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Green Synthesis of Bio-ZnO Nanoparticles via Aloe Vera Powder-Assisted Sol–Gel Method with Antibacterial Properties

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ABSTRACT

This study presents the green synthesis of zinc oxide nanoparticles (bio-ZnO NPs) using Aloe vera powder as a natural reducing and stabilizing agent through the sol–gel method. The use of Aloe vera powder eliminates the need for toxic chemicals and simplifies the synthesis process, thereby promoting sustainability in nanomaterial fabrication. The obtained bio-ZnO NPs were characterized by UV–Vis spectroscopy, FTIR, XRD, FESEM, TEM, and EDX analyses. Results confirmed the successful formation of wurtzite hexagonal ZnO with uniform nanoscale morphology. The optical band gap was found to decrease slightly with increasing Aloe vera concentration, indicating the influence of phytochemical compounds on crystal growth and electronic structure. Antibacterial activity against Escherichia coli demonstrated significant inhibition zones, suggesting strong biological functionality of the synthesized nanoparticles. This work highlights the effectiveness of Aloe vera powder as a sustainable and low-cost precursor for producing high-quality ZnO nanoparticles with potential applications in environmental and antimicrobial technologies.

Keywords: Bio-ZnO NPs, Aloe vera powder, Green synthesis, Sol-gel method.

1. INTRODUCTION

In line with the growing technological advancements, the application of nanomaterial technology is gaining increasing emphasis today. Nanomaterials are increasingly gaining a high reputation for their applications in engineering, healthcare, the military, the food industry, and other sectors [1]. Their unique properties arise from their nanoscale dimensions (1–100 nm), which impart distinctive chemical reactivity and superior physical, optical, thermal, and mechanical properties compared with those of bulk materials. In recent years, the green synthesis of metal oxide nanoparticles has attracted considerable research attention. Biosynthetic routes have been successfully applied in the preparation of various oxides, including aluminium oxide [2], silver [3], Zinc oxide [4–6], titanium oxide[7], silica [8] and inorganic compound zeolite [9], Such green approaches offer notable advantages: they are environmentally friendly, low in toxicity, cost-effective, and capable of producing stable compounds with reduced risk compared to conventional chemical or physical synthesis techniques [10]. ZnO is a metal oxide widely used in

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numerous commercial applications across industries, including photocatalysts [11], transducers [12], ethanol gas sensors, and pharmaceuticals [13]. ZnO exhibits remarkable properties, including a wide band gap (3.34 eV), high exciton binding energy, environmental safety, and strong UV absorption, making it highly suitable for photocatalytic and optoelectronic applications [14]. Additionally, ZnO possesses intrinsic antibacterial properties, making it a promising material for antimicrobial coatings and medical uses [6,14]. Traditionally, ZnO nanoparticles have been synthesized through physical, chemical, and biological routes [10]. However, green synthesis has recently gained prominence as a sustainable alternative that employs biological sources such as algae, bacteria, fungi, and plants. Among these, plant-mediated synthesis is particularly attractive due to its simplicity, safety, and eco-friendly nature.

Aloe vera (Aloe barbadensis Miller), a perennial succulent plant belonging to the family *Xanthorrhoeaceae*, is extensively used in the pharmaceutical, food, and cosmetics industries [11,12]. In addition, the production of *Aloe vera* extract is one of the largest industries in the world, with estimated spending of 125 million US dollars and 110 billion US dollars, respectively, for Aloe raw materials and products [1]. The plant contains rich phytochemicals, including polysaccharides, flavonoids, and phenolic compounds, which enable it to act as a natural reducing and capping agent during nanoparticle synthesis [4]. Consequently, Aloe vera has been effectively used for the biosynthesis of various metal oxides, including silver [15], indium oxide [16], titanium oxide [17, 18], gold [19], and tin oxide [20]. Although numerous studies have explored *Aloe vera*-mediated synthesis, the use of Aloe vera powder for the biosynthesis of ZnO nanoparticles remains limited. Powder-based synthesis offers several advantages, including ease of storage, consistent phytochemical concentrations, and scalability for industrial applications. Therefore, this study aims to develop a simple, environmentally friendly sol-gel approach for synthesizing bio-ZnO nanoparticles from *Aloe vera* powder. The synthesized nanoparticles were characterized to determine their structural, morphological, and optical properties, and their antibacterial performance was evaluated.

