Green Synthesis of Zinc Oxide Nanoparticles Using Colocasia Esculenta Stem Extract: Mechanism, Characterization, And Applications

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doi.org/10.64643/IJIRTV12I8-190847-459

Abstract*— Green nanotechnology offers a sustainable platform for synthesizing metal oxide nanoparticles using plant-derived biomolecules. In the present study, zinc oxide (ZnO) nanoparticles were synthesized via an eco-friendly approach utilizing Colocasia esculenta stem extract as a natural reducing, capping, and stabilizing agent. The phytochemicals present in the extract—including phenolics, flavonoids, and antioxidants—played a key role in the rapid bio reduction of zinc ions under mild reaction conditions without the need for hazardous chemicals. The formation of ZnO nanoparticles was confirmed through UV–Visible spectroscopy, which displayed a characteristic absorption peak around 360–380 nm. FTIR analysis revealed functional groups responsible for nanoparticle stabilization, while XRD confirmed the hexagonal wurtzite crystal structure with nanoscale crystallite size. SEM micrographs showed predominantly spherical to irregularly shaped particles with good dispersion. The biosynthesized ZnO nanoparticles demonstrated notable antimicrobial activity against selected pathogenic strains, indicating their potential application in biomedical and environmental fields. This study highlights the effectiveness of Colocasia esculenta stems—an underutilized plant resource—as a promising biogenic precursor for green nanoparticle synthesis, contributing to sustainable nanomaterial development.

Keywords—Colocasia esculenta, Plant extract, green synthesis, nanoparticles, phytochemical reduction.

I. INTRODUCTION

Zinc oxide (ZnO) is a wide-bandgap semiconductor (~3.37 eV) with large exciton binding energy (~60 meV), making it attractive for optoelectronic, sensing, and biomedical applications [1]. At the nanoscale, ZnO exhibits increased surface area and enhanced reactivity, enabling applications in antimicrobial agents, drug delivery, photocatalysis, and sensors [2]. Traditional chemical and physical synthesis methods, such as sol–gel, hydrothermal, and chemical precipitation, often require hazardous chemicals, high temperatures, and costly equipment, limiting sustainability [3].

Green synthesis methods utilize biological entities—plants, microbes, or algae—to mediate NP formation. Plant extracts are rich in phytochemicals such as phenolics, flavonoids, and terpenoids, which can reduce metal ions and stabilize NPs, yielding biocompatible and environmentally friendly nanoparticles [4].

Colocasia esculenta, commonly known as cocoyam, is cultivated in tropical regions. While its leaves and tubers have been studied for NP synthesis, the stem remains underutilized. Rich in bioactive compounds, the stem extract can serve as reducing and capping agents, converting agricultural waste into value-added nanomaterials [5].

This review focuses on ZnO NP synthesis using C. Esculenta stem extract, analyzing mechanisms, characterization, applications, and research gaps to guide future studies.

II. PHYTOCHEMICALS IN C. ESCULENTA STEM EXTRACT AND MECHANISMS OF NP FORMATION

The stem of C. Esculenta contains phenolics, flavonoids, polysaccharides, saponins, and amino acids, which contribute to nanoparticle formation [6].

A. *Reduction Mechanism*

Zn^{2+} ions from precursors such as zinc nitrate or zinc acetate interact with phytochemicals, forming complexes. Phenolics donate electrons, reducing Zn^{2+} to ZnO, while other biomolecules stabilize the nanoparticles, preventing aggregation [7].

B. *Nucleation and Growth*

Nucleation occurs under controlled pH and temperature, followed by growth influenced by capping biomolecules. The size and morphology of ZnO NPs depend on the concentration of extract, metal precursor, pH, and temperature [8].

C. *Stabilization*

Phytochemical capping ensures colloidal stability and introduces functional groups (–OH, –COOH) on the NP surface, impacting biological and catalytic activity [9].

