



Green Synthesis of Coconut Shell-based Nanobiochar and Its Antibacterial Activity against Pathogenic Bacteria

Vasamsetti Sai Sruthi¹, J. Aravind Kumar^{2*}, N Padmamalini³, R Venkatasubramanian⁴,
Veeramalli Naveen Sahithi¹ and Sorimuthu Revathi⁵

¹Department of Biotechnology, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Science (SIMATS), Chennai, TN, India

²Department of Energy and Environmental Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Science (SIMATS), Chennai, TN, India

³Department of Physics, St. Joseph's Institute of Technology, Chennai, TN, India

⁴Department of Electrical and Electronics Engineering, New Prince Shri Bhavani college of engineering and technology, Chennai, TN, India

⁵Department of Emergency Medicine, Saveetha Institute of Medical and Technical Science, Thandalam, TN, India

Received: 27.04.2026 Accepted: 29.05.2026 Published: 30.06.2026

*aravindkumarj.sse@saveetha.com



ABSTRACT

The development of sustainable nanomaterials from renewable biomass has gained attention in environmental nanotechnology. This is due to their low-cost production, functional surface properties, and potential biological and environmental applications. In the present study, coconut shell, an abundant lignocellulosic agro waste, was utilized as a precursor for the green synthesis of nanobiochar with antibacterial potential against selected pathogenic microorganisms. Coconut shell-derived biochar was produced through controlled pyrolysis, followed by chemical activation, acid purification, mechanical ball milling, ultrasonication, and particle-size fractionation to obtain nanobiochar. The synthesized nanomaterial was characterized using Fourier Transform Infrared Spectroscopy (FTIR), Dynamic Light Scattering (DLS), X-ray Diffraction (XRD), Scanning Electron Microscopy and Energy Dispersive X-ray analysis (SEM-EDAX). The FTIR analysis confirmed the presence of hydroxyl, carbonyl, aromatic, phenolic, and C–O functional groups, indicating chemically active surface moieties. The DLS analysis showed an average particle size of 308 nm, confirming the nanoscale formation. While the XRD revealed a predominantly amorphous to semi-amorphous carbon structure with limited graphitic ordering, the SEM-EDAX demonstrated rough, irregular, flake-like morphology with mineral-associated elemental composition. The antibacterial activity of nanobiochar was evaluated using agar well diffusion method against *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, and *Pseudomonas aeruginosa*. A dose-dependent increase in inhibition zones was observed from 25 μ L to 100 μ L, with the highest activity against *Staphylococcus aureus*. The findings suggest that coconut shell-derived nanobiochar is a promising green nanomaterial for microbial control, supporting its relevance in environmental, biological, and sustainable nanotechnology applications.

Keywords: Coconut shell; Nanobiochar; Green synthesis; Environmental nanotechnology; Sustainable environment; Antibacterial activity.

1. INTRODUCTION

The rapid spread of pathogenic bacteria and the increasing emergence of antimicrobial resistance have become major concerns for public health, environmental safety, and food security (Kannan *et al.* 2024). Conventional antibiotics and chemical disinfectants are gradually losing effectiveness due to resistance development, biofilm formation, and microbial adaptation (Hasan *et al.* 2024). In addition, many synthetic antibacterial agents are associated with ecological drawbacks such as toxic residues, poor biodegradability, and long-term environmental persistence (Polianciuc *et al.* 2020). These limitations have created a strong need for sustainable, low-toxicity, and effective antibacterial materials that can control microbial contamination through alternative mechanisms (Ren *et al.* 2026).

In recent years, biomass-derived carbon nanomaterials have gained attention because of their renewable origin, surface reactivity, tunable structure, and environmental compatibility (Guchhait *et al.* 2024). Among these materials, nanobiochar has emerged as a promising antibacterial candidate due to its porous carbon structure, high surface area, reactive functional groups, and ability to interact with microbial cells (Singh *et al.* 2026). Biochar is generally produced through the thermochemical conversion of biomass under oxygen-limited conditions (Pal and Mahmood, 2026; Li *et al.* 2026). When converted into nanoscale particles, its surface area, dispersibility, and number of active sites increase significantly, thereby improving its interaction with bacterial membranes and enhancing its potential biological activity (Bhandari *et al.* 2023). The choice of biomass precursor is important because it strongly

influences the physicochemical and antibacterial properties of nanobiochar. Coconut shell is an ideal feedstock due to its high lignin content, high fixed carbon fraction, low ash content, mechanical strength, and favorable pyrolytic behavior (Chaubey *et al.* 2024). It is also widely available as an agro-industrial waste, especially in tropical and subtropical regions. However, coconut shell is often underutilized or disposed of through open burning and low-value applications. Therefore, converting coconut shell waste into nanobiochar provides a sustainable waste-to-resource approach that supports biomass valorisation, circular bioeconomy, and green material development (Ajien *et al.* 2022).

