

Sustainable Fabrication of Banana Pseudo-stem (*Musa paradisiaca* L.)-derived ZnO/Carbon Composite as a Photo-antibacterial Agent

Diah Nur Syafitri¹, Fasih Bintang Ilhami², I Gusti Made Sanjaya^{1*}

¹Department of Chemistry, Faculty of Mathematics and Natural Sciences, State University of Surabaya, Surabaya, East Java, 60231, Indonesia

²Department of Science, Faculty of Mathematics and Natural Sciences, State University of Surabaya, Surabaya, East Java, 60231, Indonesia

*Corresponding author: igmasanajaya@unesa.ac.id

Abstract

Bacterial infections and antimicrobial resistance (AMR) represent critical global health challenges, necessitating sustainable antibacterial alternatives. This study presents the hydrothermal synthesis of ZnO nanoparticles integrated with banana pseudo-stem-derived carbon (BPS-C) nanocomposite as a photo-antibacterial agent. Structural characterization confirmed crystalline hexagonal wurtzite ZnO formation (XRD), with ZnO nanoparticles distributed within the amorphous BPS-C matrix (broad halo $2\theta \approx 20-30^\circ$), verified by FTIR, SEM-EDS (C, O, Zn peaks), and DLS analysis. These composites exhibited significantly reduced hydrodynamic diameter (377 nm) compared to pure ZnO (826 nm) and BPS-C (19,602 nm), suggesting that the incorporation of BPS-C influenced the dispersion behavior of the composite particles. Furthermore, the incorporation of BPS-C influenced the optical properties and charge-carrier behavior of the composite material. More importantly, antibacterial activity was assessed using *Staphylococcus aureus* (Gram-positive) and *Escherichia coli* (Gram-negative) as representative bacterial strains showed that ZnO/BPS-C composite demonstrated effects against the Gram-positive *Staphylococcus aureus*, whereas its impact on the Gram-negative *Escherichia coli* compared to pure ZnO. The observed photo-antibacterial activity may be associated with ROS generation from the ZnO phase under light irradiation. Lower *E. coli* sensitivity (maximum inhibition zone 7.23 mm) may be associated with the protective lipopolysaccharide rich outer membrane; pristine BPS-C showed no activity (6.00 mm). These finding demonstrate the feasibility of utilizing banana pseudo-stem as a sustainable biomass precursor for ZnO/carbon composite fabrication. Moreover, the ZnO/BPS-C nanocomposite emerges as a promising sustainable candidate for photo-antibacterial applications.

Keywords

Photo-Antibacterial Agent, ZnO/Carbon Nanomaterial Composite, Banana Pseudo-Stem

Received: 13 April 2026, Accepted: 14 August 2026

<https://doi.org/10.26554/sti.2026.11.4.1608-1618>

1. INTRODUCTION

Bacterial infections remain a primary global health challenge, particularly in Indonesia, where they significantly contribute to high morbidity and mortality rates across all age groups (Ministry of Health of the Republic of Indonesia, 2024). Recent studies have reported a high prevalence of *Escherichia coli* (70.4%) and *Staphylococcus aureus* (55.2%) in environmental samples, many of which exhibit multi-drug resistance (Tyasningsih et al., 2022). This issue is further exacerbated by nosocomial infection rates reaching 10-15%, creating a substantial socio-economic burden and necessitating the development of intensive infection control strategies (Winarno and Octavia, 2025). In this context, advanced materials have emerged as potential replacements for conventional antibiotics, particularly in overcoming the limitation associated with antimicrobial resistance. Among these, nanoparticle-based system has gained

increasing attention due to their potential as effective antibacterial agents, as they exhibit unique mechanisms. Specifically, nanoparticles can bypass bacterial drug resistance by penetrating the cell wall and membrane, disrupting essential molecular processes, and inhibiting biofilm formation as well as other virulence-related mechanisms (Ozdal and Gurkok, 2022).

Building upon these findings, various alternative strategies have been developed to address antimicrobial resistance, including the use of gold and silver nanoparticles, as well as photocatalytic and photodynamic systems (Rabiee et al., 2022). Among these, nanomaterials composed of carbon are recognized as highly favorable candidates due to their high surface area, excellent optical properties, and chemical stability (Dong et al., 2018). Microbial membranes and DNA can be effectively damaged by Reactive Oxygen Species (ROS) including singlet oxygen (1O_2) and hydroxyl radicals ($\bullet OH$), produced by these materials (Meziani et al., 2016). Recent trends have

shifted toward integrating carbon materials with inorganic semiconductors like Zinc Oxide (ZnO) to enhance photocatalytic efficiency. The appropriate bandgap of ZnO has made it a well-known material in this field, allowing it to interact with bacterial cells and inhibit growth through ROS generation (Sirelkhatim et al., 2015; Baig et al., 2025). Nevertheless, the conventional synthesis of ZnO is generally associated with high energy consumption, toxic chemical reagents, and complex processing steps, limiting their environmental sustainability and large-scale applicability. Moreover, converting biological waste into carbon structures through pyrolysis or hydrothermal treatment is rapidly gaining attention as an eco-friendly and cost-effective approach (Khan et al., 2019).

Despite these advancements, research concerning carbon nanomaterials derived specifically from banana pseudo-stem remains relatively limited. While previous studies have explored precursors like peanut shells (Ilhami et al., 2024) or coconut husks (Sharma et al., 2024), the high lignocellulose content (60-65% cellulose) of banana pseudo-stem offers potential as a sustainable carbon precursor for biomass-derived carbon materials for producing aromatic carbon structures with active surface functional groups (Nahda et al., 2025). Banana pseudo-stem is an abundant agricultural waste with low economic value and high cellulose content, making it a promising precursor for biomass-derived carbon materials. In addition, the presence of oxygen-containing functional groups may facilitate interaction with metal oxide particles and contribute to composite formation. Only limited studies have investigated the synergistic effect between banana pseudo-stem derived nanocarbon and ZnO/BPS-C composite for photo-antibacterial applications. Herein, we successfully synthesized a banana pseudo-stem based ZnO/carbon nanocomposite and evaluated its photo-antibacterial activity against Gram-positive bacteria (*Staphylococcus aureus*) and Gram-negative bacteria (*Escherichia coli*). This study aims to provide a sustainable solution for infection control while contributing to repurposing agricultural and industrial byproducts for applications in medicine and environmental sustainability. Overall, this material demonstrates capacity for application in sustainable material design for future photo-antibacterial application.

2. EXPERIMENTAL SECTION

2.1 Materials

The primary carbon precursor used in this study was dried banana pseudo-stem (*Musa paradisiaca* L.), collected from local agricultural waste near Probolinggo, Indonesia. Reagents of analytical purity were employed in their as-received state, including Sodium Hydroxide (NaOH, 99%, Merck), Sodium Chloride (NaCl, 99.5%, Merck), and Zinc Acetate Dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$, 98%, Sigma-Aldrich) were employed for composite synthesis. Deionized water (DI, resistivity 18.2 M Ω -cm, Millipore) and Aquadest were employed for all synthesis and cleaning processes. For the antibacterial assay, the biological material included Mueller-Hinton Agar (MHA, Hi-Media) as the growth medium and a 0.5 McFarland standard

solution ($\sim 1.5 \times 10^8$ CFU/mL) for adjusting the bacterial suspension. Antibacterial evaluations were carried out using *Staphylococcus aureus* (ATCC 25923) and *Escherichia coli* (ATCC 25922), representing Gram-positive and Gram-negative bacteria, respectively. Ciprofloxacin antibiotic discs (5 μg , Oxoid) and sterile blank discs (6 mm diameter) were used as controls for the sensitivity tests.

