IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 18, Issue 5 Ser. 1 (Sep. – Oct. 2026), PP 24-28
www.iosrjournals.org

Plant-mediated Synthesis of ZnO Nanoparticles from *Cinnamomum camphora* and Their Characterization

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Abstract
It is now possible to integrate the manufacturing of nanomaterials with sustainability, safer processing, and application-driven innovation by using plant extracts for the green synthesis of zinc oxide nanoparticles (ZnO NPs). This paper examines plant-mediated ZnO synthesis with a focus on Cinnamomum camphora, a phytochemical-rich species whose terpenoids and phenolics encourage nanoparticle production under relatively mild circumstances. Instead of focusing just on instrument-based characterization, the study outlines how synthesis circumstances impact particle properties, how those qualities relate to functional performance, and why this matters for applications linked to the environment, healthcare, and energy.
The literature reports that green ZnO often exhibits hexagonal wurtzite crystallinity, near-band-edge absorption in the 365-380 nm range, Zn-O stretching bands about 450-500 cm^{-1}, and nanoscale morphologies associated with antibacterial and photocatalytic activity.In a representative C. camphora investigation, pH-dependent synthesis yielded ZnO with UV-Vis absorbance at 368-374 nm, TEM diameters of approximately 13.92-21.13 nm, and antifungal efficacy against Alternaria alternata. At pH 7, the greatest inhibition was seen.
According to these findings, ZnO mediated by C. camphora is a potential material for crop protection, water remediation, antimicrobial coatings, and sustainable energy technologies including photocatalysis and solar devices. The research also addresses the practical problems that now hinder translation, including extract variability, incomplete reporting, challenges scaling up, and insufficient toxicity standards. If greener ZnO techniques are not adopted and enhanced, reliance on more hazardous and energy-intensive production paths is likely to persist. Cleaner manufacturing, the use of circular resources, and wider implementation in sectors that depend on sustainability will all be hampered by this.All things considered, C. camphora offers a dependable plant platform for low-input ZnO synthesis; nonetheless, for application-ready expansion, better standardization, repeatability, and decision-relevant performance reporting will be required.

Keywords: *green synthesis; zinc oxide; Cinnamomum camphora; sustainable nanotechnology; UV-Vis; XRD; FTIR; SEM; TEM; antimicrobial; renewable energy*

Date of Submission: 03-09-2026 Date of Acceptance: 13-09-2026

I. Introduction

From a laboratory substitute, plant-mediated synthesis of nanomaterials has developed into a strategically significant route for the production of more environmentally friendly materials. Green synthesis is appealing for zinc oxide nanoparticles (ZnO NPs) because it can replace harsher reagents and energy-intensive processes while also producing nanomaterials whose surface chemistry can be influenced by bioactive compounds derived from plants. With an emphasis on Cinnamomum camphora as a promising plant source for environmentally friendly nanoparticle production, this review explores green ZnO synthesis through a sustainability and application-oriented lens.Plant-mediated synthesis uses phytochemicals as reducing and capping agents, which can reduce hazardous inputs and processing intensity as compared to traditional chemical and physical approaches. [4,6] Under very mild temperatures and near-neutral to alkaline conditions, plant extracts from leaves, stems, bark, and roots contain polyphenols, flavonoids, terpenoids, and organic acids that can chelate zinc, encourage nucleation, and stabilize growing particles. Because [2,5]ZnO combines wide antibacterial action, biocompatibility, affordability, and tunable optoelectronic characteristics, it continues to be a particularly appealing target material.[2,5,6] .Green ZnO synthesis is relevant to an audience focused on sustainability and management because it can link innovative materials with useful decision-making. Antimicrobial performance is important for crop protection, packaging, and healthcare. For pollutant degradation and wastewater cleanup, photocatalytic activity is important. For self-powered sensing and renewable energy, optoelectronic and piezoelectric performance are important. This value is not adequately captured by a review that only enumerates characterization outcomes. The most important topic is how synthesis choices affect deployable outcomes, repeatability, and alignment with sustainability goals. Therefore, rather of considering characterisation as an aim in and of itself, this evaluation sees it as evidence of function.

