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REVIEW ARTICLE

Biochar and nanobiochar for antibacterial applications: Production, mechanisms, modifications, and environmental perspectives

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Abstract

The creation of sustainable nanomaterials from renewable biomass has become a focal point in environmental nanotechnology due to their affordability, widespread availability, adjustable surface properties, and potential use in environmental and biological contexts. In this regard, coconut shell—a common lignocellulosic agricultural byproduct—emerges as a promising source for producing nanobiochar. This material is generated by breaking down biochar to the nanoscale, which enhances its specific surface area, porosity, surface functionality, adsorption capacity, and catalytic activity compared to traditional biochar. Such attributes make nanobiochar a viable candidate for antimicrobial uses. The rising issue of antimicrobial resistance has created an urgent demand for alternative and eco-friendly antimicrobial agents that can effectively manage pathogenic and multidrug-resistant microorganisms. Nanobiochar can engage with microbial cells via surface adsorption, electrostatic interactions, membrane disruption, and reactive surface functionalities, effectively inhibiting bacterial proliferation and biofilm development. Waterborne pathogens, especially *Escherichia coli*, pose significant environmental and public health risks due to their link to gastrointestinal and systemic infections. Thus, nanobiochar derived from coconut shells holds promise as a sustainable antibacterial solution for water treatment and various environmental applications. This review covers the production, physicochemical properties, antibacterial mechanisms, and environmental uses of biochar and nanobiochar, with a particular focus on those derived from coconut shells. This reviewalso emphasizes the potential of nanobiochar to mitigate microbial contamination while facilitating the valorization of agricultural waste. Future investigations should aim to refine synthesis methods, clarify antibacterial mechanisms, evaluate environmental safety, and assess the long-term efficacy of nanobiochar in practical applications.

Keywords: Coconut shell; Biochar; Nanobiochar; Antibacterial activity; Antimicrobial resistance; Water treatment; Sustainable nanomaterials; Environmental applications

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1. Introduction

Biomass-derived carbonaceous materials have garnered considerable attention in environmental nanotechnology because of their affordability, eco-friendliness, and potential uses in healthcare, environmental cleanup, and microbial management. Among such materials, biochar (BC) and nanobiochar (nano-BC) stand out as promising carbon-

rich options because of their unique physicochemical attributes, porous structures, extensive surface areas, and varied surface functional groups. BC is typically produced through the thermochemical conversion of biomass in low-oxygen conditions, while nano-BC is derived from reducing BCto the nanoscale or through specific synthesis and modification techniques aimed at enhancing its surface properties (Bhandari *et al.*, 2023; Deepshikaa *et al.*, 2024).

The rising issue of antimicrobial resistance poses a significant global public health challenge, leading to an urgent demand for alternative antimicrobial materials effective against harmful microorganisms. Traditional antimicrobial agents often encounter limitations related to microbial resistance, environmental persistence, and toxicity concerns. In this context, carbon-based nanomaterials have emerged as an area of considerable research due to their physicochemical properties that enhance interactions with microbial cells. Nano-BC, in particular, offers a viable alternative as it can be sourced from low-cost renewable biomass and modified for better antimicrobial effectiveness. Recent studies have explored the antimicrobial capabilities of carbon nanostructures, emphasizing the growing significance of nano-BCcompared to other carbon-based nanomaterials (Nishshankage *et al.*, 2024; Sizov *et al.*, 2026). The antibacterial efficacy of BCand nano-BCis linked to various physicochemical features, including surface porosity, particle size, surface charge, functional groups, mineral makeup, and presence of reactive chemicals. These characteristics may affect bacterial adhesion, cell envelope integrity, oxidative stress, and the availability of essential nutrients or cellular components. Additionally, depending on the feedstock, production temperature, and modification method, BCmaterials may exhibit antimicrobial effects through adsorption. Their porous structures and functional surfaces may also disrupt microbial attachment and biofilm formation. However, the effectiveness of these mechanisms can differ based on the type of material and the target microorganism, necessitating further experimental validation to confirm their efficacy and safety (Min *et al.*, 2025; Nishshankage *et al.*, 2024). Nano-BCgenerated from biomass presents further opportunities for developing sustainable antimicrobial materials by transforming agricultural and forestry waste into valuable products. Resources such as coconut shells, rice husks, wheat straw, bamboo, and sugarcane bagasse serve as potential feedstocks for carbon-rich materials. Notably, coconut shells are particularly appealing due to their availability and lignocellulosic composition. Sruthi *et al.* (2026) examined the environmentally friendly synthesis of coconut-shell-based nano-BCand its antibacterial effects against pathogenic bacteria, underscoring the promise of waste-derived nanomaterials for antimicrobial applications. Such approaches not only enhance waste valorization but may also decrease reliance on traditional raw materials. Nonetheless, the environmental advantages of nano-BCproduction depend on synthesis conditions, energy consumption, chemical inputs, and the responsible management of the resultant materials.

