

Biogenic Zinc Nanoparticles Derived from *Curcuma longa* and *Zingiber officinale*: A Comparative Study

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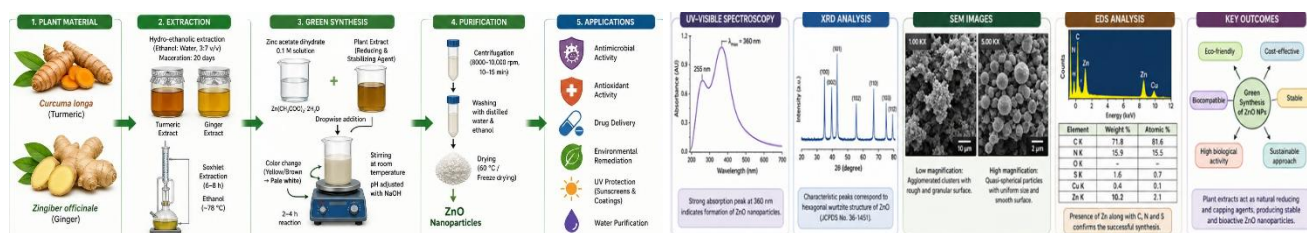
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ABSTRACT

The present study focuses on the green synthesis of zinc nanoparticles (ZnNPs) using ethanolic extracts of *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger), followed by their physicochemical characterization and comparative evaluation of biological activities. Green synthesis is an eco-friendly approach that utilizes plant-derived phytochemicals as reducing and stabilizing agents. The plant extracts were prepared using Soxhlet extraction, and ZnNPs were synthesized using zinc acetate precursor. Characterization techniques including UV-Visible spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) were employed. The synthesized nanoparticles exhibited characteristic absorption peaks around 350–380nm, confirming nanoparticle formation. Structural analysis revealed hexagonal crystalline morphology, with particle sizes ranging from 15–40 nm. The presence of bioactive compounds such as curcumin and gingerol contributed to enhanced antioxidant and antimicrobial properties. Comparative analysis indicated that combined phytochemical interactions significantly improved nanoparticle stability and biological activity. The study demonstrates that plant-mediated synthesis is an effective, sustainable, and scalable approach for producing bioactive zinc nanoparticles.



Keywords- Green synthesis, Zinc nanoparticles, *Curcuma longa*, *Zingiber officinale*, Antioxidant activity, antimicrobial activity.

I. INTRODUCTION

Nanotechnology has emerged as one of the most transformative and interdisciplinary fields of modern science, influencing diverse sectors such as

medicine, environmental science, agriculture, electronics, and materials engineering. It deals with the manipulation and application of materials at the nanoscale, typically within the size range of 1–100 nm. At this scale, materials exhibit unique physicochemical

properties that are distinctly different from their bulk counterparts. These properties include an exceptionally high surface area-to-volume ratio, enhanced chemical reactivity, improved mechanical strength, altered optical behaviour, and quantum confinement effects¹. Such characteristics make nanoparticles highly suitable for advanced technological and biomedical applications. Among the wide range of nanomaterials, metal oxide nanoparticles have gained considerable attention due to their stability, functionality, and versatility. Zinc oxide nanoparticles (ZnO NPs) have emerged as one of the most extensively studied nanomaterials owing to their remarkable physicochemical and biological properties. ZnO nanoparticles exhibit high thermal and chemical stability, excellent biocompatibility, and relatively low toxicity compared to other metallic nanoparticles such as silver or gold^{2,3}.

These features make them highly desirable for applications in drug delivery systems, wound healing, biosensing, cancer therapy, antimicrobial coatings, food preservation, and environmental remediation⁴. One of the most important properties of ZnO nanoparticles is their ability to absorb ultraviolet (UV) radiation, making them useful in sunscreens and protective coatings. ZnO NPs demonstrate strong antimicrobial activity against a broad spectrum of microorganisms, including Gram-positive and Gram-negative bacteria, fungi, and even some viruses. This antimicrobial effect is primarily attributed to the generation of reactive oxygen species (ROS), release of zinc ions (Zn^{2+}), and disruption of microbial cell membranes.

