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Biogenic Synthesis of Zinc Oxide Nanoparticles Using *Zingiber officinale*: Process and Characterization

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ABSTRACT : *Zinc oxide (ZnO) nanoparticles have attracted significant attention due to their unique structural, optical, and catalytic properties. In the present study, ZnO nanoparticles were synthesized using an environmentally benign green synthesis approach employing ginger (Zingiber officinale) extract as a natural reducing and stabilizing agent. The use of plant-based extracts offers an ecofriendly, cost effective, and nontoxic alternative to conventional chemical synthesis methods. The synthesis was carried out through a wet chemical co precipitation method, followed by thermal decomposition to obtain crystalline ZnO nanoparticles. The phytochemicals present in Zingiber officinale, such as phenolic compounds and flavonoids, play a crucial role in controlling particle formation and stability during the synthesis process. This method eliminates the need for hazardous chemicals and high energy conditions, making it suitable for sustainable nanomaterial production. The structural properties were characterized using X-ray Diffraction (XRD), which confirmed the formation of a highly crystalline hexagonal wurtzite structure with no detectable impurity phases. The diffraction peaks were indexed to the standard JCPDS 36-1451, demonstrating superior structural integrity. Field Emission Scanning Electron Microscopy (FESEM) analysis revealed a unique morphological transition from typical spherical particles to an interconnected 2D nanoflake architecture. This anisotropic growth is attributed to the selective capping of polar crystal facets by ginger derived phytochemicals such as gingerols and shogaols, which inhibited vertical growth and promoted lateral expansion. The resulting hierarchical, porous network of nanoflakes offers a significantly high surface to volume ratio. The findings suggest that this biogenic approach not only eliminates the need for toxic surfactants but also produces structurally robust ZnO nanostructures suitable for advanced applications in photocatalysis, gas sensing, and antimicrobial coatings.*

KEYWORDS - *Green Synthesis; Zinc Oxide; Ginger Extract (Zingiber officinale); Nanoflakes; XRD; FESEM; Wurtzite Structure.*

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I. INTRODUCTION

Nanotechnology has gained significant attention in recent decades due to its applications in various fields including medicine, electronics, environmental science and materials engineering. Nanoparticles, typically ranging from 1 to 100 nm in size, show unique physical and chemical properties such as high surface area and quantum size effects as compared to its bulk counterpart [1]. Owing to these characteristics, nanoparticles play an important role in the development of advanced functional materials. In comparison to other metal oxide, ZnO possesses interesting structural, biological and physicochemical properties such as strong photocatalytic activity, excellent UV absorption capability, chemical stability, optical transparency, semiconducting behaviour, biocompatibility, and antibacterial activity. ZnO is a II–VI semiconductor with a wide direct band gap of approximately 3.37 eV and a high exciton binding energy of about 60 meV at room temperature [2-4] Therefore, they are broadly used in photocatalysis, UV-blocking materials, optoelectronic devices, gas sensors, drug delivery systems, biosensors, environmental remediation, and solar energy conversion devices [5]. Additionally, their strong antibacterial activity against both Gram-positive and Gram-negative bacteria has led to increasing applications in biomedical and environmental fields [6-8]. Metal oxide nanoparticles such as ZnO, CuO, MgO, Co2O3 and TiO2 can be synthesized using wet chemical method, sol–gel methods, hydrothermal synthesis, precipitation techniques, chemical vapor deposition, and thermal decomposition.[9-12].These methods can produce nanoparticles with controlled size and morphology at the cost of high energy consumption, toxic reagents, complex processing conditions, expensive instrumentation, and harsh reaction conditions such as elevated temperature and pressure. In-order to prevent long term hazards to the environment, an alternative eco-friendly method is used. This alternate method is called green synthesis which uses biological resources such as microorganisms, enzymes, and plant extracts for nanoparticle formation [13,14]. Among these, plant-mediated synthesis has gained significant popularity due to its simplicity, cost-effectiveness, and ability to produce stable nanoparticles without the need of harmful chemicals. Plant extracts contain various phytochemicals including

