



Sustainable Green Synthesis of ZnO Nanoparticles using Syzygium Cumini Fruit Extract: Structural, Optical, and Antibacterial Investigations

R. Anupriya^a, V. Kalaiselvi^{b,*}, P. Yasotha^a, S. Gopi^c

^a Department of Physics, Navarasam Arts and Science College for Women, Arachalur, Erode, Tamil Nadu, India

^b Department of Internet of Things, Vellalar College for women, Thindal, Erode, Tamil Nadu, India.

^c Department of Physics, Sri Ramakrishna Mission Vidyalaya College of Arts and Science, Coimbatore, Tamil Nadu, India.

* Corresponding author Email: nk.arthi.kalai@gmail.com

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Abstract: An eco-friendly and biocompatible alternative to the conventional chemical and physical synthesis methods ZnO nanoparticles were synthesized using Syzygium cumini fruit extract through a simple and eco-friendly green synthesis route. The phase formation and purity of ZnO nanoparticles were identified by XRD analysis, showing distinct diffraction peaks corresponding to the hexagonal wurtzite structure of ZnO with high crystallinity and average crystallite size in the nanometer range. FTIR spectroscopy confirms the presence of hydroxyl, carbonyl, and amine groups, indicating that plant biomolecules are involved in nanoparticle stabilization. Further, the surface morphology of the synthesized ZnO nanoparticles was revealed by SEM analysis, which exhibited predominantly spherical to irregularly shaped nanoparticles with slight agglomeration due to the presence of plant-derived capping agents. UV-Visible spectral analysis showed a sharp absorption peak at around 310 nm, confirming the optical properties of ZnO nanoparticles with an estimated band gap of 2.8 eV, suggesting nanoscale dimensions and quantum confinement effects. Antibacterial studies show strong inhibitory effects of the synthesized ZnO nanoparticles against Gram-positive *Propionibacterium acnes* (*P. acnes*) and Gram-negative *Bacteroides fragilis* bacteria, which can thus be said to constitute evidence of their effective antibacterial potential. The synergistic action of ZnO nanoparticles and Syzygium cumini phytochemicals enhances ROS generation and disrupts bacterial cell integrity.

Keywords: Syzygium cumini fruit extract, ZnO nanoparticles, Sustainable Green Synthesis, SEM

1. Introduction

The term nanotechnology was first used in 1974 by Japanese scientist Norio Taniguchi, but its roots date back to 1959 [1]. It has emerged as the most recent, innovative, creative, and well-known area of research in modern science due to its distinctive qualities and the significant importance of nanoparticles. Nanoparticles widely used in the domains of electronics, optics, biology, and materials research. Their innovative solutions in various scientific domains have led to their surprising rise in prominence in recent years [2]. In the field of food science, advanced applications of nanotechnology are being developed, and it has become a crucial factor in food production, processing, storage, and quality control [3]. One of the metal oxide nanomaterials such as zinc oxide nanoparticles (ZnO-NPs), is a useful and versatile inorganic molecule because of its distinct physical and chemical properties. They have a wide range of

absorption spectrum, a high electrochemical coupling coefficient, good photostability, and high chemical stability [4]. A wide range of commercial additive products, such as ceramics, cement, plastics, glass, ointments, lubricants, adhesives, sealants, pigments, batteries, ferrites, fire retardants, cosmetics, sunscreens, and foods as a source of zinc nutrients, have made use of ZnO-NPs [5,6]. Nanosized ZnO particles exhibit strong antibacterial properties because of their small size. Once inside the bacterial cell, they can trigger various bactericidal mechanisms, such as the bacterial surface or bacterial core, produce ROS (reactive oxygen species), release Zn²⁺, and even be endocytosed by cells [7,8]. Special attention is given to green synthesis from plants, bacteria, and fungi with a focus on extraction methods, reaction conditions, and precursors, characterization methods, and particular surface morphology [9]. Metallic and metal-oxide nanoparticles, such as Cu, Zn, Ag, and Au shown

excellent antibacterial capabilities due to the significant nanoscale effect. Among them, low-cost, low-toxicity ZnO nanoparticles are widely used in antibacterial applications, including medical implants and air purification [10].