The use of nano-BCin water disinfection is another promising area of research. Microbial contamination in drinking water is a major public health challenge, particularly in areas without reliable water-treatment systems. *Escherichia coli*, a significant indicator of fecal contamination, is linked to severe gastrointestinal infections and health issues. Consequently, BC-based nanocomposites, especially those infused with antimicrobial metals like silver, have drawn interest for their potential in treating microbial water contamination. Stuvart *et al.* (2026) reviewed silver–BCnanocomposites for sustainable E. coli disinfection, highlighting the relevance of BCmaterials in developing alternative disinfection methods. However, practical applications necessitate thorough evaluation of antimicrobial effectiveness, metal leaching, environmental toxicity, regeneration potential, and long-term stability. Despite promising advancements, several challenges must be overcome for the widespread adoption of nano-BCas an antibacterial agent. These challenges include variations in feedstock composition, difficulties in controlling particle size and surface chemistry, inconsistent antimicrobial testing methodologies, a limited understanding of bacteria–nano-BCinteractions, and inadequate evidence regarding long-term environmental and biological safety. Therefore, standardized synthesis protocols, extensive physicochemical characterization, systematic antimicrobial testing, and appropriate toxicity evaluations are critical for establishing reliable structure–activity relationships (Bhandari *et al.*, 2023; Deepshikaa *et al.*, 2024).

In this context, this review explores the antibacterial properties of nano-BC, focusing on its biomass sources, synthesis and modification methods, physicochemical traits, proposed antibacterial mechanisms, and potential applications in healthcare, water treatment, food safety, and environmental management. It also addresses the primary challenges, safety issues, and future research prospects associated with nano-BC-based antimicrobial technologies. A comprehensive understanding of these elements may help propel the development of effective, affordable, and environmentally sustainable antibacterial materials.