flavonoids, phenolic compounds, terpenoids, and alkaloids that can act as reducing as well as stabilizing agents during nanoparticle synthesis. These biomolecules facilitate the conversion of metal ions into nanoparticles while also preventing excessive aggregation. Trifolium pratense, Aloe vera, Nephelium lappaceum, Azadirachta indica, L. leschenaultiana, and Carica papaya are among the many plants whose leaf, seed, fruit, flower, and peel extracts have been used for the green synthesis of ZnO nanoparticles[15,16]. Ginger (Zingiber officinale) is used as a medicinal plant known for its rich phytochemical composition, anti-inflammatory, antimicrobial, antioxidant, antidiabetic, anticancer activities and therapeutic properties. The rhizome of ginger contains biologically active compounds such as gingerols, shogaols, flavonoids, and polyphenols that exhibit strong antioxidant and reducing capabilities[17]. Due to the presence of such phytochemicals, ginger extract can be used in the synthesis of ZnO nanoparticles. Ginger is not only used as a reducing agent, but the organic molecules present in the extract can also stabilize nanoparticles and influence their morphology and size distribution. During the biosynthesis process, the phytochemicals present in ginger extract interact with zinc precursor salts, facilitating nucleation and growth of ZnO nanoparticles. Besides these, biomolecules may also function as capping agents, preventing agglomeration and improving nanoparticle stability[18] As a result, ZnO nanoparticles synthesized through plant extracts often demonstrate enhanced biological activity and improved environmental compatibility compared with those produced by conventional chemical routes. The present study focuses on the green synthesis of zinc oxide nanoparticles using ginger extract as a natural reducing and stabilizing agent. This method offers a simple, eco-friendly, and cost-effective approach for nanoparticle production while avoiding the use of toxic chemicals and evaluates their physicochemical properties.

II. LITERATURE REVIEW

Maind R. et al. reported an eco-friendly biomimetic synthesis of ZnO nanoparticles using leaf extracts of Cheilocostus speciosus and Gardenia gummifera, where plant phytochemicals acted as reducing and stabilizing agents. The nanoparticles possessed a hexagonal wurtzite structure with nanoscale crystallite sizes approximately 22–25 nm and spherical or conical morphology, confirmed through XRD, FTIR, UV–Vis, XPS, SEM, and TEM analyses. Optical studies showed size-dependent band gaps of the order of 3.07 and 2.74 eV, while biological evaluations demonstrated significant cytotoxicity against lung cancer cells along with strong antibacterial, antifungal, and antioxidant activities. [19]. Al-darwesh M.Y. et al. presented a comprehensive review on plant extract mediated green synthesis of ZnO nanoparticles, emphasizing the role of phytochemicals as reducing and stabilizing agents. The study correlates synthesis parameters with nanoparticle size, morphology, crystallinity, and surface properties, highlighting improved biocompatibility and reduced toxicity compared to chemically synthesized ZnO NPs. It summarizes extensive biomedical applications, including antibacterial, antifungal, antioxidant, anti-inflammatory, anticancer, wound healing, drug delivery, and antiviral activities. The review also discusses characterization techniques, synthesis mechanisms, and current challenges in large-scale production and clinical translation [20]. Monica S. et al. synthesized ZnO nanoparticles using aqueous bulb extract of Eleutherine bulbosa, where plant phytochemicals acted as reducing and capping agents. The ZnO NPs exhibited a crystalline hexagonal wurtzite structure with 27 nm crystallite size and flake-like/spherical morphology, showing good thermal stability and an optical absorption peak at 360 nm. Biologically, the nanoparticles demonstrated strong antioxidant activity and potent anticancer effects against breast cancer cells , and effective photocatalytic degradation of about 80% of methylene blue, indicating multifunctional biomedical and environmental potential[21] Vamsi Krishna B.V. et al. presented a comparative review on green synthesis of ZnO nanoparticles using five medicinal leaf extracts (Moringa oleifera, Azadirachta indica, Ocimum sanctum, Hibiscus spp., Citrus sinensis), outlining standardized synthesis protocols and phytochemical roles in reduction and capping. The biosynthesized ZnO NPs consistently exhibited

hexagonal wurtzite structure, UV absorption in the 320–380 nm range, Zn–O FTIR bands (400–600 cm^{-1}), and varied morphologies depending on plant extract chemistry. The review correlates physicochemical properties with enhanced antibacterial and antioxidant performance, highlighting the influence of plant-derived capping agents on nanoparticle bioactivity and reproducibility [22]. Ramesh M. et al. reported the green synthesis of ZnO nanoparticles using leaf extract of Pelargonium odoratissimum, where plant phytochemicals functioned as reducing, stabilizing, and capping agents. The ZnO NPs showed a crystalline hexagonal wurtzite structure with nanoscale particle size, characteristic UV–Vis absorption near 370 nm, Zn–O vibrational bands in FTIR, and predominantly spherical morphology confirmed by SEM/TEM analyses. The biosynthesized nanoparticles exhibited notable antibacterial activity against both Gram-positive and Gram-negative bacteria along with significant antioxidant potential, indicating suitability for biomedical and antimicrobial applications [23]. Suresh D. et al. described the green synthesis of ZnO nanoparticles using aqueous leaf extract of Delonix elata, where phytochemicals served as natural reducing and stabilizing agents. The nanoparticles showed strong antibacterial activity against common pathogenic strains along with significant antioxidant potential, highlighting their applicability in biomedical and antimicrobial fields [24]. Fakhari S. et al. reported the green synthesis of ZnO