The antibacterial activity of nanobiochar is mainly attributed to its multi-target mode of action. Unlike conventional antibiotics that usually act on specific cellular targets, nanobiochar may inhibit bacterial growth through surface adsorption, disruption of cell membrane integrity, oxidative stress generation, nutrient sequestration, and interference with cellular metabolism (Urper *et al.* 2026). Its surface functional groups, such as hydroxyl, carboxyl, phenolic, and carbonyl groups, may promote electrostatic and hydrophobic interactions with bacterial cell walls and membranes (De Rossi *et al.* 2025). These combined mechanisms may reduce the likelihood of rapid resistance development and make nanobiochar a suitable candidate for antibacterial applications (Mridha *et al.* 2025). Pathogenic bacteria such as *Escherichia coli*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Salmonella* spp., and *Klebsiella pneumoniae* are commonly associated with foodborne infections, hospital-acquired infections, wound contamination, and waterborne diseases (Kannan *et al.* 2026; Sahli *et al.* 2022). Since Gram-positive and Gram-negative bacteria differ in cell wall structure and membrane composition, their response to nanobiochar may vary (Beveridge, 1999). Therefore, evaluating coconut shell-derived nanobiochar against representative pathogenic bacteria is essential to understand its antibacterial effectiveness and possible mechanism of action. In the present study, coconut shell-derived nanobiochar was synthesized through a sustainable approach and evaluated for its antibacterial potential against pathogenic bacteria. The synthesized nanobiochar was characterized using Dynamic Light Scattering (DLS) for particle-size distribution, Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM-EDAX) for surface morphology and elemental composition, X-ray Diffraction (XRD) for crystalline nature, and Fourier Transform Infrared Spectroscopy (FTIR) for surface functional groups. Its antibacterial efficacy was assessed using standard microbiological assays such as disc diffusion and zone of inhibition methods (Katika and Boddu, 2025). This study highlights the potential of coconut shell waste as a renewable precursor for developing green antibacterial nanomaterials and

contributes to the broader field of sustainable nanobiotechnology.

2. METHODOLOGY

2.1 Preparation of Coconut Shell Biomass

The coconut shells were collected from local shops and sun dried for 7 days to remove moisture and avoid fungal growth. After drying, the shells were manually broken into small pieces using a clean hammer. The shell fragments were washed with tap water followed by and distilled water until all the dirt and debris were removed. The washed pieces were dried in a hot air oven at 80 °C for 24 hours to get an oven-dried biomass (Nuryana *et al.* 2020). The dried coconut shell pieces were then ground into smaller particles using a mechanical grinder and sieved to obtain uniform particle size (Chadar, 2025).

2.1.1 Production of Coconut Shell Biochar

The dried coconut shell powder was pyrolysed in an oxygen-starved environment. A ceramic crucible with a lid was filled with about 100 g of dried coconut shell powder and heated in a muffle furnace to 400-500 °C at 2-3 hours. The absence of oxygen favoured the pyrolysis of biomass to produce biochar. Once pyrolysis was complete, the furnace was cooled down to room temperature. The resulting black carbon product was carefully removed, crushed and kept in a sealed container for future use (Da Silva *et al.* 2024).

2.2 Purification of Biochar

The prepared biochar was chemically activated using potassium hydroxide through an alkali impregnation method. Briefly, biochar and KOH were mixed at a 1:1 weight ratio in 100 mL of deionized water and stirred continuously for 4 hours at room temperature to ensure uniform activation. The resulting slurry was dried at 80 °C overnight and subsequently reheated at 500 °C for 1 hour under limited oxygen conditions. After cooling, the activated biochar was washed thoroughly with 0.1 M HCl to remove residual inorganic impurities and unreacted KOH. Washing continued until neutral pH was achieved, followed by rinsing with deionized water and oven-drying at 80 °C for 12 hours (Fan and Zhang, 2025).

2.3 Preparation of Nanobiochar

The dried activated biochar was further processed to obtain nanobiochar through mechanical size reduction and ultrasonic dispersion. Briefly, the activated biochar powder was subjected to planetary ball milling at 300 rpm for 4 hours using zirconia milling jars and balls to reduce the particle size to the nanoscale range. The resulting milled powder was then dispersed in ethanol at

a concentration of 10 g L⁻¹ and ultrasonicated in a bath sonicator for 1 hour to break down particle aggregates and improve dispersion stability. After sonication, the suspension was centrifuged at 3000 rpm for 10 minutes to separate larger particles from the finer fraction. The supernatant containing uniformly dispersed nanobiochar particles was carefully collected. Ethanol was subsequently removed by rotary evaporation at 60 °C, and the concentrated nanobiochar fraction was oven-dried at 80 °C for 6 hour (Fig. 1). The final nanobiochar powder was stored in airtight vials for characterization and further experimental applications (Naghdi *et al.* 2017).

2.4 Characterization of Synthesised Nanobiochar

The synthesized coconut shell-derived nanobiochar was characterized using standard analytical techniques to confirm its nanoscale properties, structural features, surface morphology, elemental composition, and functional groups. Dynamic Light Scattering analysis was performed to determine the average particle size distribution and dispersion stability of the nanobiochar suspension. X-ray Diffraction analysis was used to evaluate the crystalline or amorphous nature of the synthesized nanobiochar. Surface morphology and particle structure were examined using SEM-EDAX analysis coupled with SEM was employed to determine the elemental composition of the sample. Fourier Transform Infrared Spectroscopy was carried out to identify the major surface functional groups present on the nanobiochar, including hydroxyl, carbonyl, carboxyl, and aromatic groups. These characterization techniques collectively confirmed the successful synthesis,

nanoscale formation, and physicochemical properties of coconut shell-derived nanobiochar (Aziz *et al.* 2023).

