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Synthesis and Characterization of ZnO Nanoparticles Using Activated Carbon Derived from Biomass (*Borassus Flabellifer*) and Assessment of Potential Antimicrobial Activity

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ABSTRACT

Nanoparticles possess unique properties and have attracted great attention from the research and scientific community. Metal oxides like Zinc Oxide (ZnO) are used in medical applications for several purposes, including nanocoatings, drug delivery, and more. A feature common among these nanoparticles is their ability to prevent and protect human health from various bacteria. In our study, ZnO nanocomposites were synthesized using ZnO nanoparticles doped with activated carbon derived from *Borassus Flabellifer* (BF) with varying ratios. Characterization was carried out using X-ray diffraction, Scanning Electron Microscopy, and Fourier-transform infrared spectroscopy, and antimicrobial activity was evaluated against four different bacteria. XRD patterns indicated the presence of a hexagonal wurtzite structure of ZnO. In the FTIR spectrum, Zn-O stretching suggested that the activated carbon was bound to zinc. SEM images showed that the nanocomposites exhibited irregular, agglomerated morphology. Antimicrobial activity was evaluated using zones of inhibition. ZnO, when doped with activated carbon derived from Borassus flabellifer, was successfully synthesized. Among the developed composites with varying ratios, the 1:3:0.3 (ZnO:ABFC:PVP) showed notable characteristics and effective antimicrobial activity against Pseudomonas sp., with the widest Zone of Inhibition compared to other bacteria.

Keywords: Metal oxide; Composite; Antimicrobial activity; Nanoparticles; Zinc oxide.

1. INTRODUCTION

Nanotechnology was first introduced by Richard Feynman in 1959 (Bouttier-Figueroa *et al.* 2024). Over the past three decades, the widespread development and application of nanoscale materials have established a new paradigm in materials science. Owing to their unique size-dependent biological, physical, and chemical properties, nanomaterials exhibit characteristics that differ significantly from those of their bulk counterparts, resulting in their extensive use across a wide range of applications. Advancements in technology have enabled the invention of nanoparticles with varying particle sizes. Nanoparticles (NPs) derived from metals and metal oxides are gaining global attention from scientific research communities. Improvements in nanoparticle characteristics are attracting various researchers to take nanotechnology as their field of research (Amendola *et al.* 2020). The nanoscale range they possess is a major advantage for easy interaction with proteins, cell membranes, etc., of the human biological system. This main property of nanoparticles has made them widely used in biomedical applications. Additionally, they have other medicinal uses like antimicrobial, drug transport, and cancer treatment. A wide range of metal and metal oxide nanoparticles has been explored for biomedical applications; this line of investigation provides a path for extensive research (Khursheed *et al.* 2022). Focusing on characterization helps modify intrinsic characteristics, including surface properties. The properties stated are changed by modifying the size, shape, or aspect ratio of the nanoparticle. Nanoparticles are synthesized and modified to improve their various properties, such as mechanical and optical properties. Nanoparticle modification concerning size, shape, and structure results in a high surface-to-volume ratio. In recent years, many industries such as medicine, textiles, pharmaceuticals, and sensors have shown extensive use of nanoparticles prepared from metals and metal oxides (Jeevanandam *et al.* 2018).

Zinc is one of the essential elements required for the human body. Zinc in the human body supports various processes, including immune function, protein synthesis, memory, and enzymatic reactions (Islam *et al.* 2022). ZnO-NPs are odourless, white-coloured, and their molecular weight is 81.38 g/mol. It has a large band width of 3.37 eV and has a wurtzite crystalline structure. Exceptional features of zinc oxide nanoparticles (ZnO NPs), like catalytic, optical, and photochemical capabilities, have made it a notable constituent in biomedical applications (Salim, 2024). Also, these particles exhibit low toxicity and good biocompatibility, making their use safe in the medical field. With these unique features, ZnO-NPs mainly promise use in healthcare applications. ZnO-NPs exhibit antimicrobial activity, making them promising for coating surgical implants, promoting wound healing, and treating cancer (Gudkov *et al.* 2021). Hence, ZnO-NP formation is scientifically valuable due to its uses. Previously, ZnO-NPs were created using various physical and chemical techniques. Two approaches, namely Top-down and Bottom-up approaches, are used to develop ZnO-NPs. Sol–gel process is one commonly used bottom-up process in which ZnO nanoparticles are developed using zinc metal-based precursors (Irfan *et al.* 2022; Dagdag *et al.* 2022; Gomez *et al.* 2013). In recent years, ZnO has attracted attention in nanomedicine research, and ZnO-NPs are inorganic metal oxides that meet the requirements of the medical field and are used as antimicrobial agents without risk (El-Khawaga *et al.* 2025; Ahamad *et al.* 2023).