To the best of our knowledge, this study is the first report of the sol–gel biosynthesis of ZnO nanoparticles using Aloe vera extract powder, providing a promising route for sustainable nanomaterial production. The main novel contributions of this work can be summarized as follows. First, the study demonstrates the use of Aloe vera extract powder as a stable, reproducible bio-precursor for the green synthesis of ZnO nanoparticles, offering improved storage stability and a more consistent phytochemical composition compared to conventional fresh plant extracts. Second, a simplified green sol–gel synthesis approach is introduced to produce bio-ZnO nanoparticles without the use of additional toxic chemical reducing or stabilizing agents, thereby enhancing the environmental sustainability of the synthesis process. Third, the antibacterial performance of the synthesized bio-ZnO nanoparticles is compared with that of commercial ZnO nanoparticles, providing clear evidence of the biosynthesized material's enhanced antibacterial activity against *Escherichia coli*. Overall, these findings present a sustainable and scalable strategy for producing ZnO nanoparticles with promising applications in antimicrobial and environmental technologies.

2. MATERIAL AND METHODS

2.1 Materials

Zinc nitrate (99% purity) was used as the precursor for ZnO NPs synthesis due to its high solubility and ability to form uniform Zn^{2+} ions in solution. Aloe vera extract powder supplied by Emory Chemical (USA) was employed as a natural reducing and stabilizing agent. The powdered form was selected over fresh extract because it offers improved storage stability, a more consistent phytochemical composition, and better reproducibility of the biosynthesis process. Acetone purchased from QReC Instrument (Malaysia) was used as the solvent because of its rapid evaporation and compatibility with the sol–gel process, which facilitates gel formation during nanoparticle synthesis.

2.2 Synthesis of Bio-ZnO NPs via Aloe vera powder

In this study, zinc nitrate (99% purity) was used as the precursor material for the synthesis of bio-ZnO NPs. Initially, 5 g of zinc nitrate was dissolved in 20 mL of acetone under continuous magnetic stirring to ensure complete dissolution and homogeneous precursor distribution. Subsequently, 1 g of Aloe vera extract powder was added to the solution while stirring vigorously at 900 rpm. The mixture was maintained at 60 °C for 2–3 h to promote interaction between Zn^{2+} ions and the phytochemicals present in Aloe vera, which act as natural reducing and capping agents during nanoparticle formation. During this process, the solution gradually transformed into a pale lemon-colored gel, indicating the formation of a ZnO precursor network via sol–gel. The resulting gel was transferred into a ceramic crucible and calcined at 400 °C for 2 h in a furnace to remove residual organic compounds and promote crystallization of ZnO nanoparticles. The obtained white powder was ground using a mortar and pestle and sieved to obtain finer particles for further characterization. This synthesis route follows green chemistry principles by using plant-derived biomolecules as reducing and stabilizing agents, thereby avoiding hazardous chemical additives commonly used in conventional nanoparticle synthesis.

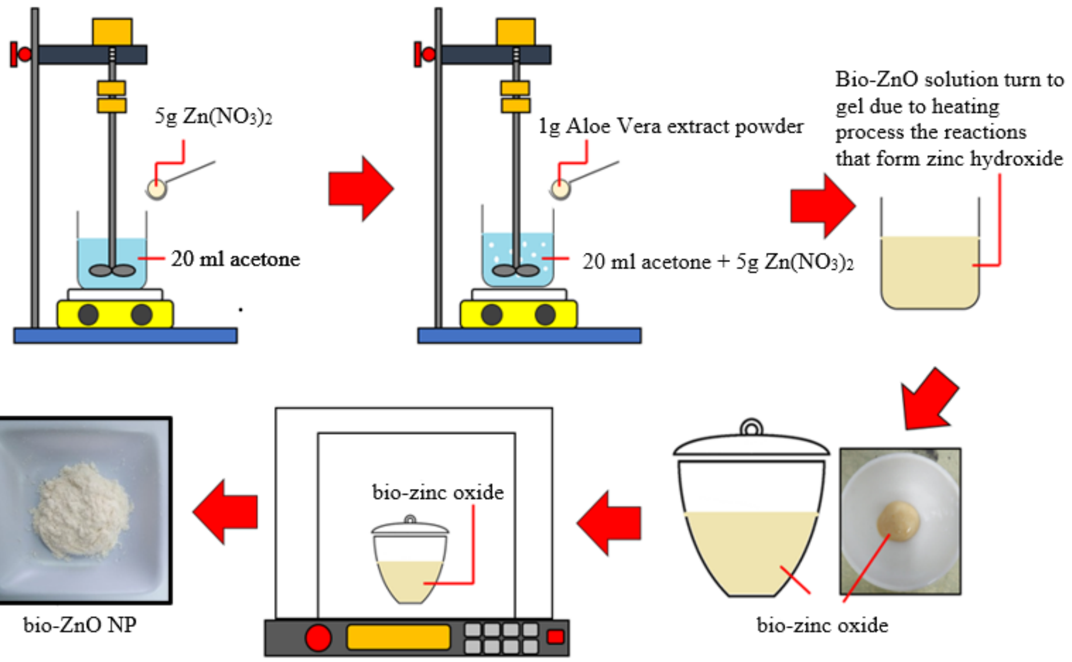

Figure 1: Green synthesis process of bio-ZnO NPs through aloe vera-mediated sol-gel.

