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Antimicrobial, Antioxidant and Photoluminescence Application of Phyto-Mediated ZnO Nanoparticles Produced from *Euphorbia caducifolia* Plant

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Abstract

This work aims at the eco-production of zinc oxide nanoparticles (ZnO-NPs) using the plant extract of *Euphorbia caducifolia* and the assessed of their antimicrobial, antioxidant, and photoluminescence properties. Biosynthesis approach offers an cost-effective, sustainable and environmentally friendly method as compared to chemical approach because it employs the phytocompounds which are present in a plant extract as natural reducing and also stabilizing agents. Evaluate the synthesized ZnO nanoparticles properties using different analytical techniques like UV-Visible, Fourier Transform Infrared Spectroscopy (FTIR), X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) and Photoluminescence (PL) analysis. UV-Visible demonstrated that the nanomaterial was formed as shown by the characteristic peak in absorption peak around 361 nm and FTIR analysis suggested that the bioactive functional groups participated in the production and stabilization of the nanoparticles. The XRD results revealed that the nanoparticles of zinc oxide are crystalline in nature and have hexagonal wurtzite structure, whereas SEM analysis showed predominantly spherical to hexagonal morphology with nanoscale dimensions. The synthesized nanoparticles showed good antimicrobial activity against the bacterial pathogens. The result of Antioxidant assessment by the DPPH assay showed that it contained concentration-dependent free radical scavenging activity with good antioxidant potential. A Photoluminescence study showed characteristic very intense ultraviolet peak and showed very less intense visible emission peak corresponding to the intrinsic defects and oxygen vacancies in the ZnO crystal lattice. The results prove that the *Euphorbia caducifolia*-mediated ZnO nanoparticles possess remarkable biological and optical properties, which makes them promising candidates for use in antimicrobial formulations, antioxidant therapies, biosensing, photocatalysis, and optoelectronic devices.

Keywords: *Euphorbia caducifolia*; Phyto-mediated Zinc Oxide Nanoparticles; Antimicrobial Activity; Antioxidant Activity; Photoluminescence; Biomedical Applications.

How to Cite This Article

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INTRODUCTION

Nanotechnology has emerged as one of the most rapidly advancing fields of science and technology, offering innovative solutions across biomedical, pharmaceutical, environmental, agricultural, and industrial sectors (1). Among various nanomaterials, zinc oxide nanoparticles (ZnO-NPs) have attracted considerable attention due to their unique physicochemical properties, including high surface area-to-volume ratio, excellent biocompatibility, chemical stability, semiconducting behavior, and remarkable optical characteristics (3). These properties make ZnO nanoparticles highly suitable for diverse applications such as antimicrobial agents, antioxidants, drug delivery systems, biosensors, photocatalysts, and optoelectronic devices (11).

Traditional synthesis routes for the prepration of ZnO nanoparticles have used chemical reducing agents and high-energy physical processes which can result in hazardous by-products and pose environmental concerns. To overcome these drawback, green synthesis method has become an important consideration in recent years. Green or phyto-mediated synthesis involves the use of biomolecules derived from plants as natural reducing, capping, and stabilizing agents which is a natural way to synthesize nanoparticles that is eco-friendly, cheap and sustainable to the traditional methods (4). Extract of plant parts contain a wide variety of bioactive molecules such as phenolics, flavonoids, alkaloids, terpenoids, tannins, and proteins that help to reduce metal ions and form stable metal nanoparticles while reducing the toxicity. Bhat et al. explored phyto-mediated nanotechnology as a sustainable and eco-friendly strategy for biomedical applications. The authors highlighted the role of plant-derived phytochemicals like phenolics, flavonoids alkaloids, and terpenoids play important role in reduction process and also act as stabilizing agents for the nanoparticles. Their review highlights the application of phyto-mediated nanoparticles in antimicrobial, antioxidant, anticancer, and drug delivery applications and their reduced environmental impact when compared to chemically mediated methods (5). Panchal et al. (2025) reviewed bio-medicinal use of phyto-mediated silver (Ag), gold (Au), and zinc oxide (ZnO) metallic nanoparticles. The study also examined the future prospects of combining these nanoparticles with graphitic carbon nitride to improve therapeutic efficacy. The authors reported that plant-mediated nanoparticles have huge antimicrobial, anticancer, antioxidant, and drug delivery capabilities (6). The synthesized nanoparticles exhibited notable photoluminescence, photocatalytic, and antimicrobial properties. The study demonstrated the effectiveness of plant-assisted synthesis in producing ZnO nanoparticles with diverse functional applications.

