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Biochar

REVIEW

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Biochar-supported microbial systems: a strategy for remediation of persistent organic pollutants

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Abstract

As widespread toxicants that cause cancer and affect the endocrine system, persistent organic pollutants, such as polycyclic aromatic hydrocarbons, pesticides, and chlorinated solvents, are harmful to the environment and human health. This review aims to highlight biochar-supported microbial systems as a transformative solution for remediating these contaminants, with a particular focus on current challenges and future perspectives. Conventional pollutant-remediation techniques based on physicochemical treatments are expensive and inefficient. Bioremediation technology faces challenges, such as low microbial survival and environmental sensitivity. Biochar-supported microbial systems have become attractive because of their strong adsorption characteristics and microbial degradation. Biochar-supported microbial systems offer promising solutions that combine the superior adsorption capacity of biochar with its microbial degradation capabilities. Biochar produced from pyrolyzed biomass has a porous structure and functional groups that immobilize pollutants and support microbial growth. Recent research demonstrates that integrating nutrient-enriched biochar with symbiotic microbial communities extends their remediation potential to a wider range of pollutants, including persistent organic pollutants. However, challenges, such as long-term microbial viability, biochar aging, and field-scale economic feasibility, remain unresolved. Further research is required to optimize these systems for real-world applications. By addressing these gaps, biochar-microbial remediation can become a sustainable and scalable strategy for environmental rehabilitation, supporting circular economic goals.

Keywords Biochar, Microbial systems, Pollutant remediation, Environmental health

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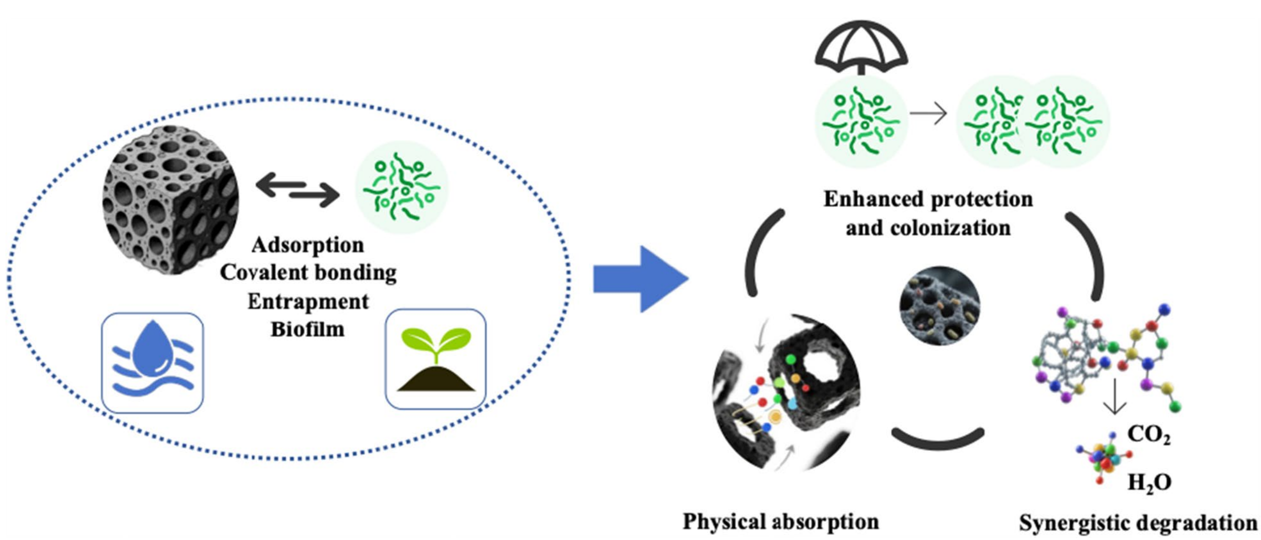
Graphical Abstract



1 Introduction

The widespread presence of organic pollutants in terrestrial and aquatic ecosystems has emerged as one of the most pressing environmental challenges of the twenty-first century. Derived from industrial discharge, agricultural runoff, and improper waste disposal, persistent organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), petroleum hydrocarbons, pesticides, and chlorinated solvents, exhibit high toxicity, bioaccumulation potential, and resistance to natural degradation (Kumar et al. 2024). These pollutants, which have been linked to neurotoxicity, endocrine disruption, and cancer, pose serious threats to human health and ecosystem integrity (Bolan et al. 2023; Lu et al. 2024). Despite global regulatory efforts, their environmental persistence is exacerbated by hydrophobic partitioning into soil organic matter (SOM) and sediments, rendering conventional remediation strategies ineffective or economically unsustainable.

Conventional remediation approaches, such as physicochemical methods (e.g., soil washing, thermal desorption, and chemical oxidation) and excavation disposal, have significant limitations such as high energy input, secondary pollution risks, and soil structure disruption, which restrict their scalability, particularly for large-scale or in situ applications (Wang et al. 2005; Falciglia et al. 2017). Bioremediation, which harnesses microbial metabolic activity for pollutant degradation, is a more sustainable alternative (Bala et al. 2022). However, poor microbial survival rates, nutritional constraints, and the toxicity of pollution intermediates often restrict their effectiveness. Moreover, environmental variables (e.g., pH fluctuations, oxygen availability, and temperature shifts) further destabilize microbial performance, highlighting the need for innovative strategies to enhance microbial resilience and pollutant sequestration (Pourfadakari et al. 2019; Ayilara and Babalola 2023; Kuppan et al. 2024).

This review highlights biochar-supported microbial systems as a transformative solution that synergizes the adsorptive advantages of biochar with the catalytic potential of specialized microbial consortia. Biochar is a carbonaceous substance made by pyrolyzing biomass under oxygen-limited conditions. It has a high surface area, a hierarchically porous structure, and a large number of functional groups (such as hydroxyl, carboxyl, and quinones) that work together to improve pollutant immobilization and establish ideal microhabitats for microbial colonization (Lu et al. 2020; Chen et al. 2023). Extracellular electron transfer, which is essential for breaking down recalcitrant pollutants, is further facilitated by its redox-active components (Zhang et al. 2021a; Zhao et al. 2021). When functionalized with pollutant-degrading microbes (e.g., *Pseudomonas, Sphingomonas*, or white-rot fungi), biochar acts as a protective carrier, mitigating environmental stressors while concentrating nutrients and substrates near microbial cells (Xiang et al. 2022). This symbiosis not only accelerates degradation kinetics but also minimizes the leaching of toxic intermediates (Weng et al. 2021; Liu et al. 2022).

The development of biochar-supported microbial systems has evolved from early empirical observations to deliberate design strategies guided by advances in materials science and microbial ecology. Early studies demonstrated that the pore network of biochar shelters microbes from predation and desiccation while its surface chemistry modulates electron flow for anaerobic reductive dechlorination or aerobic oxidative pathways (Chen et al. 2022; Viotti et al. 2024). Recent innovations include the preconditioning of biochar with nutrients to stimulate microbial activity and co-immobilization of multiple microbial strains to exploit metabolic cross-feeding (Wang et al. 2021). For instance, biochar loaded with *Mycobacterium* and *Rhodococcus* strains achieved high PAH degradation rates in contaminated soils (Li et al. 2025b; Xiao et al. 2025). Furthermore, engineered biochars with tailored surface properties (e.g., nitrogen doping or iron impregnation) have expanded biochar-supported microbial systems applicable to heterogeneous pollution scenarios, including mixed heavy metal–organic co-contaminants (dos Reis et al. 2023).