2.2 Synthesis of Banana Pseudo-Stem Carbon

The banana pseudo-stem was first dried and cut into small pieces prior to carbonization. The dried samples were pyrolyzed in a furnace at 250°C for 2 h under limited oxygen. After cooling naturally to ambient temperature, the obtained product was pulverized into a fine powder. The obtained carbon was then sieved through a 100-mesh matrix for uniform particle sizing. Next, 0.1 g of carbon powder was dispersed in 50 mL of distilled water and ultrasonicated for 45 min to obtain a stable carbon suspension. The resulting dispersion was then filtered using a 0.22 μm syringe filter to remove larger particulates, yielding a stable carbon suspension suitable for subsequent characterization and further applications.

2.3 Preparation of Banana Pseudo-Stem Carbon/ZnO Composite

The synthesis of the BPS-C/ZnO composite was conducted using a modified hydrothermal method. Initially, 0.1 g of $\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$ was dissolved in 10 mL of DI water and subsequently mixed with 40 mL of BPS-C suspension under constant stirring at 600 rpm at room temperature. A sodium hydroxide solution was added dropwise until the mixture reached pH 10, followed by continuous stirring 600 rpm for 15 minutes (Ilhami et al., 2024). The obtained mixture was placed into 100 mL Teflon-lined stainless-steel autoclave, occupying approximately 50% of the total reactor volume, and heated at 120°C for 3 hours (Turdini et al., 2025; De Oliveira and da Silva Abreu, 2021). Following the reaction, the synthesized product was recovered by centrifugation at 7000 rpm for 5 minutes, followed by repeated washing with deionized water to remove impurities and neutralize the pH. The synthesized precipitate was dried at 60°C for 24 h and stored for further characterization and antibacterial testing. Prior to application, the suspension was filtered using a 0.22 μm syringe filter to ensure uniformity (Ilhami et al., 2024).

2.4 Characterization

2.4.1 X-ray Diffraction (XRD)

The structural phase evaluation was performed via XRD analysis using a MiniFlex600 X-ray diffractometer (Rigaku, Japan) in the 2θ range 10-80°, employing Cu K α radiation ($\lambda = 1.5419$ Å) operated at 30 kV and 10 mA.

2.4.2 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier-transform infrared (FTIR) spectra were acquired using the potassium bromide (KBr) pellet technique with Nicolet Summit Lite spectrophotometer (Thermo Scientific, USA).

to investigate the functional group and chemical interactions in pristine BPS-C, ZnO, and BPS-C/ZnO composite. Data acquisition was carried out across the 600-4000 cm^{-1} spectral region.

2.4.3 Scanning Electron Microscopy (SEM)

Scanning electron microscopy paired with energy-dispersive X-ray spectroscopy (SEM-EDS) was employed for characterization and performed using a JSM-6500 instrument (JEOL, Japan) to evaluate the surface microstructures and elemental distribution of prepared material.

2.4.4 Dynamic Light Scattering (DLS)

Dynamic light scattering (DLS) analysis was employed to measure the hydrodynamic particle diameter and size distribution of the specimens. Dispersion stability was assessed at room temperature of pristine BPS-C, ZnO, and ZnO/BPS-C composites.

2.4.5 UV-Vis Spectrophotometry

The UV-Vis absorption spectra of pristine BPS-C and ZnO/BPS-C composites were recorded using UV-Vis spectrophotometer (Shimadzu UV-1800, Japan) over a wavelength range of 200-800 nm to evaluate their optical properties.

2.4.6 Photoluminescence Spectrophotometry

The photoluminescence (PL) spectra of pristine BPS-C and ZnO/BPS-C composites were acquired using a Shimadzu RF-6000 spectrofluorophotometer operating at an excitation wavelength (λ_{ex}) of 310 nm over an emission range of 290-800 nm.

2.5 Photo-antibacterial Activity Assay

The antibacterial efficacy of BPS-C, Pure ZnO, and ZnO/BPS-C composites was evaluated against *Escherichia coli* (Gram-Negative) and *Staphylococcus aureus* (Gram-Positive) bacterial strains via the agar well diffusion technique on Mueller-Hinton Agar (MHA). MHA medium was prepared according to the manufacturer's instructions, sterilized in an autoclave at 121°C for 15 minutes, and poured into Petri Dishes to solidify (Balouiri et al., 2016).

Bacterial suspensions were adjusted to a 0.5 McFarland standard ($1-2 \times 10^8$ CFU/mL) and inoculated uniformly into the MHA surface using sterile cotton swabs (CLSI, 2023). Samples were dispersed in sterile distilled water and sonicated to obtain homogeneous suspensions, then introduced into two conditions: dark (no light) and visible red-light laser (660nm) for 10 min. All plates were subsequently incubated at 37°C for 24 hours (Balouiri et al., 2016). Antibacterial potency was quantified by measuring the clear zone of inhibition diameters around each well, with the difference in zone size between dark and irradiated conditions serving as an indicator of photo-antibacterial efficiency.

3. RESULTS AND DISCUSSIONS

3.1 Synthesis of Banana Pseudo-Stem Carbon/ZnO Composite

In the synthesis stage, banana pseudo-stem (*Musa paradisiaca* L.) was prepared by washing, drying, and grinding into coarse powder, followed by carbonization at 250°C to obtain partially carbonized biomass-derived carbon. The relatively low carbonization temperature was selected to preserve oxygen-containing functional groups and to prevent complete decomposition of the biomass structure. At this temperature range, the resulting material is expected to consist of amorphous carbon-rich structures rather than highly graphitized carbon. ZnO was deposited onto the carbon surface via the hydrothermal method using zinc acetate precursor, forming the ZnO/BPS-C composite (Ilhami et al., 2024). Visually, increasing ZnO content shifted the powder color to brownish and increased fragility. This observation suggests enhanced ZnO loading and improved particle distribution on the carbon surface. Higher ZnO levels also promoted homogeneity of the mixture, reduced aggregation, and facilitated composite dispersibility. These observations will be verified through subsequent characterization to assess ZnO structure and morphology.