Euphorbia caducifolia, a xerophytic medicinal plant which is the member of Euphorbiaceae family, is found extensively in the arid and semi-arid area of India. The plant has been extensively utilized in traditional medicine for the treatment of various ailments due to its rich phytochemical composition (7,9). Several studies have reported the presence of flavonoids, polyphenols, diterpenes, triterpenes, and other bioactive constituents in *Euphorbia caducifolia*, which possess significant antioxidant, antimicrobial, anti-inflammatory, and therapeutic properties (7,8). These phytochemicals make the plant an ideal candidate for the eco-production of metal oxide nanomaterials, particularly ZnO nanoparticles.

The antimicrobial effect of ZnO nanoparticles has attracted substantial research interest because of their growing challenge of antimicrobial resistance among pathogenic microorganisms. ZnO nanomaterial shows broad-spectrum antimicrobial effects against bacteria, fungi, and other pathogens through multiple procedures like as the production of reactive oxygen species (ROS), disruption of microbial cell membranes, interference with cellular metabolic activity and release of zinc ions etc. The nanoscale dimensions of ZnO particles enhance their microbial cells interaction, thereby improving their antimicrobial effectiveness. Consequently, phyto-mediated ZnO nanoparticles are being explored for applications in wound dressings, coatings, medical devices, food preservation, and pharmaceutical formulations (12).

The antimicrobial effect of ZnO nanomaterial is accompanied by a high antioxidant activity (2). Oxidative stress which is caused by production of too many reactive oxygen and free radicals, is associated with numerous chronic illness such as diabetes, cancer, cardiovascular and neurodegenerative illness. Phytochemicals which is present on the surface of the nanomaterials are generally increase the antioxidant activity of phyto-mediated nanomaterial. These biomolecules contribute to free radical scavenging, hydrogen donation, and electron transfer processes, thereby protecting biological systems from oxidative damage. Hence, the use of eco-synthesized ZnO nanoparticles for biomedical and therapeutic applications where antioxidant protection is required is emerging as a promising approach. Ramesh et al. eco-produced zinc oxide nanoparticles using *Borreria hispida* plant extract through a phyto-fabrication approach. The synthesized ZnO nanoparticles demonstrated excellent visible light-driven photocatalytic activity and significant antioxidant potential.

Another remarkable property of ZnO nanoparticles is their photoluminescence behavior. ZnO is a wide bandgap semiconductor nanomaterial having a bandgap energy of around 3.37 eV and a high exciton binding energy. The properties of ZnO nanoparticles make it possible to obtain the strongest emission of ultraviolet and visible light, which are associated with the nature of the intrinsic defects, zinc interstitials, processes of electron-hole recombination and oxygen vacancies. Photoluminescence studies provide valuable information regarding the optical quality, crystal defects, and electronic structure of ZnO nanoparticles. The unique luminescent properties of ZnO nanoparticles have led to their application in light-emitting diodes, ultraviolet lasers, photocatalysis, solar cells, biosensors, imaging systems, and other optoelectronic devices (13).

The integration of antimicrobial, antioxidant, and photoluminescence properties within a single nanomaterial significantly enhances its multifunctional potential. Green synthesized *Euphorbia caducifolia* (E. caducifolia) based zinc oxide (ZnO) nanoparticles are characterized by a very high biological activity of Euphorbia phytochemicals along with the intrinsic properties of ZnO, making the nanomaterial more efficient and biocompatible. Such multifunctional nanoparticles offer promising opportunities for developing advanced materials for healthcare, environmental remediation, sensing technologies, and nanomedicine. The current research concentrate on the eco-production of zinc oxide nanoparticles (ZnO-NPs) using *Euphorbia caducifolia* plant extract and the assessment of their antimicrobial, antioxidant, and photoluminescence properties.