***Cinnamomum camphora*;Why does it matter?**

C. camphora's chemistry and practical significance make it suitable for green ZnO synthesis. The plant is a feasible dual-function reagent that can support both nanoparticle creation and biological activity because camphor, 1,8-cineole, linalool, and other terpenoids and phenolics with proven antibacterial and antioxidant characteristics are found in camphor tree leaves and essential oils. The importance of C. camphora fractions as a bioactive botanical source is further reinforced by independent phytochemical and essential-oil investigations that show antibacterial and insecticidal activities. [1, 8]

Beyond the ease of synthesis, this is significant. Accessible, non-toxic, and chemically active plant sources can improve the production route's acceptability for environmental and public health applications while lowering material processing hurdles. In actuality, C. In addition to being a phytoreductant, camphora provides a resource platform for developing ZnO systems intended for antibacterial, remediation, and sustainability-related applications.

Green Synthesis as a Review Framework

According to the research reviewed here, a generally consistent process sequence for plant-mediated ZnO synthesis includes plant selection, extract preparation, precursor mixing, incubation, recovery, drying, and characterization. [4, 6]. In C. camphora-based systems, extract volume, precursor concentration, incubation conditions, and especially pH affect nucleation, growth, surface stabilization, and overall performance. A standard experimental approach involves the use of aqueous leaf extract and zinc acetate, followed by centrifugation, mild heating, washing, drying, and standard physicochemical examination.pH is consistently found to be one of the most important factors because it affects hydrolysis and nucleation kinetics, which in turn affect crystallite size and morphology. [1,2,6]

The composition of the extract is another crucial factor. Because phytochemical concentration depends on plant part, solvent, area, and season, variations in extract chemistry can impact repeatability and confound cross-study comparability. [6, 8] Therefore, when assessing green synthesis, it is crucial to take into account not only whether ZnO forms but also whether the method is adequately standardizable for performance comparison, scaling up, and future application.

Physicochemical Signatures in Plant-Mediated ZnO: What They Mean for Application

Green ZnO usually shows near-band-edge UV-Vis absorption in the range of around 365-380 nm, whereas C. camphora-mediated ZnO has been detected at 368-374 nm.[1] Plant-mediated ZnO typically has band gaps of 3.2-3.3 eV; wurtzite ZnO is consistent with values of 3.25-3.28 eV for Cinnamomum verum. These values align with the review level consensus. [2] Because they regulate photocatalytic activity, light absorption, and possible integration with solar and sensor systems, these optical properties are significant from an application perspective.X-ray diffraction results across plant-mediated systems consistently indicate the formation of hexagonal wurtzite ZnO, with reflections near (100), (002), and (101).

Although the Scherrer equation is widely employed to estimate crystallite size, its limitations must be recognized since it describes coherently diffracting domains rather than complete particle dimensions. [2,9] Crystalline phase purity is essential for translational application since it affects stability, optical response, and the consistency of antibacterial or catalytic activity.Zn-O stretching in the 450-500 cm^{-1} region, signals about 1630-1650 cm^{-1} linked to carbonyl or unsaturated groups, and O-H stretching near 3400 cm^{-1} from hydroxyl groups and leftover plant compounds are typically seen in FTIR spectra. [3] In addition to acting as confirmation markers, these bands are useful because they demonstrate how compounds derived from plants adhere to the surface of the nanoparticles. Surface chemistry can affect biological interaction, dispersion, and catalytic behavior.