2.5 Application of Nanobiochar for Antibacterial Activity

The antibacterial activity of coconut shell-derived nanobiochar was assessed against *Escherichia coli*, *Staphylococcus spp.*, *Bacillus spp.*, and *Pseudomonas spp.* using the agar well diffusion method. Fresh bacterial cultures were maintained on nutrient agar slants and sub-cultured before analysis. The bacterial suspension was adjusted to standard turbidity and uniformly swabbed onto sterile nutrient agar plates. Wells were prepared aseptically using a sterile corkborer, and nanobiochar suspension was added into each well. Plates were incubated at 37 °C for 24 hours. A standard antibiotic was maintained as positive control, while sterile distilled water served as negative control. Antibacterial activity was recorded by measuring inhibition zones in millimetres, similar to the way recorded by Sisay *et al.* (2023).

3. RESULTS AND DISCUSSION

3.1 Synthesis of Nanobiochar

Nanobiochar was successfully synthesized from coconut shell biomass through sequential drying, crushing, pyrolysis, chemical activation, acid washing, ball milling, ultrasonication, centrifugation, and ethanol removal, as illustrated in Fig. 1. The final product appeared as a fine, dark carbonaceous powder, confirming the effective transformation of coconut shell waste into value-added nanobiochar suitable for further characterization by FTIR, SEM-EDAX, XRD, and DLS.

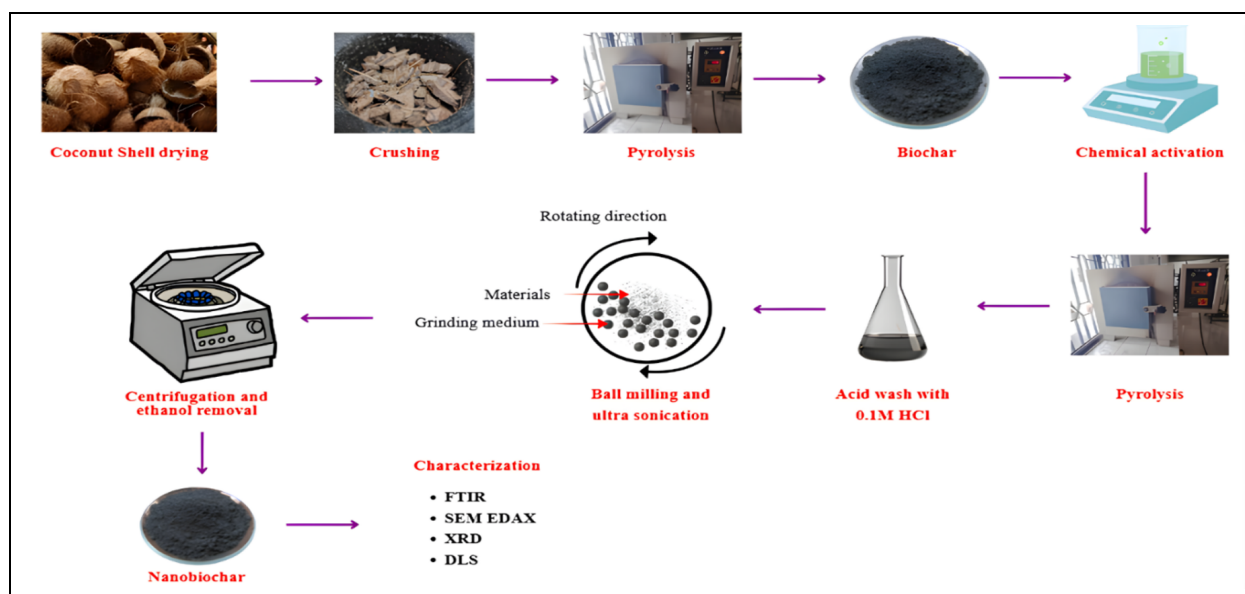


Fig. 1. Schematic representation of coconut shell-derived nanobiochar synthesis process

3.2 Characterization of Surface Functional Groups Using FTIR Spectroscopy

The FTIR spectrum of coconut shell derived nanobiochar reveals several characteristic peaks, confirming the successful conversion of lignocellulosic biomass into a functional carbonaceous nanomaterial. The weak bands around 3138–3004 cm^{-1} indicate the presence of surface hydroxyl groups and hydrogen-bonded –OH stretching, which may originate from residual phenolic, alcoholic, or adsorbed moisture groups (Zhou *et al.* 2022). The peaks observed at 2117 and 2001 cm^{-1} may be assigned to carbonized structural features, with the 2117 cm^{-1} peak corresponding to possible $\text{C}\equiv\text{C}$ stretching vibrations and the 2001 cm^{-1} peak indicating $\text{C}=\text{C}=\text{N}$ stretching or combination/overtone peaks associated with condensed aromatic carbon frameworks (Nandiyanto *et al.* 2019). A strong peak at 1602 cm^{-1} suggests conjugated $\text{C}=\text{O}$ groups, indicating the formation of stable aromatic domains during pyrolysis (Coates, 2000). Peaks at 1498, 1416, and 1382 cm^{-1} correspond to aromatic skeletal vibration, C–H bending, and phenolic/carboxylate-related groups (Al-Omran *et al.* 2023). The intense peaks between 1282 and 1047 cm^{-1} are associated with C–O, C–O–C, and phenolic stretching vibrations, reflecting oxygenated surface functionality (Alemdar *et al.* 2005). Lower-frequency peaks at 916, 831, and 764 cm^{-1} indicate aromatic C–H out-of-plane bending (Morsch *et al.* 2016). Overall, the spectrum confirms that coconut shell nanobiochar contains aromatic carbon networks with abundant oxygen-containing functional groups, supporting its surface reactivity and adsorption potential.