3.2 Structural Properties

The X-ray diffraction (XRD) patterns of BPS-C, pure ZnO, and the ZnO/BPS-C composite used to analyze the crystal structure are presented in Figure 1a. For BPS-C, XRD analysis reveals a singular, broad diffraction feature spanning $2\theta \approx 20-30^\circ$, which is characteristic of amorphous carbon materials. The absence of a sharp graphitic (002) peak confirms that the carbon derived from the pyrolysis of banana pseudo-stem is amorphous. Minor signals observed in this region likely originate from trace inorganic mineral residues commonly found in biomass-derived carbon (Nahda et al., 2025). In contrast, the diffraction patterns for both pure ZnO and the ZnO/BPS-C composite display sharp, well-defined peaks at $2\theta \approx 31.7^\circ$, 34.4° , 36.2° , 47.5° , 56.6° , 62.8° , and 68° . These peaks correspond to the (100), (002), (101), (102), (110), (103), and (112) crystallographic planes of the hexagonal wurtzite ZnO structure (PDF#36-1451). The emergence of these peaks in the composite sample confirms the successful formation of crystalline ZnO within the carbon matrix. The maximum diffraction peak of ZnO nanoparticles was observed at $2\theta = 36.23^\circ$, corresponding to the (101) plane of the hexagonal wurtzite structure, with lattice parameters $a = 3.291$ Å and $c = 5.200$ Å. Meanwhile, the ZnO/BPS-C composite exhibits its maximum diffraction peak at the 36.2° with lattice parameters $a = 3.256$ Å and $c = 5.200$ Å. The lattice parameter was determined using Equations (1) and (2) based on the (100) plane, while the lattice parameter c was calculated using Equations (3) and (4) based on the (002) plane.

$$d_{100} = \frac{\lambda}{2\sin\theta} \quad (1)$$

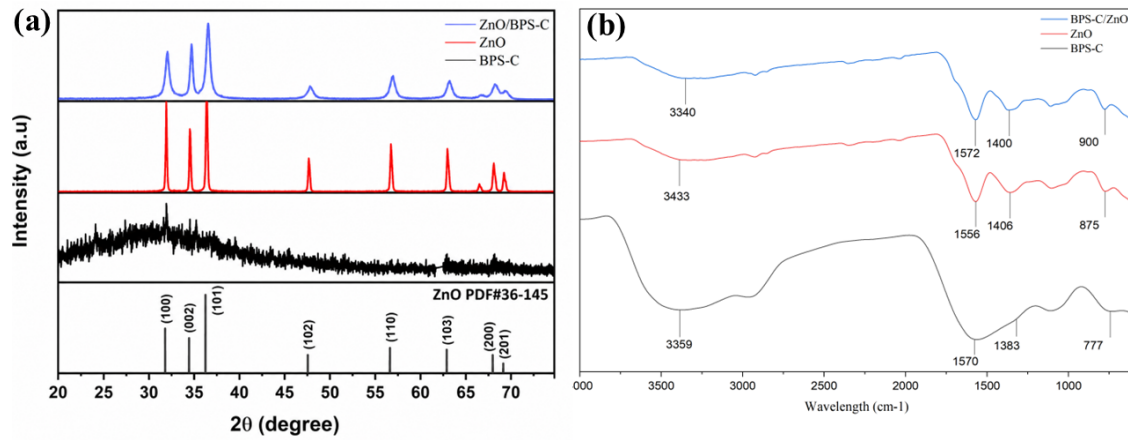


Figure 1. (a) XRD Patterns, (b) FTIR Spectra Recorded for Pristine BPS-C, Pure ZnO, and ZnO/BPS-C Nanocomposites

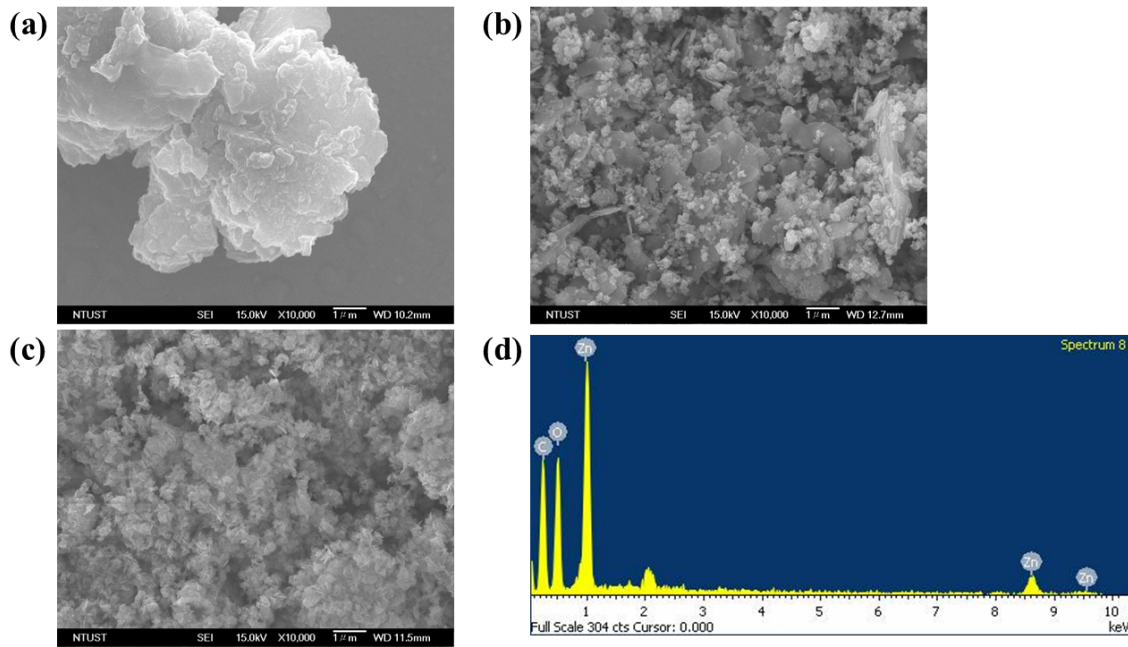


Figure 2. (a) SEM Image of BPS-C, (b) SEM Image of ZnO, (c) SEM Image of ZnO/BPS-C Composite, and (d) EDS Spectrum of the ZnO/BPS-C Composite

$$a = \frac{2}{\sqrt{3}} \times d_{100}$$

$$d_{002} = \frac{\lambda}{2 \sin \theta}$$

$$c = 2 \times d_{002}$$

$$D = \frac{k\lambda}{\beta \cos \theta}$$

(2) The crystallite size of ZnO and ZnO/BPS-C composite was further calculated using the Scherrer equation (Ilhami et al., 2024) based on the (101) diffraction peak, as expressed in Equation (5).