nanoparticles using Myristica fragrans (nutmeg) seed extract, where bioactive phytochemicals acted as natural reducing and stabilizing agents. The ZnO NPs displayed a crystalline hexagonal wurtzite structure with nanoscale particle size, characteristic UV–Vis absorption in the near-UV region,. The biosynthesized nanoparticles exhibited significant antibacterial activity and notable antioxidant properties, demonstrating the potential of spice-derived phytochemicals in eco-friendly nanomaterial production [25]. Al-Salhi M.S. et al. reported the green synthesis of ZnO nanoparticles using Limonium pruinosum (sea lavender) extract, where plant phytochemicals facilitated reduction and stabilization during nanoparticle formation. The ZnO NPs exhibited a hexagonal wurtzite crystalline structure, nanoscale particle size, characteristic UV absorption in the near-UV region, and Zn–O functional vibrations in FTIR spectra, with morphology confirmed through electron microscopy. The biosynthesized nanoparticles demonstrated notable antibacterial and antioxidant activities, indicating their promise for ecofriendly biomedical and antimicrobial applications[26]. Monica S. et al. reported the green synthesis of ZnO nanoparticles using Cayratia pedata leaf extract, where plant phytochemicals acted as natural reducing and stabilizing agents. The biosynthesized nanoparticles demonstrated significant antibacterial and antioxidant activities, highlighting their potential for eco-friendly biomedical applications [27]. Hameed et al. synthesized ZnO nanoparticles using Spirogyra hyalina extract via a green, eco-friendly method, confirming hexagonal Wurtzite structure with particle sizes approximately 20 to 80 nm. The algal biomolecules acted as reducing and capping agents, ensuring stability and biocompatibility of the nanoparticles. The biosynthesized ZnO NPs exhibited strong antibacterial activity against Gram positive and Gram negative bacteria and showed enhanced antioxidant activity compared to crude algal extract[28]. Sharma et al. synthesized ZnO nanoparticles using Thymus vulgaris (thyme) leaf extract via a green, ecofriendly route. The phytochemicals in thyme extract acted as reducing and stabilizing agents, preventing agglomeration and enhancing nanoparticle stability. The biosynthesized ZnO NPs showed improved physicochemical properties, suggesting potential applications in photocatalysis and antibacterial fields [29]. Hashemi et al. synthesized ZnO nanoparticles using Olea europaea (olive) leaf extract via a green, ecofriendly method, confirming hexagonal Wurtzite structure. The phytochemicals such as flavonoids, glycosides, proteins, and phenols in the leaf extract acted as reducing and capping agents, stabilizing the nanoparticles [30] Misbah Gul et al. reviewed ecofriendly green synthesis routes for ZnO nanoparticles using plant extracts, microorganisms, and biomolecules as natural reducing and stabilizing agents. The review emphasized that green synthesized ZnO NPs are cost effective, biocompatible, and promising for biomedical, environmental, and catalytic applications [31]. Brilianti et al.synthesized ZnO nanoparticles using Terminalia catappa (ketapang) leaf extract via a green sol gel route, confirming hexagonal Wurtzite structure with approximately 17.5 nm crystallite size through FTIR and XRD analyses. The biosynthesized ZnO NPs showed strong photocatalytic activity, achieving up to 87.91% degradation of methylene blue dye under UV light[32]. Swain et al. reviewed green synthesis of ZnO nanoparticles using various plant extracts and biological sources, highlighting environmentally friendly reduction and stabilization processes.Synthesized ZnO NPs were shown to possess enhanced biocompatibility and wide applications in antibacterial, photocatalytic, and biomedical fields[33]. Xu et al. reviewed green synthesis of ZnO nanoparticles using plant extracts, emphasizing sustainable, low cost methods . It covered key factors affecting morphology and size of ZnO NPs and explored their antibacterial mechanisms against pathogens. Synthesized ZnO NPs were highlighted for their strong antibacterial properties and potential use in antibacterial textiles and related applications [34]. Jatrana et al. synthesized ZnO nanoparticles using Mesua ferrea leaf extract confirming hexagonal Wurtzite structure with an average crystallite size of about 20 nm .The biosynthesized ZnO NPs exhibited strong antibacterial and antifungal activity, showing maximum inhibition zones of 1.5 cm against Pseudomonas aeruginosa and 2.0 cm against Aspergillus awamorii.[35] Yadav et al. synthesized ZnO nanoparticles using Evolvulus alsinoides plant extract producing crystalline ZnO with predominantly spherical morphology as confirmed by UV-Vis, FTIR, XRD, FESEM, and HRTEM analyses[36] Al-Saadi et al. synthesized ZnO nanoparticles using Salvadora persica (miswak) leaf or root extract confirming hexagonal Wurtzite structure with nanoscale particle dimensions, synthesized ZnO NPs exhibited notable antibacterial activity against common pathogenic bacteria[37]. Anik et al. synthesized ZnO nanoparticles using Justicia adhatoda leaf extract The biosynthesized ZnO NPs exhibited excellent sunlight driven photocatalytic activity for methylene blue degradation, demonstrating strong potential for wastewater remediation applications [38]. Anupriya et al. synthesized ZnO nanoparticles using Syzygium cumini fruit extract via a green, ecofriendly route, confirming a hexagonal wurtzite structure with nanoscale crystallite size through XRD, FTIR, SEM, and UV-Vis analyses. The phytochemicals in S. cumini extract acted as natural reducing and capping agents, ensuring nanoparticle stability and controlled growth. The biosynthesized ZnO NPs exhibited strong antibacterial activity against Propionibacterium acnes and Bacteroides fragilis, indicating their potential for biomedical applications [39]. Alahmdi et al. synthesized rod shaped ZnO nanoparticles using Clitoria ternatea flower extract through a green synthesis approach. The bioactive phytochemicals in the flower extract functioned as reducing and stabilizing agents, producing stable and well dispersed nanoparticles. The biosynthesized ZnO NPs showed significant antibacterial, antibiofilm, antioxidant activity, and dose dependent cytotoxicity against MCF-7 breast cancer cells via the intrinsic apoptotic pathway [40]. Abdelmigid et al. prepared ZnO nanoparticles using