Although traditional methods have been utilized for many years, studies have shown that green approaches are more successful in producing NPs because they are less expensive and are simpler to characterize. Plant-based NP synthesis is absolutely not a difficult process; a metal salt is created using plant extract, and the reaction takes a few minutes to many hours at room temperature. The potential for green synthesis techniques to decrease the toxicity of NPs makes them highly desirable. As a result, the usage of vitamins, amino acids, and plant extracts is commonly increasing [11, 12]. *Syzygium cumini*, commonly referred to as jamun, jambul, jambolao, java plum, Indian blackberry, and black plum, is a member of the Myrtaceae family (synonyms: *Eugenia jambolana*, *Syzygium jambolana*, *Eugenia cumini*) [13]. Traditionally, *S. cumini* has been utilized as a medicinal herb. The plant's bark, leaves, seeds, and fruit, among other parts, have all been used to treat a variety of disorders [14]. In this research paper, we have taken the *S. cumini* fruit extract and the chemical compounds, such as zinc acetate and sodium hydroxide, which are converted into ZnO nanoparticles using a green synthesis method. Overall, the study confirms that *Syzygium cumini* fruit extract provides a sustainable and cost-effective approach for synthesizing ZnO nanoparticles with promising biomedical and environmental applications.

2. Experimental Details

2.1. Materials and Methods

The chemical compounds used for synthesis include zinc acetate ($\text{Zn}(\text{C}_4\text{H}_6\text{O}_4)$) and sodium hydroxide (NaOH), with additional purification steps. *Syzygium cumini* fruit, collected from Tamil Nadu, was also used in the process. De-ionized water served as the aqueous solution for the general synthesis of ZnO nanoparticles, which were then analyzed using various analytical techniques.

2.2. Preparation of *Syzygium Cumini* Fruit Extract

The *Syzygium cumini* fruits were harvested from Nathakadaiyur in the Erode district of Tamil Nadu, India. A 30g sample of the fruit was washed

thoroughly with distilled water, and then boiled in 100ml of distilled water for 25 minutes. The boiling process resulted in a pink-colored solution. The extract was subsequently filtered and stored at room temperature for further use.

2.3. Synthesis of ZnO Nanoparticles Using *Syzygium Cumini* Fruit Extract

In this process, 20 mL of *Syzygium cumini* fruit extract and 0.4 M zinc acetate solution were each separately mixed with 150 mL of distilled water and stirred well for 30 minutes. Then, the *Syzygium cumini* fruit extract was added to the zinc acetate solution. The stirring process continued for another 30 minutes, during which time the color changed from white to green. A pH of 10 was maintained by adding dropwise 5 g of sodium hydroxide solution. During the next 30 minutes, the color of the solution changed from green to pale yellow. The synthesized sample was aged for 24 h to complete the nanoparticle formation. Further, the precipitate was dried under microwave radiation at 75 W for 30 minutes, which serves as an alternative and rapid drying approach. Finally, the dried sample was crushed into a fine powder using a mortar. Fine *Syzygium cumini* fruit extract-capped ZnO nanoparticles were obtained. In this approach, the two most attractive features have been combined: the natural extract acted as a capping agent, while microwave radiation was used for drying purposes, hence presenting an improved approach in the synthesis of nanoparticles.

3. Result and Discussion

3.1. X-ray Diffraction Infrared Spectroscopy

XRD was employed to investigate the crystalline structure of zinc oxide nanoparticles synthesized using *Syzygium cumini* fruit extract. The diffraction pattern is represented in Figure .1 and it shows distinct and sharp peaks at 2θ values of 31.7° , 34.4° , 36.2° , 47.5° , 56.5° , 62.8° , 66.3° , 68.0° , and 69.1° , corresponding to the lattice planes (100), (002), (101), (102), (110), (103), (200), (112), and (201), respectively. These reflections are in good agreement with the standard JCPDS card No. 36-1451, confirming the crystalline hexagonal wurtzite structure of ZnO [15]. No impurity peaks indicate the high purity of the synthesized nanoparticles without secondary phases or unreacted residues from the plant extract. The intense and narrow diffraction peaks reflect the high crystallinity of ZnO nanoparticles. The average