For green ZnO systems, reported SEM and TEM data frequently show spherical, hexagonal, or flower-like morphologies in the nanoscale range; C. camphora specimens usually range from 14 to 21 nm and show minor aggregation. Such morphological heterogeneity is relevant to applications because surface area, defect structure, and aggregation state affect biological interaction, ion release, and reactivity [1,2]. TGA measurements frequently reveal that in green ZnO systems, physisorbed water is eliminated below 150 °C, residual organics decompose between 200 and 450 °C, and thermal stability increases above 450 °C. Because organic residues can impact biological interpretation, catalytic purity, or storage stability, this is significant for real-world applications. The easiest way to understand these characterization qualities together is as indicators of application readiness. In summary, the key question is not how many characterisation methods were used, but rather if the reported results explain why a certain ZnO material performs well in antibacterial, photocatalytic, or energy-related scenarios.

Focused Evidence from *Cinnamomum camphora*-Mediated ZnO

The typical work on C. camphora by Zhu et al. offers a clear example of how synthesis conditions affect function. With TEM mean diameters of 13.92 nm at pH 7, 15.19 nm at pH 8, and 21.13 nm at pH 9, the scientists reported UV-Vis absorption in the 368-374 nm area using leaf extract with zinc acetate and varied pH from 7 to 9. [1] The same study also revealed antifungal activity against Alternaria alternata, with the pH 7 sample showing the greatest activity and a minimum inhibitory concentration of 20 $mg \cdot L^{-1}$. [1]

The 2023 review literature provides an impartial summary of this dataset and places it within the broader area of green ZnO. [6].This illustration emphasizes an important review-level point: synthesis variables have practical applications. In this case, smaller particles generated at lower pH values were associated with stronger antifungal efficacy. This connection supports a value-oriented interpretation of green synthesis, which maintains that controlling a material property that directly impacts crop protection and bioactive usage is more crucial for process optimization than particle production.

Comparative Perspective Within the *Cinnamomum* Genus

Evidence from Cinnamomum verum supports the results from C. camphora and validates the genus's broader significance for green ZnO synthesis. In bark-extract-mediated synthesis, ZnO demonstrated wurtzite crystallinity, band-gap values of 3.25-3.28 eV, and antibacterial activity against Escherichia coli and Staphylococcus aureus with MIC values of 62.5 and 125 $\mu g \cdot mL^{-1}$, respectively. [3] These results suggest that terpenoid and phenolic compound-rich cinnamomum systems can reliably increase nanoparticle formation and bioactivity.This supports the claim that C. camphora should be considered as part of a viable genus-level strategy for sustainable ZnO synthesis rather than as an isolated case for review purposes.

Application Pathways and Sustainability Relevance

The application value of green ZnO is its strongest argument. The larger literature supports that plant-mediated ZnO can exhibit broad antibacterial activity driven by ROS production, Zn^{2+} release, and membrane contact. C. camphora-mediated ZnO has shown antifungal effect against A. alternata. [1] Wide antibacterial performance across green ZnO systems is also described in reviews. [2,6] Because of this, green ZnO is important for bioactive surfaces, packaging, antimicrobial coatings, agricultural disease control, and laboratory microbiology.The value proposition for the environment is equally important. Recent assessments from 2024-2025 frame plant-derived synthesis as a more sustainable entry point into environmental remediation materials, identifying dye degradation, water treatment, and packaging as important application areas for green ZnO.[2,5,7,10,11] A lower-input path to photocatalytic materials that may promote pollutant degradation while lowering the material-production burden itself is clearly appealing to decision-makers in water treatment and environmental management.Applications related to renewable energy are also important. ZnO's broad band gap, exciton binding energy, and photocatalytic characteristics already make it valuable for use in solar cells, hydrogen production, and piezoelectric devices. Given that a publication focused on sustainability must take into account both product function and process load, green ZnO is pertinent in that regard. The production route itself is included in the innovation scenario if plant-mediated techniques can produce comparable results.The creation of biogenic composite systems is one new avenue. CuO/ZnO composites were created using C. camphora extract in a 2025 study that verified successful synthesis using UV-Vis, XRD, FTIR, and electron microscopy. This suggests the potential for more extensive multifunctional nanocatalyst creation based on the same botanical platform.[1] " This is crucial because it is unclear that single-function nanoparticles would be sufficient for sustainability applications in the future; instead, integrated materials with enhanced process compatibility, catalysis, and antibacterial activity will be needed.