pomegranate peel and solid coffee ground extracts. The plant waste phytochemicals acted as effective reducing and capping agents, yielding stable nanoparticles with controlled morphology. The green-synthesized ZnO NPs showed strong antibacterial activity against multiple pathogens and lower cytotoxicity toward Vero cells compared to chemically synthesized ZnO NPs. Malaiappan et al. synthesized ZnO nanoparticles using Catharanthus roseus extract The FTIR spectra confirmed the presence of plant-derived functional groups (O–H, C–O, C=C, N–O), indicating successful capping and stabilization of nanoparticles. The C. roseus-mediated ZnO nanoparticles exhibited strong antiinflammatory up to 89% and antioxidant activity, suggesting potential biomedical and therapeutic applications [41]. Chan et al. synthesized ZnO nanoparticles through a plant mediated green route, confirming nanoscale, hexagonal wurtzite structure using UV- Vis, XRD, FTIR, and electron microscopy [42]. Batra et al. prepared ZnO nanoparticles using a green synthesis approach The synthesized ZnO NPs exhibited significant antimicrobial and catalytic activity, suggesting usefulness in biomedical and wastewater treatment applications [43]. Verma et al. also used green synthesis[44]. Król et al. reviewed physical, chemical, and biological methods for synthesizing ZnO nanoparticles . They also reported that while ZnO NPs show selective antitumor activity, they may cause cytotoxic and genotoxic effects in some normal human cells, emphasizing the need for safer design and application [45]. Sangeetha et al developed an ecofriendly green synthesis method for ZnO nanoparticles using Aloe barbadensis Miller leaf extract, producing spherical nanoparticles with tunable size and optical properties [46]. Sharma et al. developed an ecofriendly green synthesis method for ZnO nanoparticles using Azadirachta indica (neem) leaf extract, producing crystalline nanoparticles with controlled morphology and size. The synthesized ZnO nanoparticles exhibited antimicrobial and functional properties suitable for biomedical and environmental applications [47]. Kumar et al. reported a green synthesis method for ZnO nanoparticles using orange peel extract, yielding nanoscale particles with defined crystalline structure and surface functional groups.