Despite these advances, critical knowledge gaps persist regarding long-term microbial viability, biochar aging effects, and the fate of degradation byproducts. Additionally, the economic feasibility of biochar-supported microbial systems for field-scale deployment requires systematic evaluation, particularly in comparison with emerging technologies such as phytoremediation or nanomaterial-based catalysis. This review synthesizes contemporary insights into biochar-supported microbial system design principles, mechanistic interactions, and environmental performance while identifying key research priorities to bridge laboratory-scale success with real-world implementation. By addressing these challenges, biochar-supported microbial systems hold promise as scalable and eco-friendly platforms for rehabilitating polluted environments and advancing circular economic goals.

2 Interactions between biochar and microorganisms

2.1 Characteristics of biochar and microorganisms

Biochar exhibits unique physicochemical properties that influence microbial activity in various environments (Song et al. 2023). Its highly porous structure with a large surface area provides extensive habitats for microbial colonization. The pore distribution (encompassing micro-, meso-, and macropores) affects microbial accessibility and nutrient diffusion. The surface chemistry of biochar is defined by functional groups (e.g., carboxyl, hydroxyl, and phenolic groups), which influence nutrient retention, pH buffering, and electron exchange (Liao et al. 2021; Mukherjee et al. 2022). Additionally, biochar may contain ash components (e.g., K, Ca, Mg, and P), thereby altering soil biogeochemistry. Due to its aromatic carbon structure, biochar is highly resistant to microbial degradation, ensuring long-term stability in soil (Cui et al. 2021). It is worth noting that although the aromatic core of biochar can resist the mineralization process by microorganisms, the partial surface oxidation mediated by lignin-decomposing enzymes (such as laccase) can still enhance its porosity and nutrient retention capacity.

Microorganisms play crucial roles in organic matter decomposition, nutrient cycling, and pollutant degradation. Their interactions with biochar exhibit several key characteristics:

(i) Degradation Efficiency: Certain microbial groups (e.g., Actinobacteria, Fungi) exhibit high enzymatic capabilities for breaking down complex organic compounds, including lignin and cellulose, which may alter biochar surfaces over time (Hsin et al. 2025). For example, ligninolytic fungi secrete peroxidases and laccases that oxidize biochar, thereby enhancing its porosity and nutrient retention capacity. Similarly, phosphate-solubilizing bacteria improve phosphorus availability by metabolizing organic acids adsorbed on biochar (Wang et al. 2025; Zhang et al. 2025).

(ii) Environmental Adaptability: Microorganisms vary in their tolerance to pH, moisture, and redox conditions, while biochar can modulate these factors by buffering soil acidity, improving water retention, and creating microaerophilic zones (He et al. 2022). Acidophilic bacteria thrive in low-pH biochar-amended soils, whereas nitrogen-fixing rhizobia benefit from the neutralization of alkaline soils (Hailegnaw et al. 2019; Huang et al. 2023). Additionally, the porous structure of biochar provides a refuge for moisture-sensitive microbes during drought (He et al. 2023).

(iii) Community Synergism: Microbial consortia often work synergistically, where one group metabolizes the byproducts of another. Biochar enhances such interactions by providing niche differentiation through its heterogeneous surface, reducing competition for resources. For example, methanotrophs and nitrifiers coexist on biochar, where methane oxidation by *Methylomonas* supports nitrifier activity (Le and Lee 2023). Similarly, biochar-facilitated electron transfer promotes syntrophic relationships between fermentative bacteria and methanogens in anaerobic systems (Huang et al. 2025).

By selecting for these microbial traits, biochar can optimize soil functionality, bioremediation, and carbon sequestration.

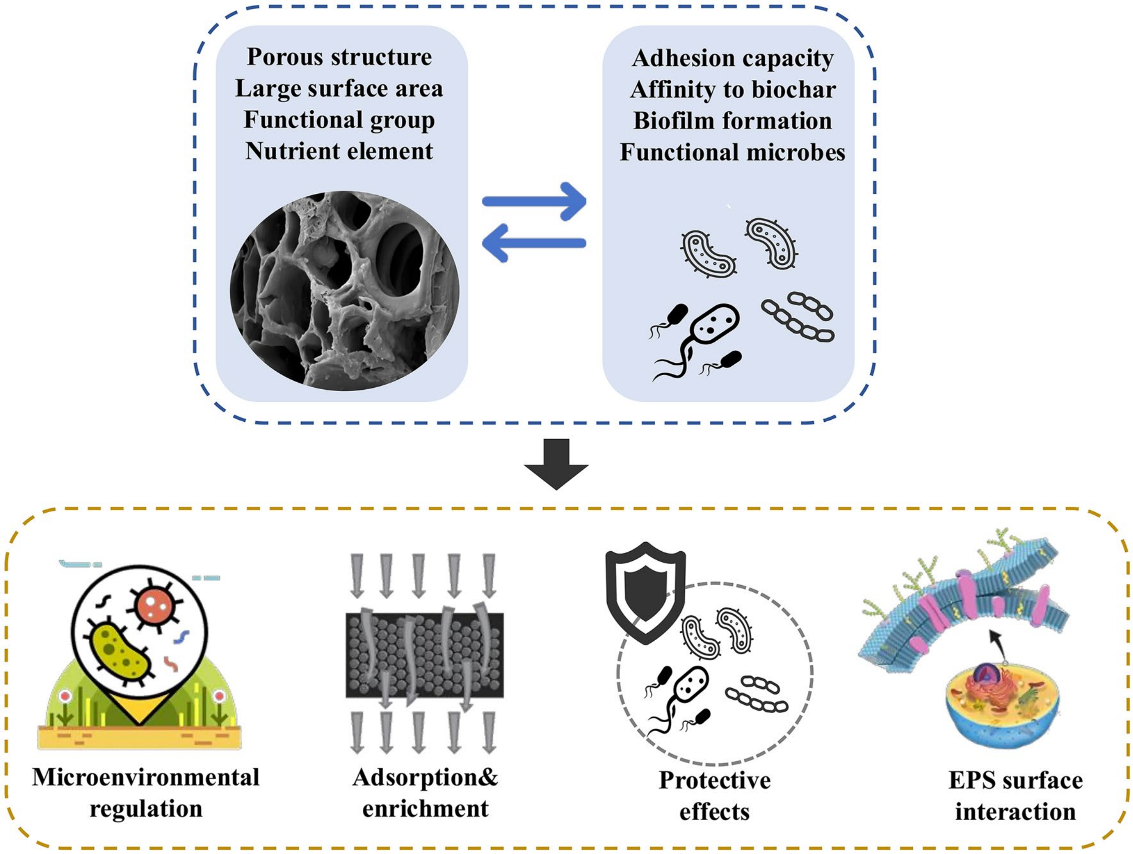


Fig. 1 Mechanisms of biochar–microorganism interactions

2.2 Mechanisms of biochar–microorganism interactions

The porous structure and surface functional groups of biochar facilitate the adsorption of organic molecules, nutrients, and signaling compounds, creating nutrient hotspots that attract microorganisms (Bolan et al. 2023). This enrichment effect can increase microbial biomass by providing carbon and energy sources (e.g., labile organic matter trapped in biochar pores) and can also selectively promote specific microbial taxa (e.g., plant growth-promoting rhizobacteria) owing to preferential nutrient retention (Kumar et al. 2025). Consequently, the mechanisms of biochar–microorganism interactions include microenvironment regulation, extracellular polymeric substance (EPS) regulation, physical protection, and microbial energy metabolism regulation (Gorovtsov et al. 2020)(Fig. 1).

