

REVIEW

Open Access



# Biochar immobilized microbes for sustainable soil remediation and agriculture enhancement: from lab to farmland

Xinyi Li<sup>1†</sup>, Qianyi Lyu<sup>2†</sup>, Caiting Han<sup>2</sup>, Na Duan<sup>1</sup>, Zhidan Liu<sup>1</sup>, Miao Gao<sup>2\*</sup> and Xiao Zhao<sup>1\*</sup> 

## Abstract

Soil degradation and contamination pose a critical threat to global agricultural sustainability, necessitating innovative remediation strategies. Biochar-immobilized microbes (BIMs), which synergistically integrate physicochemical advantages of biochar with microbial metabolic functions, represent a transformative approach to enhance soil health and crop productivity. This review provides a data-driven analysis, with evidence from 92 published articles to summarize advancements in BIM development from 85 pot experiments and 11 field applications, and to elucidate the underlying mechanisms. Biochar serves as a stable microbial habitat, enhancing colonization through adsorption, entrapment, covalent bonding, and crosslinking. Key factors such as biochar porosity, microbial surface characteristics, and environmental conditions critically influence microbe immobilization efficiency and functional longevity. The compiled data indicate that BIMs can ameliorate soil properties (e.g., elevating pH by 0.5–1.5 units, increasing cation exchange capacity by 12.25–39.05%), and enhance soil enzyme activities (e.g., urease, dehydrogenase). These improvements contribute to effective remediation of contaminated soils, with reported efficiencies up to 95% for heavy metals and 90% for organic pollutants. Furthermore, field applications demonstrate that BIMs can enhance crop yields by up to 45%, primarily through improved nutrient availability and stress resilience. However, scalability challenges persist, as field trials show variable microbial survival under climatic stresses. The transition from predominantly lab-scale research to fewer documented field validations highlights the need for more long-term, on-farm studies. By systematically bridging lab innovations to farmland practicality, BIMs align with the UN Sustainable Development Goals, offering a promising pathway for soil restoration and sustainable agriculture. Future research must prioritize long-term field validations, lifecycle assessments, and farmer-centric optimization to unlock their full potential.

## Highlights

- BIMs synergize the advantages of biochar and microbial metabolic functions for soil remediation and agricultural enhancement.
- Immobilization strategies (adsorption, entrapment, covalent bonding, and crosslinking) optimize microbial survival and activity.
- Field trials reveal that BIMs boost crop yields up to 53% via improved root development, nutrient cycling, and pathogen suppression.

<sup>†</sup>Xinyi Li and Qianyi Lyu have contributed equally to this work.

\*Correspondence:

Miao Gao

gaomiao@caas.cn

Xiao Zhao

xiaozhao88@cau.edu.cn

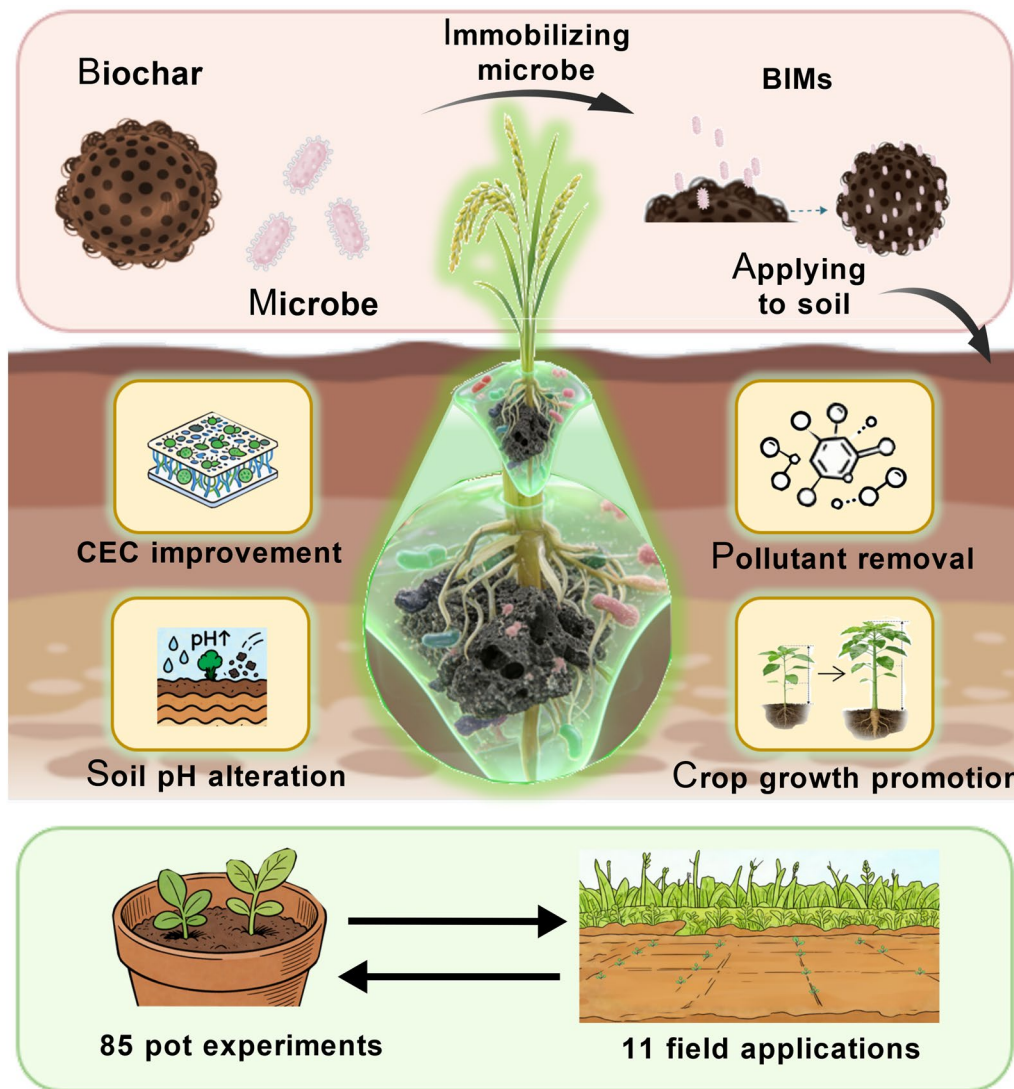
Full list of author information is available at the end of the article

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

- This review establishes a data-intensive paradigm, moving beyond narrative synthesis to deliver a quantitative and visual knowledge landscape of the field.