2.3 Characterization of Bio-ZnO NPs

Multiple characterization techniques were employed to comprehensively evaluate the structural, optical, and morphological properties of the synthesized Bio-ZnO NPs. Prior to detailed characterization, the aqueous suspension of Bio-ZnO NPs was initially analyzed using UV–visible absorption spectroscopy (Shimadzu UV-2450). The crystalline structure and phase purity of the synthesized Bio-ZnO NPs were examined by X-ray diffraction (XRD) using a PANalytical diffractometer with Cu Kα radiation (λ = 0.1540 nm), operated at a scanning rate of 0.02° s^{-1} over a 2θ range of 30°–80°. Functional groups present on the surface of the Bio-ZnO NPs were identified by Fourier Transform Infrared (FTIR) spectroscopy (PerkinElmer 100). The morphology, particle size, and shape of the nanoparticles were investigated using Field-Emission Scanning Electron Microscopy (FESEM; JEOL, USA) and Transmission Electron Microscopy

(TEM). Elemental composition was qualitatively assessed through Energy Dispersive X-ray (EDX) analysis. In addition, the antibacterial activity of the Bio-ZnO NPs was evaluated.

3. RESULTS AND DISCUSSION

3.1 Optical studies of Bio-ZnO NP

Figure 2 presents the UV–vis spectroscopy spectrum of the synthesized Bio-ZnO NPs. The UV–vis absorption analysis was employed to confirm the successful formation and optical properties of the Bio-ZnO NPs, with the nanoparticles dispersed in distilled water and distilled water used as the reference medium [21]. The use of this simple dispersion approach demonstrates the effectiveness of the synthesis method in producing stable, well-dispersed semiconductor ZnO nanoparticles. As observed in the spectrum, a pronounced excitonic absorption peak appears at approximately 370 nm, which corresponds to the intrinsic band-gap absorption of ZnO. This absorption arises from electronic transitions from the valence band to the conduction band, specifically involving O2p–Zn3d orbitals [7]. The presence of this characteristic absorption peak confirms the formation of ZnO nanoparticles with a wide band gap and nanoscale characteristics. In addition, the slight broadening of the absorption peak suggests a distribution of particle sizes and the influence of Aloe vera–derived phytochemical capping agents, which contribute to nanoparticle stabilization and reduced agglomeration. The absorption behavior observed in this study is in good agreement with previously reported work on Aloe vera-mediated ZnO nanoparticle synthesis [17–20].

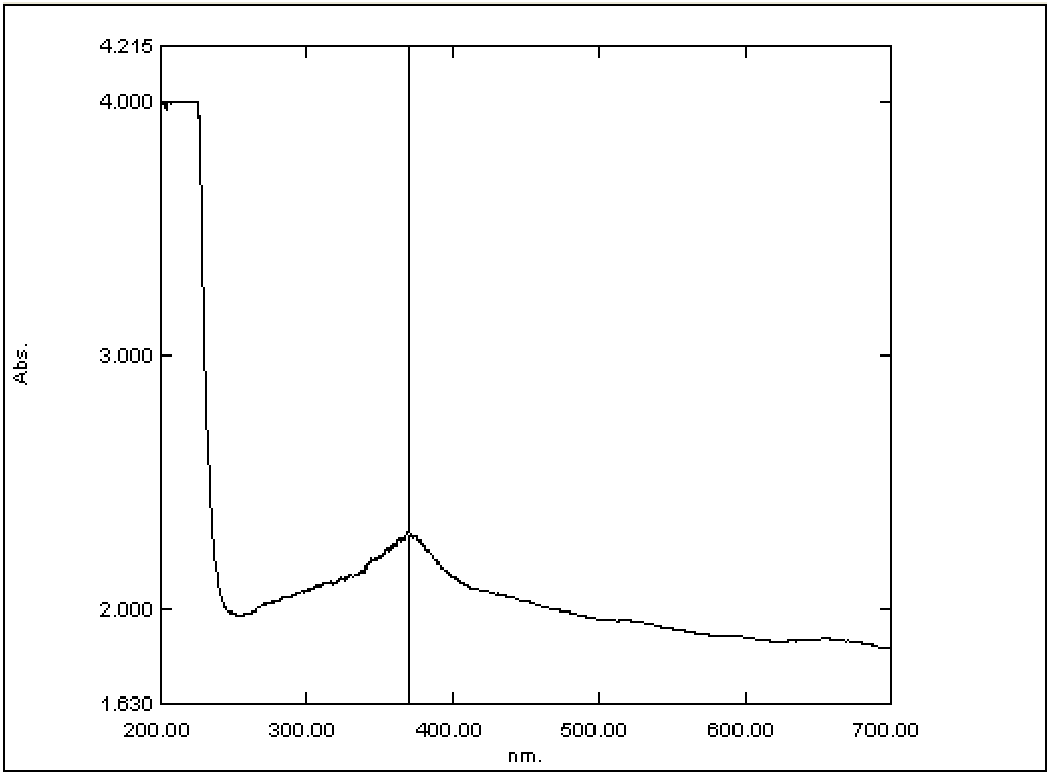

Figure 2: Uv-vis spectroscopy of synthesized Bio-ZnO NPs.