Phenolics and flavonoids in the extract acted as reducing and capping agents, enabling stable nanoparticle formation. The biosynthesized ZnO nanoparticles showed potential antimicrobial and catalytic applications, highlighting agro-waste based nanoparticle synthesis [48]. Singh et al. synthesized ZnO nanoparticles via a green route and evaluated their effects on Solanum lycopersicum germination and metabolism. Low concentrations of ZnO nanoparticles enhanced seed germination, growth, and biochemical parameters, whereas higher concentrations caused inhibitory effects. The study demonstrated concentration dependent physiological responses of plants to ZnO nanoparticles for agricultural applications [49]. Patil and Taranath synthesized silver and ZnO nanoparticles using Limonia acidissima leaf extract, producing spherical nanoparticles in the nanometer size range. The synthesized nanoparticles exhibited significant antibacterial activity, with silver nanoparticles showing higher efficacy than ZnO, indicating biomedical and food packaging potential [50]. Karthik et al. developed a green synthesis approach for ZnO nanoparticles using plantain peel extract, producing nanoscale particles with defined crystalline structure. The synthesized ZnO nanoparticles exhibited potential antimicrobial and catalytic applications, demonstrating the valorization of agro waste resources [51]. Geetha et al. reported synthesis of ZnO nanoparticles using Euphorbia Jatropha latex, yielding hexagonal crystalline nanoparticles with size controlled by latex concentration. The synthesized nanoparticles exhibited promising photoluminescence and optoelectronic properties for multifunctional applications [52]. Muthukathija et al. synthesized ZnO nanoparticles via a green route using Pisonia alba leaf extract, producing hexagonal crystalline nanoparticles with an average size of about 48 nm. Phytochemicals such as phenolics and proteins acted as reducing and capping agents during nanoparticle formation. The biosynthesized ZnO nanoparticles demonstrated significant antibacterial activity and potential applications in biomedical and packaging fields [53].

III. EXPERIMENTAL

3.1 MATERIALS AND REAGENTS

All chemical reagents, including Sodium Hydroxide (NaOH) and zinc nitrate, were of analytical grade and used without further purification. Fresh ginger rhizomes were procured from a local market. Deionized (DI) water was used throughout the synthesis and washing processes to ensure the absence of ionic impurities.

3.2 PREPARATION OF AQUEOUS GINGER EXTRACT

The ginger piece was washed multiple times with distilled water to remove soil and debris, followed by surface drying. The ginger was finely chopped and crushed to increase the surface area for extraction. Approximately 20 g of the processed ginger was boiled in 100 mL of deionized water at 80°C for 30 minutes. During this process, the bioactive phytochemicals such as gingerols and shogaols, which act as natural reducing and capping agents, were leached into the aqueous phase. The extract was cooled to room temperature and filtered using Whatman No. 1 filter paper to obtain a clear broth, which was stored at 4°C for the synthesis stage.