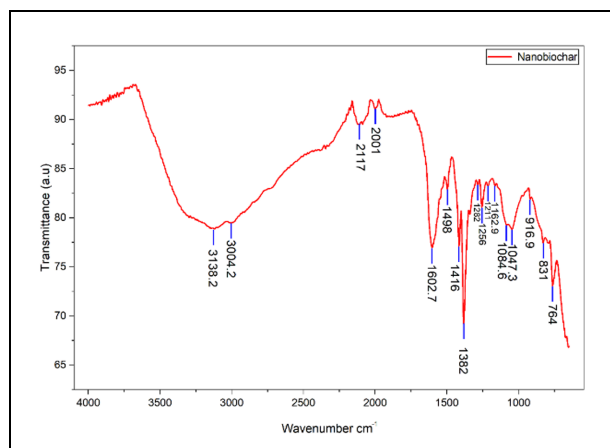


Fig. 2: FTIR spectrum of nanobiochar synthesised using coconut shell

3.3 Dynamic Light Scattering

Dynamic light scattering was employed to determine the hydrodynamic diameter and particle-size distribution of the synthesized nanobiochar in colloidal suspension by measuring Brownian motion-induced fluctuations in scattered light intensity. The nanoparticles

exhibited a z-average diameter of 308 nm, confirming their nanoscale dimension and indicating moderate dispersion stability (Fig. 3).

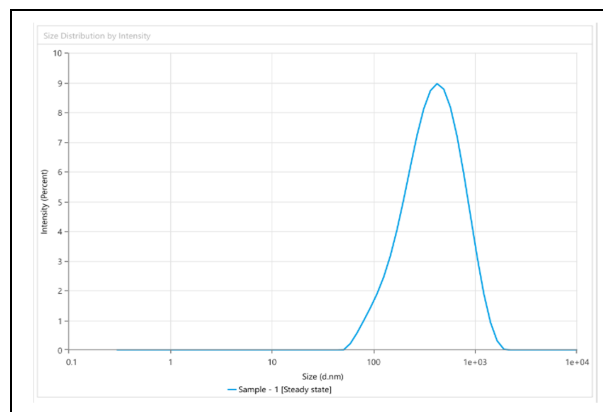


Fig. 3: Dynamic Light Scattering (DLS) analysis graph of synthesized nanobiochar

3.4 XRD Patterns of Nanobiochar Synthesised Using Coconut Shell

The XRD pattern of coconut shell-derived nanobiochar shows a predominantly broad and low-intensity diffraction profile, confirming the formation of an amorphous carbonaceous structure after pyrolysis, chemical activation, acid washing, ball milling, and ultrasonication. Several weak crystalline reflections were observed at approximately $2\theta = 5.0^\circ, 6.3^\circ, 8.3^\circ, 11.0^\circ, 12.6^\circ, 15.6^\circ,$ and 16.8° , which may be tentatively indexed to low-order planes such as (001), (010), (011), (020), (021), (110), and (111), indicating the presence of residual ordered carbon domains or trace mineral-associated phases (Koutenaei *et al.* 2022; Aftab *et al.* 2022; Özgün *et al.* 2025). The broader reflections around 23.8° and 25.5° can be indexed to the (002) lattice plane, characteristic of turbostratic or partially graphitized carbon structures. The peak near 35° may be assigned to the (100)/(101) plane, suggesting limited in-plane ordering of aromatic carbon layers (Fig. 4). The absence of sharp, highly intense peaks indicates poor long-range crystallinity, which is typical for biochar-derived nanomaterials (Ngernyen *et al.* 2023). The XRD results confirm that the synthesized nanobiochar possesses a semi-amorphous carbon framework with limited graphitic ordering, a structural feature favorable for high surface reactivity and adsorption behaviour.

3.5 SEM Coupled with EDAX of Coconut Shell-derived Nanobiochar

The SEM micrographs of coconut shell-derived nanobiochar revealed an irregular, fragmented, and rough surface morphology with flake-like carbonaceous particles distributed over a heterogeneous matrix. The surface showed visible grooves, cracks, layered textures, and fine particulate deposits, indicating that pyrolysis,

chemical activation, acid washing, ball milling, and ultrasonication effectively disrupted the original lignocellulosic structure. The presence of broken flakes and small agglomerated particles suggests successful size reduction and formation of nanobiochar with increased surface irregularity, which may enhance surface reactivity, adsorption sites, and interactions (Fig. 5a & 5b). The EDAX spectrum confirmed the mineral-rich nature of the synthesized nanobiochar. The major elements detected were Si (38.56 wt%) and O (31.92 wt%), followed by Zn (13.03 wt%), Cl (12.03 wt%), P (3.53 wt%), and Al (0.93 wt%) (Fig. 5c). The strong oxygen signal supports the presence of oxygen-containing functional groups, consistent with FTIR observations, while Si, P, Al, and Cl indicate residual inorganic/ash-associated components derived from coconut shell biomass and processing steps. Carbon was not prominently quantified in the displayed EDAX table, possibly due to instrumental setting or carbon-tape/background exclusion. Thus, SEM–EDAX confirms the successful development of structurally rough, mineral-associated nanobiochar with reactive surface characteristics.