Research Methodology

Collection and Plant Extract prepration: Fresh aerial parts of *Euphorbia caducifolia* were collected, washed thoroughly, shade-dried, and powdered. About 20 g of the powdered substance was mixed with 205 mL of methanol and heated at 50–60°C for 30 minutes. Filtration was done on Whatman grade 1 filter paper and this filtrate was retain at 4°C to be used in the production of more nanoparticles.

Synthesis of Phyto-Mediated ZnO Nanoparticles: The plant extract was prepared and mixed with solution of 0.1 M zinc acetate dihydrate and stirred continuously. Sodium hydroxide solution was utilize to adjust the pH of the reaction mixture to 10. The mixture was boiled for 3-4 hours at 50°C until it turned white. The precipitate obtained was centrifuged, washed with deionized water and ethanol after than dried.

Results And Discussion

Characterization of Phyto-Mediated ZnO Nanoparticles

1. UV-Visible Spectroscopic Analysis

A preliminary method was used to confirm the production of ZnO nanoparticles using UV-Visible spectroscopy. The synthesized nanoparticles showed an absorption peak in the UV range between 350–370 nm, which is a common feature of nanostructures of ZnO. The presence of this absorption band suggested the presence of excited electrons in the conduction energy band after transition from the valence energy band, which confirmed the formation of nanoparticles. The sharpness of the peak suggested a relatively uniformly-graded particle size distribution and high purity of the synthesized ZnO nanoparticles. The observed absorption is similar to the previously reported phyto-mediated ZnO nanoparticles.

The UV spectral graph of the eco-produced ZnO nanoparticles showed successful transformation of zinc precursor into the nanocrystals of ZnO.

Table 1. *UV-Visible Spectral Characteristics of Synthesized ZnO Nanoparticles*

Parameter	Observed Value
Absorption Maximum (λmax)	361 nm
Optical Band Gap	3.32 eV
Absorption Range	300–400 nm
Nature of Peak	Sharp and Intense
Confirmation	ZnO Nanoparticle Formation

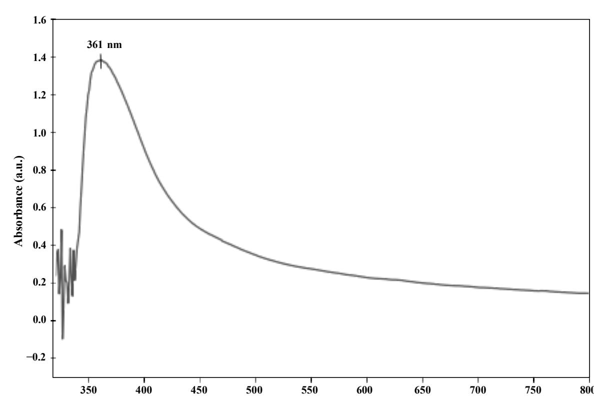

Fig. 1. *UV Spectral graph of Phyto-synthesized ZnO nanoparticles*

The absorption peak observed around 361 nm corresponds to the intrinsic band-gap absorption of ZnO nanoparticles. The blue shift in absorption differentiate to bulk ZnO indicates nanoscale particle formation due to quantum confinement effects. Similar absorption characteristics have been describe for green production ZnO nanoparticles derived from medicinal plant extracts.

2. FTIR Spectral Analysis

FTIR analysis was carryout to identify the biological molecules responsible for the reduction and stabilization of ZnO nanoparticles. The spectrum exhibited several prominent peaks corresponding to carbonyl and aromatic functional groups sourced from plant phytochemicals.

The FTIR spectral profile demonstrated the interaction between plant metabolites and ZnO nanoparticles, confirming successful phytochemical capping of the synthesized nanomaterial.

A peak around 1149 cm^{-1} corresponded to C-O stretching vibrations and 2924 cm^{-1} and 1422 cm^{-1} peaks indicated C-H stretching vibrations and C-H bending vibrations. Peak observed near 1593 cm^{-1} indicated C=O stretching or aromatic C=C streching of proteins, flavonoids and phenolic compounds. The absorption peak below 600 cm^{-1} represented Zn-O stretching vibrations, confirming the production of zinc oxide nanoparticles. These functional groups likely participated in nanoparticle synthesis and stabilization.