Despite the promising behaviour of ZnO-NPs, their use in nanomedicine remains limited due to intrinsic limitations, such as the low stability of ZnO particles in biological fluids and the uncontrolled release of Zn^{2+}, a cytotoxic species (Vandebriel *et al.* 2012; Pandurangan and Kim, 2015). Therefore, further increased efforts are needed to develop ZnO NPs and make them more attractive. To accomplish this, ZnO doping can serve as an effective technique to improve existing functionalities or confer new ones. Inserting Dopants into the crystalline structure of ZnO customizes various chemical and physical properties of ZnO NPs for a specific function (Mazitova *et al.* 2019; Bognar *et al.* 2022; Murali *et al.* 2026). ZnO doped with appropriate dopants could optimize and strengthen electromechanical, optical, and other properties (Nibret *et al.* 2015). But in some cases, ZnO doped with elements exhibited distinct properties compared with the pure material (Han *et al*. 2019; Laurenti *et al.* 2015). Hence, doping ZnO with an appropriate dopant presents a thought-provoking quick fix to overcome the limitation mentioned above and further extend the use of ZnO NPs in biomedical applications (Mascarenhas-Melo *et al.* 2023; Masthan *et al*. 2025).

Interest in ZnO-doped nanomaterials for biomedical applications is very interesting and quite recent. Studies on ZnO is rapidly growing and new innovations is needed to improve the capabilities of doped ZnO (Mohammed *et al.* 2022). The synthesis of new ZnO nanoparticles and their microbial activity have drawn keen attention in recent decades (Abdelbaky *et al.* 2022). However, the potential of ZnO NPs for biomedical and other applications has been highlighted in a few previous studies. There are very few studies in the literature that emphasize the importance of ZnO, ZnO doping, and ZnO NPs, and the significant progress they have made in biomedical applications. Antimicrobial activity was examined in previous studies on ZnO, showing that size, shape, aspect ratio, and surface area are some factors that directly affect the antimicrobial activity (Olani et al. 2024) and also showing that ZnO is a good antimicrobial agent due to the photocatalytic property it possesses (Jha *et al.* 2023). ZnO as an antimicrobial agent, combined with different materials forms ZnO composites. ZnO, along with Activated carbon, can be used as an antimicrobial composite. Composite preparation helps improve mechanical and other specific properties by leveraging those of its constituents. The high surface area, mechanical strength, and chemical stability of Activated carbon make it suitable for antimicrobial applications (Burchacka *et al.* 2023). Carbon exists in different forms, but has been observed to exhibit highly alluring properties under distinct conditions. Any material that is rich in carbon can be used to prepare activated carbon. Activated carbon can be prepared using wasted materials (Biomass) like Sugarcane bagasse (Rahmawati *et al.* 2024), Lemon leaves (El-Beltagi *et al.* 2026; Vasanthakumar *et al.* 2025), *Borassus Flabellifer* husk (Selvam *et al.* 2023), Lemon and Orange peels (Al-Farsi *et al.* 2016), Coconut shell (Sujiono *et al.* 2022), Fruits (Debebe *et al.* 2018), Mango peels (Nair *et al.* 2023) and many such biomasses. Activated carbon can be prepared by activating biochar derived from biomass using chemical or physical processes. The characteristics and properties of Activated carbon depend on the activation conditions.