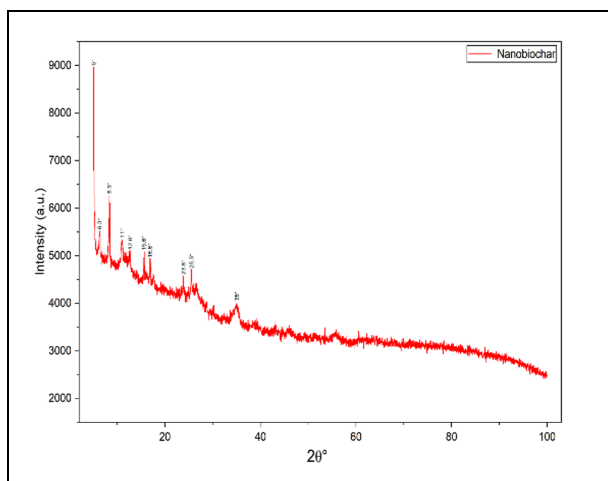


Fig. 4: XRD pattern of nanobiochar synthesised using coconut shell

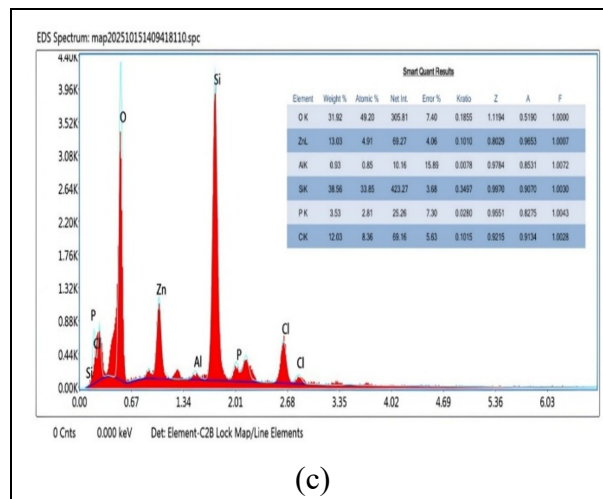
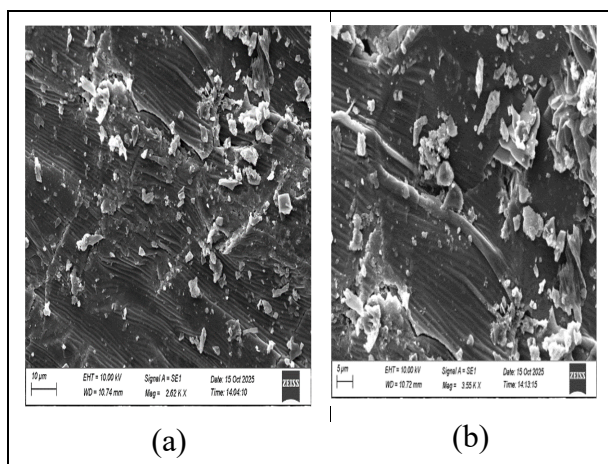


Fig. 5. (a) SEM image of coconut shell-derived nanobiochar at 2.62 KX magnification (b) SEM image at 3.55 KX magnification and (c) EDX spectrum of coconut shell-derived nanobiochar

3.6 *In vitro* Antibacterial Activity Assay

The antibacterial activity of coconut shell-derived nanobiochar showed a clear dose-dependent response against all tested bacterial strains. The inhibition zone increased progressively with increasing nanobiochar volume from 25 μ L to 100 μ L, indicating that higher nanobiochar loading enhanced antibacterial efficacy. Among the tested organisms, *Staphylococcus aureus* showed the highest sensitivity, followed by *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa*. The comparatively stronger inhibition against Gram-positive bacteria may be related to their relatively simpler cell wall structure, whereas the lower response of *Pseudomonas aeruginosa* may be associated with its higher intrinsic resistance and protective outer membrane characteristics (Sathe *et al.* 2023).

Table 1. Antibacterial activity of coconut shell-derived nanobiochar

Bacterial Strain	25 μ L	50 μ L	75 μ L	100 μ L	Positive Control	Negative Control
<i>Escherichia coli</i>	7.6 $\pm$ 0.3	10.4 $\pm$ 0.4	13.2 $\pm$ 0.5	15.6 $\pm$ 0.5	26.4 $\pm$ 0.7	0.0 $\pm$ 0.0
<i>Staphylococcus aureus</i>	9.8 $\pm$ 0.4	13.1 $\pm$ 0.5	16.4 $\pm$ 0.6	19.1 $\pm$ 0.6	30.2 $\pm$ 0.8	0.0 $\pm$ 0.0
<i>Bacillus subtilis</i>	8.9 $\pm$ 0.3	12.2 $\pm$ 0.4	15.3 $\pm$ 0.5	17.4 $\pm$ 0.5	28.5 $\pm$ 0.7	0.0 $\pm$ 0.0
<i>Pseudomonas aeruginosa</i>	6.5 $\pm$ 0.2	8.9 $\pm$ 0.3	11.1 $\pm$ 0.4	13.2 $\pm$ 0.4	24.3 $\pm$ 0.6	0.0 $\pm$ 0.0

At the maximum tested dose of 100 μ L, the nanobiochar produced inhibition zones ranging from 13.2 $\pm$ 0.4 mm to 19.1 $\pm$ 0.6 mm, confirming its

promising antibacterial potential (Table 1). The positive control exhibited the highest inhibition zones, validating the assay, while the negative control showed no inhibition (Fig. 6). The results suggest that coconut shell-derived nanobiochar possesses concentration-dependent antibacterial activity and may be considered a sustainable bio-based nanomaterial for antimicrobial applications.