3.2 X-ray diffraction analysis (XRD)

The X-ray diffraction (XRD) patterns of Bio-ZnO NPs are presented in Figure 3. The analysis was performed using Cu Kα radiation (λ = 0.1540 nm) at a scanning rate of 0.02° s^{-1} over a 2θ range of 30°–80°. The diffraction peaks observed at 2θ values of 31.806°, 34.487°, 47.576°, 56.605°, 62.902°, 66.374°, 68.148°, 69.215°, 72.55°, and 77.076° correspond to the (011), (012), (110), (013), (020), (112), (021), (004), (022), (014), and (023) crystallographic planes of the hexagonal ZnO phase, respectively. These results are in good agreement with the standard data reported in the JCPDS card No. 36-1456 [22]. The presence of sharp, intense diffraction peaks indicates a highly crystalline structure, with crystallinity approaching 98%, as confirmed by deconvolution analysis (Figure 4). The absence of additional diffraction peaks suggests that all reducing agents were completely decomposed during synthesis and that no secondary crystalline phases were present. These findings confirm the successful formation of phase-pure ZnO nanoparticles. The average crystallite size of the Bio-ZnO NPs was estimated from the peak broadening of the XRD patterns using the Scherrer equation.

$$LC = \frac{180}{\pi} \cdot \frac{\kappa \cdot \lambda}{\cos\theta \cdot \sqrt{FWHM^2 - s^2}} \quad (1)$$

where π = 3.142, λ is the wavelength of Cu K_α radiation (1.5406 Å), κ is the Scherrer constant (0.89), s is the instrumental broadening (0), FWHM is the full-width at half-maximum of the (1 1 0) plane, and θ is the angle corresponding to the (1 1 0) plane. The FWHM and θ were taken from the deconvolution of XRD data. The crystallite size of bio-ZnO NPs was calculated based on Equation 1 at plane 110 of XRD. The estimated average particle size of the Bio-ZnO NPs was approximately 10-25 nm, which is generally similar to the trend observed in the FESEM, TEM images, and particle size distribution.

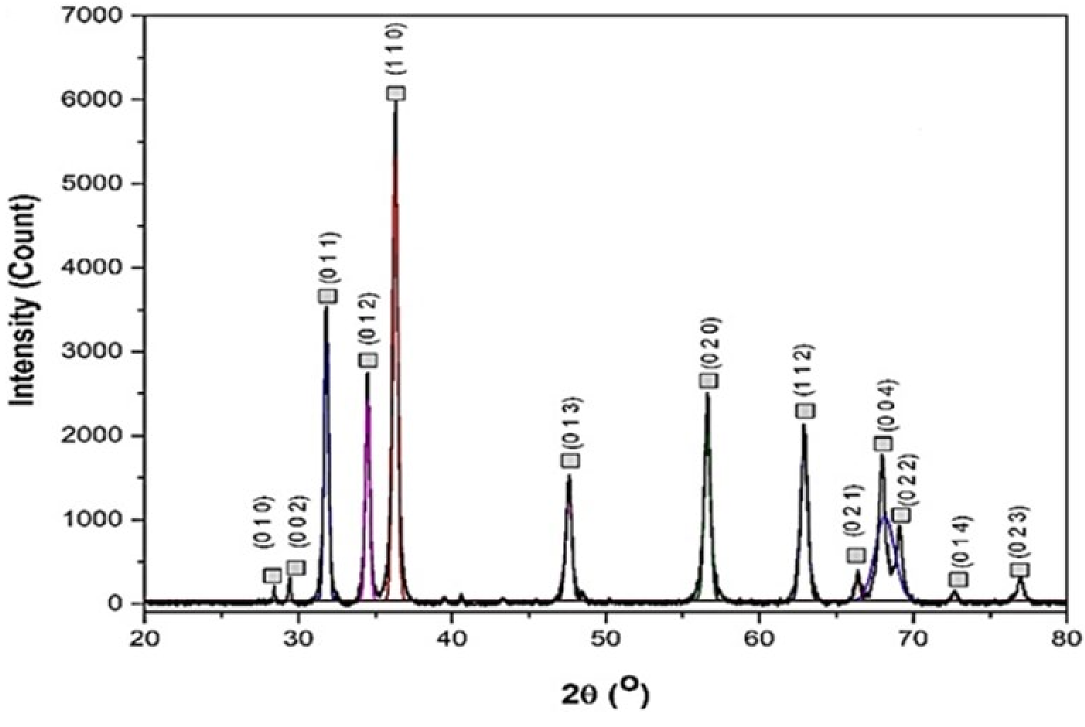

Figure 3: XRD pattern for Bio-ZnO NPs.