crystallite size estimated by Debye–Scherrer’s equation, $D=0.9\lambda/\beta\cos\theta$, lies in the range of 20–30 nm (Table 1), indicating the nanocrystalline nature of the sample. Slight broadening of peaks at higher angles indicates the presence of strain and small particle size effects [16]. Biomolecules in *Syzygium cumini* fruit extract, such as polyphenols and flavonoids, play the role of capping and stabilizing agents; hence, they prevent agglomeration and control nucleation during synthesis. Thus, XRD results confirm that the green synthesis route utilizing *Syzygium cumini* extract successfully prepared pure, crystalline ZnO nanoparticles with nanoscale dimensions suitable for biological and catalytic applications [17].

3.2 Fourier Transform Infrared Spectroscopy Analysis

The FTIR analysis of the zinc oxide nanoparticles synthesized using *Syzygium cumini* fruit extract afforded information on the chemical groups responsible for nanoparticle formation and stabilization [18]. In the spectrum recorded between 4000–400 cm^{-1} , an absorption band at 3420 cm^{-1} was observed, which can be ascribed to stretching vibrations of hydroxyl (–OH) groups.

Table.1 X-ray Diffraction for ZnO Nanoparticles

Sampe Code	2θ	D- Spacing	FWHM	HKL value	Lattice Constant		Crystalline Size* 10^{-9}	Unitcell volume	Dislocation Density 10^{15}	Macro strain
					a=b	C				
AZS	36.1518	2.48262	0.2896	101	3.25	5.24	29.80	47.93	112.236	0.2218
	47.4169	1.91577	0.4108	102	3.23	5.22	21.10	47.16	223.238	0.2338
	62.7213	1.48014	0.3864	103	3.24	5.22	24.45	47.45	166.789	0.1585
	67.8103	1.38091	0.391	112	3.25	5.22	24.50	47.74	165.971	0.1454
	76.8405	1.23957	0.4126	202	3.22	5.22	24.76	46.87	163.448	0.1300
	81.2736	1.18276	0.5442	104	3.19	5.22	19.35	46.00	701.571	0.1585
	89.4784	1.09436	0.5308	203	3.22	5.24	21.12	47.05	224.512	0.1339
Averages					3.22	5.22	23.5828	47.17533	227.282	0.14974