As for microenvironmental regulation, the high surface area and porous structure of biochar enable the adsorption and immobilization of a wide range of pollutants, thereby reducing their concentrations in contaminated media (Gorovtsov et al. 2020). Moreover, the inherent buffering capacity of biochar can stabilize soil pH, creating a more favorable environment for microbial activity. This characteristic is particularly beneficial for alleviating the stress imposed by the acidic or alkaline conditions often encountered in polluted soils (Wang et al. 2020b; Jiang et al. 2025). By providing a stable habitat and essential nutrients, biochar significantly shortens the lag phase of microbial communities, allowing them to adapt rapidly and initiate the degradation of organic contaminants. In addition, the porous structure of biochar enhances its water-holding capacity thereby sustaining microbial hydration under arid conditions (Chandi et al. 2024). Biochar can also act as an electron shuttle, facilitating microbial redox reactions (e.g., denitrification and methanogenesis). Because of its unique surface properties and porous structure, biochar can significantly influence microbial community interactions by providing a spatially diverse environment that facilitates niche differentiation (Kayoumu et al. 2025; Li et al. 2025a). This allows the coexistence of diverse microbial species, enabling the formation of efficient syntrophic relationships. For instance, biochar can support the co-metabolism of fermentative bacteria and methanogens in anaerobic systems, enhancing overall organic contaminant degradation efficiency (Liu et al. 2021b).

Biochar also possesses properties such as toxin sequestration and strong resistance. For example, its adsorption of heavy metals and organic pollutants reduces microbial toxicity (Wilson 1966). In addition, opaque biochar particles can mitigate UV damage, while moisture retention prevents desiccation (Yadav and Bag 2023). Moreover, the interaction between microbial EPSs and biochar surfaces plays a pivotal role in shaping microbial habitats. EPS significantly enhances microbial colonization efficiency in environmental media by increasing cell surface hydrophobicity (reducing hydration repulsion forces and optimizing molecular conformation) and dynamically modulating charge properties (shielding electrostatic repulsion and bridging with carriers), synergistically lowering interfacial energy barriers (Antonangelo et al. 2019). These modifications facilitate the formation of complex biofilms, in which microbial communities exhibit enhanced metabolic cooperation and environmental resilience (Zhang et al. 2024b). Over time, biofilm activity contributes to biochar weathering through physical and chemical structural alterations.

The conductive properties of biochar enable extracellular electron transfer, which is a critical mechanism in microbial energy metabolism. Electroactive bacteria such as *Geobacter* and *Shewanella* species utilize biochar as an electron conduit for anaerobic respiration, while syntrophic relationships between fermentative bacteria and methanogens are enhanced through biochar-mediated electron exchange in anaerobic digestion systems. These interconnected processes demonstrate how the physicochemical properties of biochar fundamentally influence microbial ecology and biogeochemical cycling, with significant implications for environmental applications, including bioremediation and bioenergy production.

3 Technical approaches for constructing biochar-supported microbial systems

The construction of biochar-supported microbial systems integrates materials engineering and microbial technology, synergistically enhancing environmental remediation efficiency by optimizing carrier properties and microbial activity. Key characteristics across different techniques are summarized in Table 1.

3.1 Adsorption

In the construction of efficient and stable biochar-supported microbial systems, various immobilization techniques exhibit distinct advantages and limitations in different application scenarios owing to their unique mechanisms and characteristics. Currently, the main methods for constructing biochar-supported microbial systems include adsorption, covalent bonding, entrapment, and biofilm formation (Fig. 2). Driven by the unique physical and chemical properties of biochar, the adsorption method has emerged as the predominant approach for constructing biochar-supported microbial systems (Li et al. 2022a; Wu et al. 2022). This method primarily relies on the interaction of non-specific forces—such as surface tension and adhesion—between microorganisms and biochar to facilitate microbial colonization within the biochar matrix (Saravanan et al. 2023). Tao et al. prepared biochar via the pyrolysis of corn straw and subsequently mixed it with a phosphate buffer to create a stock solution. This solution was then combined at a 1:1 volume ratio with a suspension of the atrazine-degrading strain DNS32. After 30 min of adsorption at 30 °C, the mixture was centrifuged to obtain a composite material of biochar loaded with DNS32 (Tao et al. 2019). The oxygen- and nitrogen-containing active functional groups on the surface of bamboo biochar exhibited good biocompatibility with microorganisms, thereby promoting their active attachment to the biochar surface (Zhang et al. 2014). In addition, most microorganisms adhere to the surface of biochar materials through cross-linking and adhesion mediated by extracellular secretions. Some studies have used modified bamboo biochar to immobilize the strain *Acinetobacter venetianus*, establishing a novel biomaterial for diesel biodegradation (Chen et al. 2016). Scanning electron microscopy and gas

Table 1 The characteristics and advantages of different Biochar-supported Microbial System construction technologies

Technique	Binding strength	Microbial activity impact	Applicable pollutant/scenario	Scaling cost	Key limitation
Adsorption	Weak	Minimal effect	Low-toxicity, stable environments	Low	Easily desorbed
Covalent Bonding	Strong	Potential damage	High-toxicity wastewater, continuous-flow reactors	Medium–High	Requires harsh reaction conditions
Encapsulation	Moderate	Highly protective	High-toxicity soil/wastewater, shock loads	Medium	Mass transfer blockage for macromolecules
Biofilm Formation	Self-forming	Enhanced stress resistance	Complex pollutants, long-term systems	Low	Slow startup, reduced metabolism in inner layers