3.3 Fourier transform infrared spectroscopy (FTIR)

Figure 4 shows the FTIR spectra for (a) Aloe Vera powder and (b) bio-ZnO NPs. As shown in Figure 4 (a), Aloe Vera powder shows the broad infrared bands centered at 3267 $cm^{-1,}$ which is associated to the stretching of -OH groups, a carbohydrate monomer including mannose and uronic acid. This suggests the existence of carbohydrates in the powder [10]. Carbohydrates are essential organic compounds composed of carbon, hydrogen, and oxygen atoms, often found in plant tissues. The identification of carbohydrate monomers like mannose and uronic acid is notable, as these are fundamental building blocks within larger carbohydrate structures.

Mannose is a hexose sugar, and uronic acids are derived from aldohexoses that carry a terminal carboxylic acid group. Their presence hints at the polysaccharide composition of Aloe Vera, which may contribute to its unique properties. Overall, infrared spectroscopy provides valuable insights into the molecular composition of Aloe Vera powder, aiding in the understanding of its potential applications across industries such as cosmetics, pharmaceuticals, and healthcare. Meanwhile, C=O stretching at 1583 cm^{-1} illustrates the carbonyl groups in the aloe Vera samples. These carbonyl groups are likely associated with compounds such as organic acids, esters, or other molecules containing carbonyl functionalities, contributing to the overall chemical complexity and potential bioactive properties of Aloe Vera. The absorption peaks at 1313 cm-1 and 11074 cm-1 correspond to the asymmetrical and symmetrical -COO- stretching of carboxylate groups in aloe vera.

To be noted, the simultaneous presence of these peaks suggests the existence of molecules like organic acids or salts, indicating the potential presence of bioactive components contributing to the therapeutic and chemical complexity of Aloe Vera. The absorption peak at 1025 cm^{-1} corresponds to the C-O-C stretching of $-COCH_3$. It is interesting to note that the presence of methyl esters in the sample, potentially originating from compounds like fatty acids or other esterified components within the Aloe Vera, adds to the diverse array of molecules contributing to its chemical composition. This observation data is similar to that reported by G. Zhang et al.[23]. Meanwhile, the FTIR obtained from bio-ZnO NPs (Figure 4(b)) apparently shows an absorption band between 900 to 500 cm^{-1}. This clearly shows that the involvement of biomolecules in the reduction and capping agents from aloe vera powder is possibly due to a carborcyclic group compound that interacts with the zinc surface.

In addition, the FTIR absorption band at 1048 cm^{-1} corresponds to the C-O-C stretching vibration, which typically arises from the presence of surface-adsorbed or incorporated organic compounds. In this regard, this band is often associated with the interaction of bio-ZnO NPs with residual organic ligands from the synthesis process or with absorbed atmospheric species. The C-O-C stretching vibration indicates the presence of ether or ester functional groups, suggesting the attachment of organic molecules to the bio-ZnO NPs surface. This phenomenon can impact the surface properties, stability, and reactivity of bio-ZnO NP, making it significant for various applications, including catalysis and adsorption for heavy metal removal [23]. The FTIR absorption band at 1362 cm^{-1} in bio-ZnO NPs spectra corresponds to the C-O stretching vibration, indicating the presence of organic compounds or species with C-O bonds either adsorbed onto the bio-ZnO NP surface or interacting with the material. This band can arise from functional groups such as alcohols, ethers, or carbonyl compounds. The FTIR absorption band at 1633 cm^{-1} corresponds to the C=O stretching vibration, indicative of the presence of carbonyl groups within the material or adsorbed organic species. This band typically originates from carbonyl-containing compounds like ketones, aldehydes, or carboxylic acids. Herein, this band suggests interactions with organic molecules, potentially arising from surface adsorption or from the synthesis process itself. The analysis confirms that Aloe Vera biomolecules successfully capped the bio-ZnO nanoparticles, introducing organic functional groups, including C-O-C (ether/ester), C-O (hydroxyl/ether/carbonyl), C=O (carbonyl), and O-H (hydroxyl). These groups enhance the stability, adsorption capacity, and potential reactivity of bio-ZnO NPs, contributing significantly to their performance in antibacterial applications.