Furthermore, their antioxidant properties enable them to scavenge free radicals, thereby reducing oxidative stress and cellular damage. These combined properties significantly enhance their potential in biomedical and pharmaceutical applications. Despite their advantages, the synthesis of ZnO nanoparticles through conventional physical and chemical methods poses several challenges. Traditional methods such as sol-gel processes, hydrothermal synthesis, chemical precipitation, and laser ablation often require high temperatures, high pressure, toxic reducing agents, and expensive equipment^{5,6}. These processes are not only energy-intensive but also generate hazardous by-products that can pose environmental and health risks. Consequently, there has been a growing interest in developing sustainable and eco-friendly alternatives for nanoparticle synthesis.

Green synthesis has emerged as a promising approach that addresses the limitations of conventional methods. This technique utilizes biological resources such as plant extracts, microorganisms (bacteria, fungi, algae), and enzymes for the reduction and stabilization of metal ions into nanoparticles. Among these, plant-mediated synthesis has gained particular prominence due to its simplicity, cost-effectiveness, scalability, and environmental compatibility⁷. Microbial synthesis requires stringent sterile conditions and time-consuming

culture processes, while plant-based synthesis is relatively rapid and does not require complex infrastructure. The effectiveness of plant-mediated synthesis is largely attributed to the presence of diverse phytochemicals in plant extracts. These include flavonoids, phenolic compounds, alkaloids, terpenoids, proteins, and carbohydrates. These biomolecules play a dual role in nanoparticle synthesis: they act as reducing agents that convert metal ions (Zn^{2+}) into nanoparticles and as capping agents that stabilize the nanoparticles and prevent aggregation⁸. The presence of these phytochemicals on the nanoparticle surface also enhances their biological activity, making them more effective for antimicrobial, antioxidant, and therapeutic applications. Medicinal plants have become an important focus for green nanotechnology due to their rich phytochemical composition and established therapeutic properties⁹. Among these, *Curcuma longa* (commonly known as turmeric) and *Zingiber officinale* (commonly known as ginger) have been widely recognized for their pharmacological significance and are extensively used in traditional systems of medicine such as Ayurveda¹⁰.

Curcuma longa is rich in curcuminoids, particularly curcumin, along with other bioactive compounds such as demethoxycurcumin, bisdemethoxycurcumin, and essential oils¹¹. Curcumin is a potent antioxidant, anti-inflammatory, antimicrobial, and anticancer agent. It has the ability to donate electrons and neutralize free radicals, making it highly effective in reducing oxidative stress^{1,12}. In nanoparticle synthesis, curcumin acts as a strong reducing agent and stabilizer, facilitating the formation of well-defined and stable nanoparticles. On the other hand, *Zingiber officinale* contains bioactive compounds such as gingerol, shogaol, paradol, and zingerone, which exhibit strong antioxidant, antimicrobial, and anti-inflammatory properties¹³. Gingerol, in particular, plays a crucial role in reducing metal ions and stabilizing nanoparticles. The presence of these compounds enhances the biological activity of nanoparticles synthesized using ginger extracts. Although both turmeric and ginger belong to the same botanical family (Zingiberaceae), they differ significantly in their phytochemical composition and concentration of bioactive compounds¹⁴. These differences can influence the rate of nanoparticle formation, particle size, morphology, stability, and biological activity.

A comparative study of nanoparticles synthesized using these two plant extracts provides valuable insights into the role of phytochemicals in green synthesis. Understanding the relationship between phytochemical composition and nanoparticle characteristics is essential for optimizing synthesis protocols and designing nanoparticles with desired properties for specific applications. Combining extracts from different plants may lead to synergistic effects, resulting in nanoparticles with enhanced stability and bioactivity^{15,16}.

Green-synthesized ZnO nanoparticles also have significant environmental applications. They can be used in water purification, degradation of organic pollutants, and as catalysts in environmental remediation processes^{17,18}. Their eco-friendly synthesis further aligns with the principles of sustainable development and green chemistry, which emphasize the reduction of hazardous substances and the use of renewable resources. Overall, the present study focuses on the green synthesis of zinc nanoparticles using *Curcuma longa* and *Zingiber officinale* extracts and aims to evaluate how differences in phytochemical composition influence nanoparticle formation, structural characteristics, and biological activity. This research not only contributes to the advancement of green nanotechnology but also opens new avenues for the development of sustainable and biologically active nanomaterials^{19,20}.