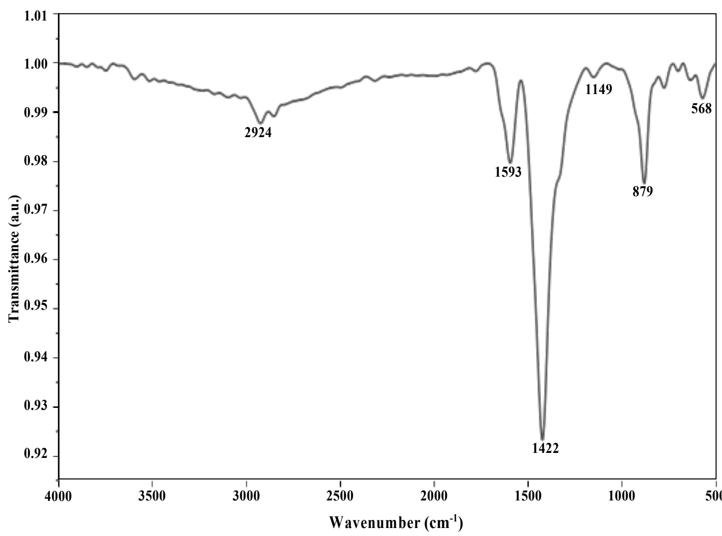

Fig. 2. *FTIR Spectral analysis of synthesized phyto-mediated ZnO nanomaterial*

3. X-Ray Diffraction (XRD) Analysis

The synthesized ZnO nanoparticles were characterized using X-ray diffraction (XRD) analysis to study the crystalline nature and the phase purity of the prepared nanoparticles. The crystal structure of ZnO showed the diffraction pattern with clear peaks related to the hexagonal wurtzite type crystalline structure.

The XRD diffractogram showed high crystalline nature of ZnO nanoparticles without any significant impurity phases.

Table 2. *XRD Peak Analysis of Synthesized ZnO Nanoparticles*

2θ (Degree)	Crystal Plane (hkl)	Relative Intensity (%)
31.8	(100)	100
34.4	(002)	66
36.2	(101)	58
47.5	(102)	39
56.6	(110)	29

The observed diffraction peaks corresponded well with standard ZnO crystal planes (JCPDS card No. 36-1451). The sharp diffraction peaks indicated good crystallinity and nanoscale dimensions. The mean crystallite size was just about 25 nm.

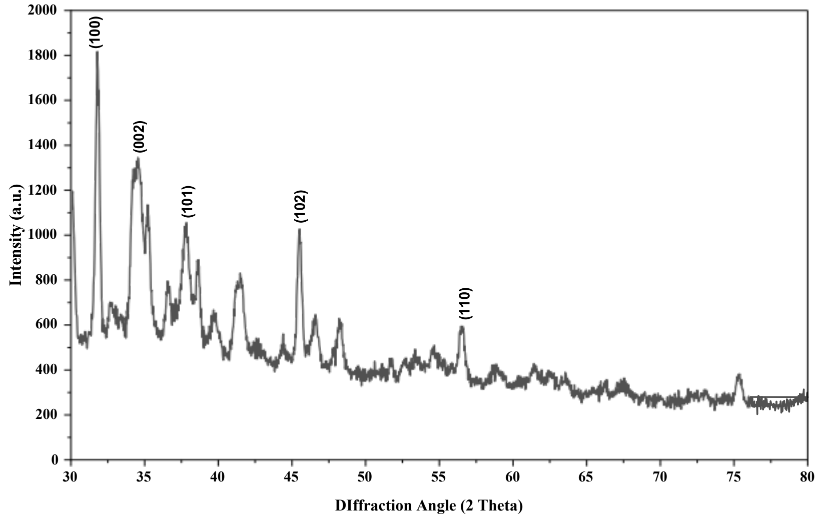

Fig. 3. *XRD analysis of Eco-produced ZnO nanoparticles*

4. SEM Analysis

The surface morphology and particle arranging of the synthesized nanomaterials were evaluated by SEM analysis. The SEM micrograph showed that particles are mostly spherical to hexagonal in shape with slight agglomeration.

The SEM image shows ZnO particles with nanometer size that were distributed over the surface with moderate clustering, caused by high surface energy.