In this study, the ZnO-based nanocomposite samples are synthesized using ZnO NPs and activated Carbon NPs as a dopant. To our knowledge and as per surveyed literature, there is still scarce literature on ZnO nanocomposites using Carbon nanoparticles. In order to develop carbon NPs, *Borassus Flabellifer* (Biomass) is used. The use of biomass is nontoxic and doesn't have any hazardous effect on the human body. Our work focuses on the synthesis of ZnO nanocomposites using activated carbon nanoparticles and investigates the effect of Carbon volume/concentration on ZnO NPs particle size. Characterization of the developed ZnO nanocomposites with varying carbon volume was performed using XRD, FTIR, and SEM. Also, the antimicrobial activity of the synthesised ZnO nanocomposites was investigated against four different bacterial isolates. Accordingly, this study focuses on recent achievements in ZnO nanocomposites prepared using ZnO NPs and activated Carbon NPs for biomedical applications. Nano-dentistry is a developing field, and the potential of nanoparticles addresses cutting-edge and modernization in dentistry applications. Incorporation of carbon nanoparticles with ZnO nanoparticles to prepare ZnO nanocomposites can be useful in dentistry as Nanocoatings for dental implants.

2. MATERIALS AND METHODS

2.1 Synthesis of Activated Carbon Nanoparticles

In our study, Borassus Flabellifer (BF), commonly called toddy palm or ice apple, was used to prepare carbon nanoparticles. Incorporating carbon nanoparticles into ZnO nanoparticles to prepare ZnO nanocomposites can be useful for biomedical applications. Fresh *Borassus Flabellifer*, 10 in number, were collected in Koneru Lakshmaiah Education Foundation (KLEF) campus, from the local green city area, Vaddeswaram, Vijayawada district, Andhra Pradesh, India. So obtained BF from trees is cleaned to remove soil, dust, and other contaminants using water. Later, to prevent mold, the BF is dried at 105 °C for 24 hours. The dried BF is then packed in an airtight cover to prevent moisture. Approximately 2 numbers of collected Borassus flabellifer are burned once to obtain charcoal. Carbonization of Bf is performed by heating to 400 °C and maintaining this temperature for 1 hour in a muffle furnace. Once the charcoal obtained from Bf is cooled, it is crushed and powdered using a stone mortar. This *Borassus Flabellifer* charcoal (BFC) powder was packed in an airtight container to prevent moisture. Carbonized BFC is mixed with an NaOH solution, which is added dropwise in a 500ml beaker, and the mixture is stirred for 24 hours. Later, this was filtered to obtain only charcoal, then carbonized by heating to 900 °C for 2 hours in a muffle furnace. The Activated BFC (ABFC) was washed with deionized water until neutral pH was reached, dried at 105 °C for 24 hours, and stored in an airtight container to prevent moisture. Figure 1 shows the preparation of Active BFC.

2.2 Synthesis of Zinc Oxide Nanocomposites

ZnO nanoparticles (ZnO NPs) were purchased from "National Scientific Products" and were used for ZnO nanocomposite preparation. A total of 8.137 g of ZnO NPs was accurately weighed using an analytical balance and transferred to a clean beaker. The beaker used to store ZnO particles was thoroughly cleaned by ultrasonic cleaning to remove dust and dirt. Synthesis of ZnO nanocomposite was carried out by dissolving the weighed ZnO and activated BFC in 50 mL deionized water under constant agitation (350 rpm). Polyvinylpyrrolidone (PVP) was added in small amounts and acts as a binding agent. The agitation can be varied from 300rpm to 400rpm based on the mixture concentration. A magnetic stirrer was used to thoroughly mix the mixture to obtain homogeneity, and it was stirred for 24 hours at room temperature. Later, centrifugation was done to separate the precipitate, and the resulting precipitate was washed with deionized water and ethanol. Finally, it was dried at 60 °C for 6 hours. Figure 2 shows the preparation of ZnO nanocomposites. The ZnO nanocomposite samples thus synthesized were stored in sample boxes for characterization. ZnO nanocomposites were prepared in the following ratios (ZnO: ABFC: PVP) (1:1:0, 1:1:0.1, 1:2:0.2, 1:3:0.3, 1:4:0.4, 1:5:0.5) as shown in Table 1. Figure 3 presents the flowchart for the synthesis of ZnO nanocomposites.