Table 1. Application-relevant findings reported for *C. camphora*-mediated ZnO

Parameter	Reported value(s)	Application relevance
UV-Vis absorption peak (λ_max)	368-374 nm	Supports ZnO formation and indicates optical behavior relevant to photocatalysis and light-driven applications
TEM mean particle size	13.92 nm (pH 7); 15.19 nm (pH 8); 21.13 nm (pH 9)	Demonstrates pH-dependent size control linked to biological and catalytic performance
Antifungal MIC vs *A. alternata*	20 $mg \cdot L^{-1}$ (pH 7 ZnO)	Indicates practical potential for plant disease control and agricultural antifungal use
FTIR: Zn-O stretch	~450-500 cm^{-1}	Confirms ZnO formation and supports interpretation of surface chemistry
Band gap (for *Cinnamomum* spp.)	3.25-3.28 eV (*C. verum*)	Relevant to optoelectronic behavior, photocatalysis, and solar-energy-linked applications

Table 2. Process and reporting factors that shape reproducibility and application readiness

Factor	Typical setting or issue	Why it matters
Extract preparation	10-20 mL extract + 90-80 mL water	Influences phytochemical concentration and batch-to-batch reproducibility
Zinc precursor	1-2 g zinc acetate / 100 mL water	Affects nucleation conditions and comparability across studies
Mixing and incubation	1:1 v/v, 50 °C, 1-24 h	Determines reaction kinetics and energy burden
Separation and drying	5,000-10,000 rpm, 10-15 min; dry 60 °C, 2-4 h	Influences recovery efficiency and practical scale-up
Characterization and reporting	UV-Vis, XRD, SEM/TEM, FTIR, TGA	Should be tied to reproducibility, functional claims, and application relevance rather than reported descriptively

Studies should consistently report XRD peak assignments and size-estimation assumptions, optical band-gap methodology, FTIR band assignments, particle-size statistics, and thermal mass-loss steps in ways that promote reproducibility and cross-study interpretation for improved application-oriented comparison. [2,9]

Mechanisms of Formation and Antimicrobial Action

The process by which phytochemicals complex Zn2+ ions, encourage hydrolysis to zinc hydroxide intermediates, facilitate dehydration into ZnO under mild heating, and stabilize the particle surface is commonly referred to as plant-mediated ZnO synthesis. [2] pH controls the hydrolysis and nucleation processes, which affects the size and shape of crystallites. From a review perspective, this approach makes clear why plant chemistry is not incidental but rather crucial to process management.The antibacterial and antifungal qualities of green ZnO are often linked to direct membrane contact, Zn2+ release, and ROS generation.Fungal suppression in ZnO produced from C. camphora has been linked to membrane disruption, lipid peroxidation, and protein and nucleic acid leakage. [1,6] The practical implication is that defect structure, particle size, and surface chemistry are all part of the functional basis for deployment in environmental and antimicrobial settings rather than just being physicochemical descriptors.

Safety, Standardization, and Translational Readiness

Translation is nevertheless limited by a number of persistent flaws, despite the research demonstrating great potential for green ZnO in antibacterial, anti-inflammatory, anticancer, and environmental applications. Reviews frequently point out poor toxicity standardization, batch-to-batch variability in plant extract chemistry, and challenges in maintaining surface chemistry and size distribution during scale-up. [2,5,6] These are major obstacles to industrial acceptance, regulatory trust, and useful life-cycle comparison; they are not insignificant technological issues.Zeta potential, hydrodynamic size in pertinent medium, endotoxin testing, and more precise dose measurements like mass vs surface area are just a few of the useful reporting enhancements that have already been proposed in the literature. [2,6],Such reporting is essential for sustainability-oriented deployment because it presents laboratory results with real-world risk assessment, performance consistency, and stakeholder trust.