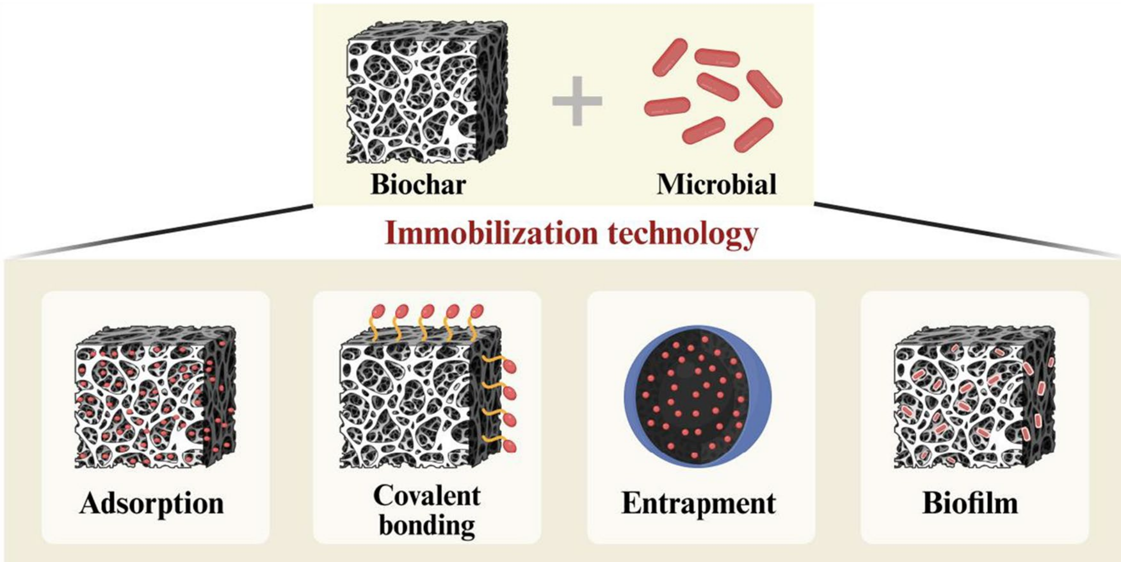


Fig. 2 Immobilization technique of microbes on biochar

chromatography-mass spectrometry (GC–MS) analyses confirmed that the microorganisms effectively adhered to the pores and surfaces of the modified bamboo biochar. However, the interaction between biochar and extracellular secretions may result in uneven microbial distribution. In another study, Wang et al. immobilized the petroleum-degrading strain ODB-1 onto three different biocarriers — expanded graphite, expanded perlite, and bamboo biochar — and found that ODB-1 formed strong binding interactions with the carriers via secreted extracellular polysaccharides. This significantly enhanced the diesel removal efficiency of the strain (Wang et al. 2015).

Adsorption has been extensively utilized in immobilization technologies because of its environmentally friendly nature, cost-effectiveness, operational simplicity, and minimal impact on microbial viability. However, despite the general reusability of the adsorptive matrix, the interactions between microorganisms and supporting materials are often relatively weak and unstable, making microorganisms prone to desorption and detachment from the biochar surface (Wu et al. 2022). This limitation is particularly critical under conditions involving high pollutant concentrations or complex environmental stresses, which ultimately compromise the treatment efficiency and long-term stability of biochar-supported microbial systems. Therefore, for practical applications, further optimizing the immobilization conditions and modifying the physicochemical properties of the biochar matrix is essential to enhance the binding strength and stability between microorganisms and biochar.

3.2 Covalent bonding

To compensate for the deficiencies associated with the adsorption method, researchers have gradually shifted their focus to the covalent bonding method, which is characterized by high stability and strong binding strength (Li et al. 2022a; Wu et al. 2022). This method typically relies on covalent reactions between the active functional groups on the surface of biochar (such as carboxyl, hydroxyl, and phenolic hydroxyl groups) and the reactive functional groups on the surface of microbial cells (such as thiol, amino, and hydroxyl groups) to immobilize the cells (Ahmad and Khare 2018; Nguyen Thi Hai et al. 2022). This approach not only enhances the environmental tolerance of microorganisms but also effectively improves their sustainability and reusability in pollution control. Najim et al. reviewed the significant role of covalent immobilization techniques in improving the degradation efficiency of microorganisms for organic pollutants, such as benzene compounds, pesticides, and dyes. They indicated that covalent bonding in magnetic floating biochar gel carriers can enhance the mass transfer rate of pollutants in the aqueous phase, thereby significantly improving treatment efficiency (Najim et al. 2024). Similarly, Yang et al. immobilized *Pseudomonas putida* on biochar via a covalent bonding method to remove the herbicide paraquat. The experimental results showed that the herbicide degradation efficiency achieved with this method was significantly higher than that of free bacterial strains (Yang et al. 2023). Some studies have indicated that compared with adsorption methods, the covalent bonding method has a stronger capacity for removing organic pollutants. Ha et al. compared the performance of paraquat removal using covalent bonding and adsorption methods, and their results showed that the removal rate of the former (90.61%) was higher than that of the latter (82.05%) (Nguyen Thi Hai et al. 2022).

Compared with adsorption methods, the covalent bonding method has higher stability and resistance to shock, making it particularly suitable for water pollution treatment systems that require long-term operation or function under extreme conditions. However, the formation of covalent bonds involves vigorous reactions that may lead to microbial inactivation. Additionally, the complex cell surface structure with various membrane proteins and lipopolysaccharides may hinder covalent bonding between cells and carriers, which has been a research challenge (Li et al. 2022a). Therefore, addressing these issues will help make the immobilization of biochar and microorganisms more reliable and reduce the impact on microbial activity, thereby enabling the application of covalent bonding methods in a wider range of fields.

3.3 Entrapment

When confronted with complex or highly toxic environments, single adsorption or covalent bonding methods may be insufficient to maintain microbial activity and long-term functionality. In such cases, entrapment is widely employed as a protective immobilization technique. The entrapment method primarily involves immobilizing target microorganisms by embedding them within the porous structure of the biochar or using high-molecular-weight organic compounds to encapsulate the microorganisms during the formation of gels or polymers (Mahari et al. 2020; Liu et al. 2023b). This structure prevents the leaching of microorganisms from the carrier while allowing small-molecule substrates and products from the external environment to freely diffuse in and out of the carrier. Compared with adsorption or covalent bonding methods, entrapment has significant advantages in protecting microbial activity, extending the biodegradation lifespan, and providing a controlled-release effect. It is particularly suitable for pollution control in highly toxic or unstable environments (Wu et al. 2022; Saravanan et al. 2023). Entrapment materials include natural polymers [e.g., sodium alginate (SA), chitosan, and gelatin] and synthetic polymer compounds (e.g., polyvinyl alcohol and polyacrylamide). A typical entrapment approach involves the formation of composite gel beads from SA and biochar. Lu et al. constructed SA-encapsulated PAH-degrading bacterial composite beads, achieving a PAH removal rate of over 87% in simulated industrial wastewater. The beads also demonstrated good reusability and mechanical stability (Lu et al. 2021). Furthermore, Liu et al. developed a chitosan–biochar composite carrier to encapsulate a consortium of microorganisms used for crude oil-contaminated soil remediation. Within a 45-day treatment period, the system achieved nearly 75% crude oil degradation and significantly improved the soil microecosystem (Liu et al. 2023a). Other studies have shown that the combined immobilization of microbial consortia using polyvinyl alcohol/SA and biochar effectively enhanced the sustained adsorption and degradation of dyes and pharmaceutical pollutants (Najim et al. 2024).

This method is characterized by low toxicity to microorganisms, high particle strength, and broad application scope. However, only small-molecule substrates can penetrate the interior of particles, making it unsuitable for the degradation of large-molecule pollutants. Moreover, increased mass transfer resistance can also affect oxygen diffusion. Currently, the development of this method is trending toward modularization and multifunctionalization, such as integrating nutrient release systems or incorporating electrochemical assistance systems (Qiao et al. 2020; Deepa et al. 2022), to achieve the synergistic removal of complex pollutants.