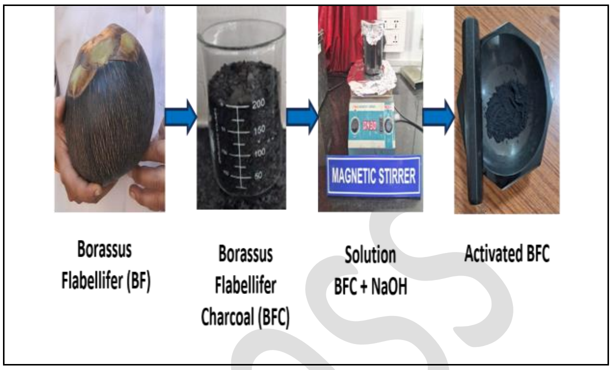

Fig. 1: Steps in preparation of active BFC

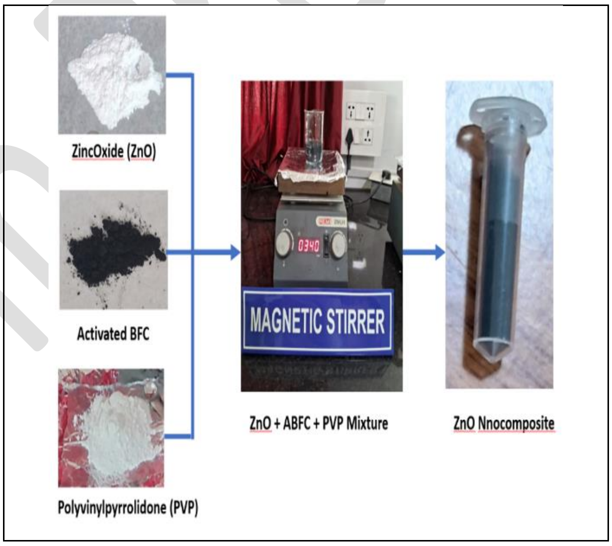

Fig. 2: Steps in preparation of ZnO nanocomposite

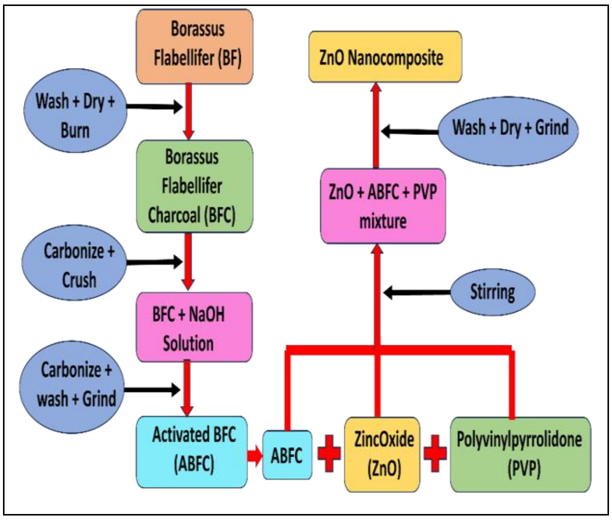

Fig. 3: Flowchart of ZnO nanocomposite using active BFC

Table 1: Composition ratios of ZnO/ABFC/PVP nanocomposites prepared using different ZnO, ABFC, and PVP proportions

Sample Code	ZnO	ABFC	PVP	Composition Ratio (ZnO: ABFC: PVP)
ZAP-1	1	1	0.0	1:1:0
ZAP-2	1	1	0.1	1:1:0.1
ZAP-3	1	2	0.2	1:2:0.2
ZAP-4	1	3	0.3	1:3:0.3
ZAP-5	1	4	0.4	1:4:0.4
ZAP-6	1	5	0.5	1:5:0.5

3. RESULTS AND DISCUSSION

3.1 Characterization of Synthesized ZnO Nanocomposites

In our study, several popular and important characterization methods, such as X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Scanning Electron Microscopy (SEM), were employed to characterize the synthesized ZnO nanocomposite samples.