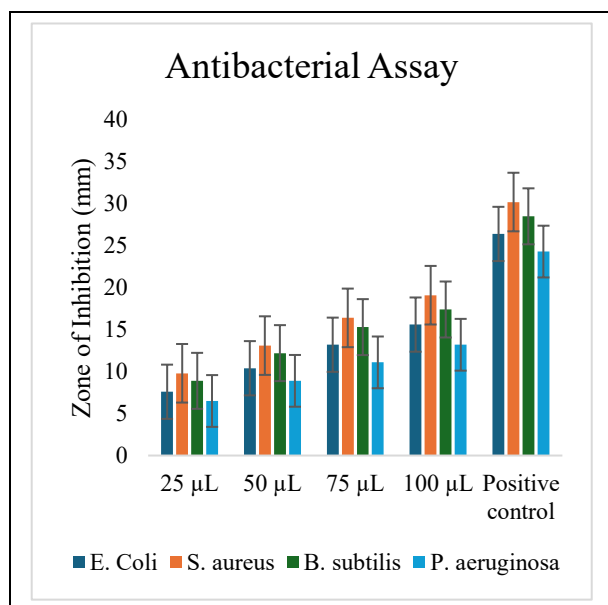


Fig. 5: Antibacterial activity of coconut shell-derived nanobiochar

4. CONCLUSION

The present study successfully demonstrated the green synthesis of coconut shell-derived nanobiochar as a sustainable and low-cost antibacterial nanomaterial. The characterization results confirmed the formation of functional nanobiochar with reactive surface groups, nanoscale particle distribution, semi-amorphous carbon structure, rough surface morphology, and mineral-associated elemental composition. FTIR indicated the presence of hydroxyl, carbonyl, aromatic, and C–O functional groups, while DLS confirmed nanoscale formation. XRD revealed a largely amorphous carbon framework, and SEM–EDAX showed irregular, flake-like particles with surface features that may enhance microbial interaction. The antibacterial assay revealed a clear concentration-dependent inhibition against *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, and *Pseudomonas aeruginosa*, with the strongest activity observed against *Staphylococcus aureus*. These findings suggest that coconut shell waste can be effectively converted into value-added nanobiochar for antimicrobial applications. Further studies should evaluate its mechanism of antibacterial action, cytotoxicity, long-term stability, activity against broader microbial strains, and practical application in water treatment, biomedical coatings, and environmental disinfection systems.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Aftab, Z., Aslam, W., Aftab, A., Shah, A. N., Akhter, A., Fakhar, U., Siddiqui, I., Ahmed, W., Majid, F., Wróbel, J., Ali, M. D., Aftab, M., Ahmed, M. A. A., Kalaji, H. M., Abbas, A. and Khalid, U., Incorporation of Engineered Nanoparticles of Biochar and Fly Ash Against Bacterial Leaf Spot of Pepper, *Sci. Rep.*, 12(1), 8561 (2022). <https://doi.org/10.1038/s41598-022-10795-8>
- Ajien, A., Idris, J., Sofwan, N. M., Husen, R. and Seli, H., Coconut Shell and Husk Biochar: A Review of Production and Activation Technology, Economic, Financial Aspect and Application, *Waste Manage. Res.*, 41(1), 37–51 (2022). <https://doi.org/10.1177/0734242x221127167>
- Alemdar, A., Güngör, N., Ece, O. I. and Atici, O., The Rheological Properties and Characterization of Bentonite Dispersions in the Presence of Non-Ionic Polymer PEG, *J. Mater. Sci.*, 40(1), 171–177 (2005). <https://doi.org/10.1007/s10853-005-5703-4>
- Al-Omran, A. M., Awad, M. M., Alghamdi, A. G. and Alkhasha, A., Impact of Nanoparticles from Ball-Milled Date Palm Biochar on the Hydro-Physical Characteristics of Sandy Soils, *Appl. Sci.*, 13(13), 7781 (2023). <https://doi.org/10.3390/app13137781>
- Aziz, S., Uzair, B., Ali, M.I., Anbreen, S., Umber, F., Khalid, M., Aljabali, A. A., Mishra, Y., Mishra, V., Serrano-Aroca, Á., Naikoo, G. A., El-Tanani, M., Haque, S., Almutary, A. G. and Tambuwala, M. M., Synthesis and Characterization of Nanobiochar from Rice Husk Biochar for the Removal of Safranin and Malachite Green from Water, *Environ. Res.*, 238, 116909 (2023). <https://doi.org/10.1016/j.envres.2023.116909>