**Keywords** Biochar immobilized microbes (BIMs), Soil remediation, Biochar, Sustainable agriculture, Plant growth-promoting bacteria

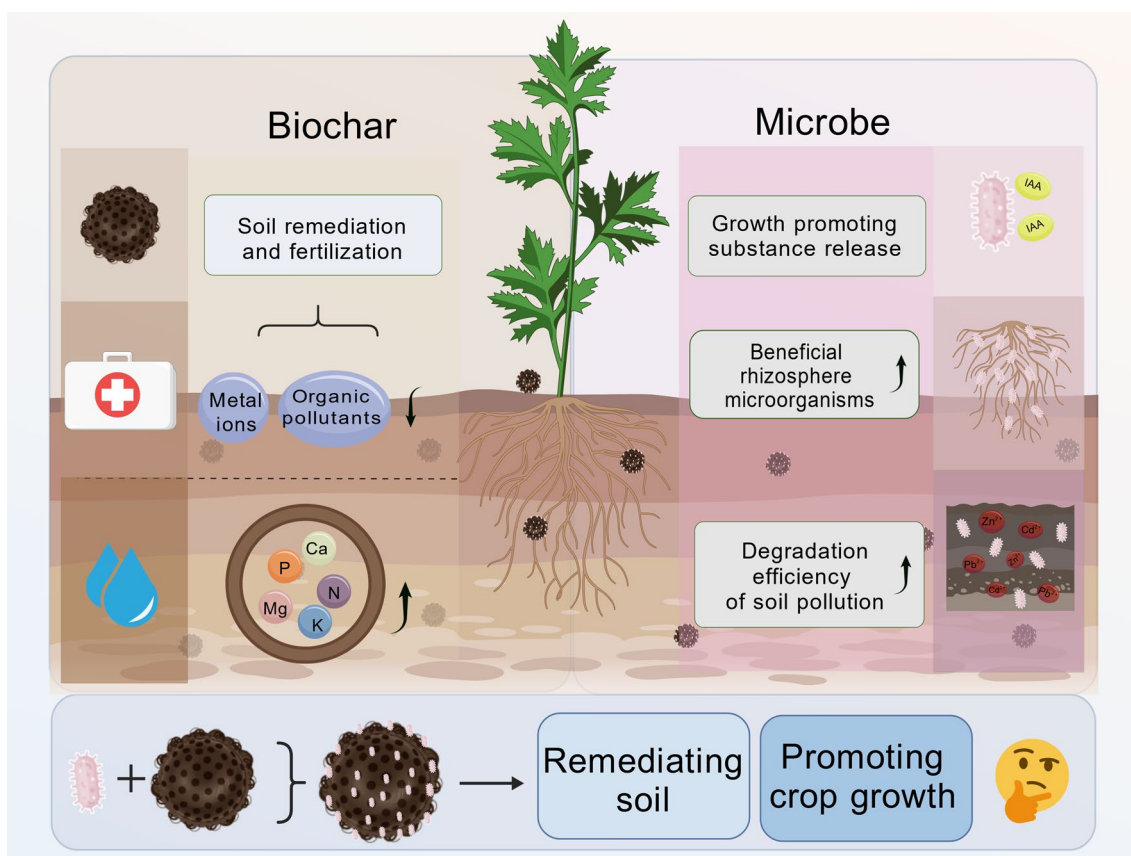
**Graphical Abstract**



**1 Introduction**

Biochar has garnered increasing attention as a sustainable solution for soil remediation and agriculture enhancement over recent decades (Lehmann et al. 2009; Li et al. 2024a). This carbon-rich material is commonly produced through the pyrolysis of biomass and can improve soil

health through multifaceted mechanisms (Chu et al. 2024; Tao et al. 2025). The primary functions of biochar include improving soil structure, increasing water retention, supplying soil nutrients, remediating pollutants, and providing a habitat for beneficial microorganisms (Fig. 1) (Bolan et al. 2014; Yang et al. 2025). The porous structure