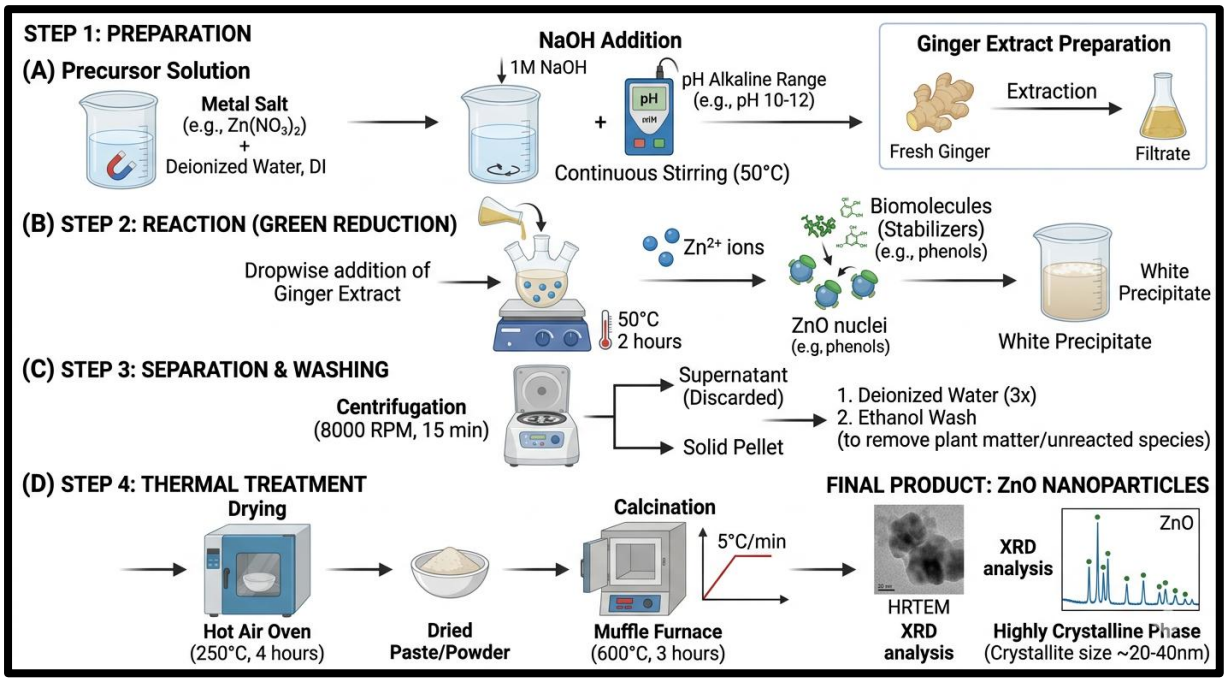

Figure 1. Experimental workflow for the green synthesis of ZnO nanoparticles using ginger extract, detailing the precursor preparation, bio-mediated reaction, purification, and two-stage thermal treatment.

3.3 GREEN SYNTHESIS OF ZNO NANOPARTICLES

The synthesis was carried out via a modified precipitation method. A precursor solution was prepared by dissolving the metal salt in deionized water. The pH of the solution was monitored and adjusted to an alkaline range using a 1M NaOH solution. The prepared ginger extract was added dropwise to the precursor solution under continuous magnetic stirring at a controlled temperature of 50°C. The reaction was maintained for 2 hours until a visible change in color and the formation of a white precipitate was observed. The ginger extract facilitates the stabilization of the particles, preventing excessive agglomeration during the nucleation phase.The resulting colloidal suspension was subjected to high-speed centrifugation at 8,000 RPM for 15 minutes to separate the solid phase from the liquid supernatant. The obtained pellet was washed three times with deionized water followed by an ethanol wash to remove any residual plant matter or unreacted inorganic species. This purification step is critical for ensuring the high phase purity required for XRD analysis. The recovered thick paste (precipitate) was transferred to a porcelain crucible and placed in a hot air oven at 250°C for 4 hours to remove physically adsorbed water. To achieve the final crystalline oxide phase, the dried powder was subjected to calcination in a muffle furnace. The temperature was increased at a heating rate of 5°C/min until it reached 600°C, where it was held for 3 hours. This high-temperature treatment ensures the complete conversion of hydroxides into stable oxide nanoparticles.

IV. RESULTS AND DISCUSSIONS

4.1 X-RAY DIFFRACTION (XRD) SPECTROSCOPY

The crystalline structure and phase purity of the green-synthesized Zinc Oxide nanoparticles (ZnO NPs) were investigated using X-ray diffraction analysis. Figure [2] illustrates the XRD pattern of the sample synthesized using Zingiber officinale (ginger) extract and calcined at 600°C.

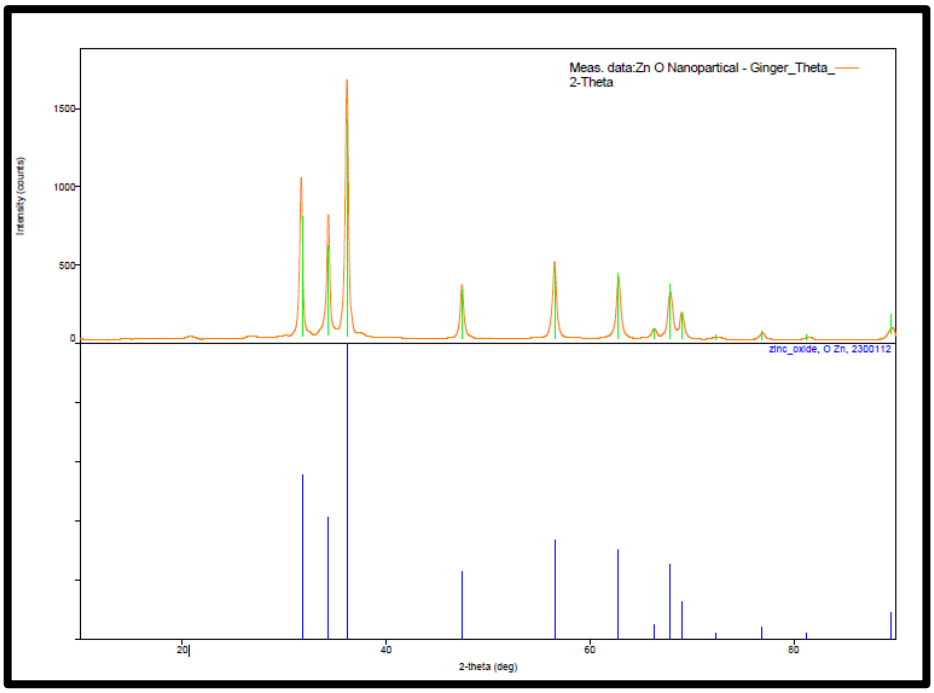

Figure 2. X-ray diffraction (XRD) pattern of green-synthesized ZnO nanoparticles using Zingiber officinale extract compared with the standard reference pattern.