3.4 Biofilm

In addition to the three aforementioned major immobilization strategies, biofilm methods have attracted increasing attention in recent years because of their ability to mimic natural microbial attachment and cooperative behaviors. Compared with physical adsorption or chemical bonding, biofilm-based immobilization offers a more natural and highly efficient approach to microbial immobilization. The principle of this method involves the adsorption, proliferation, and biofilm formation of microorganisms on the surface of biochar, during which biochar provides stable attachment sites and a nutrient-rich microenvironment (Wu et al. 2022). Owing to the porous structure and abundant functional groups of biochar, it can effectively enhance the attachment strength of microorganisms during biofilm formation and improve the system's resistance to external organic pollution stress (Li et al. 2022b). Moreover, the EPS layer within the biofilm can significantly increase microbial tolerance to recalcitrant organic compounds, such as phenols and PAHs, thereby enhancing system stability and pollutant biodegradation efficiency (Najim et al. 2024). Notably, the quorum sensing (QS) mechanism within biofilm systems plays a pivotal role in regulating collective microbial behavior. By releasing and detecting signaling molecules, such as *N*-acyl homoserine lactones, microorganisms can initiate a series of population-level responses once a threshold cell density is reached. These responses include the synthesis of EPSs, release of virulence factors, expression of pollutant-degrading enzymes, and enhancement

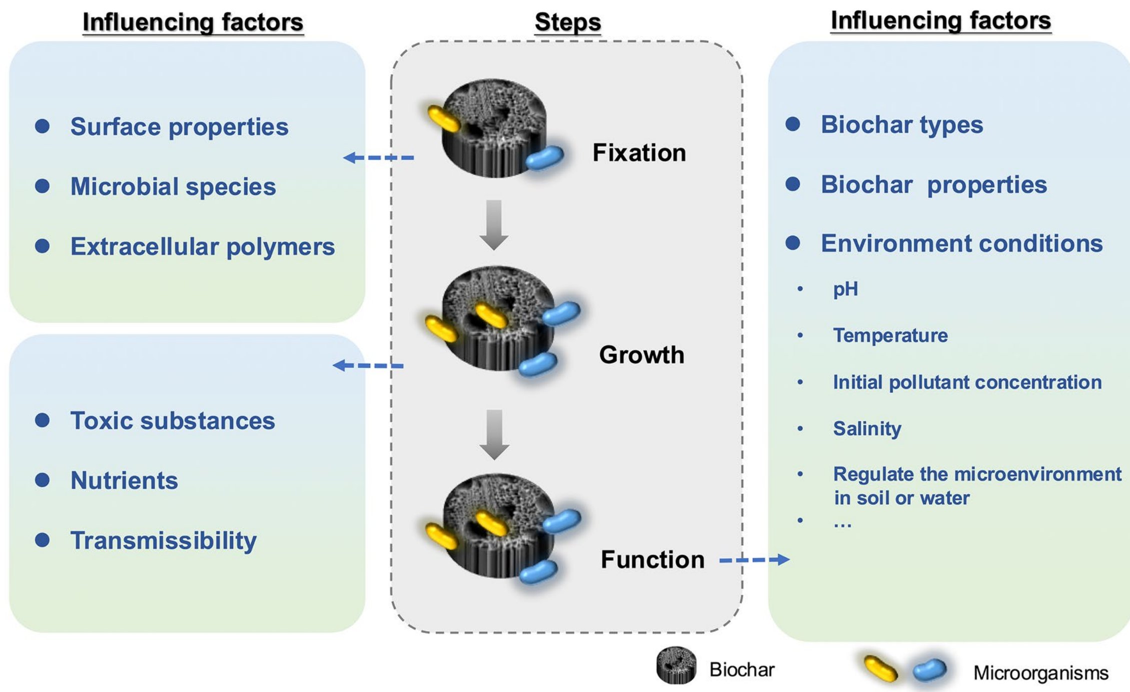


Fig. 3 Factors influencing the effect of BIM on removal of organic pollutants

of stress resistance (Miller and Bassler 2001). This density-dependent regulatory mechanism strengthens intercellular communication and metabolic cooperation, thereby enhancing the overall stability and stress adaptability of the biofilm system (Yadav et al. 2023). Studies targeting atrazine as a pollutant have shown that biochar-loaded functional bacteria can form stable biofilms, removing over 99% of atrazine within 48 h. The removal efficiency was 1.23–1.48-fold higher than that of single- and mixed-strain biofilms. Concurrently, the expression levels of genes related to biofilm formation (QS, EPS synthesis and secretion, and cell motility) were significantly increased (Zhang et al. 2024a). Additionally, in moving bed biofilm reactors, biochar enhances the structural integrity and microbial community diversity of microbial biofilms, synergistically improving the removal efficiency of nitrogen and organic matter (Faggiano et al. 2023).

The biofilm method has significant advantages for enhancing microbial tolerance to toxicity, sustainability, and pollutant removal efficiency. The synergistic interactions between biofilms and biochar materials provide the potential for constructing highly efficient bioremediation systems. However, biofilm formation typically requires a longer induction period and slower start-up time. As the biofilm thickens, substrate mass transfer becomes limited, and the metabolic efficiency of microorganisms in the inner layers of the biofilm decreases (Jagaba et al. 2024). Moreover, the microbial community structure of biofilms may be unstable under different environmental conditions, leading to fluctuations in degradation performance.

4 Factors influencing organic pollutant removal by biochar-supported microbial systems

In the biochar-supported microbial systems, multiple factors influence the removal efficiency of organic pollutants, including the physicochemical properties of biochar, the type and activity of microorganisms, the characteristics of the pollutants, and environmental conditions (Fig. 3). Understanding these factors is crucial for achieving high remediation efficiency.

4.1 Properties of biochar

The pore structure, surface area, surface functional groups, and metal elements loaded onto biochar directly affect the adsorption capacity and colonization ability of microorganisms. The surface structure and porosity of biochar provide an excellent environment for microbial attachment and colonization. High porosity and suitable surface area promote microbial colonization and proliferation, enhancing microbial activity and organic pollutant degradation (Ji et al. 2022). These properties are typically influenced by biomass feedstock composition, pyrolysis temperature, conditions, and process parameters. Owing to differences in cellulose, hemicellulose, and lignin contents, biochars from different plant sources form distinct pore structures during pyrolysis. Pyrolysis temperature is a key factor in regulating biochar porosity and surface area. As the temperature increases, volatile components within biochar are gradually released, resulting in the formation of more micro- and mesopores, which enhance surface area and pore structure (Leng et al. 2021). Additionally, the surface chemical properties formed at different temperatures influence colloidal properties and mobility in the medium (Yang et al. 2020b), thereby altering pollutant degradation efficiency. Moreover, process parameters, such as the pyrolysis rate and residence time, also affect biochar structure. For instance, slow pyrolysis favors the formation of stable and porous carbon structures, whereas fast pyrolysis may result in fewer pores.