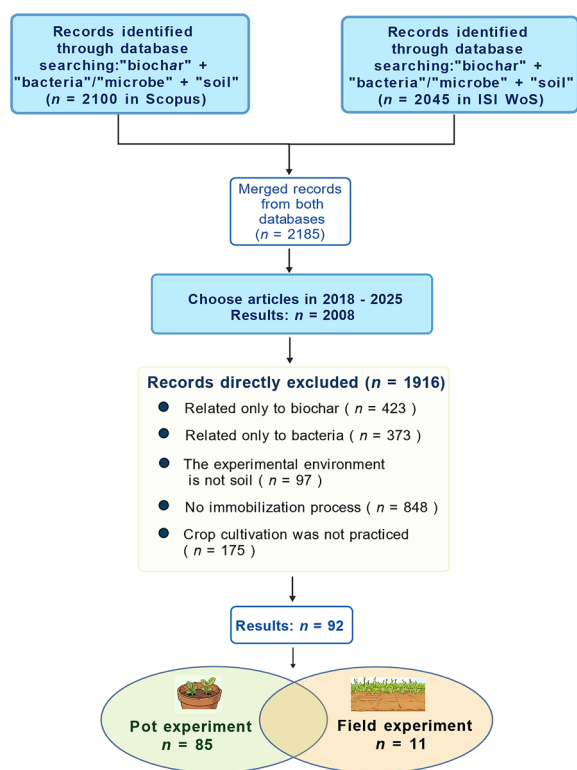


**Fig. 1** Beneficial roles of biochar and functional microbes in the soil matrix

of biochar enhances soil aeration, water retention, and drainage (Wu et al. 2025). This prevents compaction and waterlogging, while fostering a healthy environment for root growth and microbial activity. Additionally, the high surface area of biochar provides habitats for beneficial microorganisms, promoting a thriving microbial community in the soil matrix (Jorge et al. 2021). Biochar can also trap essential soil nutrients (nitrogen, phosphorus, and potassium) (Wang et al. 2021) and stabilize their bioavailable forms to plants. Furthermore, owing to its alkaline nature, biochar neutralizes acidic soils to create a balanced pH environment for diverse plant species with high nutrient availability (Ren et al. 2022a). Moreover, biochar can function as a soil remediating agent to bind to various heavy metals and pollutants, and to reduce their bioavailability (Huang et al. 2025; Xiong et al. 2025). As a stable carbon source, biochar sequesters carbon in the soil (Pathak et al. 2024), contributing to carbon dioxide reduction and combating climate change (Zhang et al. 2024). By improving soil structure, water retention, and microbial activity, biochar creates an optimal environment for plant roots (Wu et al. 2024), leading to healthier plants, higher crop yields, and more resilient soils. These

combined physical, chemical, and biological benefits of biochar enhance soil remediation (Bi et al. 2025; Ma et al. 2025), improve nutrient cycling, and increase crop yields (Li et al. 2025), thus positioning biochar as a critical tool for sustainable agriculture (Li et al. 2024b).

In parallel, the application of functional bacteria and other microbes for soil remediation and agricultural enhancement has also been widely investigated. Microbial techniques have been employed to restore soil health and fertility, particularly in degraded or contaminated soils. Microbes can also improve soil properties through key mechanisms, including nutrient cycling, organic matter decomposition, and solubilization of essential minerals (such as phosphorus) (Luo et al. 2025; Zeng et al. 2025). Specific microbes, such as plant growth-promoting rhizobacteria (PGPR or PGPB), have been used to enhance plant growth (Ren et al. 2022a). Typical objectives of using PGPB include improving the release of essential nutrients, producing phytohormones, and suppressing plant pathogens. Additionally, certain bacteria can improve biofilm formation in the rhizosphere, which not only enhances stress tolerance of plants but also improves nutrient availability in soil (Bai et al. 2024b).



**Fig. 2** BIMs case search flowchart (2018–2025)

The integration of microbial inoculants into agricultural practices has been shown to improve crop yields and resilience against environmental stresses. For example, Luo et al. demonstrated that inoculating tomato plants with phosphorus-solubilizing bacteria (PSB) resulted in a 24.7% increase in yield (Luo et al. 2025). Similarly, Sharma et al. reported that sugarcane yield could be enhanced by 23.20% through the application of microbial inoculants (Sharma et al. 2023). Additionally, Peng et al. found that microbial inoculation significantly boosted cucumber yield by improving soil aggregate stability (Peng et al. 2025). Despite their efficacy, microbial survival and functionality in field conditions remain limited, highlighting the need for carriers/supports to optimize their application in farmland.

## 2 Search strategy, data collection and visualization

Our objective is to address whether, how, and to what extent BIMs generate synergistic benefits for sustainable soil remediation and agricultural enhancement. Initially, we searched both Scopus and ISI Web of Science Core Collection for related articles, limiting the topics to "biochar," "bacteria/microbes," and "soil". After careful screening (Fig. 2), we finally selected 92 published articles closely related to our theme (85 and 11 articles on pot tests and field trials, respectively).

The original data from articles were obtained from their tables or supporting information files. Online software (Getdata Graph Digitizer: <https://getdata-graph-digitizer.com/>) was used to extract data from Plots. The distribution of data was plotted as box and/or violin plots using Origin 2021. Data were plotted across control (CK), biochar (B), microbe (M), and BIM groups. To give fair comparisons within the same case, we calculated the within-study data and plotted the results as B/CK, M/CK, and BIM/CKs. In a typical chart, hollow black rectangles denote the mean of the data cluster. The horizontal line within the box denotes the median. The upper and lower edges of the box correspond to the upper and lower quartiles, respectively. The lines extending from the box indicate the minimum and maximum values (excluding outliers). The symbol *n* represents the number of cases. The *p*-value (based on the *t*-test) was calculated by Origin 2021 to determine statistical significance between the data groups.

Some other scheme figures were created using the Generic Diagramming Platform (GDP) (Jiang et al. 2025), a dedicated scientific diagramming tool. No AI-generated figures were used in this work.

## 3 Synthesis of BIMs

### 3.1 Biochar synthesis

The biochar used in most of the studies was synthesized by typical pyrolysis methods. Raw materials (e.g., straw, rice husk, or corn straw, with straw being dominantly used in 52 of 92 reviewed cases) were collected and washed with deionized water to remove impurities. Biomass was then air- or oven-dried (usually at 80 °C) and ground into powder (particle size: 0.15–0.25 mm). The biomass powder was pyrolyzed in a muffle/tube furnace at 400 °C–700 °C (usually with N<sub>2</sub>) (Wu et al. 2024). Heating rates and residence times were controlled to optimize porosity, surface area, and chemical functionality of produced biochar. After pyrolysis, the biochar was cooled, rinsed, dried, and then sieved to ensure homogeneity. Generally, biochar produced at higher pyrolysis temperatures (>500 °C) exhibited enhanced surface area and aromaticity, which are critical for pollutant adsorption (Wang et al. 2021). These physicochemical properties can also directly influence the efficacy of biochar as microbial carriers.