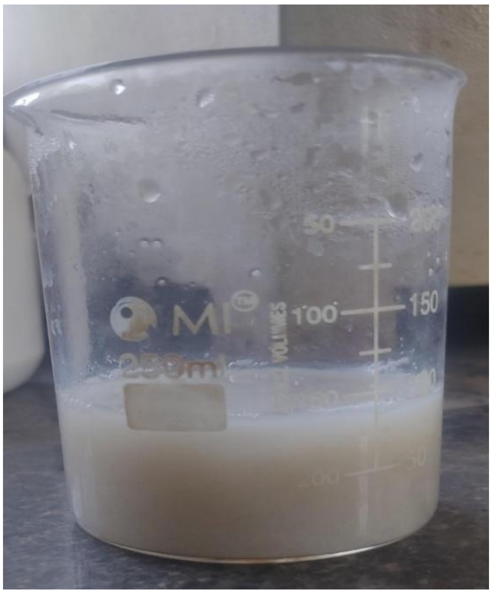

Fig: Formation of Zno Nanoparticles

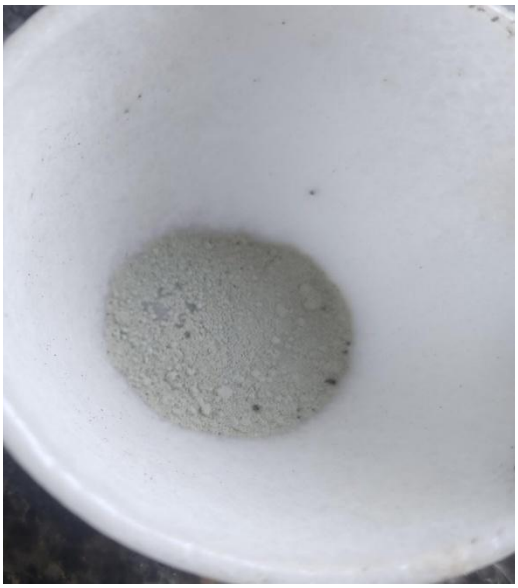

Fig: Porous Powder of ZnO Nanoparticles

III. FACTORS AFFECTING SYNTHESIS

Key synthesis parameters include:
pH: Alters ionization of functional groups, affecting reduction and chelation [10].

Temperature: Influences nucleation and growth kinetics; higher temperature accelerates reactions but may increase aggregation [11].

Extract concentration: Determines availability of reducing and capping agents; excessive extract may slow nucleation [12].

Precursor concentration: Affects yield and size; imbalance with extract concentration can lead to aggregation [13].

Reaction time: Longer times allow particle growth but may promote Ostwald ripening [14].

IV. CHARACTERIZATION TECHNIQUES

A. *UV–Visible Spectroscopy*

Monitors NP formation via absorption spectra; excitonic peaks indicate size and formation [15].

B. *X-Ray Diffraction (XRD)*

Confirms crystalline wurtzite structure; Scherrer equation estimates crystallite size [16].

C. *Fourier-Transform Inf* rared morphology *Spectroscopy (FTIR) and Electron Microscopy (SEM/TEM)*

Detects functional groups on NP surface, identifying capping agents [17].

SEM shows and size; TEM provides high-resolution imaging and crystallinity [18]

V. APPLICATIONS OF ZNO NPS

A. *Biomedical Applications*

Antimicrobial: ROS generation and membrane disruption [21].

Antioxidant/Anti-inflammatory: Phenolic capping enhances free radical scavenging [22].

Antidiabetic/Metabolic: NP-mediated enzyme inhibition [23].

B. *Environmental Applications*

Photocatalysis: Degradation of dyes and pollutants [24].

Water Purification: Adsorption and catalytic removal of contaminants [25].

C. *Agriculture and Electronics*

Nano-fertilizers: Controlled Zn delivery

Pathogen Control: Antimicrobial activity against plant pathogens [26].

Semiconducting and piezoelectric properties enable sensors and UV detectors [27].

VI. CURRENT STATUS AND RESEARCH GAPS

Limited studies focus on C. Esculenta stem extract. Most work uses leaves or tubers [28]. Major gaps include:

A. *Lack of systematic phytochemical profiling of stems*

B. *Optimization of synthesis parameters.*

VII. CHALLENGES AND LIMITATIONS

Reproducibility: Variation in plant source and extract preparation [29].

Stability: Phytochemical-capped NPs may degrade over time [30].

Toxicity: ROS generation poses cytotoxic risks [31].

Scale-Up: Maintaining uniform NP properties at large scale is difficult.

Regulatory Compliance: Environmental and biomedical applications require rigorous safety assessment [32].

VIII. FUTURE DIRECTIONS

1.*Phytochemical Profiling*: Identify active biomolecules in stem extract

Phytochemical profiling helps determine the active biomolecules present in the Colocasia esculenta stem extract, such as flavonoids, phenolics, alkaloids, and proteins. These compounds play a crucial role in reducing zinc ions and stabilizing the formation of ZnO nanoparticles during green synthesis.

2.*Optimization*: Systematic study of pH, temperature, concentrations.

Optimization involves systematically adjusting pH, temperature, and reactant concentrations to enhance the efficiency of ZnO nanoparticle synthesis.
The pH influences the ionization and activity of phytochemicals, directly affecting nucleation and particle size.
Temperature controls the reaction rate and crystalline structure formation.
Concentration ratios of extract and precursor determine yield, stability, and uniformity of the nanoparticles.

3.*Mechanistic Studies*: In-situ spectroscopy and computational modeling.

Mechanistic studies use in-situ spectroscopy to track real-time changes during nanoparticle formation and identify reaction intermediates.
Computational modeling supports this by predicting biomolecule–metal interactions and reaction pathways. Together, they help clarify how the extract drives ZnO nanoparticle synthesis.

IX. CONCLUSION

Green synthesis of ZnO nanoparticles using C. Esculenta stem extract offers a sustainable, biocompatible alternative to conventional methods. While the stem is underexplored, its phytochemicals facilitate reduction and stabilization of ZnO NPs. Further research in phytochemical profiling, process optimization, characterization, and biosafety evaluation is required to enable practical applications in biomedicine, environmental remediation, agriculture, and electronics.

X. ACKNOWLEDGEMENT

I express my sincere gratitude to all those who supported me throughout the preparation of this review paper titled “Green Synthesis of Zinc Oxide Nanoparticles Using Colocasia esculenta Stem

Extract: Mechanism, Characterization, and Applications.”

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