The diffraction pattern exhibits prominent peaks at 2θvalues of approximately 31.77°, 34.42°, 36.25°, 47.54°, 56.60°, 62.86°, 67.94°, and 69.06°. These peaks correspond to the crystalline planes of (100), (002), (101), (102), (110), (103), (112), and (201), respectively. All observed reflection peaks are in excellent agreement with the standard JCPDS data (Card No. 36-1451), confirming the formation of a hexagonal wurtzite structure with a space group of P63mc.The absence of any additional peaks related to Zn(OH)2, metallic zinc, or organic residues from the ginger extract indicates that the 600°C calcination process was sufficient to achieve complete thermal decomposition and phase transformation. The high intensity and narrow Full Width at Half Maximum (FWHM) of the (101) peak suggest that the bio-mediated synthesis yielded nanoparticles with a high degree of crystallinity. The ginger extract served as an effective capping and stabilizing agent, facilitating controlled nucleation which is reflected in the well-defined Bragg reflections. The average crystallite size of the ZnO NPs was estimated using the Debye-Scherrer equation. The calculated average crystallite size of the order of 20-50 nm indicates the formation of particles in the nanometer range, consistent with the stabilization provided by the phytochemicals present in the ginger extract.

4.2 MORPHOLOGICAL ANALYSIS (FESEM):

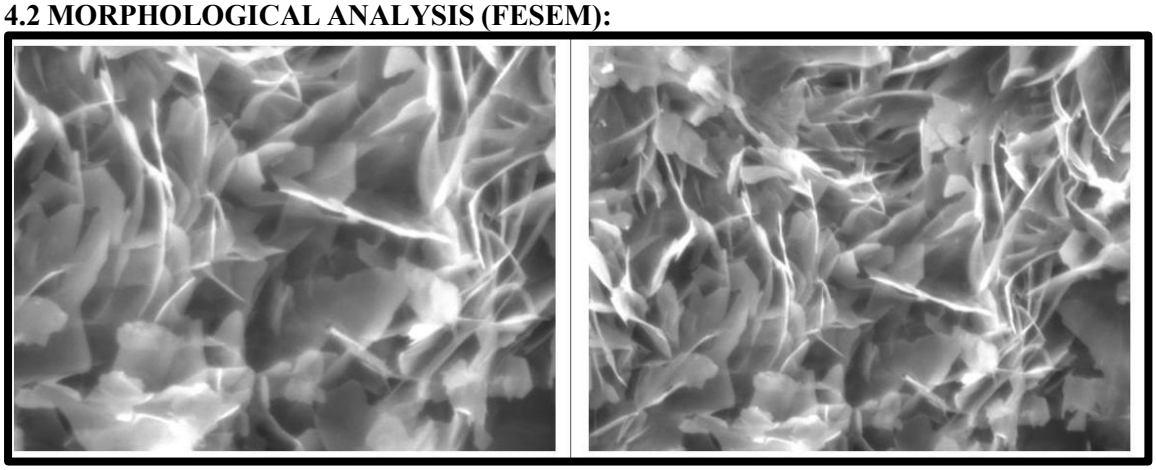

Figure 3. FESEM micrographs of ZnO nanoflakes synthesized using ginger extract at two different magnifications, showing the interconnected 2D sheet-like architecture

The surface morphology and structural orientation of the green synthesized ZnO nanoparticles were examined using Field Emission Scanning Electron Microscopy (FESEM), as shown in figure 3 .The micrographs reveal a highly uniform and distinct 2D nanoflake-like morphology. The ZnO nanostructures consist of thin, interconnected flakes with sharp edges, creating a porous, flower-like hierarchical arrangement. This high surface area morphology is typical for ZnO synthesized via the precipitation method where ginger extract acts as a template-directing agent. The formation of these nanoflakes suggests a preferential growth along the non-polar planes, likely influenced by the capping action of phytochemicals present in the ginger extract. These biomolecules selectively adhere to specific crystal facets, inhibiting vertical growth and promoting lateral expansion into sheets. The random orientation and interlacing of the flakes create a network of voids and pores. This architecture is highly advantageous for applications in photocatalysis and gas sensing, as it provides a larger active surface area for molecular interaction. Despite the dense packing, the individual flake boundaries remain clearly visible, indicating that the green synthesis route successfully prevented excessive fused agglomeration during the 600°C calcination process.