### 3.2 Functional microorganism cultivation

The microorganisms capable of degrading/immobilizing pollutants are primarily obtained through enrichment and cultivation from the contaminated soil environment (Yin et al. 2023). In enrichment culture, continuously increasing the pollutant concentrations could select for microbial communities tolerant to and/or capable of degrading

pollutants (Li et al. 2023). Dominant strains with high degradation activity were then isolated by sequentially transferring the culture to fresh basal salt medium containing pollutants as the sole carbon or nitrogen source (Wahla et al. 2020). As the pollutants were degraded, the domesticated culture was transferred multiple times in the enrichment experiments (Li et al. 2023). The final enriched culture was then diluted continuously (Sun et al. 2020) and purified through streak-planting on agar supplemented with target pollutants (Wu et al. 2022).

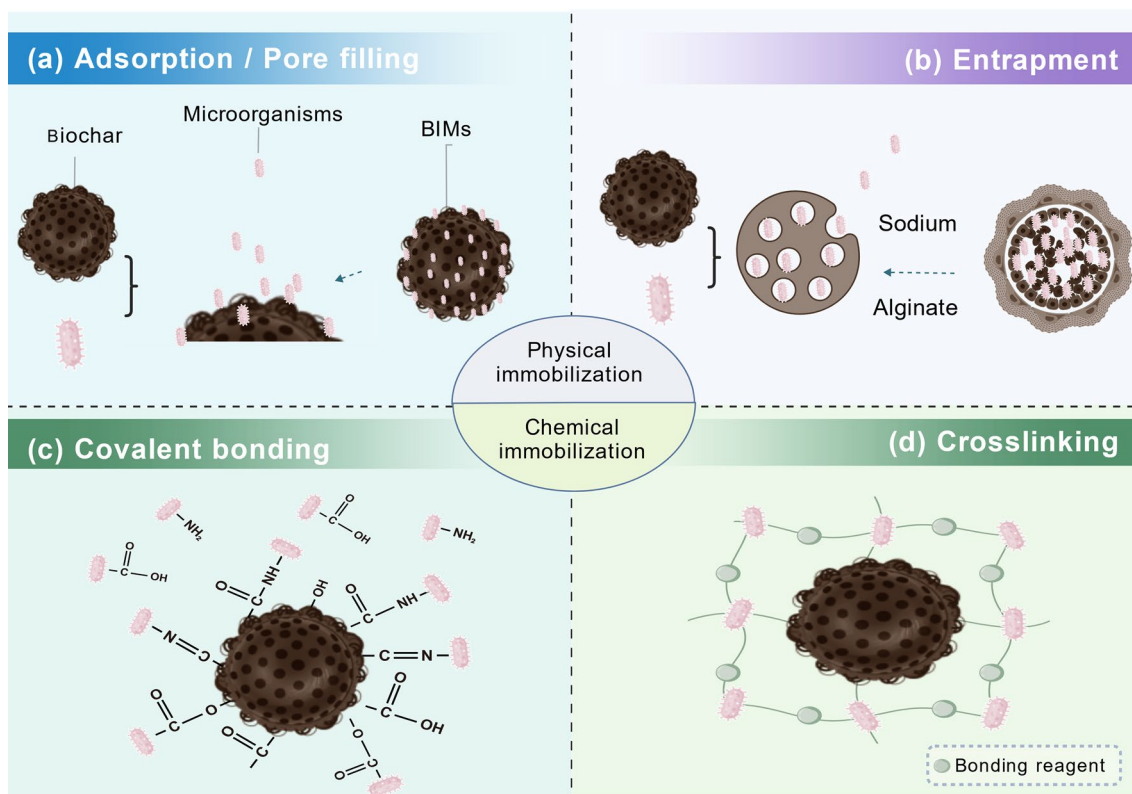
### 3.3 Microbe immobilization mechanisms and protocols

Immobilization of functional microbes onto biochar to produce BIMs can be categorized into four primary mechanisms (Fig. 3): adsorption, entrapment, covalent bonding, and crosslinking. Adsorption and entrapment are typical physical methods, while covalent bonding and crosslinking are mainly chemical.

- a) **Adsorption** (surface adsorption, pore adsorption, or pore filling) is a physical immobilization technique that relies on physical attractive forces to attach

microbial cells to the biochar surface (Fig. 3a). Weak attractive forces are mainly van der Waals forces and hydrogen bonds, while some relatively strong forces (mainly electrostatic attraction) also exist. This method is characterized by its simplicity, high microbe loading, cost-effectiveness, and minimal damage to microorganisms.

The physical adsorption strategy is very straightforward and relies on the direct interactions between microorganisms and biochar to adsorb and bind together (Ma et al. 2021). This method predominated in our reviewed studies (54 out of 92 cases). A typical process is as follows (Fig. 3a): first, introduce the target bacterial solution (usually 1–3% wt.%) to the medium and incubate for 24–48 h to an optical density (OD600) of 1.0 (Tu et al. 2020). After cultivation, mix the resulting cell suspension with biochar in a certain proportion (W/V) for 24 h. Subsequently, BIMs are obtained by centrifugation and then washed three times with sterile physiological saline solution (usually 0.8–1%) to remove free cells (Zhang et al.



**Fig. 3** Typical mechanisms for immobilization of microbes to biochar: **a** adsorption/pore filling, **b** entrapment, **c** covalent bonding, and **d** crosslinking

2019). However, physically adsorbed microbe cells could be prone to leakage (Wu et al. 2021).

- b) **Entrapment** (embedding) refers to the process of physically enclosing microbial cells within the biochar matrix/pores. This method effectively prevents the loss of microbes into the surrounding environment, thereby improving their activity.

In this method, additives are needed to achieve entrapment or embedding. Sodium alginate (SA) is a commonly used agent and was applied in 17 out of 92 cases we reviewed. SA is a low-cost and natural polymer gel carrier with high mass transfer ability (Jiang et al. 2022; Qu et al. 2025). The addition of SA can prevent microbes from seeping out of the biochar carrier, while small-molecule substrates and products from the external environment can freely enter or exit the carrier. In a typical process (Fig. 3b), after incubating biochar and microorganism suspension, the SA solution is added (resulting in 2–4 wt%) to improve the immobilization. The mixed solution is then dropped into a  $\text{CaCl}_2$  solution (2–4%) and gently stirred to form micro-scale immobilized spheres (Chen et al. 2012). Then the microspheres are aged at 4 °C for 6–12 hours (Qi et al. 2021), and then collected and washed with NaCl solution, and finally stored at 4 °C (Ren et al. 2022b). Alternatives to SA as embedding agents include agar, kappa-carrageenan, polyacrylamide, and cellulose (Hajieghrari et al. 2020).