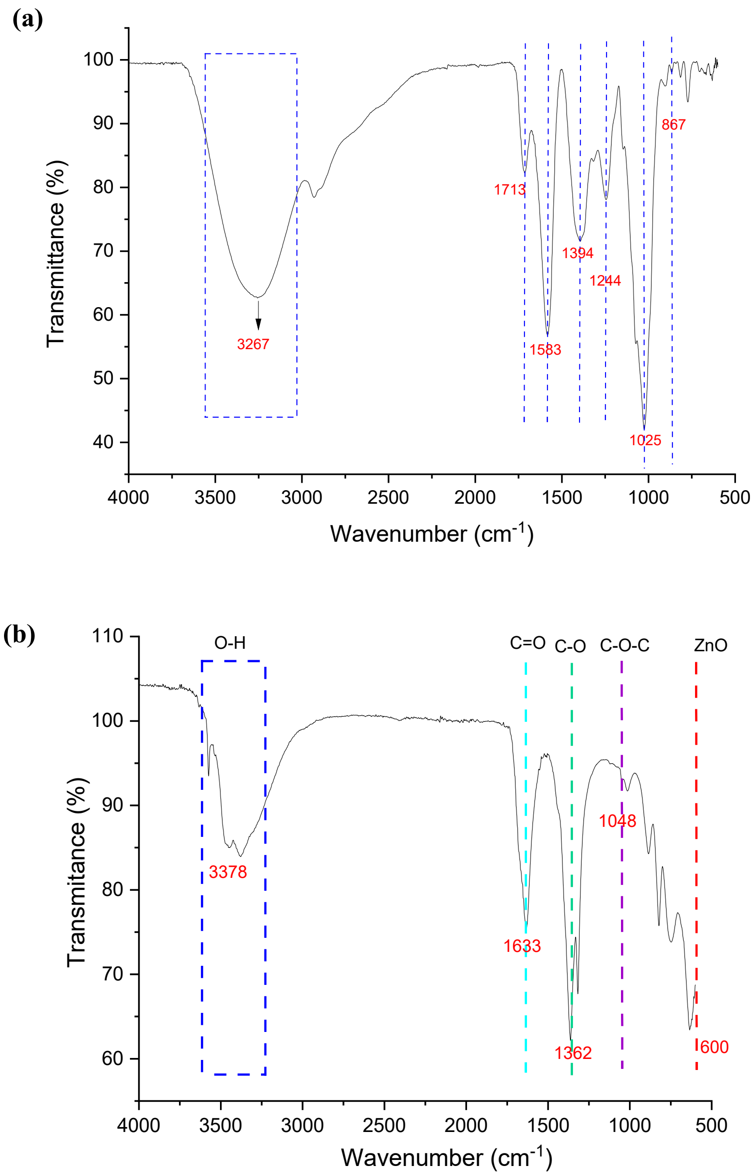

Figure 4: FTIR spectrum of (a) Aloe Barbadensis miller powder, (b) bio-ZnO NPs.

3.4 Morphology structure of Bio-ZnO NPs

Figure 5 illustrates the Field Emission Scanning Electron Microscopy (FESEM) images, Energy Dispersive X-ray (EDX) analysis, Transmission Electron Microscopy (TEM) images, and particle size distribution (PSD) of the synthesized materials used in this study. As depicted in Figure 5(a), the prepared bio-ZnO nanoparticles (NPs) exhibit a well-defined nanocrystal-like structure. The presence of such nanocrystalline morphology is particularly advantageous for antibacterial applications. The complex surface architecture and high surface area of the nanoparticles provide numerous active sites that facilitate interactions between the nanoparticles and bacterial cell membranes. These interactions may enhance antibacterial activity through mechanisms widely reported for ZnO nanomaterials, including membrane disruption, the generation of reactive oxygen species (ROS), and the release of Zn^{2+} ions [24]. Although these mechanisms were not directly investigated in the present study, previous studies have suggested that they play an important role in bacterial inactivation when ZnO nanoparticles interact with microbial cells.

The EDX spectrum presented in Figure 5(b) confirms the high purity of the synthesized bio-ZnO NPs, with no detectable impurities. High material purity is essential for antibacterial performance, as impurities can interfere with ROS generation and reduce antimicrobial efficacy. The TEM image shown in Figure 5(c) reveals that the bio-ZnO NPs possess a uniform spherical morphology with weak agglomeration. In addition, a thin capping layer surrounding the nanoparticles is clearly observed. The presence of capping agents provides valuable insight into the stabilization and functionalization of the bio-ZnO NPs. These capping agents, typically organic compounds derived from biological sources, form a protective shell around the ZnO cores [25]. This shell effectively prevents excessive agglomeration, enhances colloidal stability, and improves nanoparticle dispersion in aqueous media, which is crucial for ensuring consistent contact with bacterial cells. Moreover, the capping layer can facilitate stronger interactions between the nanoparticles and bacterial membranes, thereby enhancing antibacterial activity.