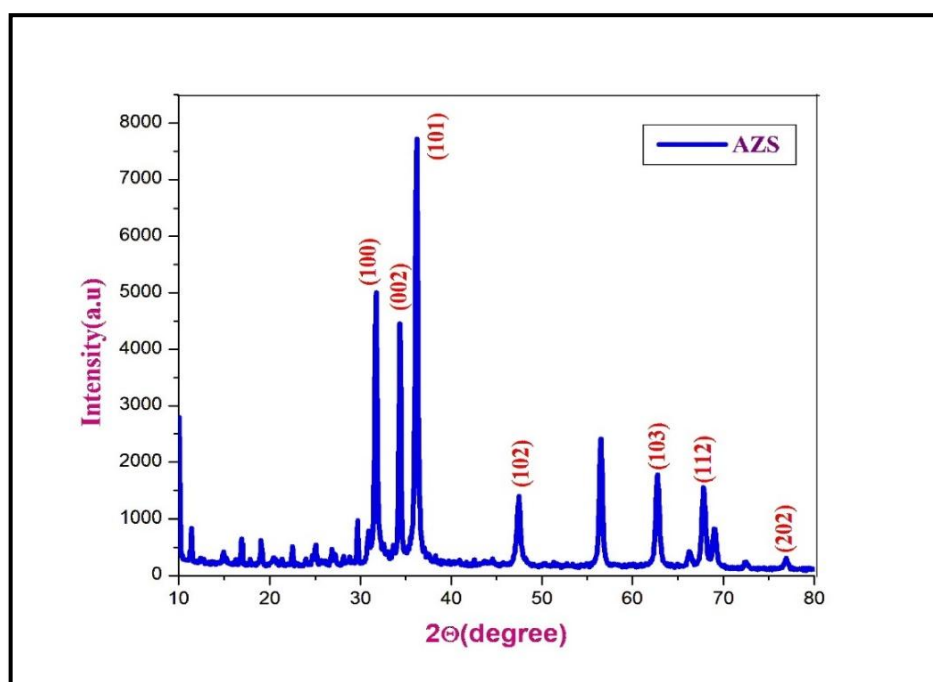


Figure 1. XRD Analysis Pattern ZnO Nanoparticles

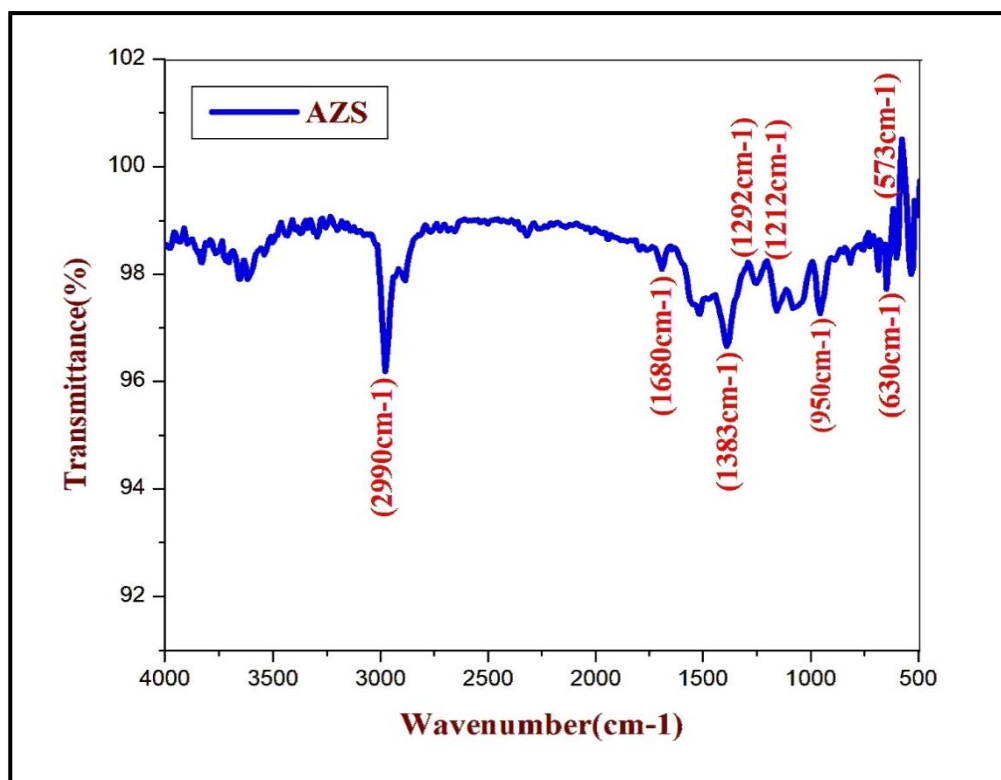


Figure 2. FT-IR Spectrum of ZnO Nanoparticles

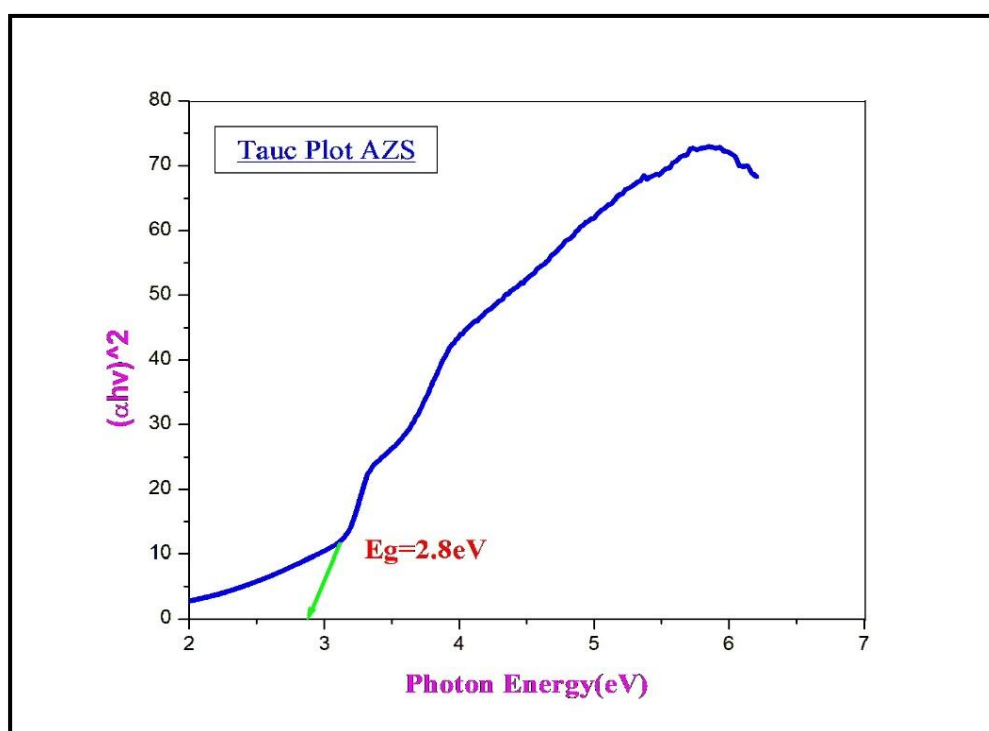


Figure 3. UV Spectrum of Tauc Plot

Hydroxyl groups, present in phenolic compounds and alcohols in the fruit extract, are indicative of strong hydrogen bonding on the ZnO surface. The characteristic peak at 2920 cm^{-1} corresponded to C-H stretching vibrations belonging to aliphatic groups, which may participate as capping

agents. Further, the band near 1630 cm^{-1} represented C=O stretching vibrations, usually characteristic of amides or carbonyl groups. This supports the participation of proteins and polyphenols in the reduction and stabilization of Zn^{2+} ions, leading to the formation of ZnO nanoparticles.

Peaks in the 1380–1420 cm^{-1} region showed C-N stretching vibrations associated with amine groups. More significantly, the strong band detected between 470 and 520 cm^{-1} confirmed the Zn-O stretching vibration, which falls in the fingerprint region given by zinc oxide nanoparticles [19]. FTIR results revealed that bioactive phytochemicals such as flavonoids, tannins, and phenolic acids present in *Syzygium cumini* contributed to the reduction of metal ions and acted as capping agents for the reduction process. These compounds have helped in synthesizing stable ZnO nanoparticles, as shown in Figure 2 [20].

