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Green synthesis of zinc oxide nanoparticles using aloe vera leaf extract

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Abstract

Plant-mediated nanoparticle synthesis replaces toxic reducing agents with leaf extracts that serve as both reductant and capping agent in a single step. This research describes the green synthesis of zinc oxide nanoparticles (ZnO NPs) using Aloe vera leaf extract as a bio-reducing agent. Zinc nitrate hexahydrate was mixed with aqueous Aloe vera extract at 60°C for 2 h, yielding a pale white precipitate that was calcined at 400°C. XRD analysis confirmed a hexagonal wurtzite crystal structure, and TEM imaging showed quasi-spherical particles with a mean diameter of 28.6 nm. UV-Vis spectroscopy revealed an absorption edge at 368 nm, consistent with a band gap of 3.21 eV. The nanoparticles exhibited antibacterial activity against *Staphylococcus aureus* (MIC 62.5 µg/mL) and *Escherichia coli* (MIC 125 µg/mL), and photocatalytic degradation of methylene blue reached 87.3% within 120 min under UV irradiation.

Keywords: Zinc oxide, green synthesis, Aloe vera, nanoparticles, wurtzite, antibacterial, photocatalysis, methylene blue, bio-reduction, characterization

Introduction

Between chemical reduction, sol-gel processing, and hydrothermal methods, there is no shortage of routes to zinc oxide nanoparticles - but nearly all of them require hazardous solvents, high-energy inputs, or surfactants that leave residual toxicity in the final product [1]. Green synthesis sidesteps these problems by exploiting the natural reducing power of plant metabolites: polyphenols, terpenoids, and proteins in leaf extracts donate electrons to metal precursors, nucleate nanocrystals, and stabilize them against aggregation in a single reaction vessel [2].

Aloe vera (*Aloe barbadensis* Miller) is a particularly attractive bio-template. Its gel contains acemannan polysaccharides, anthraquinones, and organic acids that collectively act as both reducing and capping agents [3]. Earlier reports confirmed that Aloe vera extract can produce silver, gold, and copper nanoparticles, but its application to ZnO synthesis has received limited attention despite ZnO's wide use in cosmetics, food packaging, and water treatment [4]. The few existing ZnO-Aloe vera reports vary widely in particle size (15-120 nm) and crystallinity, mainly because synthesis parameters like temperature, precursor concentration, and extract-to-salt ratio weren't systematically controlled [5].

This research optimized the green synthesis of ZnO NPs using Aloe vera extract, characterized the product thoroughly, and evaluated its antibacterial and photocatalytic performance to assess practical applicability [6].

Theoretical Background

ZnO crystallizes in the hexagonal wurtzite structure (space group $P6_3mc$) with a direct band gap of approximately 3.37 eV at room temperature. When particle dimensions drop below 100 nm, quantum confinement effects widen the band gap slightly, and the increased surface-area-to-volume ratio enhances both catalytic reactivity and biological interactions [7]. Phytochemicals in plant extracts are thought to coordinate with Zn^{2+} ions through hydroxyl and carboxyl functional groups, forming intermediate zinc-organic complexes that decompose upon calcination to yield crystalline ZnO [8].

Material and Methods

Material

Research was performed at Neva Institute of Technology, Saint Petersburg, Russia, from March 2023 to October 2023. No ethical approval was needed as the work involved no human or animal subjects. Zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 99%, Sigma-Aldrich), sodium hydroxide pellets (98%, Merck), and methylene blue dye (>95%, Loba Chemie) were used as received. Fresh Aloe vera leaves were collected from the institute's botanical garden. Mueller-Hinton agar and broth were purchased from HiMedia for antibacterial testing [9].