Functional groups on the surface of biochar play a key role in the interactions between microorganisms and pollutants. These functional groups not only enhance pollutant adsorption but also regulate microenvironmental pH, promoting the activity of specific degrading enzymes and thus improving organic pollutant degradation (Song et al. 2024). The types and quantities of functional groups are directly determined by the chemical composition and structure of the raw biomass (e.g., agricultural residues, forestry waste, or food processing byproducts). These functional groups mainly include aromatic structures, alkyl chains, and oxygen-containing groups (e.g., carboxyl, hydroxyl, ether bonds) (Janu et al. 2021). For example, biochar derived from straw is rich in fused aromatic ring structures and glycosidic bonds (anomeric O-C-O carbon), both of which significantly affect its pH and electrical conductivity (EC) (Li et al. 2013). The surface functional groups of biochar are also influenced by pyrolysis conditions. Plant-derived biochars typically contain more aromatic and alkyl hydrophobic groups, and as the biochar ages, its surface gradually becomes enriched with hydrophilic oxygen-containing groups, shifting the surface properties from hydrophobic to hydrophilic (Yang et al. 2020b). This transformation affects not only the environmental stability and mobility of biochar but also its adsorption capacity and soil improvement effects. In addition, among the groups on the surface of biochar, environmentally persistent free radicals (EPFRs) are a type of free radicals that have a long lifespan in environmental media and possess unpaired electrons. EPFRs have a strong electron exchange capacity, acting as a carbon-negative electron source to promote the reduction reactions of organic pollutants and microbial metabolic processes (Yuan et al. 2022). EPFRs can also stimulate changes in microbial community structure, promote the enrichment of specific degrading bacteria, and enhance the microbial degradation of organic pollutants (Liu et al. 2021a). Therefore, the stability of EPFRs makes them long-lasting and effective pollutant-remediation factors. However, it is imperative to assess potential environmental risks and management strategies to safeguard ecological safety.

Functionalized biochar, such as biochar loaded with metals such as iron or manganese, can further promote the degradation of organic pollutants through catalytic reactions (Gao et al. 2024; Chen et al. 2025a, b). By introducing metal active sites, biochar materials can effectively activate peroxides (e.g., peroxymonosulfate and hydrogen peroxide), generating highly oxidative radicals or non-radical species that facilitate organic pollutant degradation. Iron- or manganese-loaded biochar acts as a catalyst in advanced oxidation processes, activating peroxymonosulfate (PMS) or hydrogen peroxide (H_2O_2) to generate sulfate radicals ($SO_4\cdot^-$) and hydroxyl radicals (·OH), which have strong oxidation abilities to break down complex organic pollutants (Shi et al. 2022). The adsorption and catalytic capacities of biochar can be further enhanced by modifying its surface with oxygen-containing functional groups. These groups not only strengthen the interaction between pollutants and the catalyst surface but also facilitate electron transfer, accelerating organic pollutant degradation (Dai et al. 2021). Notably, while modification techniques can enhance certain functions, excessive modification may lead to structural instability, increased energy consumption, and secondary pollution (Dai et al. 2021; Murtaza et al 2024). These adverse effects not only threaten key soil ecological functions but also highlight the need for rational design and moderation in biochar modification. Therefore, a balanced approach should be considered during design and application (Zhang et al. 2021b), and systematic safety assessments should be integrated into the development framework to ensure long-term environmental compatibility and ecological safety.

4.2 pH value

Biochar is typically alkaline, allowing it to regulate soil pH. The pH of the biochar, combined with the background pH of the soil, determines the final pH of the soil (Wang et al. 2024). For example, studies have shown that biochar has a differing pH-regulating effect in various soils, significantly lowering soil pH in acidic soils but with negligible effect in alkaline soils (Zhang et al. 2019b). This regulation directly affects microbial community structure and metabolic activity.

Microorganisms are sensitive to environmental pH, with different species exhibiting varying degrees of adaptability to both acidic and alkaline conditions. Most microorganisms thrive in a pH range of 6.0–8.0 (Chen et al. 2021). For example, in a biochar–SA immobilized system with *Bacillus licheniformis* WL08, the removal efficiency of fenoxaprop-p-ethyl was approximately 90%

when the pH was below 6.0 or above 8.0. However, at a pH between 6.0 and 8.0, the immobilized microorganisms achieved nearly 95% removal (Zhang et al. 2020). Additionally, biochar can indirectly influence microbial diversity, enzyme activity, and SOM stabilization mechanisms by altering soil pH, further affecting the removal efficiency of organic pollutants (Hill et al. 2019). Studies have indicated that when soil pH is close to its original state (in situ), the microbial community α-diversity peaks, suggesting rich microbial species and functional diversity, which are favorable for the co-degradation of complex organic pollutants (Tian et al. 2021), thus affecting the transformation pathways of organic pollutants. Moreover, changes in soil or water pH affect the concentration of dissolved organic carbon, which in turn influences the ability of microorganisms to utilize organic carbon sources, indirectly affecting organic pollutant degradation (Wang and Kuzyakov 2024).

pH also affects the chemical form and bioavailability of pollutants. Organic pollutants containing acidic or basic functional groups undergo ionization or deionization, depending on the pH of the environment. For instance, carboxylic groups tend to deprotonate at a high pH, forming anionic species and increasing water solubility, whereas they exist in non-ionized forms at a low pH, thereby enhancing hydrophobicity. This change in ionization status directly affects the solubility, mobility, and bioavailability of pollutants (Wei et al. 2016). Some organic pollutants, such as chlorinated hydrocarbons, may undergo hydrolysis or redox reactions under different pH conditions, altering their structure and toxicity (Brusseau and Chorover 2019). Furthermore, pH significantly influences adsorption capacity and mechanisms, especially when treating organic pollutants in complex industrial wastewater. Proper pH control is a key strategy for enhancing the interactions between microorganisms and organic pollutants, as well as improving the effectiveness of biochar applications (Abbas et al. 2018). Kah et al. (2017) noted that certain ionizable organic compounds, such as phenols and amines, exhibit higher adsorption at low pH values because biochar surfaces become positively charged, forming stronger electrostatic attractions with anionic pollutants (Kah et al. 2017; Liang et al. 2021). In addition to electrostatic interactions, pH also influences hydrogen bonding, π–π interactions, and hydrophobic interactions. For instance, in neutral to weakly alkaline conditions, π–π stacking and hydrophobic interactions are enhanced, favoring the adsorption of non-polar organic molecules. In contrast, these interactions may weaken under strongly acidic or alkaline conditions (Ambaye et al. 2021). Therefore, in practical applications, the pH should be adjusted according to the characteristics of target pollutants and the environmental conditions of wastewater or soil to maximize the purification effect of biochar-supported microbial systems.

4.3 Temperature

Temperature variations directly influence the metabolic activity of microorganisms and their degradation efficiencies. Elevated temperatures typically accelerate microbial metabolism and enzyme activity, thereby increasing degradation rates. However, exceeding a certain threshold can cause protein denaturation and cell function impairment, thereby reducing degradation efficiency. For instance, Zhang et al. found that the degradation efficiency of *Serratia marcescens* N80 for the herbicide thifensulfuron-methyl increased with temperature, reaching optimal degradation efficiency at 30–35 °C, pH 6.0–7.0, and 3.0% (v/v) concentration, with a degradation rate of 93.6% within 96 h. This rate significantly decreased at 40 °C (Zhang et al. 2012). Notably, biochar-supported microbial system exhibit better thermal adaptability than free cells, primarily because biochar provides a stable microenvironment that makes functional microorganisms less sensitive to minor temperature fluctuations (Yang et al. 2023). For example, Zhu et al. observed that biochar-immobilized *S. marcescens* N80 maintained a high degradation efficiency at 40 °C (Zhu et al. 2021). Overall, environmental temperature influences microbial metabolic rate, enzyme activity, and interactions with the carrier, thereby affecting the removal of organic pollutants in the biochar–microbe system. In cold regions, temperature-tolerant and adaptable strains should be selected, and biochar properties should be optimized to ensure stable microbial ecosystem operation. In warmer or fluctuating environments, the potential effects of temperature variations on system stability should be considered. The design and selection of microbial strains and biochar materials should be based on environmental temperature conditions to maximize organic pollutant removal.