The particle size distribution shown in Figure 5(d) indicates that the bio-ZnO NPs have an average particle size of approximately 20 nm. At this nanoscale dimension, the bio-ZnO NPs exhibit a high surface area-to-volume ratio, enabling extensive interaction with bacterial cells. Smaller particle sizes are known to enhance antibacterial efficiency by increasing surface reactivity, promoting ROS production, and facilitating Zn^{2+} ion release. As a result, the bio-ZnO NPs with an average size of 20 nm demonstrate strong potential as effective antibacterial agents for inhibiting bacterial growth in various biomedical and environmental applications.

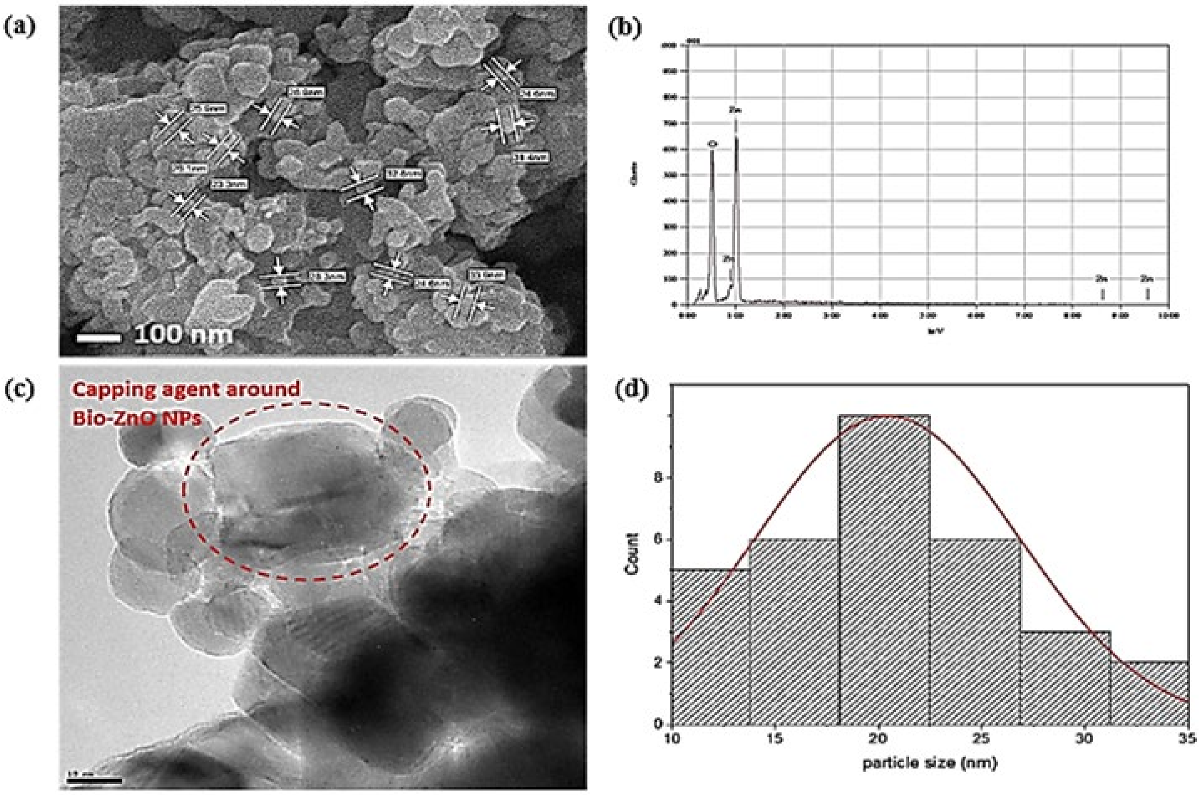

Figure 5: (a) FESEM image, (b) EDX analysis, (c) TEM image, and (d) PSD of Bio-ZnO NPs.

3.5 Antibacterial performance of Bio-ZnO NPs

Figure 6(a) and (b) present the antibacterial activity of Bio-ZnO NPs and commercial ZnO NPs against *Escherichia coli* following 24 hours of incubation, as evaluated using the inhibition zone method. The Bio-ZnO NPs exhibited a larger inhibition zone area of approximately 1.516 mm^2 compared to 1.074 mm^2 for commercial ZnO NPs (Table 3). This result indicates that Bio-ZnO NPs synthesized from Aloe vera extract powder exhibit enhanced antibacterial activity compared to their commercial counterparts. The improved antibacterial activity of Bio-ZnO NPs can be attributed to their smaller particle size and higher surface area, resulting from the biosynthesis process, which promotes closer contact between the nanoparticles and bacterial cells. Such interactions may facilitate antibacterial mechanisms commonly reported for ZnO-based nanomaterials, including the generation of reactive oxygen species (ROS) and the gradual release of Zn^{2+} ions at the nanoparticle bacteria interface [13,24]. These mechanisms have been reported in previous studies to induce oxidative stress and membrane destabilization in bacterial cells, ultimately leading to bacterial inactivation. Although these processes were not directly measured in the present study, the observed antibacterial activity is consistent with mechanisms previously reported for biosynthesized ZnO nanoparticles. In addition, the presence of Aloe vera-derived phytochemicals acting as capping agents may enhance nanoparticle dispersion and interaction with bacterial membranes, thereby further supporting antibacterial efficacy. These observations are consistent with previous studies demonstrating that Aloe vera mediated ZnO NPs exhibit effective antibacterial activity even at low concentrations [10,17].