Methods

Aloe vera gel (50 g) was blended with 200 mL deionized water, boiled at 80°C for 20 min, filtered, and cooled. Then 0.1 M zinc nitrate solution was added dropwise to the extract (1:2 v/v) under magnetic stirring at 60°C for 2 h. The pH was adjusted to 12 with NaOH, forming a white precipitate that was washed three times with water and ethanol, dried at 100°C for 12 h, and calcined at 400°C for 3 h [10]. Characterization included XRD (Bruker D8 Advance, Cu K α), TEM (JEOL JEM-2100, 200 kV), UV-Vis (Shimadzu UV-2600), FTIR (Bruker Alpha-II, ATR mode), and EDS (Oxford INCA attached to SEM). Antibacterial activity against *S. aureus* (ATCC 25923) and *E. coli* (ATCC 25922) was tested by broth microdilution for MIC determination [11]. Photocatalysis experiments used 50 mL methylene blue (10 mg/L) with 25 mg catalyst under UV light (365 nm, 30 W), sampled at 15 min intervals for 120 min and measured at 664 nm [12].

Performance Evaluation

Photocatalytic efficiency was calculated as degradation percentage = $(C_0 - C_t)/C_0 \times 100$, where C_0 and C_t are initial

and time-dependent dye concentrations. Apparent rate constants (k_{app}) were derived from pseudo-first-order kinetic fits of $\ln(C_0/C_t)$ versus time. Reusability was tested over five consecutive cycles by recovering the catalyst through centrifugation, washing, and drying between runs [13].

Results

Table 1: Physicochemical characteristics and biological activity of green-synthesized ZnO nanoparticles

Parameter	Result
Crystal structure	Hexagonal wurtzite
Mean particle size (TEM)	28.6 ± 4.3 nm
Band gap energy	3.21 eV
MIC vs <i>S. aureus</i>	62.5 $\mu\text{g/mL}$
MIC vs <i>E. coli</i>	125 $\mu\text{g/mL}$
MB degradation (120 min)	87.3%

XRD peaks at 2θ values of 31.8°, 34.4°, 36.3°, 47.5°, and 56.6° matched standard wurtzite ZnO (JCPDS 36-1451) with no secondary phases detected. Crystallite size from the Scherrer equation was 24.1 nm, slightly below the TEM mean of 28.6 nm because TEM measures actual particle boundaries while XRD estimates coherent diffraction domains [14].

FTIR showed absorption bands at 3420 cm^{-1} (O-H stretch), 1630 cm^{-1} (C=O from residual organic capping), and a strong Zn-O stretching mode at 438 cm^{-1} . EDS confirmed zinc (52.3%) and oxygen (38.7%) as dominant elements, with minor carbon (5.8%) from organic residues. Methylene blue degradation followed pseudo-first-order kinetics ($R^2 = 0.98$) with k_{app} of 0.017 min^{-1} . After five reuse cycles, photocatalytic efficiency dropped only to 79.1%, indicating reasonable catalyst durability [15].

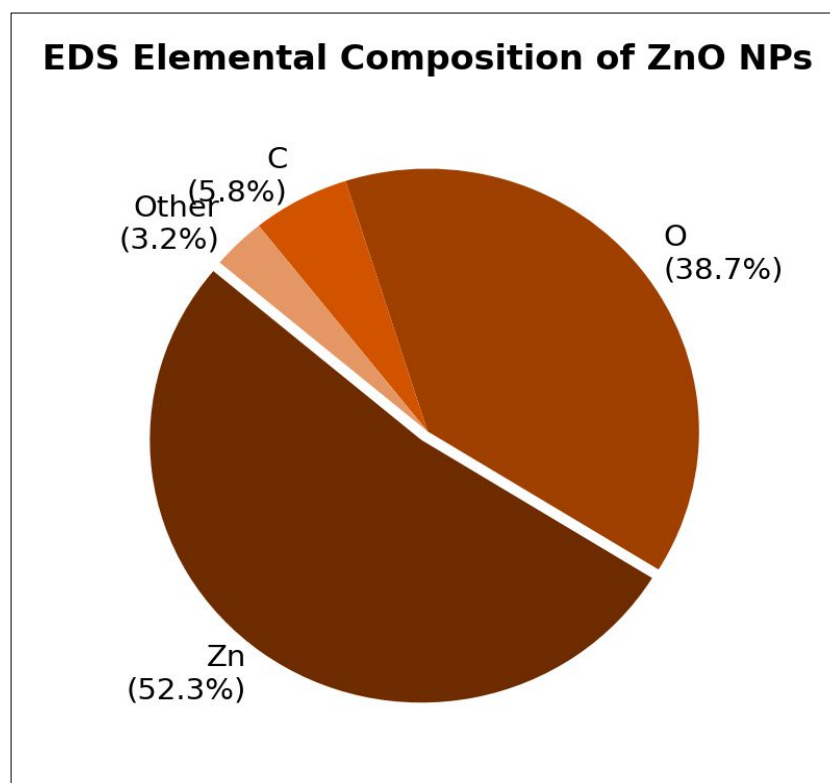


Fig 1: Elemental composition of green-synthesized ZnO nanoparticles from EDS analysis