3.1.1 X-ray Diffraction

The crystalline structure of the synthesized ZnO nanocomposite was analysed by an X-ray diffractometer. The X-ray diffraction (XRD) patterns were recorded on a "PANalytical EMPYREAN diffractometer" using Cu K α (λ=1.5405 Å) radiation. Synthesized samples were placed into the XRD analyzer by loading on the metal slides. XRD patterns were recorded using a diffractometer over the 2θ range of 20-800. X'Pert Highscore Plus software was used to identify the phases. Data recorded from the XRD with Joint Committee on Powder Diffraction Standards (JCPDS) data and the Debye–Scherer equation (Ali *et al*. 2022) can be used to calculate the nanoparticle size, and the equation is as follows:

$$D=K_{\lambda}/\beta Cos\theta \quad \ldots (1)$$

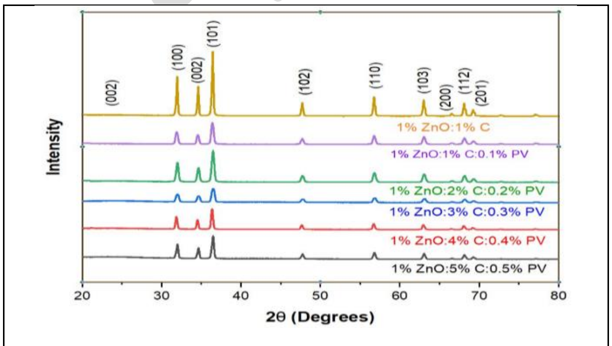

Fig. 4: XRD patterns of ZnO nanocomposite with various ratios

The recorded patterns of synthesized ZnO nanocomposites with different ratios obtained from the X-ray diffractometer are shown in Figure 4. Characteristics of a hexagonal structure with a crystalline wurtzite ZnO phase were observed for ZnO nanocomposite samples. ZnO nanocomposites synthesized for different ratios demonstrated that samples taken for study showed high purity, as exhibited with no extra peaks. Observed peaks closer to 2θ values of 31.33º, 34.01º, 35.83º, 47.13º, 56.17º, 62.49º, 66.01º, 67.55º, 68.71º, can be seen in Bragg's reflection. Miller reflections for 2θ values correspond to (100), (002), (101), (102), (110), (103), (200), (112), (201). For peak identification, JCPDS card no. 36–1451 was used as a reference, and it can be seen that the ZnO nanocomposites exhibited a hexagonal wurtzite ZnO structure (Mallika *et al.* 2014). Observing the XRD patterns reveals peak broadening, indicating the presence of small crystallites in the tested samples and an increase in crystallinity with increasing particle size. As the ratio of ZnO: ABFC: PVP increases, the broadness of peaks increases (Ghamsari *et al.* 2019). A broad peak at the 1:3:0.3 doping ratio indicates smaller crystallites in the composite. Peak intensities of all peaks decreased as the doping of ABFC increased upto 1:3:0.3 ratio of ZnO: ABFC: PVP, and the peaks start increasing beyond a 1:3:0.3 ratio of doping. A decrease in peak intensities indicates a decrease in crystalline size and an increase in particle size. The results reveal *that the presence of Borassus flabellifer (BF) atoms improves crystal quality in the* ZnO lattice. Characterized ZnO nanocomposite diffraction peaks are seen to have shifted to slightly higher diffraction angles when compared with literature results of undoped ZnO diffraction angles (Zak *et al.* 2011). Crystalline sizes of synthesized ZnO nanocomposites were determined using the Scherrer equation as stated in equation (1), and the corresponding crystallite sizes for different ratios are tabulated in Table 2. Crystallite size differences could be due to dopant atom segregation on the ZnO surface, which improves crystalline quality and presents high surface areas (Poongavanam *et al.* 2019).