2. Production and characteristics of biochar and nanobiochar

Biochar is a carbon-rich solid material produced from biomass through thermochemical conversion processes. Various production techniques are employed, including slow pyrolysis, fast pyrolysis, gasification, and carbonization. These processes convert agricultural residues, forestry and wood wastes, animal manure, and other biomass resources into carbonaceous materials with different physicochemical properties. Among these methods, slow pyrolysis under oxygen-limited conditions generally favors the formation of a larger proportion of solid BC, whereas fast pyrolysis is primarily optimized for the production of bio-oil. Gasification, in contrast, is mainly employed for the generation of synthesis gas (syngas), which can be used for heat and electricity generation. The selection of the thermochemical pathway strongly influences BCyield, surface area, porosity, aromaticity, functional groups, and overall reactivity (Salem, H, 2026). Nano-BC is an engineered nanoscale form of BCthat can be produced through physical, chemical, thermal, and hydrothermal approaches. Compared with conventional bulk BC, nano-BCgenerally exhibits a smaller particle size, higher accessible surface area, greater surface reactivity, enhanced porosity, and abundant surface functional groups. These characteristics can improve its interaction with pollutants, microorganisms, nutrients, and other environmental components. Nano-BCmay therefore provide enhanced performance in comparison with conventional BCfor applications in environmental remediation, agriculture, and water treatment (Qin *et al.*, 2018; Ramanayaka *et al.*, 2020; Salem, H, 2026). A wide range of biomass feedstocks can be utilized for nano-BCproduction, including agricultural residues, grasses, palm and peanut shells, rice husks and straw, sugarcane bagasse, bamboo, soybean residues, woody biomass, animal-derived wastes, municipal organic wastes, and sewage sludge. The nature of the precursor biomass and the processing conditions strongly influence the structural and surface properties of the resulting nano-BC. In particular, mechanical milling provides a relatively simple top-down route for reducing BCparticle size. Ramanayaka *et al.* (2020) demonstrated the preparation of graphitic nano-BCfrom bioenergy waste-derived dendro-BCusing mechanical grinding followed by centrifugation to obtain the nano-BCfraction. The resulting material exhibited graphitic characteristics and functional groups relevant to the adsorption of contaminants from aqueous media. The functional performance of nano-BCis closely associated with its surface chemistry and carbon structure. Carbon-based materials may contain persistent free radicals that participate in the transformation of refractory organic contaminants and can contribute to their environmental reactivity (Qin *et al.*, 2018). Consequently, nano-BCcan act not only as an adsorbent but also as a reactive carbonaceous material capable of participating in pollutant transformation processes. Nano-BCcan also be combined with metal or metal-oxide nanoparticles to produce BC-based nanocomposites with multifunctional properties. Incorporation of magnetic nanoparticles, for example, can facilitate the recovery and separation of BC-based materials after environmental applications. Such nanocomposites are particularly promising for wastewater treatment because adsorption, catalysis, photocatalysis, and antimicrobial activity can be integrated within a single material. Recent research has demonstrated the potential of BC-supported metal-oxide nanocomposites for simultaneous pollutant removal and microbial control. Urper *et al.* (2026) synthesizedTiO_2/BC and ZnO/BC nanocomposites using a hydrothermal method. BC enhanced dye adsorption and promoted charge separation, resulting in methyl orange degradation efficiencies of up to 92% for TiO_2/BC and 97% for ZnO/BC under light irradiation. The materials also retained more than 80% and 90% of their respective activities after three reuse cycles. In addition, the nanocomposites demonstrated antibacterial activity against *E. coli*, with inhibition rates reaching approximately 90% (Urper *et al.*, 2026). These findings indicate that nano-BCand BC-supported nanocomposites have considerable potential as multifunctional materials for wastewater treatment, pollutant adsorption, photocatalytic degradation, and antibacterial applications. Their combination of renewable biomass origin, tunable surface chemistry, adsorption capacity, and compatibility with functional nanoparticles makes them attractive candidates for sustainable environmental remediation. Nevertheless, optimization of synthesis energy requirements, particle stability, potential nanoparticle release, regeneration, toxicity, and large-scale production remains necessary before widespread practical application (Salem, H, 2026; Urper *et al.*, 2026).

3. Antimicrobial activity and modification of biochar

Biochar exhibits antimicrobial properties against a broad range of microorganisms, including bacteria, viruses, and protozoa. These properties are primarily associated with its high surface area, porous structure, surface functional groups, adsorption capacity, and physicochemical characteristics. BC can interact with microbial cells through adsorption, surface attachment, membrane disruption, and generation of reactive oxygen species (ROS), thereby inhibiting microbial growth and survival. Such properties make BCa promising material for microbial control and wastewater treatment (Xiang *et al.*, 2022). BC can be further