- c) **Covalent bonding** involves the formation of strong chemical bonds between reactive groups on microbial cells and functional groups on the biochar surface (e.g., sulfhydryl, amino, or hydroxyl groups). This method enhances the stability of the immobilized microorganisms, allowing for a more robust and selective attachment.

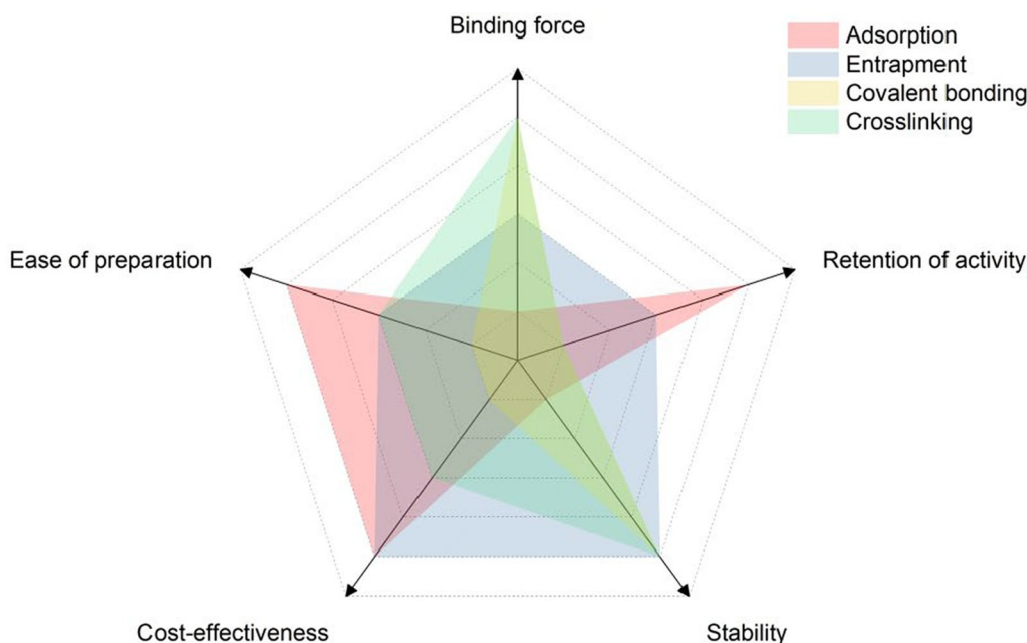
In this method, chemical covalent binders are used to enhance the covalent bonding (Nguyen Thi Hai et al. 2022). The formed bond is very strong and can improve the overall stability of BIMs (Hashem et al. 2016). Commonly used binders include ethylenediamine (EDA), polyethyleneimine (PEI), and glutaraldehyde (GA). Among them, EDA and PEI are commonly used for enzyme immobilization. GA can be used to build aldehyde groups on the biochar surface to form stable binding with microbial groups. In a typical process (Fig. 3c), biochar powder is introduced to GA solutions (0.3–5% v/v) and gently mixed overnight. Then, the modified biochar is rinsed three times with sterile salt solution to remove excess GA. To verify the successful binding, Fourier transform infrared spectroscopy (FTIR) can be used to characterize

the changes in surface functional groups of composite carrier materials (Li et al. 2022).

- d) **Crosslinking** is a chemical immobilization method that utilizes bonding reagents to create a network to improve connections between microbial cells and biochar. Common crosslinkers include GA, epoxy compounds, PEI, and so on (Zhang et al. 2021). These crosslinking agents can form stable chemical bonds on the surface of microbial cells and biochar through chemical reactions, thereby improving the stability of microorganisms. This technique is characterized by low reversibility and high stability, which minimizes the leaching of microbial cells.

The common crosslinking method is to mix microorganisms with biochar, add a crosslinking agent solution, stir evenly, and then react at a certain temperature (Fig. 3d). After the crosslinking reaction is complete, the excess crosslinking agent needs to be removed by washing with water or buffer to avoid possible toxic effects on microorganisms.

A systematic comparison of four immobilization mechanisms is summarized in a radar chart (Fig. 4) to evaluate their relative strengths across five dimensions: binding force, retention of activity, stability, cost-effectiveness, and ease of preparation. Notably, multiple immobilization mechanisms could coexist in a single technique. For instance, physical adsorption per van der Waals forces also occurs in entrapment, covalent bonding, or crosslinking. Covalent bonding could also contribute greatly to the crosslinking networks. For binding force and stability, covalent binding and cross-linking exhibit superior performance. Both techniques help form robust connections between biochar and microorganisms via chemical bonds or crosslinking agents, enhancing the mechanical stability and resistance to environmental perturbations of BIMs. Entrapment demonstrates moderate binding force but good stability, attributed to the protective role of biochar. In contrast, adsorption shows weaker binding strength and stability, owing to physical interactions such as electrostatic forces or van der Waals forces. These weaker interactions may lead to microbial detachment or deactivation under fluctuating environmental conditions. However, in terms of ease of preparation and cost-effectiveness, covalent binding and crosslinking exhibit high complexity and costs due to the requirement for additional chemical reagents and intricate operational procedures. Adsorption is the simplest and most cost-effective method. Entrapment and crosslinking have moderate preparation complexity, but entrapment has relatively low costs. For activity retention,



**Fig. 4** Comparison of four immobilization techniques

adsorption performs best in retaining microbial activity, as it relies solely on physical interactions that minimally perturb the physiological functionality of the microorganisms. In contrast, covalent bonding and crosslinking, which involve chemical reactions, may negatively impact microbial activity due to potential structural or functional modifications. The selection of an immobilization technique should be guided by the specific requirements of the application, balancing binding force, stability, difficulty of preparation, cost of immobilization, and activity retention (Fig. 5).