The aggregation observed in the SEM image is commonly reported in phyto-mediated nanoparticles and may result from intermolecular interactions among phytochemical capping agents. The particles appeared uniformly distributed, indicating efficient stabilization by the biological molecules present in *Euphorbia caducifolia* extract.

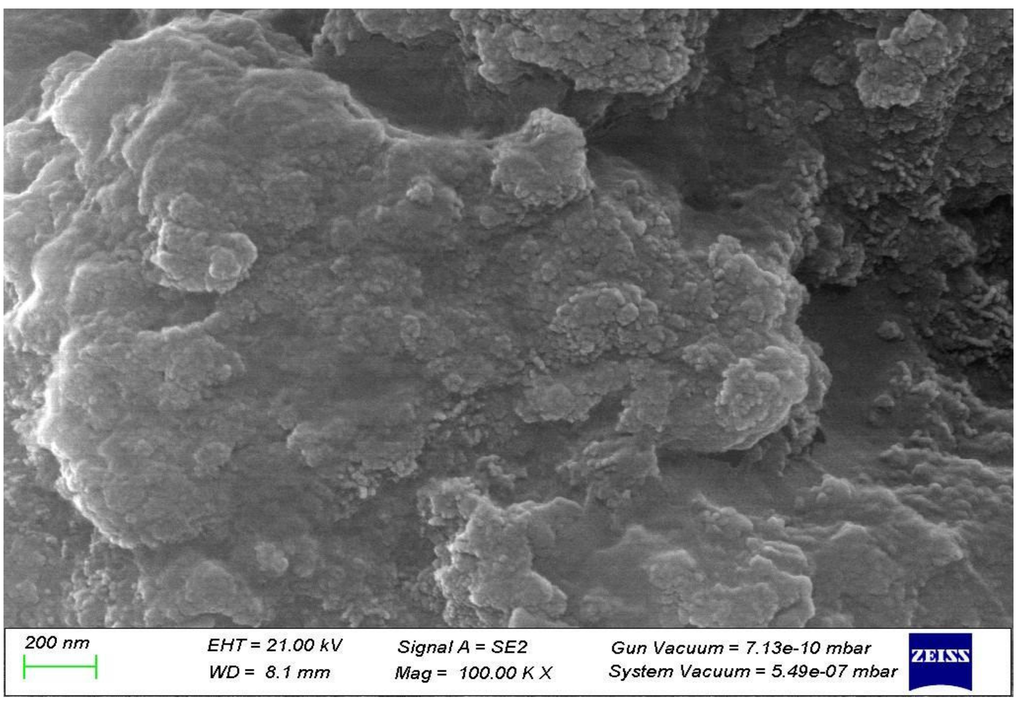

Fig. 4. *SEM Image of Phyto-mediated ZnO Nanomaterials*

Antimicrobial Activity of eco-Synthesized ZnO Nanoparticles

The antimicrobial potential of phyto-mediated ZnO nanomaterial was assessed against selected Gram-positive, Gram-negative bacterial strains utilizing the agar well diffusion test.

Table 3. *Antimicrobial Activity of ZnO Nanoparticles*

Microorganism	Zone of Inhibition (mm) at 100 µg/mL
Staphylococcus aureus	26
Bacillus subtilis	18
Escherichia coli	17
Pseudomonas aeruginosa	19
Candida albicans	13

The synthesized ZnO nanoparticles showed good antimicrobial activity against all the tested microorganisms. The maximum inhibition zone was seen against Staphylococcus aureus, which denotes that the Gram (+) bacteria were more susceptible. The antimicrobial effect can be due to the production ROS, disruption of cellular membranes, leakage of cell contents, and binding of Zn^{2+} ions with cellular components. The results indicated that the ZnO-NPs synthesized using plants have potential ues in the bio-medicinal field as antimicrobial agents.

Antioxidant Assessment of Synthesized ZnO Nanoparticles

The antioxidant activity of ZnO nanomaterials was assessed by the help of DPPH free radical scavenging assay. The synthesized nanoparticles exhibited concentration-dependent radical scavenging activity.