(3) The calculated crystallite size of pure ZnO was 40.7 nm whereas the ZnO/BPS-C composite exhibited a smaller crystallite size of 20.8 nm. The increase in FWHM value from 0.00385 rad to 0.0070 rad after BPS-C incorporation indicates reduced crystallinity and suppression of excessive ZnO crystal growth by the carbon matrix (Table 1). In addition, the lattice parameters of both samples remained relatively similar, indicating that the incorporation of BPS-C did not significantly alter the hexagonal wurtzite crystal structure of ZnO. Overall, these

Table 1. Average Crystalline Size and Unit Cell Lattice Parameters Evaluated for Pristine ZnO and the ZnO/BPS-C Calculated Using the Scherrer Equation

Sample	K	λ (nm)	β (rad)	$\cos \theta$	D (nm)	Lattice Parameters (Å)	
						a	c
ZnO	0.9	0.154	0.00385	0.95	40.7	3.291	5.200
ZnO/BPS-C	0.9	0.154	0.00700	0.95	20.8	3.256	5.200

Table 2. FTIR Wave Length

Functional Group	BPS-C (cm ⁻¹)	ZnO/BPS-C (cm ⁻¹)	ZnO (cm ⁻¹)	Frequency Area (cm ⁻¹)
O-H	3395	3340	3433	3200-3600
C=C	1570	1572	1556	1500-1600
C-H (Alkan)	1383	1400	1406	1340-1470
C-H (Alken)	777	900	875	675-995
Zn-O Stretching			~680	400-700

results suggest that BPS-C acts as a stabilizing matrix that limits particle growth and promotes smaller ZnO crystallites within the composite system. Next, FTIR analysis was performed in transmission mode to further evaluate the presence of BPS-C in the ZnO/BPS-C composite heterostructure and to examine the interaction between ZnO and BPS-C. The FTIR spectra of BPS-C, ZnO, and ZnO/BPS-C composite revealed several primary absorption bands corresponding to the characteristic functional groups of each material (Table 2). A broad O-H stretching band was detected at 3395 cm⁻¹ (BPS-C), 3433 cm⁻¹ (ZnO), and 3340 cm⁻¹ (ZnO/BPS-C), falling within the 3200–3600 cm⁻¹ range. This indicates the presence of hydroxyl groups or adsorbed water molecules on the surface of all three materials presented in Figure 1b (Lestari et al., 2026). Absorption bands in the 1500–1600 cm⁻¹ region—specifically at 1570 cm⁻¹ (BPS-C) (Chaves Fernandes et al., 2020), 1556 cm⁻¹ (ZnO), and 1572 cm⁻¹ (ZnO/BPS-C)—are attributed to aromatic C=C stretching vibrations. This confirms the aromatic framework of the carbon and suggests a contribution from C=C/C=O vibrations from residual organic species or defects on ZnO (Rahmat et al., 2023). Furthermore, the bands observed between 1383 and 1406 cm⁻¹ for all samples correspond to the 1340–1470 cm⁻¹ range, which corresponds to the C-H bending and C-O stretching modes. These peaks demonstrate the presence of oxygenated functional groups and aliphatic traces within the material matrix (Wu et al., 2001). In the lower frequency region (675–995 cm⁻¹), BPS-C shows a peak at 777 cm⁻¹, representing the out-of-plane C-H aromatic bending (Wu et al., 2001). Additionally, the absorption band observed around 670-690 cm⁻¹ may be attributed to Zn-O stretching vibration, confirming the formation of ZnO within the composite structure. The FTIR profiles confirm the presence of O-H, aromatic C=C, oxygenated groups (C-H/C-O), and Zn-O bonds within the composite. Overall, these find-

ings verify the successful integration and interaction between BPS-C and ZnO in the synthesized material. This interaction is further corroborated by X-ray diffractions data, where the slight decrease in peak intensity and a modest increase in the full width at half maximum (FWHM) were observed in the composite compared to pure ZnO. These observations further support the interaction between ZnO nanoparticles and the carbon matrix.

3.3 Morphological Properties

The surface morphological characteristics of BPS-C, pure ZnO, and the ZnO/BPS-C composite were characterized using Scanning Electron Microscopy (SEM) analysis. The SEM micrograph of BPS-C in Figure 2(a) clearly showed a bulky structure with an irregular surface and distinct flaky characteristics. In contrast, Figure 2(b) displayed the morphology of pure ZnO, consisting of dense and uniform nanoparticle assemblies resembling nanoplatelets. Upon the formation of the ZnO/BPS-C composite (Figure 2(c)), a significant transformation in surface texture is observed. Smaller ZnO particles appear relatively well distributed on the surface and within the interstices of the BPS-C carbon matrix (Salah et al., 2024). This indicates that BPS-C effectively serves as a supporting scaffold, partially suppressing ZnO nanoparticle agglomeration while providing an active surface area for material interaction. However, some degree of particle aggregation was still observed in the composite morphology, which is consistent with the DLS results showing relatively large hydrodynamic particle size. The successful synthesis and elemental purity were confirmed by Energy-Dispersive X-ray Spectroscopy (EDS) analysis, as shown in Figure 2(d). The EDS spectrum of the composite sample exhibited sharp characteristic peaks for Carbon (C), Oxygen (O), and Zinc (Zn). The presence of the C peak represents the carbon matrix derived from BPS-C, while

the emergence of Zn peaks at approximately 1 keV and 8.6 keV confirms the presence of the zinc oxide phase within the sample (Allwar and Setianingrum, 2020). Furthermore, the absence of significant peaks corresponding to foreign elements confirming the successful synthesis and structural integration of the ZnO/BPS-C composite with minimal detectable impurities. Subsequently, the hydrodynamic particle size was determined using DLS analysis. The data showed that the ZnO/BPS-C composite exhibited a considerably smaller hydrodynamic particle size (377 nm) compared to pure ZnO (826 nm), as shown in Figure 3(a). The largest hydrodynamic particle size was observed in BPS-C (19,602 nm), as shown in Figure 3(b). This unusually large size is attributed to the strong aggregation tendency of biomass-derived carbon particles in aqueous suspension, resulting in the formation of bulk agglomerates rather than individual nanoparticles (Li et al., 2020). In comparison, pure ZnO relatively a narrower size distribution. Nevertheless, its relatively large hydrodynamic diameter (826 nm) suggests significant nanoparticle agglomeration within the aqueous suspension. The ZnO/BPS-C composite demonstrates a significant reduction in hydrodynamic particle size compared to pristine BPS-C and pure ZnO. The BPS-C framework serves as an effective supporting scaffold, promoting uniform dispersion and inhibiting excessive agglomeration, which may contribute to improved particle dispersion within the composite system (Salah et al., 2024). Therefore, this synergistic interaction between ZnO and BPS-C demonstrate the suitability of the composite for environmental and antibacterial applications. It should be noted that DLS measurements represent the hydrodynamic diameter of particle agglomerates in aqueous media rather than the primary particle size. The significantly reduced hydrodynamic size of ZnO/BPS-C composite suggests improved colloidal stability, which can be ascribed to the abundance of oxygen-bearing functional groups on the BPS-C surface. These Functional groups likely provide steric and electrostatic stabilization, thereby suppressing particle aggregation and facilitating more homogeneous dispersion of ZnO nanoparticles within carbon matrix.

3.4 Optical Properties

The optical properties of BPS-C, ZnO, and ZnO/BPS-C composite were initially investigated using UV-Vis spectroscopy and Tauc plot analysis, as presented in Figure 4(a). The BPS-C samples exhibits an absorption peak at 266 nm, which is attributed to π - π^* electronic transitions within conjugated carbon aromatic domains. Pure ZnO shows an absorption peak at the 352 nm, corresponding to its intrinsic band to band transitions. For the ZnO/BPS-C composite, the absorption peak was observed at 353 nm, indicating a slight redshift (~ 1 nm) relative to pure ZnO. This confirms that the primary optical absorption feature of ZnO were obtained while demonstrating interfacial electronic interactions between the ZnO nanostructures and the BPS-C matrix. To evaluate the optical bandgap energy (Eg), Tauc plot analysis was performed using the $(\alpha h\nu)^2$ versus $h\nu$ relation for direct allowed optical transitions, as presented in

Figure 4(b). The Eg values were determined by extrapolating the linear region of the $(\alpha h\nu)^2$ curve to the photon energy axis ($Y=0$). The resulting Eg values were 3.36 eV for pure ZnO, 3.32 eV for the ZnO/BPS-C composite, and 3.10 eV for BPS-C. The slight reduction in Eg for ZnO/BPS-C compared to pure ZnO indicates a modest modification of the optical band structure following incorporation of the carbonaceous matrix, potentially extending the optical response toward lower photon energies.