- Beveridge, T. J., Structures of Gram-Negative Cell Walls and Their Derived Membrane Vesicles, *J. Bacteriol.*, 181(16), 4725–4733 (1999).
<https://doi.org/10.1128/jb.181.16.4725-4733.1999>
- Bhandari, G., Gangola, S., Dhasmana, A., Rajput, V., Gupta, S., Malik, S. and Slama, P., Nano-Biochar: Recent Progress, Challenges, and Opportunities for Sustainable Environmental Remediation, *Front. Microbio.*, 14, 1214870 (2023).
<https://doi.org/10.3389/fmicb.2023.1214870>
- Chadar, S. N., Synthesis and Characterization of Coconut Shell-Based Nanobiochar Produced by Controlled Pyrolysis for Dye Adsorption from Wastewater, *Res. Develop. Mater. Sci.*, 22(2), (2025).
<https://doi.org/10.31031/rdms.2025.22.001034>
- Chaubey, A. K., Pratap, T., Preetiva, B., Patel, M., Singsit, J. S., Pittman, C. U. and Mohan, D., Definitive Review of Nanobiochar, *ACS Omega*, 9(11), 12331–12379 (2024).
<https://doi.org/10.1021/acsomega.3c07804>
- Coates, J., Interpretation of Infrared Spectra, A Practical Approach, *Encyclopedia Anal. Chem.*, (2000).
<https://doi.org/10.1002/9780470027318.a5606>
- Da Silva, N. E. P., Bezerra, L. C. A., Araújo, R. F., Moura, T. A., Vieira, L. H. S., Alves, S. B. S., Fregolente, L. G., Ferreira, O. P. and Avelino, F., Coconut Shell-Based Biochars Produced by an Innovative Thermochemical Process for Obtaining Improved Lignocellulose-Based Adsorbents, *Int. J. Bio. Macromol.*, 275(Pt 2), 133685 (2024).
<https://doi.org/10.1016/j.ijbiomac.2024.133685>
- De Rossi, L., Rocchetti, G., Lucini, L. and Rebecchi, A., Antimicrobial Potential of Polyphenols: Mechanisms of Action and Microbial Responses—A Narrative Review, *Antiox.*, 14(2), 200 (2025).
<https://doi.org/10.3390/antiox14020200>
- Fan, W. and Zhang, X., Polydopamine Modified Coconut Shell Biochar Decorated with ZIF-8 for Improved Adsorption of Malachite Green and Rhodamine B from Aqueous Solution, *Environ. Res.*, 269, 120933 (2025).
<https://doi.org/10.1016/j.envres.2025.120933>
- Guchhait, S. K., Khatana, S., Saini, R. K., Pranay, Singh, A. D. and Sarma, A. K., Recent Advances in Biomass Derived Nano-Structured Carbon Materials for Low-Temperature Fuel Cell Application, *Appl. Catal. O Open*, 189, 206924 (2024).
<https://doi.org/10.1016/j.apcato.2024.206924>
- Hasan, N., Kannan, E. P., Hakami, O., Alamri, A. A., Gopal, J. and Muthu, M., Reviewing the Phenomenon of Antimicrobial Resistance in Hospital and Municipal Wastewaters: The Crisis, the Challenges and Mitigation Methods, *Appl. Sci.*, 14(18), 8358 (2024).
<https://doi.org/10.3390/app14188358>
- Kannan, E. P., Gopal, J. and Muthu, M., Analytical Techniques for Assessing Antimicrobial Resistance: Conventional Solutions, Contemporary Problems and Futuristic Outlooks, *TrAC Trends Anal. Chem.*, 178, 117843 (2024).
<https://doi.org/10.1016/j.trac.2024.117843>
- Kannan, E. P., Venkatachalam, P., Gopal, J., Sarkaraisamy, P. and Muthu, M., Antimicrobial Resistance Status of Small Marine Fishes off the Coastal Cities of East and West Coast of India: An Adaptive Nanopore Sequencing Based Metagenomics Raises Concerns, *Int. J. Bio. Macromol.*, 347, 150754 (2026).
<https://doi.org/10.1016/j.ijbiomac.2026.150754>
- Katika, R. M. and Boddu, S., Synthesis and Characterization of Nanobiochar for Enhanced Photo Decolouration of Azoic Dye, *J. Instit. Eng. (India): Series E*, 106(2), 115–128 (2025).
<https://doi.org/10.1007/s40034-025-00304-7>
- Koutenaci, S. S., Vatankhah, G. and Esmaeili, H., Ziziphus spina-christi Leaves Biochar Decorated with Fe₃O₄ and SDS for Sorption of Chromium (III) from Aqueous Solution, *Biomass Convers. Biorefine.*, 14(9), 10251–10264 (2022).
<https://doi.org/10.1007/s13399-022-03029-4>
- Li, P., Liu, Y., Sun, Y. and Zhang, C., Biochar Innovations for Organic Pollutant Remediation in Contaminated Soils, *Mol.*, 31(3), 432 (2026).
<https://doi.org/10.3390/molecules31030432>
- Morsch, S., Liu, Y., Greensmith, P., Lyon, S. B. and Gibbon, S. R., Molecularly Controlled Epoxy Network Nanostructures, *Polym.*, 108, 146–153 (2016).
<https://doi.org/10.1016/j.polymer.2016.11.050>
- Mridha, D., Lamsal, B. and Antonangelo, J. A., Nanotechnology in Agriculture: Innovations for Sustainability and Greenhouse Gas Mitigation—A Review, *Sci. Tot. Environ.*, 995, 180065 (2025).
<https://doi.org/10.1016/j.scitotenv.2025.180065>
- Naghdi, M., Taheran, M., Brar, S. K., Rouissi, T., Verma, M., Surampalli, R. Y. and Valero, J. R., A Green Method for Production of Nanobiochar by Ball Milling—Optimization and Characterization, *J. Clean. Prod.*, 164, 1394–1405 (2017).
<https://doi.org/10.1016/j.jclepro.2017.07.084>
- Nandiyanto, A. B. D., Oktiani, R. and Ragadhita, R., How to Read and Interpret FTIR Spectroscopy of Organic Material, *Indonesian J. Sci. Technol.*, 4(1), 97 (2019).
<https://doi.org/10.17509/ijost.v4i1.15806>
- Ngernyen, Y., Petsri, D., Sribanthao, K., Kongpenit, K., Pinijnam, P., Pedsakul, R. and Hunt, A. J., Adsorption of the Non-Steroidal Anti-Inflammatory Drug (Ibuprofen) onto Biochar and Magnetic Biochar Prepared from Chrysanthemum Waste of the Beverage Industry, *RSC Adv.*, 13(21), 14712–14728 (2023).
<https://doi.org/10.1039/d3ra01949g>