enhanced through chemical, physical, and biological modification strategies to improve its antimicrobial performance. Chemical modifications, including acid/base treatment, oxidation, and metal incorporation, can introduce additional functional groups and antimicrobial species that promote bacterial membrane damage and oxidative stress. Physical treatments such as steam activation and thermal modification can increase surface area, pore volume, and surface reactivity, thereby improving microbial adsorption and retention. Incorporation of antimicrobial materials, such as silver nanoparticles, can further enhance the bactericidal activity of BC. For example, a chitosan-coated BC–nanosilver composite demonstrated enhanced antibacterial performance and potential for drinking-water purification (Hu *et al.*, 2019). Magnetic BCrepresents another important modification in which magnetic nanoparticles, commonly iron-based materials, are incorporated into the BCmatrix. The resulting material combines the high adsorption capacity and antimicrobial characteristics of BCwith magnetic separability. Consequently, magnetic BCcan be readily recovered from treated water using an external magnetic field, improving its practical applicability in water purification and microbial control. Recent research has highlighted magnetic BCas an environmentally friendly, relatively simple, and economical material with significant antibacterial activity against waterborne pathogens. Further functionalization with antimicrobial agents can substantially improve its bactericidal performance (Mukherjee *et al.*, 2025). Among such advanced modifications, magnetic BC–quaternary phosphonium salt (MBQ) has attracted attention because of its enhanced antimicrobial properties. Quaternary phosphonium salts possess strong antimicrobial activity and can be incorporated onto modified BCsurfaces to provide additional bactericidal functionality. MBQ has demonstrated greater antimicrobial effectiveness than unmodified BCand magnetic BCagainst important waterborne pathogens, including *E. coli* and *Staphylococcus aureus*. Its antimicrobial action is associated with interaction with and disruption of bacterial cell membranes, increased oxidative stress, and subsequent cellular damage and bacterial inactivation. Thus, the combination of magnetic BCand quaternary phosphonium salt provides both antimicrobial functionality and magnetic recoverability, making MBQ a promising material for water and wastewater treatment (Mukherjee *et al.*, 2025). Waterborne microbial contamination remains a major environmental and publichealth concern. Contaminated water may harborpathogenic bacteria, including *Salmonella* spp., *Shigella* spp., *Vibrio cholerae*, and pathogenic strains of *E. coli*, which can cause serious gastrointestinal and other infectious diseases. Conventional water-disinfection methods, including free chlorine, chloramines, and ozone, are widely used to control microbial contamination. However, conventional disinfectants may generate potentially harmful disinfection byproducts and may not provide complete removal or inactivation of all microbial contaminants. These limitations have stimulated interest in alternative and complementary antimicrobial materials for water treatment. In addition to bacteria, BC-based materials have potential for controlling other microorganisms. Their porous structures and reactive surfaces can facilitate the capture and immobilization of viral particles and protozoan organisms. Modified and metal-containing BCs may additionally promote oxidative or chemical degradation of microbial components. Therefore, BC-based materials have potential applications in wastewater treatment, drinking-water purification, microbial immobilization, and environmental bioremediation. Nevertheless, further systematic research is required to establish pathogen-specific mechanisms, optimize modification methods, evaluate long-term stability, and assess the environmental safety of antimicrobial BCmaterials.

4. Carbon-based nanomaterials for antibacterial applications

Carbon-based nanomaterials encompass a diverse range of nanoscale structures, including zero-dimensional carbon dots (CDs) and carbon quantum dots, two-dimensional graphene derivatives, and three-dimensional nano-BC. These materials have attracted considerable attention for antibacterial applications because of their distinctive surface, optical, electronic, and physicochemical properties. Their antibacterial activity can occur through several mechanisms, including physical disruption of microbial membranes, generation of ROS, oxidative damage to cellular components, and inhibition of biofilm formation (Nishshankage *et al.*, 2024; Wu *et al.*, 2021). Surface functionalization and heteroatom doping can further improve their antimicrobial activity while providing opportunities to regulate their interaction with biological systems (Wu *et al.*, 2021). Carbon nanomaterials have potential applications in several biomedical and environmental fields, including wound dressings, implant coatings, self-sterilizing textiles, water purification, and antimicrobial food-packaging materials. Their tunable optical and electronic properties also make them suitable for photodynamic antimicrobial therapy, biosensing platforms, and controlled-release systems. In the context of increasing antimicrobial resistance, these materials represent promising candidates for the development of next-generation antimicrobial systems. However, challenges related to the standardization of synthesis and manufacturing, reproducibility, long-term environmental impacts, toxicity assessment, and safe clinical application

must be addressed before their widespread practical use (Nishshankage *et al.*, 2024).

5. Carbon dots and antibacterial activity

Carbon dots are small, generally spherical carbon-based nanoparticles, typically below 10 nm in size, that exhibit distinctive fluorescence and tunable surface chemistry. Their surfaces contain various oxygen- and nitrogen-containing functional groups that can be modified to enhance their interactions with microbial cells. Depending on their physicochemical characteristics and surface functionalization, CDs can exert antibacterial effects through membrane disruption, oxidative stress, ROS generation, and interference with essential cellular processes (Wu *et al.*, 2021). Green synthesis of CDs from renewable biological resources has received particular attention because it can provide a relatively simple, economical, and environmentally friendly route for producing functional nanomaterials. Gedda *et al.* (2023) reported the one-pot hydrothermal synthesis of multifunctional CDs using medicinal plant leaves as a carbon source. The synthesized CDs exhibited fluorescence and demonstrated antibacterial activity against both Gram-positive and Gram-negative bacterial strains, even at relatively low concentrations. In addition to their antimicrobial activity, these plant-derived CDs showed antioxidant and bioimaging potential, highlighting their multifunctional nature.