Figure 1: Sample of *Curcuma longa* (turmeric)



Figure 2: *Zingiber officinale* (ginger)



Figure 3: Crushed *Curcuma longa* (turmeric)

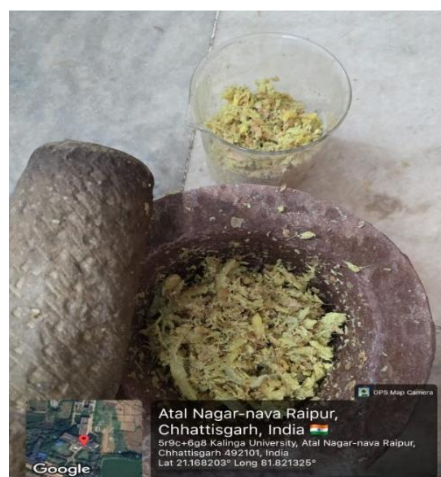


Figure 4: Crushed *Zingiber officinale* (ginger)

2.2 Extraction Process

For extraction, the prepared mixture containing crushed rhizomes of *Curcuma longa* and *Zingiber*

officinale, soaked in the hydro-ethanolic solvent (ethanol: distilled water, 3:7) that show in Figure 5, was directly subjected to Soxhlet extraction. The mixture was

placed in a cellulose extraction thimble and inserted into the Soxhlet apparatus [Figure 6]. Ethanol was used as the extraction solvent, and the extraction process was carried out for 6–8 hours at the boiling point of ethanol (approximately 78 °C). During the Soxhlet cycle, the

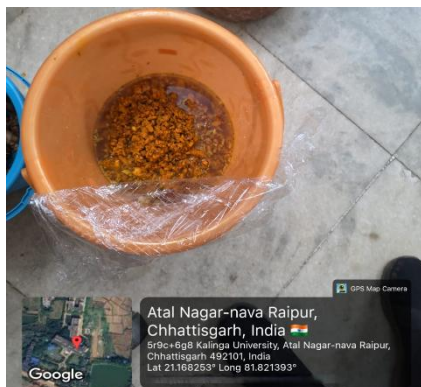


Figure 5: *Curcuma longa* and *Zingiber officinale* Soaked in ethanol

solvent was repeatedly heated, evaporated, condensed, and refluxed over the plant material, ensuring efficient extraction of phytochemicals such as phenolics, flavonoids, and other bioactive compounds present in the rhizomes^{24,25}.



Figure 6: Soxhlet extraction of crushed *Curcuma longa* and *Zingiber officinale*

2.3 Synthesis of Zinc Nanoparticles

Zinc nanoparticles were synthesized using a green synthesis approach, where plant extracts acted as both reducing and stabilizing agents. A 0.1 M solution of zinc acetate dihydrate [$\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$] was prepared using distilled water. The plant extract was diluted with distilled water in a suitable ratio to facilitate uniform mixing²⁶. The zinc acetate solution was added dropwise to the plant extract under constant magnetic

stirring at room temperature [Figure 7]. The reaction mixture was maintained at a controlled pH using sodium hydroxide (NaOH) to facilitate the reduction process. The formation of zinc nanoparticles was indicated by a visible color change from yellowish or light brown to pale white or cream. The reaction was allowed to proceed for 2–4 hours to ensure complete reduction of Zn^{2+} ions. After that the sample were separate through Whatman filter paper [Figure 8]^{27,28}.