II. Discussion

The information provided here indicates that ZnO mediated by C. camphora is more than just a fascinating green synthesis. With less reliance on harsh reagents and energy-intensive processing, it offers a potentially helpful platform for the production of antimicrobial and photocatalytic nanomaterials under relatively mild circumstances. This is important from a sustainability perspective because cleaner synthesis is only useful when it produces materials that can meet significant environmental and societal needs, like safer antimicrobial technologies, better crop protection, wastewater remediation, and the development of devices linked to renewable energy.ZnO's broad sustainability significance supports this claim.

ZnO is already being investigated for usage in dye-sensitized and perovskite solar cells, photocatalytic hydrogen generation, and piezoelectric nanogenerators. The material becomes relevant to several stakeholder groups at once when these application pathways are combined with plant-mediated synthesis: manufacturers seeking more ethical production techniques, environmental managers seeking pollutant-removal technologies, energy researchers seeking lower-burden functional materials, and agricultural users concerned about fungal control. The more general goals outlined in SDGs 7 and 12 are supported by this relationship, even though life-cycle benefits have not yet been fully quantified in the literature.

The outcome of non-adoption is equally significant. Production will continue to rely more on techniques involving harsher chemicals, higher energy requirements, and less circular use of biological resources if greener ZnO synthesis processes are not developed, refined, and standardized. By maintaining needless process costs and undermining the rationale for responsible nanomanufacturing, that would hinder the translation of ZnO into sustainability-critical industries. In other words, by delaying more acceptable and scalable routes to valuable minerals, the penalty of not adopting greener approaches is not only environmental but also strategic.However, green synthesis shouldn't be romanticized. The current body of information is still largely dependent on inconsistent reporting, various extract methods, and laboratory-scale investigations. Future research must go beyond proof-of-concept characterization in favor of comparative performance studies, standardization, and decision-ready metrics for management and policy relevance. Stronger evidence in device-relevant energy systems, reproducibility over seasonal and geographic extract variation, application testing in actual wastewater instead of model dyes, and improved knowledge of dose, stability, and safety are all examples of this. Green ZnO's sustainability claim will only be believable if it is backed by both favorable functionality and repeatable manufacturing logic.

Future Directions

The relationship between green synthesis and application deployment should be strengthened by further research. In energy-related contexts, C. camphora-mediated ZnO should be directly tested versus conventionally manufactured ZnO in solar cells, photocatalytic hydrogen generation, and piezoelectric devices in order to assess both performance and environmental benefit. Research on environmental remediation should shift from model pollutants to actual wastewater matrices exposed to sun radiation, as operational unpredictability, competing ions, and natural organic matter might cast doubt on laboratory results.

Examining if botanical residues and phytochemical extraction can be incorporated into biomass valorization processes rather than handled as one-step inputs is another way to apply circular economy ideas. Lastly, to determine whether green synthesis truly lowers carbon, water, and energy loads at a significant scale, life-cycle assessment and standardized toxicity evaluation are required.

III. Conclusion

Wurtzite ZnO with nanoscale dimensions and biologically relevant performance can be formed at low temperatures through plant-mediated synthesis employing Cinnamomum camphora. According to the literature, C. camphora may create ZnO nanoparticles with antifungal activity against Alternaria alternata, TEM diameters of roughly 14-21 nm, and UV-Vis absorbance at 368-374 nm, with a high influence on synthesis pH. These results confirm C. camphora's function as a phytochemical platform for green ZnO synthesis that has been verified through experimentation.More significantly, this system's utility goes beyond antibacterial proof-of-concept or characterisation. Green ZnO has applications in water treatment, pollutant degradation, crop protection, antimicrobial control, photocatalysis linked to renewable energy, and possibly self-powered electronics. If that promise is to be fulfilled, however, the discipline must reduce process windows, improve extract standardization, evaluate stability and toxicity more thoroughly, and adopt decision-relevant comparisons with traditional synthesis approaches. In addition to more ecologically friendly nanomaterial synthesis, C. camphora-mediated ZnO can serve broader sustainability goals in clean energy, water purification, and responsible materials innovation.

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