Table 2: Average crystalline size of ZnO nanocomposite for various ratios

Ratio of ZnO: ABFC: PVP	Average Crystalline Size D (nm)
1: 1: 0.0	29.42
1: 1: 0.1	26.50
1: 2: 0.2	25.73
1: 3: 0.3	24.38
1: 4: 0.4	25.13
1: 5: 0.5	32.99

3.1.2 Fourier Transform Infrared Spectroscopy

FTIR analysis was conducted on synthesized zinc nanocomposites to identify chemical functional groups and interactions. Synthesized samples were scanned from 400 cm^{-1} to 4000 cm^{-1} by loading them onto a holder (Rohani *et al.* 2022). A JASCO FT/IR-4700 Fourier Transform Infrared Spectrometer was used to obtain the FTIR spectra of the samples. FTIR spectra for ZnO composites for varying activated BFC ratios are depicted in Figure 5.

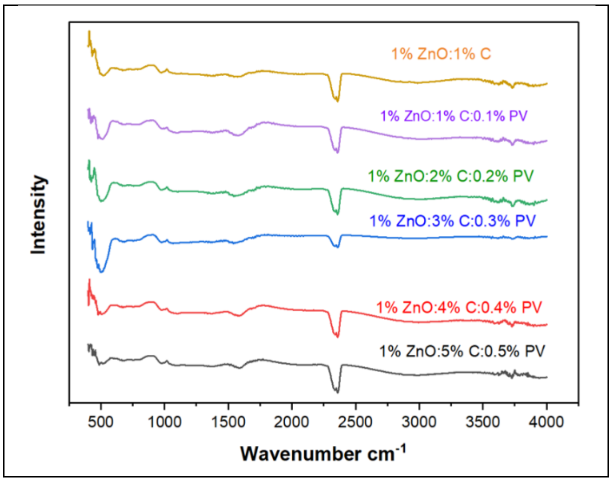

Fig. 5: FTIR spectra of ZnO nanocomposite with various ratios

The presence of functional groups in samples is indicated by peaks in the FTIR spectrum, appearing as absorption and stretching vibrations. The peak between 480 cm^{-1} and 520 cm^{-1} indicates a characteristic associated with the presence of a stretching vibration of the Zn-O bond in synthesized ZnO nanocomposites. The peak absorbance between 1530 cm^{-1} and 1570 cm^{-1} corresponds to the stretching vibration of the C=O group. Associated peaks between 1750 cm^{-1} and 1810 cm^{-1} indicate the O-H bending vibration, and absorbance peaks between 2250 cm^{-1} and 2400 cm^{-1} ascribe the stretching vibration of the C-H bond. The peaks between 3200 cm-1 and 3600 cm^{-1} are attributed to O-H stretching vibrations and hydroxyl groups (Geetha *et al.* 2020). Although the pattern of FTIR spectra remains unchanged for different sample ratios, a notable peak narrowing can be seen for the 1:3:0.3 ratio of ZnO: ABFC: PVP in the region between 480 cm−1 and 520 cm^{-1}. Findings reveal enhanced interaction and suggest improvement in structural performance and integrity of the composite materials.

3.1.3 Scanning Electron Microscopy

SEM analysis is used to derive valuable information regarding the morphologies of the synthesized samples. The TESCAN VEGA 3 SEM model, SBH TESCAN Brno S.R.O, CZECH Republic, was used for conducting the analysis. Samples were placed on a carbon tape and was gold coated to make the surface conductive. The samples were then positioned on a movable stage regulated under vacuum, and their surfaces were scanned by the electron beam in SEM. When the beam is focused on a sample-defined area, information is recorded as black-and-white images at magnifications up upto 33000x (Carofiglio *et al.* 2020).

The morphology of all synthesized samples was examined using SEM images, as shown in Figure 6. SEM images of samples with varying ratios show that particles are not uniformly distributed, and some exhibit irregular agglomerated morphology. ZnO, when doped, showed different surface morphologies (Vadiraj *et al.* 2026; Bharat *et al.* 2019). Thus, the surfaces of the synthesized composite samples exhibit greater unevenness and roughness. SEM image observations reveal that for the 1:3:0.3 ratio of ZnO: ABFC: PVP, most particles exhibit a homogeneous distribution and an agglomerated morphology with bead- and rod-shaped agglomerates, whereas for other ratios, there is a breakdown of homogeneity and reduced agglomeration. Elevation of doping on either side of the 1:3:0.3 ratio results in the formation of irregular plate-like structures due to the disappearance of tiny particles and the dominant takeover by large particles.

