 2	0.2814
53.6469	0 2 0	0.4093
58.4057	2 0 2	0.3070
61.6672	-1 1 3	0.3070
66.3748	-3 1 1	0.3070
68.1938	2 2 0	0.4605
72.5136	3 1 1	0.4093
75.2109	-2 2 2	0.5117

Figure 3: XRD spectrum of CuONPs prepared with pumpkin pulp juice and pumpkin peel extract.

3-5- Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) Analysis

SEM images **Figure 4** revealed that the particles in both samples exhibit comparable sizes within the nanometer range. However, distinct morphological differences were observed in surface arrangement. In the sample synthesized using pumpkin pulp juice, the nanoparticles appeared uniformly spherical and well-dispersed, indicating a homogeneous growth process likely stabilized by bioactive compounds present in the pulp extract. In contrast, the sample synthesized using pumpkin peel extract displayed greater agglomeration and surface roughness, with noticeable clustering of particles. This suggests a differential effect of the peel extract constituents on crystallization behavior and surface morphology.

Statistical particle size distribution analysis confirmed the similarity in average particle size for both samples, with a mean value of approximately 79 nm. This supports the notion that the type of plant extract did not significantly influence particle size but rather affected particle shape and degree of agglomeration **(Tavakoli et al., 2019).**

The EDX analysis further confirmed the elemental purity of the nanoparticles in both samples, with spectra containing only copper (Cu) and oxygen (O). In the pulp-derived sample, the copper weight percentage was 83.6%, with 16.4% for oxygen. In the peel-derived sample, copper and oxygen percentages were 77.8% and 22.2%, respectively. These close values indicate a similar elemental composition between pumpkin pulp and peel extracts.

Overall, the results demonstrate that both green synthesis methods were effective in producing high-purity CuONPs, with the plant extract significantly influencing surface morphology and particle distribution—a key factor in determining the potential applications of nanomaterials, particularly in photocatalysis and antimicrobial activity **(Franco et al., 2022).**