The charge carrier dynamics of BPS-C and the ZnO/BPS-C composite were further investigated using photoluminescence (PL) spectroscopy under an excitation wavelength of 415 nm (2.99 eV). As shown in Figure 4(c), both samples exhibit a broad emission peak in the 480–500 nm range which is associated with radiative recombination via surface defect states, localized electronic states, and oxygen-containing functional groups within the carbon network. The ZnO/BPS-C composite exhibited the highest emission intensity (9012 a.u.), followed closely by pure BPS-C (8786 a.u.), whereas pure ZnO displayed a remarkably low PL intensity (328 a.u.). the minimal emission in pure ZnO occurs because excitation photon energy (2.99 eV) is below its optical bandgap (3.36 eV), preventing direct band to band excitation. Conversely, the enhanced PL intensity in the composite suggest an increased probability of radiative recombination, which may be associated with a greater contribution of defect mediated or localized emissive states following the composite formation. Figure 4(d) shows photos of the ZnO/BPS-C composite, pure ZnO, and BPS-C carbon under visible light and UV radiation, clearly showing their fluorescence. Overall, the UV-Vis and PL result demonstrate that incorporation of BPS-C modifies the optical absorption and emission characteristics of ZnO, accompanied by an increase in radiative recombination in the composite. These optical characteristics provide a basis for further evaluation of the photo-antibacterial performance of ZnO/BPS-C.

3.5 Antibacterial and Photo-antibacterial Activity

The antibacterial and photo-antibacterial efficiencies of BPS-C, pure ZnO, and the ZnO/BPS-C composite were evaluated against *Staphylococcus aureus* and *Escherichia coli* using the inhibition zone method. All assays were conducted in triplicate ($n=3$), with data expressed as the mean $\pm$ standard deviation (SD). Based on the data presented in Figure 6(b), the BPS-C material did not exhibit significant antibacterial activity, with the inhibition zone diameter remaining at 6.00 ± 0.00 mm (equivalent to the well diameter) under both dark and light conditions. By comparison, the ZnO/BPS-C composite displayed markedly higher antibacterial activity than pure ZnO. Under dark conditions against *Staphylococcus aureus*, the ZnO/BPS-C composite produced an inhibition zone of 12.96 ± 2.43 mm, whereas pure ZnO achieved only 6.89 ± 0.98 mm. These results are visually represented in Figure 5(a, b), where the ZnO/BPS-C composite sample shows a clear zone against *Staphylococcus aureus*, while no such zone is observed for *Escherichia coli*. The

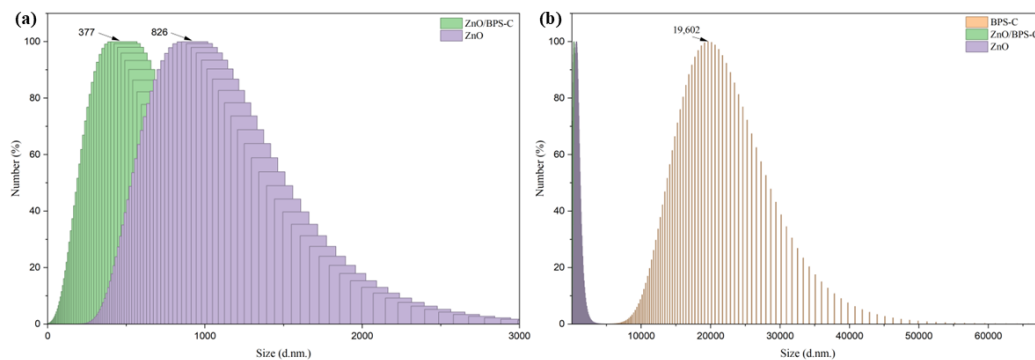


Figure 3. (a) DLS Particle Size Distribution of ZnO and ZnO/BPS-C Composite, and (b) DLS Size Distribution Analysis Depicting the Particle Size and Dispersivity of BPS-C

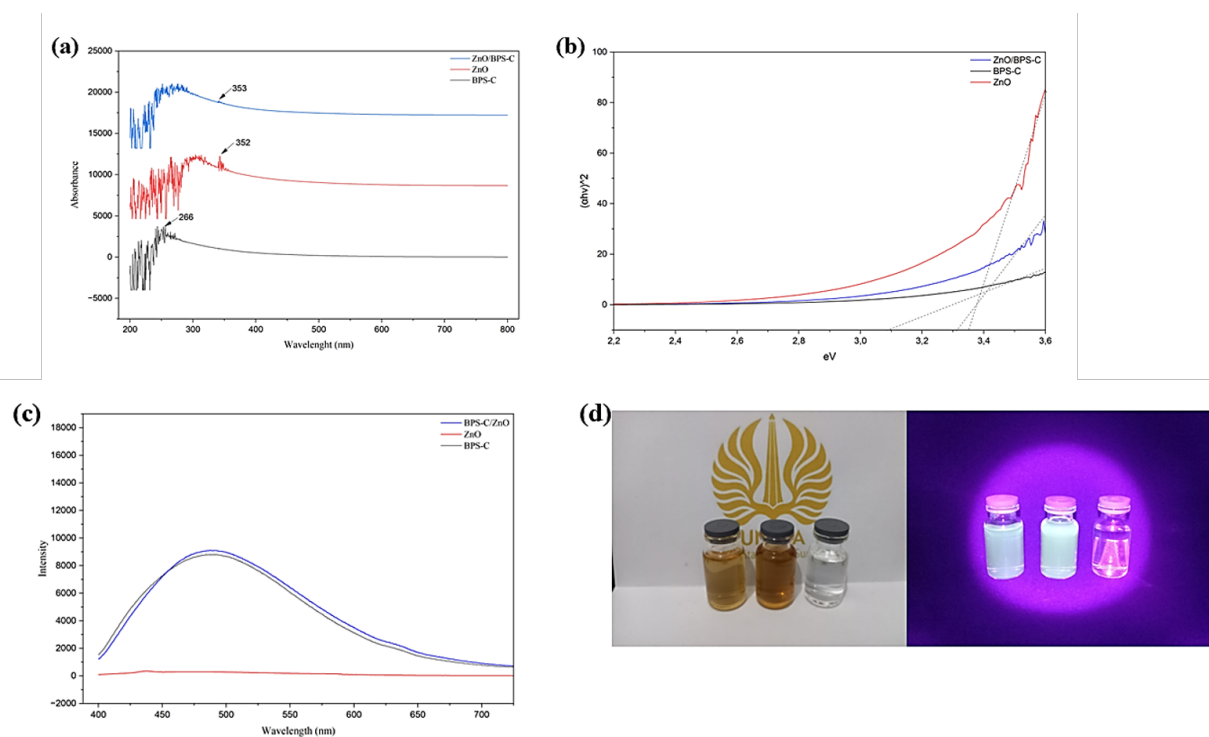


Figure 4. (a) UV-Vis Spectra Composite, (b) Tauc Plot Spectra of ZnO, BPS-C, and ZnO/BPS-C, (c) PL Spectra of ZnO, BPS-C, and ZnO/BPS-C Composite, and (d) Visual Appearance of the Samples Under Ambient Light and UV Irradiation