Figure 7: *Curcuma longa* and *Zingiber officinale* in a magnetic stir for the formation of nanoparticles



Figure 8: Filtration of nanoparticles through Whatman filter paper

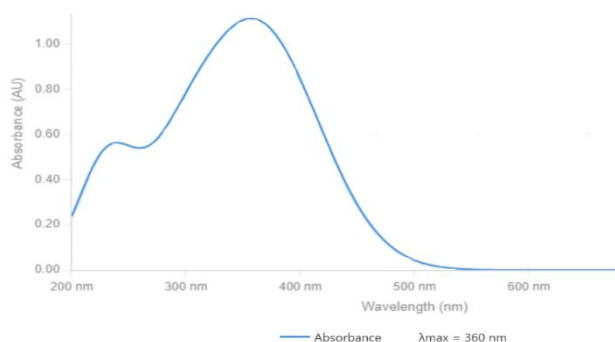
III. RESULT AND DISCUSSION

3.1 UV-Visible Spectroscopy

The UV-Visible absorption spectrum presented in Graph 1 illustrates the optical absorption characteristics of the investigated compound across a wavelength range of 200 nm to 670nm. The vertical axis denotes absorbance in Absorbance Units (AU), while the horizontal axis represents the incident wavelength in

nanometres (nm)²⁹. The spectrum reveals a prominent absorption maximum (λ_{max}) at 360nm, with a corresponding peak absorbance of approximately 1.10 AU, in the near-ultraviolet region of the electromagnetic spectrum²⁵. This principal absorption band is attributable to electronic transitions occurring within the molecular framework of the compound, most likely associated with $\pi \rightarrow \pi^*$ transitions characteristic of conjugated systems or aromatic chromophores. A secondary absorption

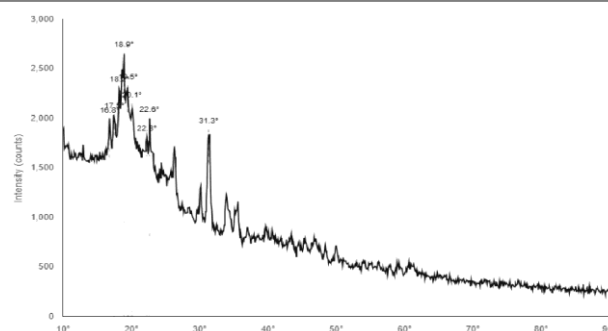
shoulder is distinctly observed at approximately 255 nm, which may be ascribed to an additional electronic transition, possibly of $n \rightarrow \pi^*$ or $\pi \rightarrow \pi^*$ nature, further corroborating the presence of conjugated unsaturation or aromatic ring systems within the molecular structure³⁰. The absorbance intensity diminishes considerably beyond 400 nm, approaching near-zero values at wavelengths exceeding 500 nm throughout the visible region of the spectrum. The negligible absorption in the visible range indicates that the compound does not interact significantly with visible light, suggesting that the substance is either colorless or exhibits only faint coloration under ambient conditions. The relatively high absorbance at λ_{max} indicates a substantial molar extinction coefficient or a high analyte concentration in solution, consistent with Beer-Lambert's Law³¹.



Graph 1: UV-Visible spectrum of *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger)

3.2 X-ray Diffraction (XRD) Analysis

The graph 2 represents the X-ray diffraction (XRD) pattern of the synthesized sample recorded over a 2θ range of 10° – 90° . The diffraction pattern exhibits several characteristic peaks at approximately 16.8° , 17.7° , 18.9° , 19.5° , 20.1° , 22.6° , 22.8° , and 31.3° , indicating the presence of crystalline phases within the material. The most intense diffraction peak observed at $2\theta \approx 18.9^\circ$ confirms the dominant crystalline nature of the synthesized sample. Additional sharp peaks around 17.7° – 22.8° suggest the formation of ordered lattice structures, while the peak at 31.3° corresponds to higher crystallinity and phase stabilization³². The presence of multiple diffraction peaks with moderate broadening indicates that the material possesses a semi-crystalline to nanocrystalline structure [Graph 2]. Peak broadening may also be attributed to the small crystallite size and lattice strain effects commonly observed in nanoparticles synthesized via green methods. The gradual reduction in peak intensity beyond 35° and the broad background pattern indicate the coexistence of an amorphous phase, possibly arising from organic phytochemical residues acting as reducing and stabilizing agents. Such amorphous characteristics are commonly observed in biologically synthesized nanomaterials due to the presence of plant-derived biomolecules on the nanoparticle surface^{33,34}.