3.3 UV-Visible Absorption Spectroscopy

UV-visible spectroscopy was used to examine the optical characteristics of zinc oxide nanoparticles made with *Syzygium cumini* fruit extract in the 200–800 nm wavelength range (Figure 3). The intrinsic band-gap absorption of ZnO nanoparticles is shown by a large and abrupt peak in the absorption spectra at 310 nm, which is caused by electronic transitions from the valence band to the conduction band ($\text{O}^{2-} \rightarrow \text{Zn}^{2+}$ charge transfer) [21]. A blue shift in the absorption peak compared with bulk ZnO, normally around 370 nm, highlights a decrease in particle size and the formation of nanosized ZnO with strong quantum confinement effects. The Tauc plot, which was derived from the UV data, plotting $(\alpha h\nu)^2$ versus photon energy ($h\nu$), gives an indication of an optical band gap energy of about 2.8 eV, slightly higher than that of bulk ZnO (3.37 eV) [22]. This increase in band gap further confirms the nanoscale dimensions of the synthesized particles. Enhanced optical absorption and a widened band gap are attributed to the effect of phytochemicals present in *Syzygium cumini* fruit extract acting as reducing and stabilizing agents during the synthesis process.

These optical properties confirm the successful biosynthesis of ZnO nanoparticles with potential applications in photocatalytic and biomedical fields [23].