antibacterial activity of the composite was further enhanced under light exposure (photo-antibacterial activity). As shown in Figure 6(a), the inhibition zone against *Staphylococcus aureus* increased to 14.16 ± 0.83 mm. This phenomenon suggests that the increased antibacterial potency is presumably linked to the photocatalytic process in the ZnO phase, which is proposed to involve the formation and accumulation of reactive oxygen species (ROS) under the light irradiation. ZnO is an II-VI transition metal functions as a wide bandgap semiconductor ($E_g \approx 3.3$ eV). Upon irradiation with energy equal to or greater than its band gap, electron-hole pairs are generated, wherein

electrons (e^-) are promoted to the conduction band (CB), leaving behind photogenerated holes (h^+) in the valence band (VB). These photo-generated holes exhibit strong oxidative potential, creating active sites which possess sufficient oxidative potential to oxidize water molecules (H_2O) or hydroxide ions (OH^-) to produce highly reactive species (Siddiqi et al., 2018). Subsequently, a cascading series of redox reactions occur, leading to the generation of reactive oxygen species (ROS), including hydroxyl radicals ($\bullet OH$) and superoxide radicals ($O_2\bullet^-$) (Yusof et al., 2019). Based on previous reports, the proposed formation of ROS in the ZnO/BPS-C composite system under light

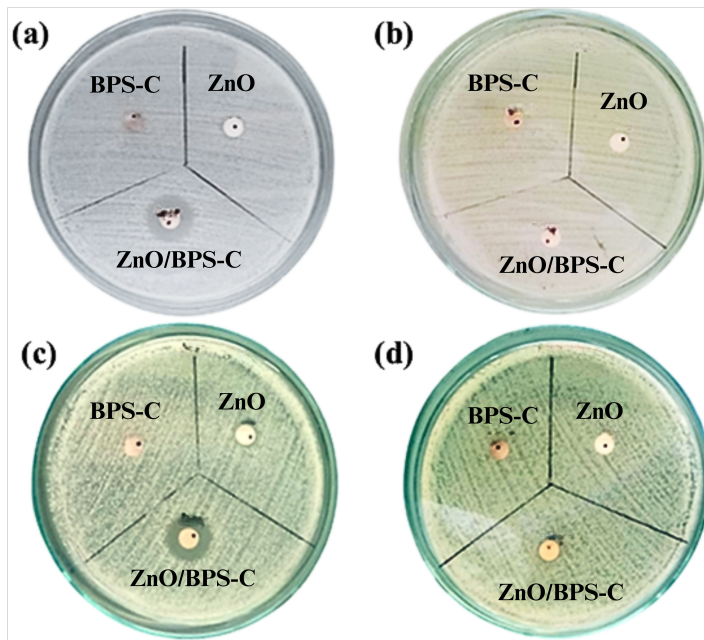


Figure 5. Antibacterial Inhibition Zones of the Samples Against (a) Gram-Positive *Staphylococcus aureus* and (b) Gram-Negative *Escherichia coli* Under Dark Conditions, (c) *Staphylococcus aureus* and (d) *Escherichia coli* Under IR Laser Irradiation, Demonstrating the Effect of Light Activation on Antibacterial Performance

irradiation may proceed through the reactions presented in Equations (6-12) and Figure 7.



The enhanced activity observed under light irradiation may be associated with photo-induced ROS generation in the antibacterial mechanism of the composite. Based on previous reports, the ROS species generated through the proposed reactions

may induce oxidative damage to bacterial cellular components, ultimately leading to cell death (Mendes et al., 2022). However, ROS generation was not directly measured in the present study, therefore this mechanism should be regarded as a proposed explanation rather than a confirmed finding.

The enhanced antibacterial activity observed under 660 nm irradiation may also be related to the role of the carbon matrix in improving the visible-light response of the composite. Although pure ZnO generally requires ultraviolet irradiation due to its wide band gap (~ 3.3 eV), the integration of carbonaceous matrices is widely documented to promote spatial charge separation, effectively retard photogenerated electron-hole recombination, and promote electron transfer under visible-light irradiation. Therefore, the BPS-C matrix may contribute to improving the utilization of the visible light and consequently enhancing the photo-antibacterial performance of the ZnO/BPS-C composite.

However, a distinct difference in sensitivity was observed between the two bacterial strains. The Gram-positive bacterium (*Staphylococcus aureus*) proved to be much more susceptible to the treatment than the Gram-negative bacterium (*Escherichia coli*). These results are in accordance with previous studies which reported that ZnO-based composites exhibit enhanced antibacterial activity, driven by the interfacial synergy established between the semiconductor oxide and the supporting carbon framework (Hao et al., 2024). As illustrated in Figure 5(c,d), the maximum inhibition zone for *Escherichia coli* only reached 7.23 ± 0.31 mm using the ZnO/BPS-C sample, whereas pure ZnO showed 6.34 ± 0.21 mm under light. The

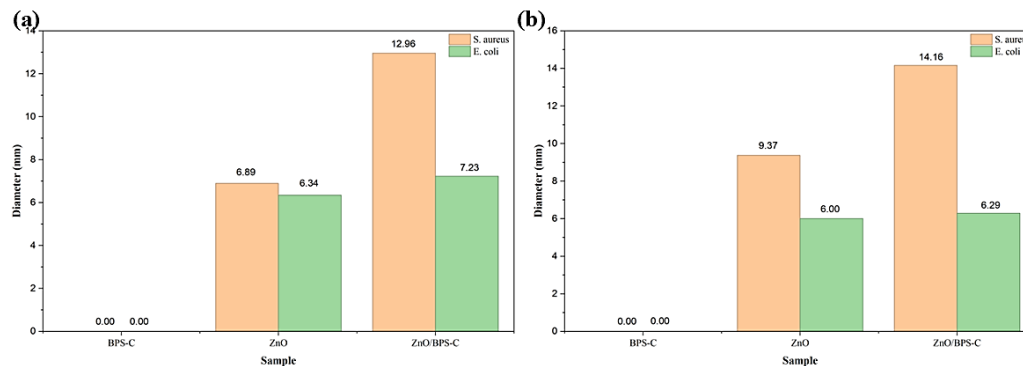


Figure 6. The Corresponding Inhibition Zone Diameters of BPS-C, ZnO, and ZnO/BPS-C Composite Against *Staphylococcus aureus* and *Escherichia coli* Are Presented in (a) Under IR Radiation and (b) Dark Conditions