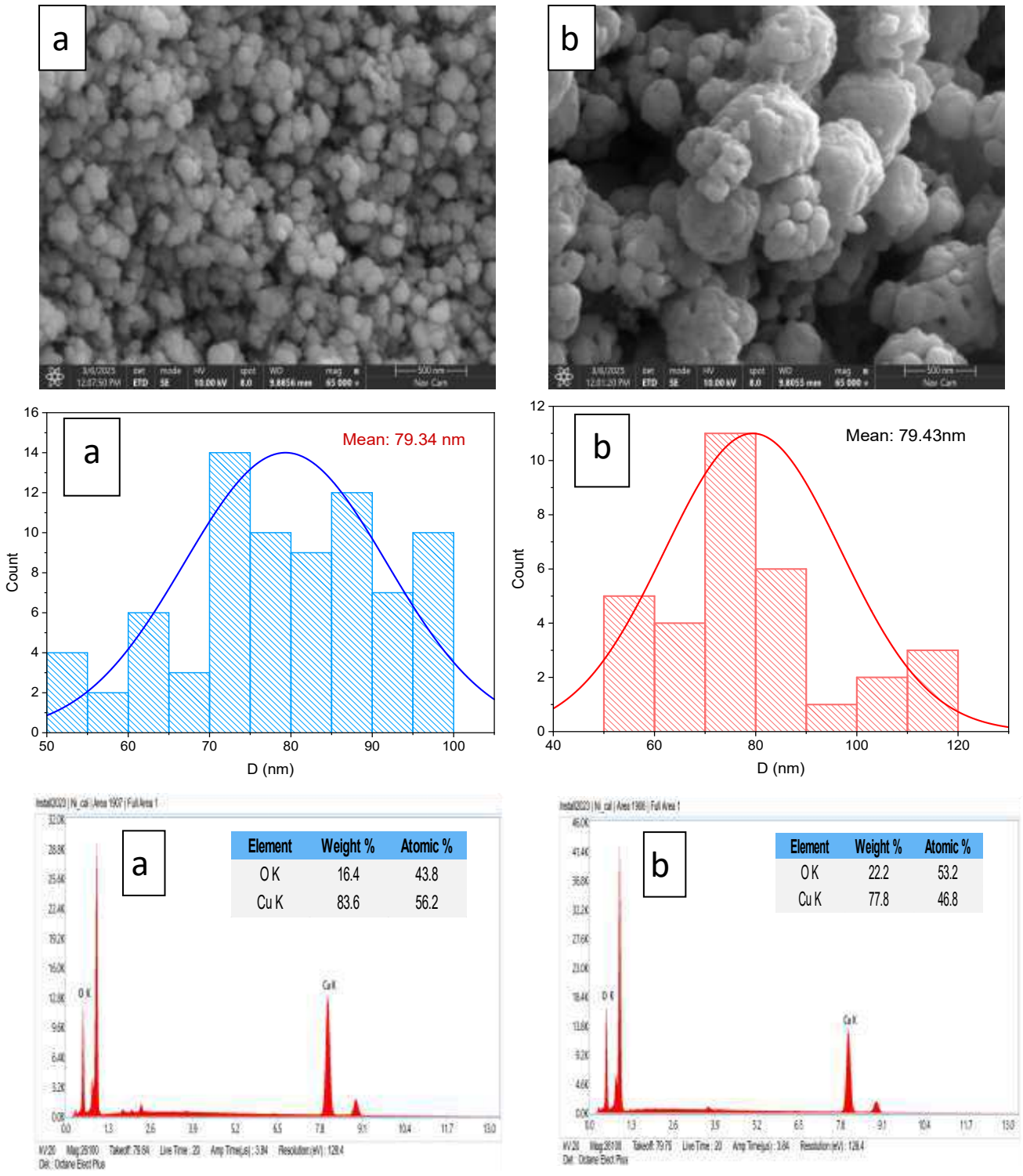


Figure 4: EDX/SEM images and particle size distribution of CuONPs a: prepared with pumpkin pulp juice. b: prepared with pumpkin peel extract.

3-6- Antimicrobial and Antifu
3-7- ngal Activity Analysis of CuONPs

The antimicrobial and antifungal activity tests of CuONPs synthesized via green methods using pumpkin pulp juice and pumpkin peel extract revealed clear differences in their biological effectiveness against the tested microbial and fungal strains.

According to Table 1, the sample prepared with pumpkin pulp juice exhibited selective antibacterial activity against *Staphylococcus aureus ATCC 25932*, with inhibition zone diameters of 18 mm at 40 mg/mL and 10 mm at 20 mg/mL. No inhibition zones were observed at lower concentrations or against *Escherichia coli ATCC 25922* and *Candida albicans ATCC 10231*. This result suggests a targeted and concentration-dependent activity of the pulp-derived CuONPs, specifically against Gram-positive bacteria, which is commonly linked to differences in cell wall permeability and interaction mechanisms **(Natan& Nagy, 2020).**

In contrast, the peel extract-derived sample showed no inhibition at any concentration for all tested strains, indicating low or absent antimicrobial activity. This may be attributed to the high degree of particle agglomeration and reduced surface reactivity, as previously noted in the SEM analysis.

These differences in biological activity between the two samples are likely due to variations in surface structure, adsorbed oxygen species, and organic surface groups, as well as differences in the effective surface contact area. These factors are crucial in determining the antimicrobial and antifungal performance of metal oxide nanoparticles **(Ren et al., 2020).** Additionally, both samples showed no activity against *Candida albicans*, suggesting limited antifungal potential under the tested conditions.

Table 1: Antimicrobial test results for copper oxide nanoparticles prepared with pulp juice

Microbial inhibition (mm) CuOJ					Co .Neg.
Strains used	**40mg/mL**	**20mg/mL**	**10mg/mL**	**5 mg/mL**	
Escherichia coli ATCC 25922	**NI**	**NI**	**NI**	**NI**	**NI**
Staphylococcus aureus ATCC 25932	**18**	**10**	**NI**	**NI**	**NI**
Anti-Candida activity CuOJ					
Candida albicans ATCC 10231	**NI**	**NI**	**NI**	**NI**	**NI**

NI = No Inhibition

Table 2: Antimicrobial test results for copper oxide nanoparticles prepared with pumpkin peel extract

Microbial inhibition (mm) CuOE					Co .Neg.
Strains used	**40mg/mL**	**20mg/mL**	**10mg/mL**	**5 mg/mL**	
Escherichia coli ATCC 25922	**NI**	**NI**	**NI**	**NI**	**NI**
Staphylococcus aureus ATCC 25932	**NI**	**NI**	**NI**	**NI**	**NI**
Anti-Candida activity CuOE					
Candida albicans ATCC 10231	**NI**	**NI**	**NI**	**NI**	**NI**

NI = No Inhibition

4- Conclusion

This study demonstrates the efficiency of green synthesis in producing copper oxide nanoparticles (CuONPs) using natural extracts derived from pumpkin, specifically pulp juice and peel extract. The findings revealed that both extracts were capable of yielding pure, well-crystallized nanoparticles in the monoclinic phase. Although the particle sizes in both samples were similar, significant differences in surface morphology and degree of agglomeration were observed, highlighting the strong influence of extract composition on the physical and surface characteristics of the nanoparticles.

Infrared spectroscopy, X-ray diffraction, and UV–Visible analyses confirmed the presence of reactive chemical bonds and functional organic groups that contributed to the reduction and stabilization of

the nanoparticles. SEM and EDX results further supported these findings, showing more uniform morphology in the pulp-based sample, while the peel-based sample exhibited noticeable agglomeration. These morphological differences were directly reflected in the biological behavior of the nanoparticles, where the pulp-derived CuONPs demonstrated antibacterial activity against Gram-positive bacteria, whereas the peel-derived ones did not—emphasizing that **surface reactivity**, rather than particle size alone, is a determining factor in biological interactions.

These results underscore that the effectiveness of nanomaterials does not depend solely on the success of the synthesis process, but also on the precise control of surface and morphological properties tailored to the intended application. Therefore, the type of plant extract used should be considered a key design parameter in the development of green nanomaterials for biomedical, environmental, or catalytic applications.

Déclarations

Ethics approval: Not applicable, because this article does not involve any studies on human participants or animals.
Consent to participate: Not applicable, as all authors are themselves the preparers of the manuscript.
Consent to publish: Not applicable, for the same reason as above.

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