The radar chart is intended to illustrate performance trends by converting descriptive features into

liquid OD in the culture medium is denoted as  $OD_0$ . The OD of supernatant after microbe immobilization is denoted as  $OD_1$  to quantify the free microbes. Thus, immobilization efficiency can be obtained as follows:

$$\text{Immobilization efficiency (\%)} = \frac{OD_0 - OD_1}{OD_0} \times 100 \tag{1}$$

The second method is plate colony counting (Lu et al. 2020). Typically, after appropriately diluting, the sample solution is added to the plate, and after cultivation, visible colonies can be formed. The bacterial count in the sample can be calculated based on its dilution ratio and sampling inoculation amount:

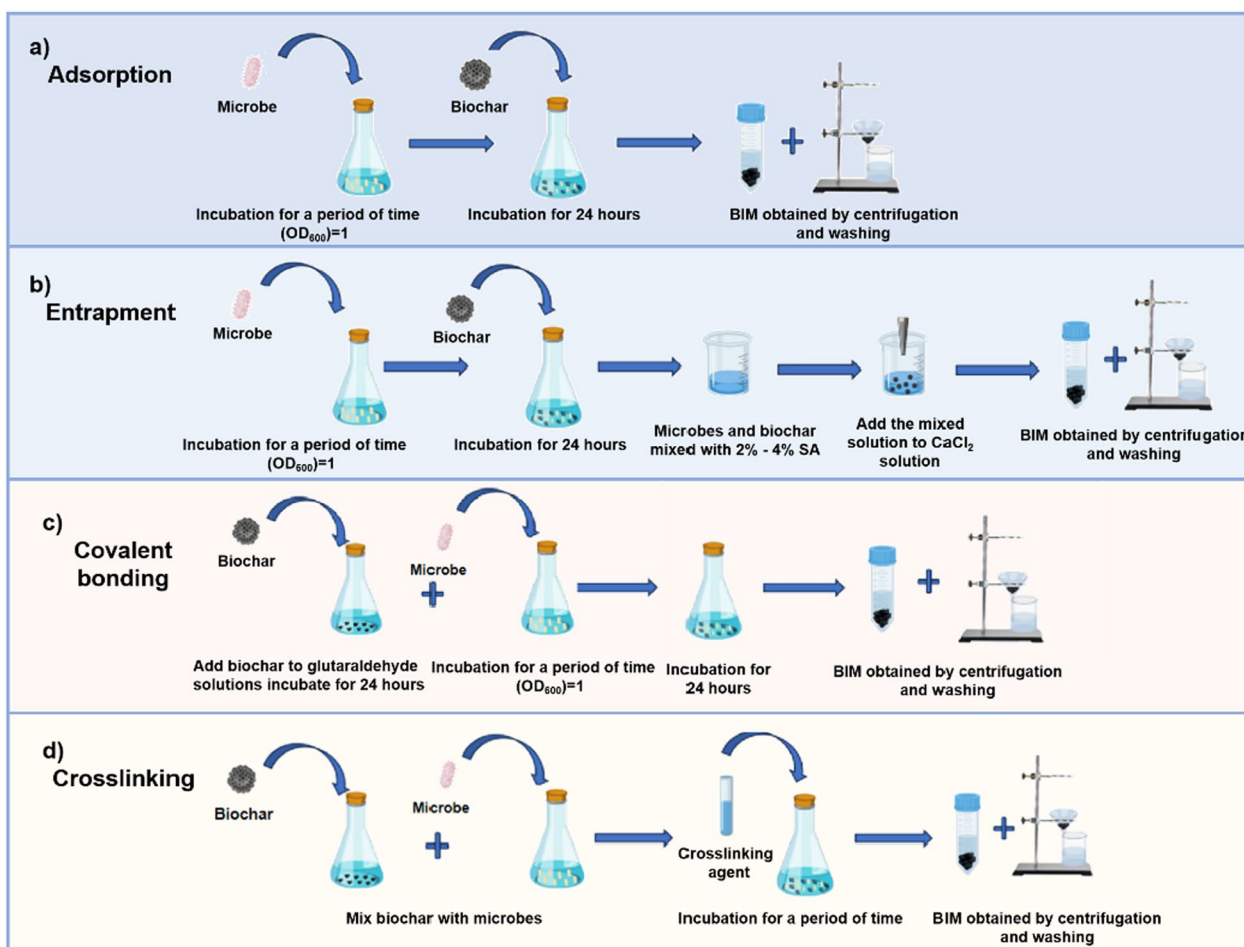
$$\text{Obtained biomass (CFU/g)} = \frac{\text{number of plate colonies} \times \text{dilution ratio}}{\text{mass of biochar}} \tag{2}$$

semi-quantitative scores, rather than to provide precise quantitative results (Zhang et al. 2021; Saravanan et al. 2023). The detailed scoring and conversion process is provided in Fig. S1.

### 3.4 Immobilization efficiency and determining factors

**Determination of immobilization efficiency.** Generally, there are three ways to quantify the amount of functional microbes fixed on biochar. The first method is to measure the optical density (OD) value at a designed wavelength (Jesionowski et al. 2014). Specifically, the initial bacterial

The third method is to examine the expression level of target genes in biochar through real-time quantitative PCR (Xiong et al. 2017). By adding fluorescent probes or dyes to the PCR system, the mass of target microorganisms is assumed to be linearly related to the signal of dyed genes, and then the copy number of the target gene in unknown samples can be quantitatively analyzed. By performing quantitative PCR reaction on immobilized samples, the cyclic threshold can be obtained, and then the copy number of the target gene in the immobilized samples can be calculated.