- Nuryana, D., Alim, M. F. R., Yahayu, M., Ahmad, M. A., Sulong, R. S. R., Aziz, M. F. S. A., Prasetyawan, H., Zakaria, Z. A. and Kusumaningtyas, R. D., Methylene Blue Removal Using Coconut Shell Biochar Synthesized Through Microwave-Assisted Pyrolysis, *Jurnal Teknologi*, 82(5), (2020). <https://doi.org/10.11113/jt.v82.14359>
- Özgün, M. İ., Erci, V., Madenci, E. and Erci, F., The Effect of Nano-Biochar Derived from Olive Waste on the Thermal and Mechanical Properties of Epoxy Composites, *Polym.*, 17(10), 1337 (2025). <https://doi.org/10.3390/polym17101337>
- Pal, G. and Mahmood, H. F., Adsorption and Removal Strategies of Biochar in Organic and Inorganic Pollutants Under Stress Conditions: Salinity, Drought, and Heavy Metals, *Biochar Remed. Tools Pollut. Removal*, 109–149 (2026). https://doi.org/10.1007/978-3-032-16746-0_5
- Polianciuc, S. I., Gurzău, A. E., Kiss, B., Ștefan, M. G. and Loghin, F., Antibiotics in the Environment: Causes and Consequences, *Med. Pharm. Rep.*, 93(3), 231–240 (2020). <https://doi.org/10.15386/mpr-1742>
- Ren, H., Gao, C., Huang, S., Du, L., Liu, S., Cao, X. and Lv, Y., Photocatalytic Antibacterial Mechanism and Biototoxicity Trade-Off of Metal-Doped M-ZIF-8 (M=Co, Cu): Progress and Challenges, *Inorg.*, 14(2), 43 (2026). <https://doi.org/10.3390/inorganics14020043>
- Sahli, C., Moya, S. E., Lomas, J. S., Gravier-Pelletier, C., Briandet, R. and Hémadi, M., Recent Advances in Nanotechnology for Eradicating Bacterial Biofilm, *Theranostics*, 12(5), 2383–2405 (2022). <https://doi.org/10.7150/thno.67296>
- Sathe, N., Beech, P., Croft, L., Suphioglu, C., Kapat, A. and Athan, E., *Pseudomonas aeruginosa*: Infections and Novel Approaches to Treatment “Knowing the Enemy” the Threat of *Pseudomonas aeruginosa* and Exploring Novel Approaches to Treatment, *Infect. Med.*, 2(3), 178–194 (2023). <https://doi.org/10.1016/j.imj.2023.05.003>
- Singh, P., Pathy, A., Sharma, S., Dhanorkar, M., Naeth, M. A. and Chang, S. X., Expanding the Frontiers of Nanobiochar and Biochar Nanocomposites as Versatile Biomaterials for Sustainable Development, *Biochar*, 8(1), 15(2026). <https://doi.org/10.1007/s42773-025-00523-6>
- Sisay, G. B., Bezabeh, B. and Getachew, E., Copper Oxide Nanobiochar from Spent Coffee Grounds for Phosphate Removal and Its Application as an Antibacterial Activity, *Res. Square*, (2023). <https://doi.org/10.21203/rs.3.rs-3758607/v1>
- Urper, O., Jothinarayanan, N., Sæbø, M., Joseph, S. and Wang, K., Photocatalytic and Antibacterial Characteristics of Biochar-Supported ZnO and TiO₂ Nanocomposites, *Clean. Waste Syst.*, 13, 100481 (2026). <https://doi.org/10.1016/j.clwas.2026.100481>
- Zhou, X., Chen, X., Han, W., Han, Y., Guo, M., Peng, Z., Fan, Z., Shi, Y. and Wan, S., Tetracycline Removal by Hercynite-Biochar from the Co-Pyrolysis of Red Mud-Steel Slag-Sludge, *Nanomater.*, 12(15), 2595 (2022). <https://doi.org/10.3390/nano12152595>