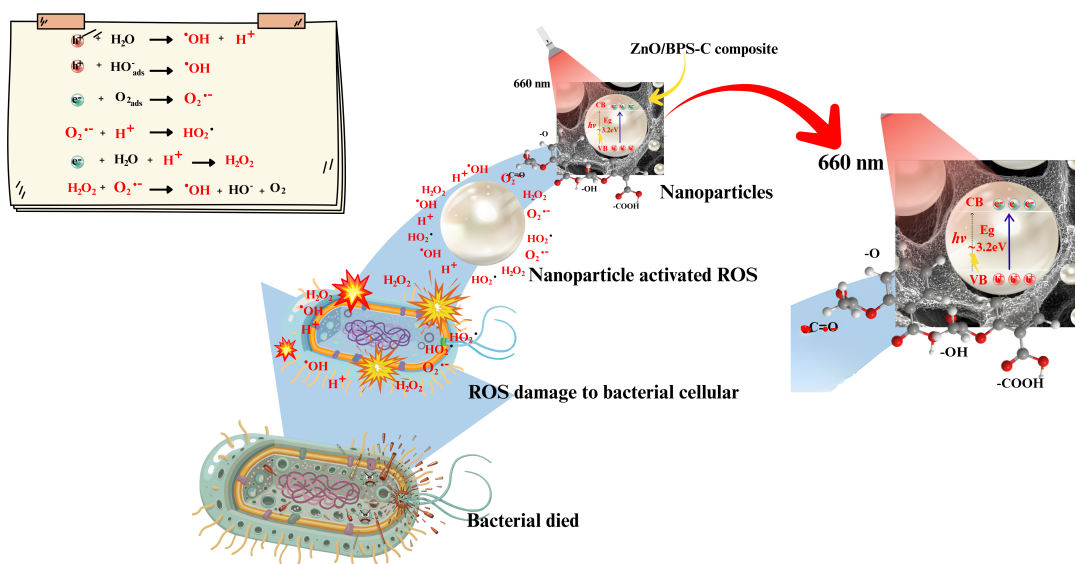


Figure 7. Schematic Illustration Depicting the Plausible Photo-Antibacterial Activity of the ZnO/BPS-C Composite Under 660 nm Irradiation, Highlighting Photogenerated Reactive Oxygen Species (ROS) Production and Subsequent Oxidative Destruction of Bacterial Membrane

lower sensitivity of *Escherichia coli* is likely attributed to the complex cell wall structure of Gram-negative bacteria. Gram-negative bacteria possess a distinct tripartite cell envelope featuring an inner cytoplasmic membrane (IM), a thin peptidoglycan layer, and an outer membrane (OM) enriched with lipopolysaccharides (LPS), protein, and lipoproteins (Fivenson et al., 2023; Ebbensgaard et al., 2018). This outer membrane acts as an additional permeability barrier against ROS and nanoparticle penetration, thereby reducing oxidative stress and limiting the interaction between antibacterial agents and intracellular targets. Consequently, Gram-negative bacteria generally exhibit lower susceptibility toward ZnO-based antibacterial materials than Gram-positive bacteria. These observations

align with prior literature, which indicates that ZnO-based materials exhibit higher antibacterial efficacy against Gram-positive strains relative to gram-negative species, a disparity primarily governed by variations in their envelope structure (Hao et al., 2024; Siddiqi et al., 2018). Overall, the data indicate that integrating ZnO into the BPS-C matrix contributes to enhanced photo-antibacterial activity through the interaction between ZnO nanoparticles and the carbon matrix. However, further experimental evidence such as ROS scavenger assays or electron spin resonance (ESR) analysis is required to confirm the exact contribution of ROS in the antibacterial mechanism.

4. CONCLUSIONS

This study successfully synthesized a sustainable photo-antibacterial composite consisting of crystalline Zinc Oxide (ZnO) nanoparticles and amorphous carbon derived from banana pseudo-stem (BPS-C) via a simple hydrothermal method. Structural and morphological characterizations (XRD, SEM-EDS, and FTIR) confirmed that the ZnO nanoparticles, exhibiting a hexagonal wurtzite structure, were homogeneously dispersed within the BPS-C matrix. UV-Vis analysis showed that the ZnO/BPS-C composite exhibited an absorption peak similar to pure ZnO, indicating the successful integration of the ZnO with the carbon matrix. Photoluminescence (PL) analysis further suggested that the incorporation of ZnO influenced the electron-hole dynamics within the composite system.

The ZnO/BPS-C composite demonstrated enhanced antibacterial performance compared to pure ZnO, particularly under visible light irradiation. The interfacial synergy established between the BPS-C support and the photocatalytic ZnO phase resulted in an inhibition zone of 14.16 mm against *Staphylococcus aureus*, can be ascribed to the collaborative synergy of ZnO and the carbon matrix, potentially involving photocatalytic processes. A lower antibacterial response was observed against *Escherichia coli* (7.23 mm), which is likely related to the structural characteristics of its outer membrane. Overall, these findings demonstrate the potential of banana pseudo-stem-derived carbon as a sustainable biomass precursor for the development of ZnO-based composite materials for antibacterial applications. However, the exact contributing of reactive oxygen species (ROS) in the antibacterial mechanism has not been experimentally verified in this study. Further investigation, such as ROS scavenging assays or electron spin resonance (ESR) analysis, are required to elucidate the detailed antibacterial mechanism.

5. ACKNOWLEDGEMENT

The authors express their sincere gratitude to the Laboratory of Gastroenterology and the Institute Tropical Disease (ITD), Universitas Airlangga, for providing excellent research facilities and technical support throughout this study. This research was conducted with support from the institutional research infrastructure at ITD Universitas Airlangga, Campus C, Surabaya, Indonesia.