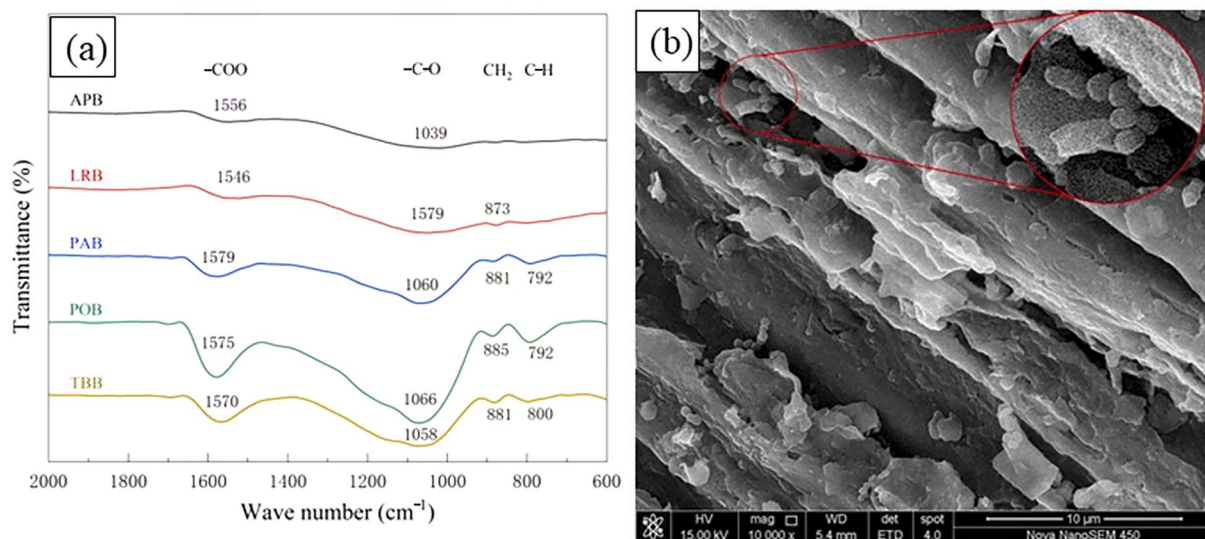


**Fig. 5** Typical protocols for immobilizing microbes on biochar: **a** adsorption, **b** entrapment, **c** covalent bonding, and **d** crosslinking

To effectively fix or immobilize functional microbes onto biochar, several influencing factors and strategies must be considered. Biochar serves as an excellent microbe carrier due to its unique physicochemical properties, such as its porous structure, high specific surface area, and surface functional groups (Shyam et al. 2025a), which facilitate microbial attachment and growth. The selection and inoculation of microbial strains are also critical, typically involving robust *Bacillus* spp. and metabolically versatile *Pseudomonas* spp., among others. To ensure controllability of the immobilization process and reproducibility of the biochar-microorganism composite performance, it is essential to standardize key synthesis parameters. These mainly include: the particle size of the biochar carrier (generally in the range of 0.15–2 mm, with 1–2 mm preferred for polycyclic aromatic hydrocarbon remediation and 0.15–0.85 mm for heavy metal remediation), feedstock and pyrolysis temperature (recommended at 400–500 °C); microbial inoculation conditions, such as cell suspension concentration (often

referenced as  $OD_{600} \approx 1.0$  or a viable count  $\approx 10^8$  CFU/mL) and the carrier-to-suspension loading ratio (commonly 1:10–1:20, w/v); as well as the immobilization incubation time (generally 24 h for microbial immobilization). The selection and inoculation of microbial strains is also critical. Additionally, environmental conditions can greatly influence microbial immobilization. The key factors are:

**Biochar properties:** Key properties of biochar, including porosity, surface area, pH, and surface functional groups, critically influence the immobilization efficiency of microbes. Generally, biochar with a well-developed porous structure and high specific surface area (SSA) enhances microorganism immobilization and survival. For example, in a study by Zhong et al. on formaldehyde removal using reed biochar (PAB) immobilized with *Microbacterium esteraromaticum* NH-001L, scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR) were employed to elucidate the micro-interfacial mechanisms (Zhong et al. 2025)



**Fig. 6** FTIR spectra and SEM characterization of biochar composites: **a** FTIR spectra of biochar pyrolyzed at 650 °C; **b** SEM images of PAB with NH-001L microbial strain (Zhong et al. 2025)

(Fig. 6). FTIR analysis indicated that oxygen-containing functional groups ( $-C=O$ ,  $-COO$ , and  $-C-O$ ) on the biochar surface served as key sites promoting both formaldehyde adsorption and microbial degradation. SEM imaging visually confirmed the successful colonization of NH-001L on the porous and layered surfaces of the biochar. Furthermore, it was observed that the unique corrugated morphology of PAB provided physical protection for the microorganisms, reducing their direct contact with the pollutant and thereby significantly enhancing the synergistic removal efficiency of the system, achieving a rate of 84.31%. The SSA of biochar highly depends on its production conditions, notably pyrolysis temperature. Alkaline biochar ( $pH > 9$ ) enhances the adsorption of positively charged microbial cells. Oxygen-containing groups on biochar (e.g.,  $-COOH$ ) could also facilitate hydrogen bonding with microbial exopolysaccharides (Li et al. 2024b).

**Microbial characteristics.** The surface properties of microbial cells are key intrinsic factors determining their successful colonization on biochar carriers. Among these, surface hydrophobicity directly influences van der Waals interactions between microbes and the typically hydrophobic biochar surface; stronger hydrophobicity generally facilitates initial physical adsorption. Simultaneously, the net surface charge carried by microorganisms at specific environmental pH levels engages in electrostatic interactions with the surface charges of biochar, which is rich in oxygen-containing functional groups (such as carboxyl and phenolic hydroxyl groups). These attractive or repulsive forces serve as important regulators of initial attachment. Furthermore, many microorganisms

actively secrete extracellular polymeric substances (EPS) during growth. EPS is a hydrophilic biopolymer network composed of polysaccharides, proteins, nucleic acids, and other components. EPS not only neutralizes cell surface charges and reduces electrostatic repulsion, but its inherent adhesive properties also function as a “biological glue.” This significantly enhances the attachment strength and stability of microbial colonies as a cohesive unit within biochar pores or on its surface, while providing a protective microenvironment for the microbial community. This EPS-mediated adhesion enhancement mechanism has been supported by relevant studies (Liu et al. 2017). Consequently, through the combined effects of these surface properties, microorganisms actively regulate their interface interactions with the biochar carrier, thereby influencing the construction efficiency and ultimate stability of BIMs.