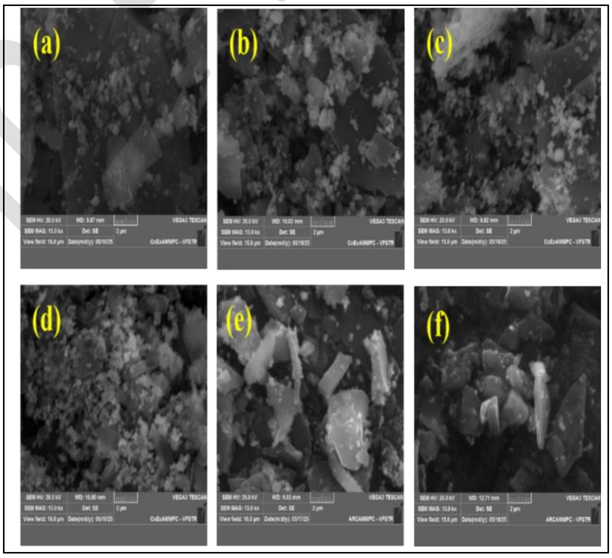

Fig. 6: SEM Images of ZnO nanocomposite with ratios

(a) 1: 1: 0.0 (b) 1: 1: 0.1 (c) 1: 2: 0.2 (d) 1: 3: 0.3 (e) 1: 4: 0.4 and (f) 1: 5: 0.5

3.1.4 Antimicrobial Activity

Antimicrobial tests were conducted on the synthesized ZnO nanocomposite samples to determine the antimicrobial potential against microbes. Antimicrobial activity was evaluated using zones of inhibition (ZOI). Antimicrobial activity was assessed against *Staphylococcus aureus*, a Gram-positive bacterium, and Pseudomonas sp, Klebsiella pneumoniae, and Escherichia coli, a Gram-negative bacterium, using a modified disc diffusion method (Bauer *et al.* 1966). Fresh bacterial cultures were grown in nutrient broth and incubated at 35 ± 2 °C in a shaking incubator at 160 rpm to promote active bacterial growth. Following incubation, 100 µL of each standardized bacterial suspension was uniformly spread on MHA (Muller Hinton agar) plates using a sterile glass spreader to form a consistent bacterial lawn (Azam *et al.* 2012). Sterile 6 mm Whitman filter paper discs were saturated with 20 µL of nanoparticle suspensions (equivalent to 50 µg/disc) and carefully placed on the inoculated agar surfaces. Ethanol was employed as the negative control, while a standard penicillin disc served as the positive control to assess comparative antimicrobial performance. All plates were incubated at 35 ± 2 °C for 24 hours, after which the zones of inhibition (ZOI) were carefully measured in millimetres using a digital Vernier calliper (Truong *et al.* 2023). The effect of growth inhibition of ZnO composites on Mueller-Hinton agar plates was observed as zones of inhibition. The zones around the discs indicate the presence of microbial growth, thereby providing a measure of antimicrobial efficacy of tested samples (Kritheka *et al.* 2024). Each experiment was conducted in triplicate, and the average inhibition zone diameter was documented for each treatment and is tabulated in Table 3. The larger the inhibition zone, the more sensitive the test microorganism is to the nanocomposite, thereby indicating the nanocomposite's effectiveness. Figure 7 shows the ZOI of all samples for different bacteria. Among the four different bacteria, *Pseudomonas sp.* showed the most pronounced antimicrobial effect. Notably, the 1: 3: 0.3 ZnO: ABFC: PVP combination produced the widest ZOI of 7 mm against Pseudomonas sp., even exceeding that of the standard penicillin disc, underscoring its strong antibacterial capability.