3.4. Morphological Studies

The surface morphology of the biosynthesized ZnO nanoparticles was examined through Scanning Electron Microscopy (SEM). The SEM micrographs, as presented in Figure 4 below, reveal that the ZnO nanoparticles exhibit mainly an irregular, granular, and agglomerated morphology [24]. Particles appear as spherical to quasi-spherical clusters, which is a

common characteristic of green-synthesized ZnO due to the presence of phytochemicals acting as capping and stabilizing agents. The surfaces of these particles reflect rough and uneven texturing, indicating the successful construction of nanostructures of ZnO. These compact agglomerates might have resulted from the phytochemicals present in *Syzygium cumini* fruit extract, such as flavonoids, phenols, tannins, and anthocyanins, which could have played a crucial role in the reduction, nucleation, and stabilization of the agglomerates. The particle size approximated from SEM images lies in the nanoscale region, hence confirming nanostructure formation, although individual particles were seen to be fused into clusters. Such agglomerated nano-structures are often desirable for biological applications due to increased surface reactivity and enhancement in antimicrobial and antioxidant effectiveness. Overall, SEM analysis confirms the successful synthesis of ZnO NPs using *Syzygium cumini* fruit extract and supports the formation of stable phytochemical-capped nanostructures suitable for further characterization and biological studies [25].

3.5. Antibacterial Application

The *in vitro* antibacterial action of *Syzygium cumini* fruit extract-mediated zinc oxide nanoparticles was assessed by agar well diffusion against *Propionibacterium acnes* and *Bacteroides fragilis* [26]. From the figure 5, 6 and Table 2 it is noted that, a well-pronounced inhibition zone could be seen around all the wells that contained ZnO nanoparticles, which indicated that the nanoparticle had a strong antibacterial action and was concentration-dependent. In *P. acnes*, a maximum zone of inhibition was observed at 500 $\mu\text{g}/\text{mL}$ (≈ 20 mm), while 250, 100, and 50 $\mu\text{g}/\text{mL}$ produced proportionately lower inhibition zones. Also, a dose-dependent antibacterial action was noticed in *B. fragilis*; the maximum inhibition zone reached about 18 mm at 500 $\mu\text{g}/\text{mL}$. The positive control gave the maximum activity, while the negative control showed nil inhibition, indicating that the bacterial suppression noticed was due to ZnO nanoparticles. The biosynthesized ZnO nanoparticles exhibited potent antibacterial action due to their small particle size and high surface-to-volume ratio, promoting adhesion to the bacterial cell membrane [28]. The nanoparticles generate reactive oxygen species (ROS) like hydroxyl radicals and superoxide ions, creating oxidative stress, rupture of the membrane, and leakage of cellular contents.