6. Key conceptsin carbon-based antibacterial nanomaterials

Several key concepts and mechanisms are relevant to understanding the antibacterial properties of carbon-based nanomaterials. The following terms provide an overview of their physicochemical characteristics, antimicrobial functions, and potential applications.

Carbon nanomaterials: Nanoscale carbon-based materials with diverse structures and electronic, optical, and surface properties. Their high surface activity and tunable physicochemical characteristics make them attractive for antimicrobial applications (Nishshankage *et al.*, 2024).

Carbon dots: Small, generally spherical carbon nanoparticles, usually less than 10 nm in size, characterized by fluorescence and tunable surface functional groups. Their antibacterial activity may involve membrane interaction, ROS generation, and oxidative damage to microbial cells (Gedda *et al.*, 2023; Wu *et al.*, 2021).

Reactive oxygen species: Highly reactive oxygen-containing species, including singlet oxygen and superoxide-related species, which can cause oxidative damage to microbial membranes, proteins, lipids, and nucleic acids. ROS generation is an important mechanism underlying the antimicrobial activity of several carbon nanomaterials (Wu *et al.*, 2021).

Photodynamic antimicrobial therapy: An antimicrobial strategy in which light-activated photosensitizing materials generate ROS that can damage and eliminate microbial cells. Carbon-based nanomaterials with suitable optical properties can serve as components of such antimicrobial platforms (Nishshankage *et al.*, 2024).

Graphene oxide: A two-dimensional oxygen-containing carbon nanomaterial with a high surface area and abundant surface functional groups. Graphene oxide can interact with bacterial membranes and contribute to antimicrobial activity through physical and oxidative mechanisms, while also serving as a platform for loading or delivering other antimicrobial agents (Nishshankage *et al.*, 2024).

Overall, carbon-based nanomaterials, particularly CDs, graphene-derived materials, and nano-BC, provide versatile platforms for antibacterial applications. Their antimicrobial performance can be tailored through control of particle size, surface chemistry, functionalization, doping, and synthesis conditions. Among these materials, biomass-derived carbon nanomaterials are especially attractive because they combine renewable feedstocks with potentially scalable and sustainable synthesis routes (Gedda *et al.*, 2023; Nishshankage *et al.*, 2024).

7. Conclusion

Biochar and nano-BC made from coconut shells are promising sustainable carbon-based materials suitable for antibacterial and environmental applications. Their renewable biomass source, porous structure, large surface area, adjustable surface chemistry, and nanoscale properties create numerous opportunities for interaction with microorganisms and pollutants. The antibacterial properties of these materials may stem from mechanisms such as surface adsorption, electrostatic interactions, disruption of membranes, generation of ROS, oxidative stress, and prevention of biofilm formation. Enhancements in their antimicrobial efficacy and practical use can be achieved through modifications such aschemical treatments, activation, incorporation of metals or metal oxides, and magnetic functionalization. In particular, nano-BCand BC-based nanocomposites hold promise for applications in water purification, wastewater treatment, microbial control, and pollutant removal. Magnetic BCand multifunctional composites additionally provide benefits through enhanced antimicrobial effects and easier recovery after use. Nevertheless, challenges remain with variations in biomass sources, synthesis conditions, particle size, surface

chemistry, antimicrobial testing methods, nanoparticle release, toxicity, and long-term stability.

Future studies should prioritize standardized synthesis and antibacterial testing, optimization of surface modifications, understanding of bacteria–nano-BCinteractions, thorough toxicity evaluations, regeneration and reusability, and long-term environmental assessments. Establishing reliable structure–activity relationships and scalable production methods will be crucial for advancing coconut shell-derived nano-BCfrom the laboratory to safe and effective antibacterial applications in real-world settings.

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