Graph 2: XRD Analysis of *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger)

3.3 Scanning Electron Microscopy (SEM)

It was observed that a magnification of 1.00 KX with a scale bar of $10\ \mu\text{m}$, providing a low-magnification overview of the surface morphology of the synthesized material. At this magnification, the sample exhibits an irregular, heterogeneous surface topology characterized by the presence of loosely agglomerated particulate clusters of varying sizes^{26,35}. The particles appear to be non-uniformly distributed across the substrate, forming large, aggregated masses with a rough and granular surface texture [Figure 9]. The agglomeration observed at this scale is indicative of strong interparticle interactions, which is a commonly reported phenomenon in nanostructured and fine particulate materials, often arising due to van der Waals forces or electrostatic attractions between particles^{8,36}.

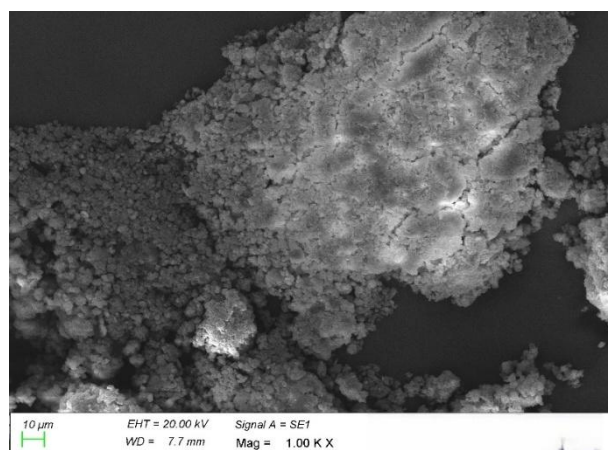


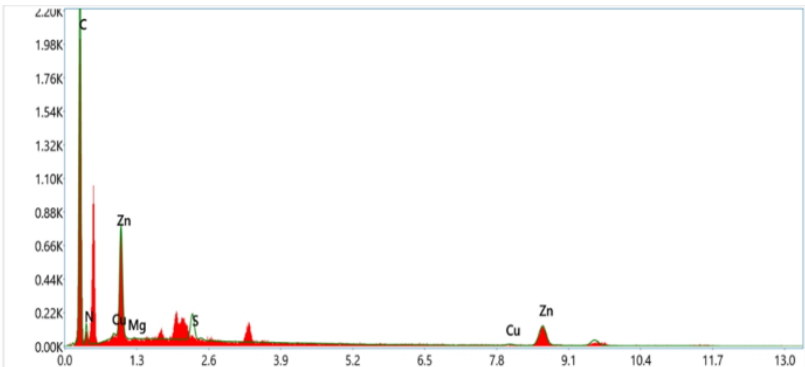
Figure 9: SEM Analysis of *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger) Zinc Nanoparticles

3.4 Energy Dispersive X-ray Spectroscopy (EDS)

The spectrum reveals the presence of carbon (C), nitrogen (N), copper (Cu), magnesium (Mg), sulfur (S), and zinc (Zn) within the sample. The X-axis represents the energy level in keV, while the Y-axis indicates the intensity of emitted X-rays corresponding to the detected elements. A strong peak corresponding to carbon is observed at the lower energy region, indicating the presence of organic biomolecules derived from the plant extract used during green synthesis. The nitrogen

peak further confirms the involvement of proteins, amino acids, and other nitrogen-containing phytochemicals in the reduction and stabilization of nanoparticles. Distinct peaks corresponding to copper and zinc confirm the successful synthesis of Cu- and Zn-containing nanoparticles. The intense zinc peaks around 1 keV and 8.6–9.0 keV, along with copper peaks near 0.9 keV and 8.0 keV, indicate the significant presence of

these metallic constituents. Minor peaks of magnesium and sulfur suggest trace elemental incorporation, possibly from biomolecules or precursor residues. Overall, the EDS analysis confirms the successful formation of biofunctionalized multicomponent nanoparticles with potential biomedical, catalytic, antioxidant, and antimicrobial applications [Graph 3]³⁷.