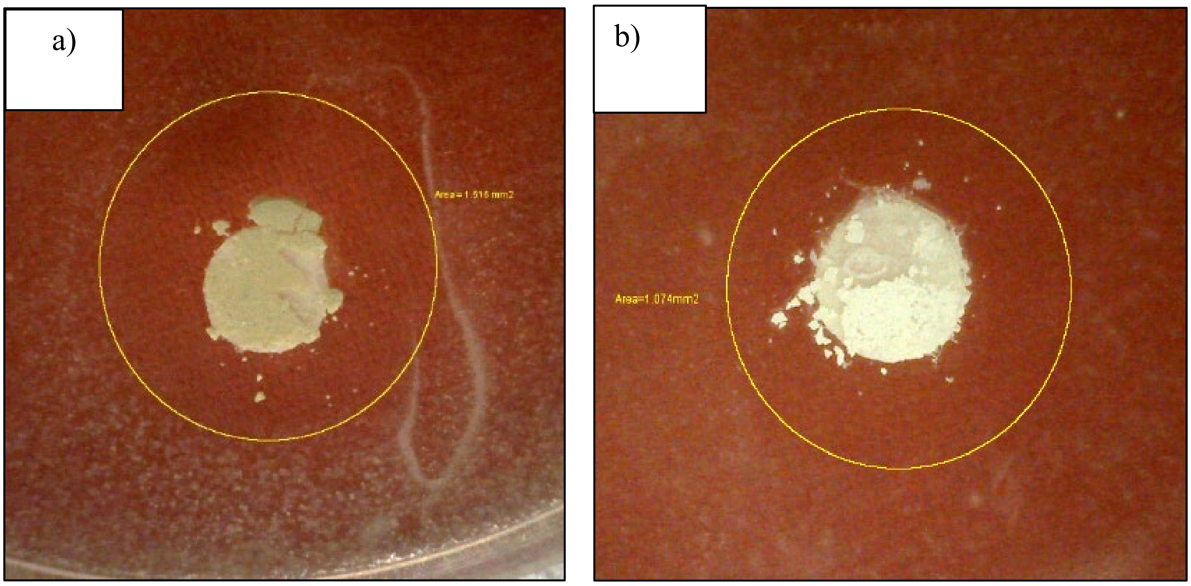

Figure 6: Inhibition zone: a) Bio-ZnO NPs and b) ZnO NPs with *E.coli.*

Table 3: Inhibition area data for Bio-ZnO and ZnO with *E.coli.*

Component	Inhibition area (mm^2)	% difference with commercial
ZnO NPs	1.074	71%
Bio-ZnO NPs	1.515	

4. CONCLUSION

In conclusion, Bio-ZnO nanoparticles (NPs) were successfully synthesized using Aloe vera extract powder via a sol-gel method, demonstrating a simple, cost-effective, and environmentally benign synthesis strategy. X-ray diffraction (XRD) analysis confirmed the formation of a well-crystallized hexagonal ZnO phase, with distinct preferential orientations at the (0 1 1), (0 1 2), (110), (0 1 3), (0 2 0), (1 1 2), (0 2 1), (0 0 4), (0 2 2), (0 1 4), and (0 2 3) planes. Morphological characterization by FESEM and TEM, together with particle size distribution analysis, verified the successful formation of uniformly nanosized particles in the range of 10–25 nm. Importantly, the synthesized Bio-ZnO NPs exhibited notable antibacterial activity against Escherichia coli, which can be attributed to their nanoscale dimensions, high surface reactivity, and the presence of Aloe vera-derived phytochemical capping agents. These characteristics likely promote effective nanoparticle-bacteria interactions and support antibacterial mechanisms commonly associated with ZnO nanomaterials.

Overall, this study introduces a novel and sustainable strategy for ZnO nanoparticle synthesis by using Aloe vera extract powder as an alternative bio-mediated precursor, replacing conventional fresh plant extracts and chemical stabilizers. The use of powdered Aloe vera not only enhances material stability, storage, and reproducibility but also simplifies the synthesis process while maintaining excellent antibacterial performance against *E. coli*. These findings highlight the strong potential of Aloe vera powder-mediated Bio-ZnO NPs for advanced applications in environmental remediation, biomedical coatings, and antimicrobial systems.

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