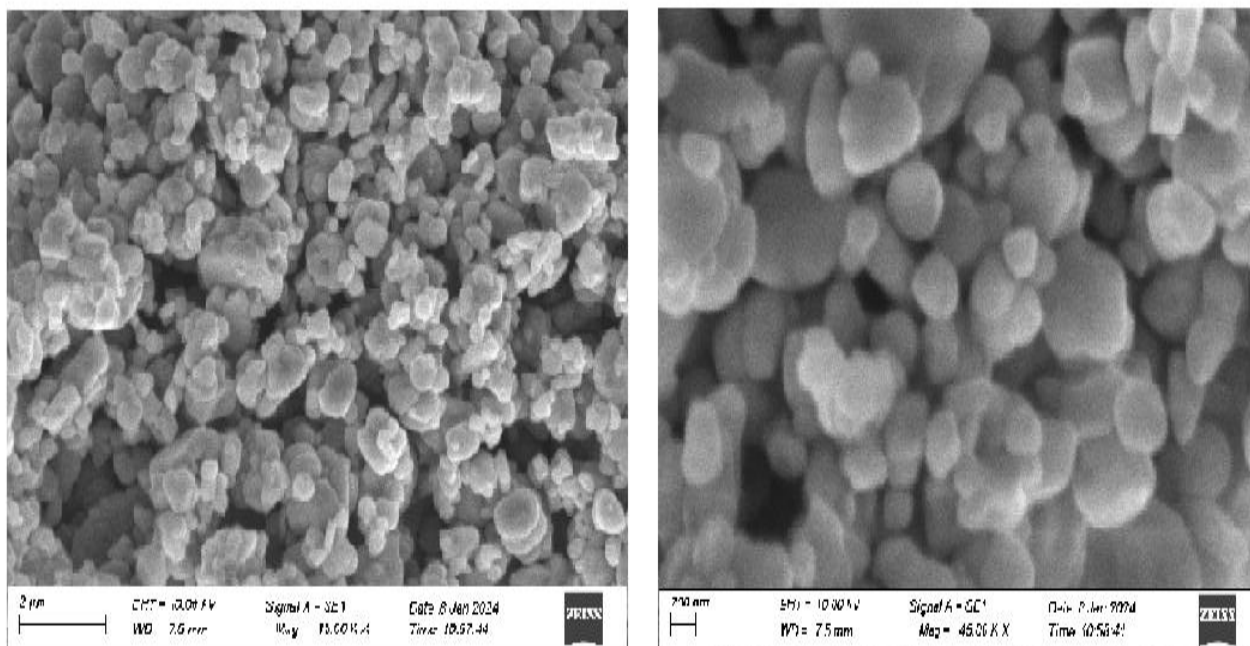


Figure 4. SEM Analysis

Table 2. Means ± SD of zone of inhibition obtained by sample AZS against *Propionibacterium acnes* and *Bacteroides fragilis*.

S. No	Name of the test organism	Name of the test sample	Zone of inhibition (mm)				
			Mean ± SD				
			500 μg/ml	250 μg/ml	100 μg/ml	50 μg/ml	PC
1.	<i>Propionibacterium acnes</i>	AZS	13.75±1.06	0	0	0	18.75±0.7
2.	<i>Bacteroides fragilis</i>		15.5±0.7071	10.25±0.35	0	0	17.75±1.06

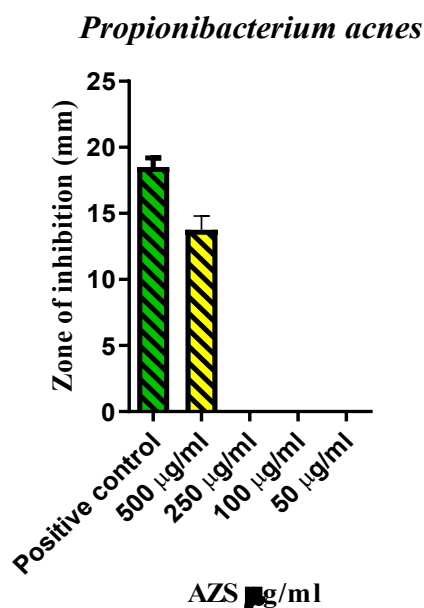
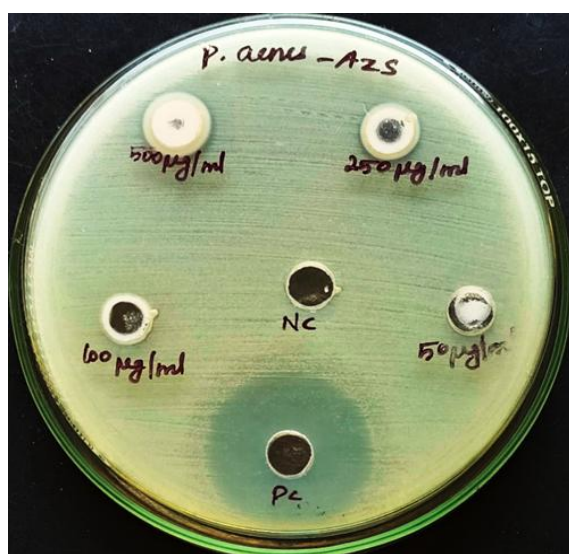


Figure 5. *P. acnes* against ZnO nanoparticles.