REFERENCES

- Allwar, A. and I. Setianingrum (2020). Synthesis and Characterization of ZnO/Al₂O₃/activated Carbon Composite from Banana Fruit Bunch Using Hydrothermal Method. In *AIP Conference Proceedings*, volume 2229. AIP Publishing, page 030027
- Baig, A., M. Siddique, and S. Panchal (2025). A Review of Visible-Light-Active Zinc Oxide Photocatalysts for Environmental Application. *Catalysts*, **15**(2); 100
- Balouiri, M., M. Sadiki, and S. K. Ibnsouda (2016). Methods for in Vitro Evaluating Antimicrobial Activity: A Review. *Journal of Pharmaceutical Analysis*, **6**(2); 71–79
- Chaves Fernandes, B. C., K. Ferreira Mendes, A. F. Dias Júnior, V. P. da Silva Caldeira, T. M. da Silva Teófilo, T. Severo Silva, V. Mendonça, M. de Freitas Souza, and D. Valadão Silva (2020). Impact of Pyrolysis Temperature on the Properties of Eucalyptus Wood-Derived Biochar. *Materials*, **13**(24); 5841
- De Oliveira, B. P. and F. O. M. da Silva Abreu (2021). Carbon Quantum Dots Synthesis from Waste and By-Products: Perspectives and Challenges. *Materials Letters*, **282**; 128764
- Dong, X., A. E. Bond, N. Pan, M. Coleman, Y. Tang, Y.-P. Sun, and L. Yang (2018). Synergistic Photoactivated Antimicrobial Effects of Carbon Dots Combined with Dye Photosensitizers. *International Journal of Nanomedicine*, **13**; 8025–8035
- Ebbensgaard, A., H. Mordhorst, F. M. Aarestrup, and E. B. Hansen (2018). The Role of Outer Membrane Proteins and Lipopolysaccharides for the Sensitivity of *Escherichia Coli* to Antimicrobial Peptides. *Frontiers in Microbiology*, **9**; 2153
- Fivenson, E. M., P. D. A. Rohs, A. Vettiger, M. F. Sardis, G. Torres, A. Forchoh, and T. G. Bernhardt (2023). A Role for the Gram-Negative Outer Membrane in Bacterial Shape Determination. *Proceedings of the National Academy of Sciences of the United States of America*, **120**(35); e2301987120
- Hao, Y., Y. Wang, L. Zhang, F. Liu, Y. Jin, J. Long, S. Chen, G. Duan, and H. Yang (2024). Advances in Antibacterial Activity of Zinc Oxide Nanoparticles against *Staphylococcus Aureus* (Review). *Biomedical Reports*, **21**(5); 161
- Illhami, F. B., Munasir, N. S. Gultom, and C.-C. Cheng (2024). Zinc Oxide/carbon Material-Embedded Supramolecular Drug Delivery System with Photoswitching Properties for Highly Selective and Effective Chemotherapy. *ACS Applied Bio Materials*, **7**(8); 5506–5518
- Khan, T. A., A. S. Saud, S. S. Jamari, M. H. Ab Rahim, J. W. Park, and H. J. Kim (2019). Hydrothermal Carbonization of Lignocellulosic Biomass for Carbon-Rich Material Preparation: A Review. *Biomass and Bioenergy*, **130**; 105384
- Lestari, D., I. Masriaha, A. Y. P. Hasibuana, and P. B. Pratiwi (2026). FTIR Analysis of ZnO-Functionalized Activated Carbon Derived from Oil Palm Empty Fruit Bunches for Potential Photocatalytic Applications. *Jurnal Bio-Geo Material dan Energi*, **6**(1); 51–57
- Li, R., Y. Zhou, W. Li, J. Zhu, and W. Huang (2020). Structure Engineering in Biomass-Derived Carbon Materials for Electrochemical Energy Storage. *Research*, **2020**; 8685436
- Mendes, C. R., G. Dilarri, C. F. Forsan, V. M. R. Sapata, P. R. M. Lopes, P. B. de Moraes, R. N. Montagnolli, H. Ferreira, and E. D. Bidoia (2022). Antibacterial Action and Target Mechanisms of Zinc Oxide Nanoparticles against Bacterial Pathogens. *Scientific Reports*, **12**; 2658
- Meziani, M. J., X. Dong, L. Zhu, L. P. Jones, G. E. LeCroy, F. Yang, and Y.-P. Sun (2016). Visible-Light-Activated Bactericidal Functions of Carbon “quantum” Dots. *ACS Applied Materials & Interfaces*, **8**(17); 10761–10766

- Ministry of Health of the Republic of Indonesia (2024). Strengthening Antimicrobial Resistance Detection. Accessed: 2025-08-21
- Nahda, D. P., A. R. Sanjaya, F. Rahmawati, A. Zulfia, A. Sumbodja, R. K. Pramadewandaru, and T. A. Ivandini (2025). Synthesis of Mesoporous Carbon from Banana Peels with Silica Gel 60 As the Hard Templates. *RSC Advances*, **15**(6); 4536–4545
- Ozdal, M. and S. Gurkok (2022). Recent Advances in Nanoparticles As Antibacterial Agent. *ADMET & DMPK*, **10**(2); 115–129
- Rabiee, N., S. Ahmadi, O. Akhavan, and R. Luque (2022). Silver and Gold Nanoparticles for Antimicrobial Purposes against Multi-Drug Resistance Bacteria. *Materials*, **15**(5); 1799
- Rahmat, A., S. Sutiharni, Y. Elfina, Y. Yusnaini, H. Latuponu, F. N. Minah, and A. Mutolib (2023). Characteristics of Tamarind Seed Biochar at Different Pyrolysis Temperatures As Waste Management Strategy: Experiments and Bibliometric Analysis. *Indonesian Journal of Science and Technology*, **8**(3); 517–538
- Salah, W., W. Djeridi, A. Houas, and L. Elsellami (2024). Synergy between Activated Carbon and ZnO: A Powerful Combination for Selective Adsorption and Photocatalytic Degradation. *Materials Advances*, **5**(4); 1667–1675
- Sharma, R., J. Thakur, V. B. Jaryal, D. S. Rana, S. Thakur, N. Gupta, and D. Singh (2024). Nitrogen and Sulfur Functionalized Microporous Carbon Nanomaterial Derived from Waste Coconut Husk for the Efficient Detection and Removal of Ofloxacin. *Chemosphere*, **346**; 140653
- Siddiqi, K. S., A. Ur Rahman, N. Tajuddin, and A. Husen (2018). Properties of Zinc Oxide Nanoparticles and Their Activity against Microbes. *Nanoscale Research Letters*, **13**(1); 141
- Sirelkhatim, A., S. Mahmud, A. Seeni, N. H. H. Kaus, L. C. Ann, S. Y. Bakhori, H. Hasan, and D. Mohamad (2015). Review on Zinc Oxide Nanoparticles: Antibacterial Activity and Toxicity Mechanism. *Nano-Micro Letters*, **7**(3); 219–242
- Turdini, S., D. Mulyadi, and L. M. Yuningsih (2025). Hydrothermal Synthesis of Carbon Dots Derived from Biomass: A Simple and Sustainable Approach. *Jurnal Biologi Tropis*, **25**(3); 4206–4212
- Tyasningsih, W., S. C. Ramandinianto, R. Ansharieta, A. M. Witaningrum, D. A. Permatasari, D. K. Wardhana, M. H. Effendi, and E. N. Ugbo (2022). Prevalence and antibiotic resistance of *Staphylococcus aureus* and *Escherichia coli* isolated from raw milk in East Java, Indonesia. *Veterinary World*, **15**(8); 2021–2028
- Winarno, E. and C. Octavia (2025). Penyuluhan Kesehatan Pencegahan Infeksi Nosokomial di Rumah Sakit Mitra Medika Tanjung Mulia. *Jurnal Nusantara Berbakti*, **3**(1); 191–198
- Wu, J. G., Y. Z. Xu, C. W. Sun, R. D. Soloway, D. F. Xu, Q. G. Wu, and G. X. Xu (2001). Distinguishing Malignant from Normal Oral Tissues Using FTIR Fiber-Optic Techniques. *Biopolymers: Original Research on Biomolecules*, **62**(4); 185–192
- Yusof, N. A. A., N. M. Zain, and N. Pauzi (2019). Synthesis of ZnO Nanoparticles with Chitosan As Stabilizing Agent and Their Antibacterial Properties against Gram-Positive and Gram-Negative Bacteria. *International Journal of Biological Macromolecules*, **124**; 1132–1136