4.4 Other environmental factors

The initial concentration of pollutants is an important parameter that influences pollutant removal efficiency. From an adsorption perspective, as the pollutant concentration increases, more molecules are captured by the adsorbent, thereby increasing the unit amount of adsorbent used. This enhances the supply of substrates available to microorganisms (Barquilha and Braga 2021). From a microbial degradation perspective, as pollutant concentration increases, the increased use of adsorbents typically leads to a higher number of available microorganisms because the greater availability of pollutants provides abundant carbon sources and energy, promoting microbial growth and reproduction (Harju et al. 2021).

However, high concentrations of pollutants can also pose a toxic threat to microbial communities, inhibiting their activity and even causing shifts in community structure, thereby affecting the overall efficiency of pollution treatment (Liu et al. 2024b). For instance, Nie et al. found that as pyridine concentrations increased, its removal rate initially increased and then decreased, with biochar-supported microbial systems achieving higher removal rates than free cells (Nie et al. 2021).

In addition, high salinity (e.g., Na^+) affects biochar-supported microbial systems application, particularly in seawater and brackish environments. High Na^+ concentrations typically lead to changes in microbial osmotic pressure, impeding nutrient absorption by microorganisms and disrupting biological activity, leading to "salt poisoning" in microbes. Moreover, salinity compresses the electrical double layer on the biochar surface, limiting electrostatic attraction between charged pollutants and surface functional groups (Ahmad et al 2014). Researchers have begun to develop salt-tolerant systems for biochar–microbe–EPSs to couple high salt adsorption capacity with nutrient supply to support microbial growth (Abd El-Mageed et al. 2020). Furthermore, biochar can indirectly influence microbial activity and pollution treatment efficiency by regulating the microenvironments of soil and aquatic systems. Biochar can modify the oxygen content in soil, benefiting the active metabolic processes of aerobic or facultative anaerobic microorganisms, which are particularly important for degrading organic pollutants (Sharma et al. 2025). Additionally, biochar improves SOM content and nutrient cycling, promoting the sequestration and cycling of soil organic carbon, thereby providing continuous nutritional support for microorganisms and further enhancing their activity. Therefore, biochar not only serves as a microbial carrier that supports microbial communities but also indirectly promotes microbial activity and pollution treatment efficiency through multiple pathways, including improved oxygen supply, organic matter content, and nutrient cycling.

5 Applications of biochar-supported microbial systems in organic pollutant removal

Biochar-supported microbial systems enhance pollutant transfer efficiency to microbial communities and promote the formation of stable biofilms through the degradation of pollutants (Wu et al. 2022). Consequently, biochar -supported microbial systems have been widely applied for the removal of organic pollutants from industrial wastewater, domestic sewage, and soils via biosorption and/or biodegradation processes.

5.1 Applications of biochar-supported microbial systems in aquatic environments

Waterbodies are a common medium for the application of biochar-supported microbial systems. Domestic sewage contains various persistent and difficult-to-degrade organic pollutants such as chlorophenols and nonylphenols (Van Aken et al. 2015). To effectively remove these pollutants, Wang et al. developed a high-bioactivity surface soil layer incorporating microorganism (BO), peanut shell (PS), or cow manure (DM) biochar to remove 2,4-dichlorophenol (2,4-DCP) from contaminated surface runoff. In a low-permeability bioactive PS + BO layer with a runoff treatment capacity of 0.33 L day^{-1}, approximately 77% of 6,000 μg L^{-1} 2,4-DCP was absorbed within 36 h (Wang et al. 2020a). Lou et al. immobilized nonylphenol-degrading bacteria onto high-surface-area BBC biochar, and the resulting composite (I-BBC) exhibited excellent removal performance and high reusability, with the degradation process being synergistically enhanced by various beneficial bacterial communities (Lou et al. 2019). To address industrial wastewater pollution, Du et al. immobilized the degrading bacterium DZ3 onto corn stover biochar, significantly improving the removal rate of polybrominated diphenyl ethers (500 mg L^{-1}), which was 63% and 83% higher than that of biochar alone and free bacteria, respectively (Du et al. 2016). For dye removal, researchers isolated bacteria from dye-rich waters, and using a continuous packed bed bioreactor, observed excellent removal performance under high dye loads, with *Bacillus alcalophilus* achieving a methylene blue removal rate of 96.2% (Bharti et al. 2019). Talha et al. employed coconut shell biochar as a carrier for *Bacillus subtilis* in batch and continuous packed bed bioreactors and observed a significant enhancement in Congo red dye bioremediation compared with non-immobilized strains (Abu Talha et al. 2018), emphasizing the advantages of composite materials.

Despite numerous studies demonstrating the potential of biochar-supported microbial systems for water remediation, some issues require further exploration. Although biochar has shown significant benefits in promoting microbial removal of water pollutants, avoiding antagonistic interactions with functional microorganisms for efficient removal is critical. Xin et al. discovered that the presence of biochar resulted in a slow, rate-limited desorption process during the biodegradation of 2,2′,4,4′-tetrabromodiphenyl ether (BDE-47), significantly reducing the degradation rate (Xin et al. 2014). Therefore, the strong affinity of biochar for certain organic pollutants may significantly inhibit the bioavailability of biochar-immobilized microorganisms, resulting in negative effects. Furthermore, the potential re-release of pollutants from the immobilized system back into the aquatic environment and the long-term ecological and health risks associated with such applications remain unclear. The adsorption mechanisms of biochar involve physical and chemical adsorption, ion exchange, and surface complexation, all of which influence the stability of pollutant–biochar binding (Li et al. 2022a). Environmental conditions such as pH, electrolyte concentration, and temperature changes can disrupt the adsorption equilibrium, causing desorption and pollutant release (Murtaza et al. 2024). Moreover, long-term environmental aging of biochar—driven by oxidative weathering, photodegradation, and microbial colonization—can progressively alter its surface chemistry and pore structure (Mia et al 2017; Wang et al 2020c, a, b). This aging process often leads to pore blockage, loss of key functional groups, reduction in overall adsorption capacity, and even the leaching or secondary formation of toxic by-products (Long et al. 2024). Such changes not only reduce the effectiveness of biochar as a microbial carrier but may also introduce new ecological hazards in treated waters. Therefore, optimizing biochar preparation processes, surface modification, and regeneration technologies to provide safe carriers for degrading microorganisms is crucial for controlling these risks.