Table 4. *DPPH Radical Scavenging Activity*

Concentration (µg/mL)	% Inhibition
20	32.5 ± 1.2
40	48.6 ± 1.5
60	63.8 ± 1.4
80	77.1 ± 1.7
100	88.4 ± 1.6

The antioxidant activity was enhanced with the increment in concentration of nanomaterials. The large scavenging efficiency might be explained by the fact that residual phytochemicals can stick to the surface of the nanoparticles. The hydrogen-donating and free radical scavenging efficiency of the phytocompounds present in *Euphorbia caducifolia* is probably due to the phenolic and flavonoid compounds. The findings herewith show that phyto-mediated ZnO nanoparticles have a significant antioxidant activity and can be potentially beneficial in the prevention of oxidative stress related to damages.

Photoluminescence Analysis

Photoluminescence spectroscopy was performed to examine the optical emission characteristics of the synthesized ZnO nanoparticles. The PL spectrum displayed strong ultraviolet and weak visible emissions attributed to intrinsic imperfection and oxygen vacancies present within the ZnO crystal lattice.

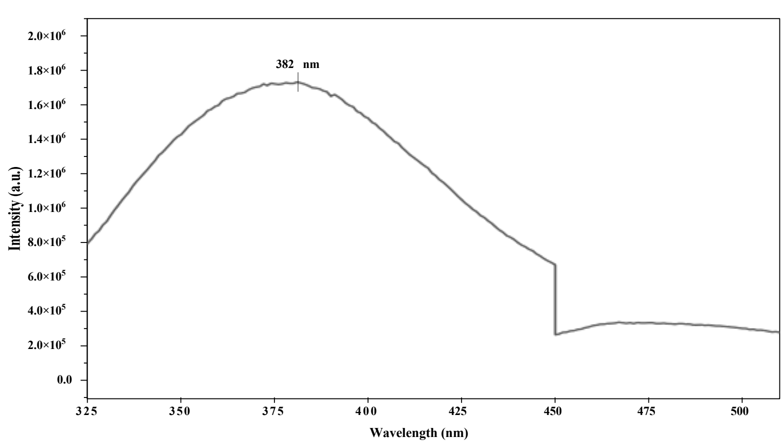

Fig. 5. *Photoluminescence spectra of Phyto-Produced ZnO nanoparticles*

The photoluminescence spectrum demonstrated characteristic emission behavior of ZnO nanoparticles produced through a eco-friendly route.

Table 5. *Photoluminescence Emission Peaks*

Emission Peak	Wavelength (nm)	Origin
UV Emission	382	Near Band Edge Transition
visible Emission	Above 400 nm	Zinc Interstitial Defects, Oxygen Vacancies

The intense ultraviolet emission at approximately 382 nm indicated effective excitonic recombination and high crystallinity of ZnO nanoparticles (14). The weak visible emissions originated from oxygen vacancies or surface defects. These defects play a role in photocatalytic, sensing, and optoelectronic applications. The observed PL behavior suggests that the synthesized ZnO nanoparticles well-ordered crystalline structure possess few defects.

Conclusion

This research successfully demonstrates the phyto-synthesized zinc oxide nanomaterials (ZnO-NPs) by employing *Euphorbia caducifolia* plant extract to act as an eco-friendly stabilizing and reducing agent. Characterization studies including UV-Visible spectroscopy, FTIR, XRD, SEM, and photoluminescence analyses verified the successful creation of nanosized ZnO particles featuring high crystallinity along with desirable optical, structural and morphological properties. The synthesized nanoparticles displayed significant antimicrobial activity against both Gram-positive and Gram-negative bacterial strains, highlighting their potential as potent antimicrobial agents. Furthermore, the nanoparticles demonstrated strong antioxidant capacity through efficient scavenging free radical, which may be attributed to the bioactive phytochemicals associated with their surface. Photoluminescence studies revealed characteristic strong ultraviolet and weak visible emissions arising from intrinsic imperfection and oxygen vacancies, which underscores their viability for use in sensing and optoelectronic systems. Overall, the findings suggest that phyto-mediated ZnO nanoparticles synthesized from *Euphorbia caducifolia* possess multifunctional biological and photophysical characteristics, making them excellent candidates for roles in pharmaceuticals, biomedicine, environmental remediation, biosensing, and advanced nanotech devices.

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