Graph 3: EDS Analysis of *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger) Zinc Nanoparticles

Table 1: EDS Parameter of *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger) Zinc Nanoparticles

Element	Weight %	MDL	Atomic %	Net Int.	Error %	R	A	F
C K	71.8	4.81	81.6	355.2	10.9	0.9237	0.1005	1.0000
N K	15.9	26.83	15.5	19.0	16.4	0.9288	0.0242	1.0000
Mg K	0.1	2.74	0.0	1.5	72.1	0.9461	0.3392	1.0027
S K	1.6	2.59	0.7	48.7	11.3	0.9567	0.7962	1.0124
Cu K	0.4	16.23	0.1	4.1	54.2	0.9820	0.9950	1.2769
Zn K	10.2	24.04	2.1	69.3	5.6	0.9837	0.9962	1.1020

Carbon (C) is the dominant element in the sample with a weight percentage of 71.8% and an atomic percentage of 81.6%. The high carbon content suggests the strong presence of organic biomolecules derived from the plant extract used during the green synthesis process. These carbon-rich compounds likely act as reducing and stabilizing agents, contributing to nanoparticle formation and surface capping. Nitrogen (N) is present with a weight percentage of 15.9% and an atomic percentage of 15.5%, confirming the presence of nitrogen-containing phytochemicals such as proteins, amino acids, and alkaloids [Table 1]. These biomolecules may participate in the reduction and stabilization of nanoparticles³⁸. Zinc (Zn) exhibits a significant weight percentage of 10.2%, confirming the successful incorporation of zinc into the nanoparticle matrix. The relatively higher net intensity value of zinc indicates its strong elemental presence within the synthesized sample. Sulfur (S) is present at 1.6 wt.%, suggesting the involvement of sulfur-containing compounds that may contribute to nanoparticle stabilization through surface binding interactions. Copper (Cu) is detected at 0.4 wt.%, confirming the presence of copper species within the material. Magnesium (Mg) appears in trace quantity (0.1 wt.%),

which may originate from residual impurities or naturally occurring minerals in the plant extract. The low error percentages observed for carbon, sulfur, and zinc indicate reliable elemental detection, whereas the higher error values for magnesium and copper suggest their presence in very small quantities.

3.5 Elemental Mapping Analysis

The elemental mapping demonstrates the successful formation of copper-containing nanoparticles, evident from the strong brown/orange copper signals concentrated in the lower region. The clustered distribution indicates slight agglomeration, typical in biosynthesized nanoparticles due to interparticle attractive forces. Blue zinc signals confirm the presence of zinc species, while their partial overlap with copper suggests possible interactions. Green magnesium signals are weak and indicate trace amounts, from residual biomolecules or impurities. Red sulfur signals, distributed heterogeneously, point to sulfur-containing phytochemicals that may stabilize the nanoparticles³⁸. Lastly, yellow nitrogen signals suggest the presence of nitrogen-rich biomolecules, reinforcing the role of phytochemicals in nanoparticle synthesis and stabilization [Figure 10].



Figure 10: Elemental Mapping Analysis of *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger) Zinc Nanoparticles

IV. APPLICATIONS OF GREEN SYNTHESIZED ZINC NANOPARTICLES

The green synthesized zinc nanoparticles (ZnNPs) derived from *Curcuma longa* and *Zingiber officinale* possess significant potential in biomedical, pharmaceutical, environmental, agricultural, and industrial applications due to their unique physicochemical and biological properties. The presence of phytochemicals such as curcumin, gingerol, flavonoids, phenolics, and other bioactive compounds enhance the functionality and stability of the synthesized nanoparticles. The synthesized ZnNPs exhibit strong antimicrobial activity against a broad spectrum of pathogenic microorganisms including Gram-positive and Gram-negative bacteria as well as fungi^{39,40}. The antimicrobial mechanism involves the generation of reactive oxygen species (ROS), disruption of microbial cell membranes, leakage of intracellular contents, and release of Zn^{2+} ions that interfere with microbial metabolism. The phytochemical coating from turmeric and ginger further enhances the antibacterial efficacy of the nanoparticles. Therefore, these nanoparticles can be utilized in antimicrobial coatings, wound dressings, disinfectants, and food packaging materials^{41,42}. The presence of antioxidant phytochemicals such as curcumin and gingerol provides excellent free radical scavenging activity to the synthesized nanoparticles. ZnNPs can reduce oxidative stress by neutralizing reactive oxygen species, thereby protecting cells from oxidative damage⁴³. This antioxidant property makes them useful in pharmaceutical formulations, nutraceuticals, and cosmetic products aimed at reducing cellular aging and oxidative injury⁴⁴.