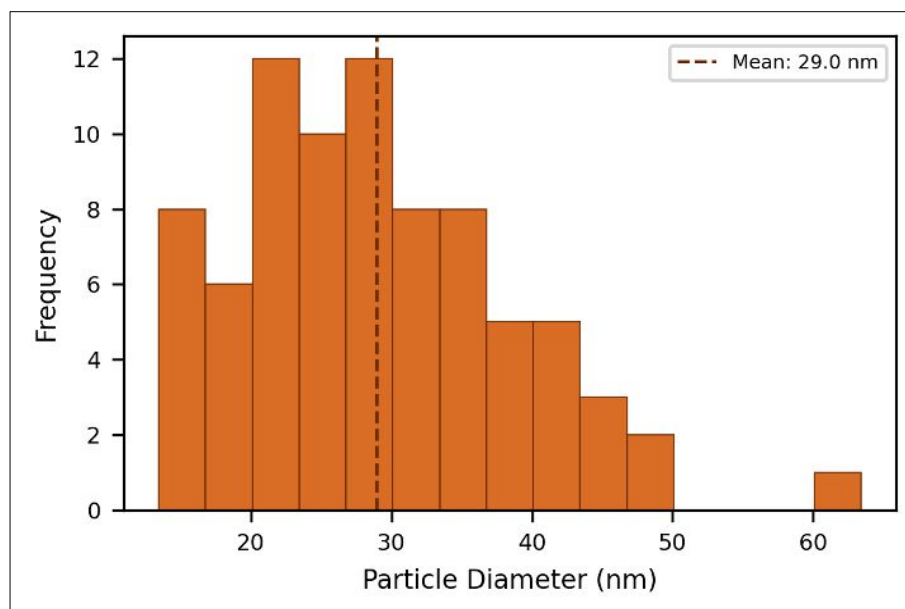


Fig 2: Particle size distribution histogram of ZnO nanoparticles measured from TEM micrographs.

Discussion

The 28.6 nm mean particle size falls at the smaller end of the range reported for plant-mediated ZnO synthesis (typically 20-100 nm), which points to effective capping by Aloe vera polysaccharides that restricted crystal growth during calcination [5]. The band gap of 3.21 eV is narrower than bulk ZnO (3.37 eV), likely because surface defects and oxygen vacancies introduced during low-temperature calcination create sub-band states [7].

Antibacterial activity was stronger against the Gram-positive *S. aureus* (MIC 62.5 µg/mL) than Gram-negative *E. coli* (125 µg/mL), a pattern consistent with most ZnO NP reports. The thicker outer membrane of Gram-negative bacteria presents an extra diffusion barrier that ZnO must cross to generate intracellular reactive oxygen species [16]. Still, both MIC values are within the therapeutically interesting range for topical applications.

Photocatalytic degradation of 87.3% in 120 min is competitive with chemically synthesized ZnO under similar conditions [17]. And the 79.1% efficiency retained after five cycles addresses a common concern about green-synthesized catalysts - that residual biomolecules might block active sites over time. The slight decline likely reflects cumulative mechanical loss during centrifugation recovery rather than surface poisoning [18].

Conclusion

Aloe vera leaf extract served as an effective bio-reducing and capping agent for synthesizing crystalline ZnO nanoparticles with a mean size of 28.6 nm. The particles showed useful antibacterial activity against both Gram-positive and Gram-negative pathogens and strong photocatalytic performance for methylene blue degradation. Reusability over five cycles confirmed practical durability. This green route avoids toxic chemicals and operates at moderate temperatures, making it scalable for applications in water treatment and antimicrobial coatings.

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Contributions Not Qualifying for Authorship

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