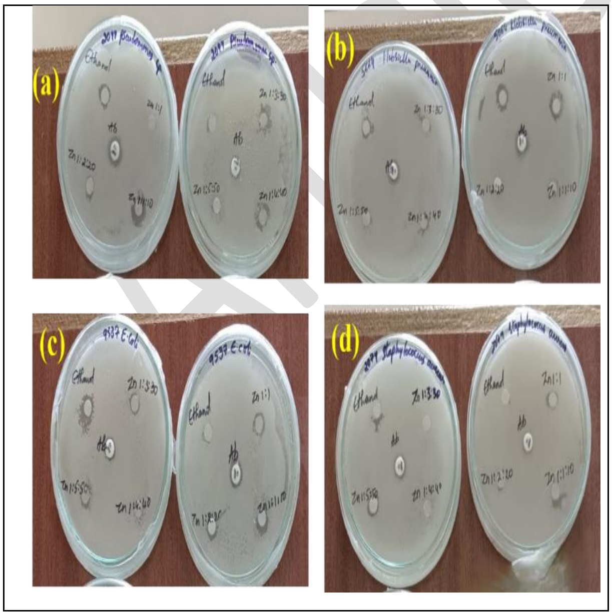

Fig. 7: Zone of inhibition for synthesized ZnO nanocomposites against different bacteria (a) *Pseudomonas sp.* (b) *Klebsiella pneumoniae* (c) *Escherichia coli* (d) *Staphylococcus aureus*

Table 3. Antimicrobial activity of synthesized ZnO nanocomposites against different bacteria

Micro Organisms	Zone of Inhibition (ZOI) in mm for Sample Ratios of ZnO: ABFC: PVP						Penicillin
	1: 1: 0.0	1: 1: 0.1	1: 2: 0.2	1: 3: 0.3	1: 4: 0.4	1: 5: 0.5	
Pseudomonas sp.	0	6	1	7	6	0	2
Klebsiella pneumoniae	3	1	0	1	2	0	4
Escherichia coli	2	4	3	2	0	2	0
Staphylococcus aureus	3	2	1	0	0	2	3

4. CONCLUSION

Advancements in nanomaterials offer many novel solutions for medical applications, treating and preventing various medical illnesses. When it comes to dental applications particularly, more concentration and consideration is given to control the microbial activity of oral pathogens. The use of metallic nanoparticles, along with doping, for Microbial disinfection is gaining significant attention and encouraging many researchers to pursue this topic as their scientific research. In our study, we attempted to develop ZnO nanocomposites using activated carbon derived from *Borassus Flabellifer* (BF). The composites were successfully synthesized at different ratios of activated BFC, characterized using XRD, FTIR, and SEM, and their antimicrobial activity was evaluated against four bacteria. XRD patterns indicated the presence of a hexagonal wurtzite structure of ZnO. In the FTIR spectrum, Zn-O stretching suggested that the activated carbon was bound to zinc. SEM images showed that the nanocomposites exhibited irregular, agglomerated morphology. When seen and compared between the composites developed for different ratios. The 1: 3: 0.3 (ZnO: ABFC: PVP) ratio of the nanocomposite showed notable peaks in XRD and FTIR, and SEM images revealed a homogeneous distribution of particles with an agglomerated morphology. Antimicrobial activity tests showed positive inhibition of tested samples against bacterial strains. The 1:3:0.3 (ZnO:ABFC:PVP) ratio produced a notable ZOI of 7 mm against Pseudomonas sp. In our study, the ZnO nanocomposite with a 1:3:0.3 ratio showed superior characteristics compared to other ratios. Conventionally, smaller particle size enhances antimicrobial activity. Greater contact between nanoparticles and bacteria results in a higher degree of inhibition in antimicrobial activity. Metallic oxides have great potential in dentistry when used effectively; they protect oral health and help combat various pathogens. Conclusions of our study suggest that a ZnO composite prepared using ZnO doped with activated carbon derived from Borassus Flabellifer may be advantageous for dental applications and could provide a new pathway for innovation in Oral health care. Further research direction involves replacing alternative metallic oxides without compromising performance.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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