4.3 PROPOSED GROWTH MECHANISM: FROM BIO-REDUCTION TO NANOFLAKES

The formation of the 2D nanoflake morphology, as observed in the FESEM micrographs, is deeply influenced by the selective capping action of the phytochemicals present in the Zingiber officinale (ginger) extract. The transition from a precursor solution to the final crystalline oxide follows a multi-step growth inhibition process. Zinc oxide is a polar crystal. During the nucleation phase, bioactive compounds in ginger (specifically gingerols and shogaols) possess functional groups such as hydroxyl (-OH) and carbonyl (C=O) that act as "capping agents." These molecules preferentially adsorb onto the high energy polar (0001) facets of the ZnO nuclei. By masking the polar facets, the ginger extract inhibits growth along the c-axis (vertical growth). This forces the crystal to grow laterally along the nonpolar (1010) and (1120) planes, resulting in the expansion of the crystals into thin, two-dimensional nanoflakes or nanosheets. As the reaction progresses at 50°C, these independent nanoflakes begin to interlock and self-assemble into the porous, interconnected network seen in the FESEM images. The high speed centrifugation and subsequent 600°C calcination serve to stabilize this architecture, removing the organic ginger template while preserving the 2D structural integrity. The interlaced arrangement of the flakes reduces the overall surface Gibbs free energy of the system, preventing the flakes from collapsing into large, dense agglomerates and maintaining a high surface-to-volume ratio.

V. CONCLUSION

In this study, a sustainable and eco-friendly green synthesis route was successfully employed to fabricate high-purity ZnO nanoparticles using Zingiber officinale (ginger) extract as a natural stabilizing agent.

The following key findings were established. XRD analysis confirmed the formation of a single-phase hexagonal wurtzite structure, indexed to JCPDS Card No. 36-1451. The high intensity of the Bragg reflections and the absence of impurity peaks demonstrated that the 600°C calcination process successfully achieved high phase purity and superior crystallinity.FESEM micrographs revealed a distinct 2D nanoflake architecture. The transition from typical spherical particles to an interconnected flake-like morphology is attributed to the selective capping of polar crystal facets by ginger-derived phytochemicals (gingerols and shogaols), which promoted anisotropic lateral growth.The modified precipitation method proved to be an efficient "bottom-up" approach, where the ginger extract acted as a template to prevent excessive agglomeration while maintaining a high surface-area-to-volume ratio.The synthesized ZnO nanoflakes exhibit promising structural and morphological characteristics. Their porous, hierarchical 2D network makes them excellent candidates for future applications in photocatalytic degradation, antimicrobial coatings, or high-performance gas sensors. The green chemistry approach utilized here offers a cost-effective and non-toxic alternative to conventional chemical synthesis methods, aligning with the global transition toward sustainable nanotechnology.

VI. Future Scope

The successful green synthesis of ZnO nanoflakes using ginger extract opens several promising avenues for future research and development. Due to the high surface to volume ratio of the observed 2D nanoflake architecture, future studies should evaluate the photocatalytic efficiency of these nanostructures in the degradation of organic pollutants, such as methylene blue or methyl orange dyes, under UV and visible light irradiation. Given the nontoxic nature of the ginge mediated synthesis, the biocompatibility of these ZnO nanoflakes can be tested against various bacterial strains and cancer cell lines to explore their potential in targeted drug delivery and antimicrobial coatings. The porous, interconnected network of nanoflakes is ideal for gas sensing applications. Future work could investigate the sensitivity and selectivity of these ZnO-based sensors toward hazardous gases like NO2, CO, or volatile organic compounds (VOCs) at different operating temperatures. Further research is required to analyze the effect of varying the ginger extract concentration and calcination temperatures (e.g., 400°C

to 800°C) on the crystal size and bandgap energy to fine tune the optical properties for optoelectronic devices.The unique 2D morphology suggests potential utility in energy storage, specifically as electrode materials for supercapacitors or lithium-ion batteries, where high surface area and structural stability are critical for charge-discharge efficiency. Moving beyond laboratory scale precipitation, future studies should focus on industrial scale production of high purity ZnO nanostructures.

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