5.2 Applications of biochar-supported microbial systems in soil

Biochar-supported microbial systems are a feasible option for reducing the harmful effects of pollutants on soil microorganisms without affecting soil properties or interrupting agricultural activities during soil remediation (Bolan et al. 2023). Soil contamination by pesticides and antibiotics is a significant environmental concern in agricultural settings. Yang et al. and Tao et al. developed biochars from corn stover and banana peel, as well as iron-modified biochar, to immobilize *Acinetobacter lwoffii* DNS32 for atrazine degradation. Compared with free-degrading strains, degradation efficiency was improved by approximately 20–40%, and the formation of microbial biofilms was promoted (Yang et al. 2017; Tao et al. 2020). Liu et al. reported that using 0.5‰ corn stover biochar to immobilize bacteria achieved the highest removal rate (82.18%) of chlorpyrifos in soil within 40 days (Liu et al. 2018). Wahla et al. demonstrated that coupling rice husk biochar with a *Deinococcus radiodurans* MB3R bacterial consortium accelerated metolachlor degradation and restored soil bacterial community structure (Weber and Quicker 2018). Zhu et al. developed a biochar-supported microbial system that maintained over 80% removal efficiency of tartaric acid thifensulfuron-methyl in soil even after five cycles of reuse; after 210 days of storage, the removal rate remained at 66.85%, far surpassing that of free cells, demonstrating the significant advantages of encapsulation and immobilization technology (Zhu et al. 2021). Additionally, Zhang et al. created a novel material combining waste fungal film biochar and *Herbaspirillum seropedicae* HHS1, achieving removal rates of 41.9% and 40.7% for oxytetracycline and enrofloxacin, respectively, while effectively removing heavy metals such as Zn and Cu.

Industrial chemicals, including toluene, phenol, polychlorinated biphenyls, and total petroleum hydrocarbons, contribute to organic nonpoint source pollution in soils from the petroleum, chemical, pharmaceutical, and textile industries. Biochar-supported microbial systems have shown remarkable effects in removing petroleum hydrocarbons, particularly PAHs. Research has indicated that immobilizing phenol-degrading bacteria on biochar via adsorption and encapsulation methods significantly improves environmental adaptability and degradation efficiency (Lou et al. 2019; Zhao et al. 2020). Kaili et al. used magnetic biochar gel beads to immobilize bacteria, achieving degradation rates of 89.8%, 66.9%, and 78.2% for pyrene (PYR), benzo(a)pyrene, and indeno(1,2,3-cd)pyrene, respectively (Zhang et al. 2019a). However, when co-contaminated with heavy metals, removal efficiency may be compromised. For example, Yang et al. observed that the removal rate of PYR decreased from 90.2% to 52.9% when cadmium was added, and after 28 days of treatment, the release rate remained as high as 88.7% (Yang et al. 2020a). Thus, developing biochar-supported microbial systems capable of synergistically removing both organic and inorganic co-contaminants is critical for future research.

When applied in soil systems, bioadsorbent materials can confer demonstrable ecological benefits but may also pose latent environmental risks. For example, biochar amendment has been reported to increase soil total carbon and particulate organic carbon by 47.4–50.4% and 63.7–74.6%, respectively (Tian et al 2016). Moreover, in a continuous ten-year field trial, biochar application increased wheat yield by 7.9% compared with straw incorporation (Chen et al 2025a, b). Conversely, other studies have indicated that biochars produced from high-lignin feedstocks may contain substantial amounts of phenolic compounds, which are highly toxic and can severely disrupt soil microbial communities, thereby impairing overall ecosystem function (Liu et al. 2024a; Parasar and Agarwala 2025). Additionally, studies have shown that the main source of toxicity in MB/NB (different types of biochar) is not yet fully understood, whether it results from the adsorption of harmful substances or from the inherent components of biochar. Further studies are needed to clarify these mechanisms and assess associated risks (Xiang et al. 2021). Notwithstanding, combining biochar with microorganisms and plants for synergistic remediation is a promising new direction in current research (Kamyab et al. 2025), but this field is still in its early stages and requires more comprehensive studies to address challenges and maximize effectiveness.

6 Advantages and challenges of biochar–microorganism systems

Biochar–microorganism systems have demonstrated significant potential for treating organic pollutants as a composite remediation technology that integrates physical adsorption and biological degradation. Biochar can adsorb pollutants through its surface functional groups, enhancing the bioavailability of pollutants and promoting microbial metabolism and degradation efficiency. This synergistic effect between material adsorption and biological degradation significantly improves the speed and effectiveness of pollutant removal. Moreover, the system is highly environmentally friendly, as it does not require large amounts of chemical reagents during the treatment process, produces fewer byproducts, consumes less energy, and effectively reduces secondary pollution, thereby aligning with the principles of green and sustainable development.

However, applying this system faces several challenges. First, to ensure the activity and survival rate of biochar-supported microbial systems during transportation and storage, identifying optimal environmental conditions is necessary. Key factors, such as temperature, humidity, and protective additives, significantly affect the physiological state of microorganisms. Large-scale, long-term field trials can provide in-depth assessments of the practical application potential and comprehensive benefits of biochar microorganism immobilization technology in agricultural production and ecological environments. Second, in complex ecosystems with multiple coexisting microorganisms, the precise regulation of interspecies competition and symbiotic relationships has become increasingly important. Antagonistic relationships between different strains can severely inhibit overall degradation capacity, whereas the rational construction of synergistic microbial communities may maximize system efficiency. Additionally, certain modified or high-dose applications of biochar may induce synergistic toxicity with coexisting pollutants, leading to significant tissue damage and oxidative stress responses in soil fauna such as earthworms (Zhang et al. 2022). These adverse effects can subsequently disrupt key soil ecological functions.

To address these issues, future research directions should primarily focus on four areas. First, researchers should focus on the development and modification of novel biochar materials—including introducing functional components such as metal oxides, chitosan, and nanomaterials—to produce functionalized composite biochars with EC, self-regulation, or targeted adsorption capabilities, thereby enhancing carrier performance and microbial attachment stability. Second, microbial strains should be engineered through directed evolution or synthetic biology to enhance their adaptability to complex field conditions—such as abrupt temperature fluctuations, high salinity, or heavy-metal stress—while using sodium-alginate–chitosan microcapsules or modified biochar encapsulation to achieve sustained release and targeted colonization of the microorganisms. Third, synthetic biology can be applied to modify microbial genetic circuits for targeted purposes, enabling multifunctional pollutant recognition, enhanced tolerance to toxicity, and regulation of microbial community behavior, thus constructing stable and efficient microbial consortia. Fourth, collaborative ecotoxicology research should comprehensively assess the persistence and ecological risks of biochar and microorganisms in the environment to prevent potential secondary pollution caused by material release or microbial escape. Furthermore, it is essential to advance the development of in situ monitoring and model construction technologies—including real-time monitoring methods, such as in situ fluorescence sensing, biochips, and near-infrared imaging—as well as pollution migration and remediation prediction models based on machine learning. These will help achieve precise and intelligent management of pollution control.

7 Conclusion

The integration of biochar-supported microbial systems presents a groundbreaking approach for organic pollutant remediation by synergistically combining the superior adsorption capacity of biochar with microbial metabolic degradation capabilities. This innovative system addresses the critical limitations of conventional methods by enhancing contaminant bioavailability while providing a protective microenvironment for microbial communities. Biochar-supported microbial systems demonstrate remarkable efficiency in degrading diverse organic pollutants, including persistent hydrocarbons and chlorinated compounds, through a combination of physical sequestration and biological transformation. The adaptability of this technology allows for the optimization of specific contamination scenarios through tailored biochar properties and microbial selection. Although challenges remain in field-scale implementation and long-term performance assessment, biochar-supported microbial systems represent a sustainable solution aligned with the principles of a circular economy. Future research should focus on a mechanistic understanding of microbe–biochar interactions and developing standardized application protocols to facilitate the widespread adoption of this promising bioremediation strategy.

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Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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