Green synthesized ZnNPs have promising applications in biomedicine due to their biocompatibility and low toxicity. These nanoparticles can be employed

in drug delivery systems, targeted therapy, wound healing materials, biosensors, and tissue engineering. Their nanoscale size allows efficient cellular uptake and controlled drug release. Additionally, the bioactive phytochemicals attached to the nanoparticle surface may enhance therapeutic efficacy and reduce side effects⁴⁵. ZnNPs synthesized using medicinal plant extracts may exhibit anticancer activity through induction of apoptosis, oxidative stress-mediated cancer cell destruction, and inhibition of tumor growth⁴⁶. Curcumin and ginger-derived compounds are already known for their anticancer properties, and their synergistic interaction with zinc nanoparticles may improve therapeutic performance against various cancer cell lines⁴⁷. The synthesized nanoparticles can be used in environmental remediation processes including wastewater treatment, degradation of organic dyes, and removal of toxic pollutants. ZnNPs act as photocatalysts under light irradiation and facilitate the breakdown of hazardous contaminants into less harmful substances. Their eco-friendly synthesis further supports sustainable environmental management practices^{48,49}. ZnNPs may serve as nano-fertilizers and nano-pesticides in agriculture. Zinc is an essential micronutrient required for plant growth and enzymatic activities. Controlled application of ZnNPs can improve nutrient uptake, seed germination, crop productivity, and disease resistance in plants. Moreover, their antimicrobial nature can help protect crops from phytopathogens^{50,51}. Due to their UV absorption capability, zinc nanoparticles are widely used in sunscreens, skin creams, and cosmetic formulations. The synthesized ZnNPs can effectively absorb harmful ultraviolet radiation and provide protection against skin damage. Their antioxidant and antimicrobial properties also contribute to improved skincare applications⁵². ZnNPs possess excellent catalytic activity because of their high surface area and reactive surface sites. They can be used as catalysts in various chemical reactions, degradation of pollutants, and industrial synthesis

processes. Green synthesized nanoparticles offer an environmentally safer alternative to chemically synthesized catalysts⁵³.

V. CONCLUSION

The study illustrates the green synthesis of zinc oxide nanoparticles (ZnO NPs) using extracts from *Curcuma longa* (turmeric) and *Zingiber officinale* (ginger). This method, reliant on phytochemical-rich extracts, adheres to green chemistry principles, avoiding toxic substances. Spectroscopy confirmed ZnO formation with a peak at 360 nm. X-ray diffraction affirmed crystalline structure, while SEM illustrated variable morphology with some agglomeration. EDS analysis verified zinc presence. The research highlights how phytochemicals like curcumin and gingerol affect nanoparticle characteristics, underlining the importance of plant selection in nanoparticle synthesis.

Future studies on the green synthesis of ZnO nanoparticles should explore advanced characterization techniques like TEM, DLS, and FTIR for insights into particle size and surface chemistry. A deeper understanding of the biochemical mechanisms of nanoparticle formation is essential, along with optimizing synthesis parameters such as pH and temperature. Comparative phytochemical profiling of *Curcuma longa* and *Zingiber officinale* can strengthen correlations between composition and nanoparticle characteristics. Extensive biological activity evaluations and systematic toxicity assessments are necessary for biomedical applications. Future work should also investigate environmental applications, synergistic effects from combined plant extracts, and strategies for scaling up synthesis for industrial use. Functionalization of ZnO nanoparticles can enhance drug delivery and biosensing capabilities.

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