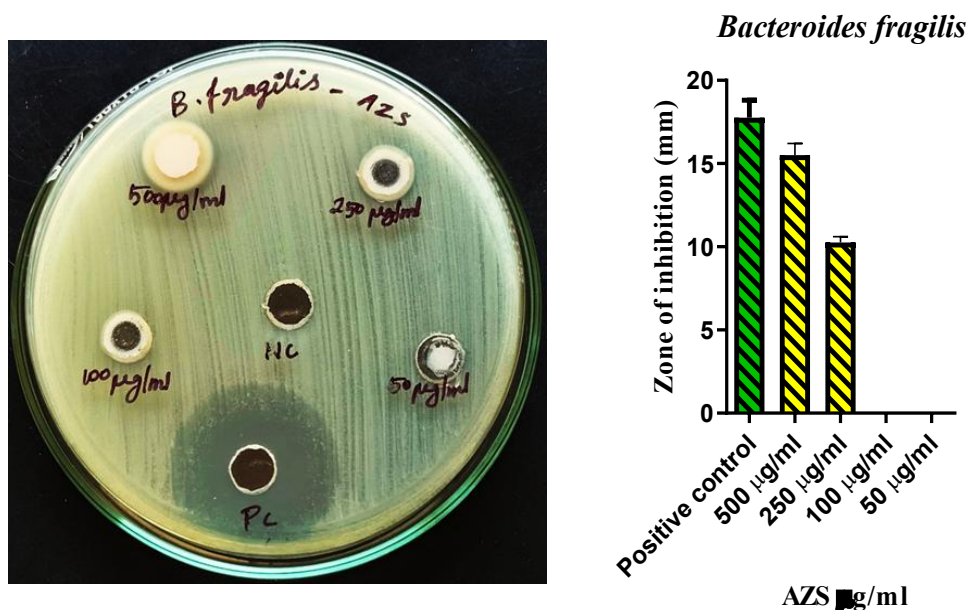


Figure 6. B. Fragilis against ZnO nanoparticles

Further, the release of Zn^{2+} ions by the nanoparticles interferes with bacterial enzymatic functions and metabolic pathways, thus enhancing the bactericidal action. The phytochemicals, such as flavonoids, phenolic acids, and tannins present in *Syzygium cumini* extract, act synergistically with ZnO, improving stability and enhancing antibacterial efficiency. These results showed that green-synthesized ZnO nanoparticles are of immense potential for use in antibacterial formulations, wound dressings, and biomedical coatings [29].

4. Conclusion

In this study, the synthesis of ZnO NPs was performed using *Syzygium cumini* fruit extract through the microwave irradiation method. Characterizations were done with XRD, FT-IR, UV spectroscopy, and SEM analysis. Through antibacterial analysis, it was found that the nanoparticles are effective in inhibiting the growth of Gram-positive and Gram-negative bacteria. Crystalline size, lattice parameters, and unit cell volume of the samples were analyzed by XRD. An average crystalline size of 4.075 nm was obtained for the samples. The presence of functional groups in the sample was analyzed through FT-IR spectroscopy. The band gap energy of the ZnO NPs estimated through UV analysis was 2.8 eV. SEM images showed that the ZnO NPs were predominantly spherical with slight quasi-spherical clusters agglomeration, and the particles were with nanoscale dimensions and well dispersed,

confirming the successful formation of nanostructures. Since the synthesized ZnO NPs are highly stable, they show significant antibacterial activity against both Gram-positive and Gram-negative strains. The green synthesis rate in the present case is comparable with the chemical methods. Hence, these nanoparticles may have applications in food preservation and could also be used in the medical field.

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Author Contribution Statement

R. Anupriya: Conceptualization, Methodology, Validation, Formal Analysis, Investigation V. Kalaiselvi: Formal Analysis, Investigation, Writing-Original Draft, Supervision. P. Yasotha: Data Curation, Writing-Review & Editing. S. Gopi: Writing-Review & Editing. All the authors read and approved the final version of the manuscript.

Does this article screened for similarity?

Yes

Conflict of interest

The Authors declares that there is no conflict of interest anywhere.

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