**Environmental conditions.** Environmental conditions such as soil pH, moisture, temperature, and pollutant type critically regulate the synergy between biochar and microbes in soil remediation and crop growth (Liu et al. 2017). Most microbes thrive in a neutral pH range (6.0–8.0). The alkaline nature of biochar neutralizes acidic soils to reduce heavy metal toxicity and protect microbial enzymatic activity. Porous structure of biochar retains water in arid soils and improves aeration in waterlogged environments, sustaining microbial hydration and aerobic degradation. Temperature significantly affects the bioremediation process by influencing microbial activity. For pollutants like heavy metals and organics, biochar immobilizes contaminants via adsorption, enabling microbes to degrade them (e.g., *Mycobacterium*

mineralizing PAHs), with plant roots further enhancing nutrient release and microbial recruitment through exudates (Xiong et al. 2017).

#### 4 Performance of BIMs for soil remediation and agriculture enhancement

BIMs represent a transformative approach in soil remediation and sustainable agriculture, merging the adsorptive benefits of biochar with the metabolic capabilities of microorganisms to mitigate soil contamination and enhance agricultural productivity. However, there is still a lack of a systematic study bridging lab-scale innovations to farmland practicality. In this section, we summarize the significant findings from lab-scale pot experiments to farmland studies to evaluate the performance of BIMs and the underlying mechanisms.

BIMs are typically applied to soil as solid amendments at predetermined weight-to-weight ratios (w/w%). The cases we reviewed show that the BIM application ranged from 1 to 10% w/w. In pot experiments, where soil volume is limited and environmental conditions are controlled, researchers often employ higher application doses to verify the theoretical remediation potential of BIMs (Liu et al. 2025). In contrast, field-scale trials place greater emphasis on the economic feasibility and long-term ecological safety of the technology. Hence, the application doses are generally more conservative (Zhang et al. 2023; Zou et al. 2024). The global median market price for biochar ranges from 1 to 2710 USD per ton, with 400 USD as the median value (Campion et al. 2023), depending on its feedstocks and synthesis method. While microbial inoculant costs are also variable, scaled production using waste substrates can render them economically feasible (e.g., production costs for agents like cellulase or citric acid can fall below 1–2 USD per kilogram) (Patel and Amaresan 2022). Consequently, dose optimization is not only an agronomic but also an economic imperative. The lack of field-based “dose–effect” data often leads to inefficient and high-dose applications. Future research must therefore develop integrated “dose–effect–cost” models to identify the minimum effective dose that aligns economic viability with desired remediation or agronomic outcomes.

For the remediation of moderately to heavily contaminated soils by heavy metals and/or organic pollutants, a relatively high application dose of BIMs (e.g., 2–5% w/w) is typically required. This dosage range is designed to provide sufficient adsorption sites for the contaminants and to offer the necessary support for the introduced functional microorganisms to establish colonization. In contrast, for supplementary applications to improve soil

fertility and plant growth, a lower BIM application rate (e.g., 1–3% w/w) is often adequate. This reduced dosage can effectively improve soil microbial activity and nutrient cycling functions, while offering greater advantages in terms of economic feasibility.

BIMs are applied as solid soil amendments, typically recommended to be uniformly incorporated into the tillage layer (usually 0–20 cm depth) using conventional farming machinery such as rotary tillers, either before sowing or during the early crop growth stages (Tu et al. 2020). Application can be conducted as a single event or in multiple rounds, depending on experimental design or agricultural practice. In some cases, BIMs are co-applied with compost or fertilizers (Azeem et al. 2021). After application, certain BIM samples are often manually extracted from the soil via methods such as collection, sedimentation, or filtration for further analysis.

It is noteworthy that critical field operational details—such as incorporation depth (surface application vs. thorough mixing in the tillage layer), timing relative to crop growth stages, single versus split applications, and compatibility with common agricultural machinery—remain insufficiently standardized in the existing literature. This lack of detailed and consistent reporting limits the extrapolation of findings from controlled experiments to real-world agricultural scenarios. Future research aimed at standardization should focus on determining optimal incorporation depths, application timings, and the need for split applications across different soil textures and crop types.

##### 4.1 Aging of BIMs

Following the application of BIMs, biochar undergoes fragmentation, dissolution, and oxidation due to environmental factors like temperature variations and microbial activities. These changes alter the physicochemical properties of biochar and can affect its immobilization efficiency of functional microbes. Concurrently, functional microbes in BIMs could also interact with both biochar and the soil environment along with the aging process.

**Aging of biochar in BIMs.** Biochar undergoes structural and chemical transformations in soil over time. Prolonged soil exposure leads to more mineral and soil particles coating on the biochar surface, altering its porosity and wettability. The initial high surface area and porosity of biochar typically diminish over time due to physical alterations and biological processes, such as the accumulation of soil organic matter within its pores (Jiang et al. 2022). Generally, aged biochar becomes more hydrophilic due to oxidation and adsorption of polar organic compounds. Aging increases oxygen-containing functional groups (e.g., carboxyl, hydroxyl) on biochar surfaces through abiotic oxidation. After a certain time of

aging, biochar might not function well as a microbial carrier (Chen et al. 2012).

**Changes of microbes in BIMs.** Both the population and community structure of microbes in BIMs will adapt to biochar aging. Aging of biochar alters soil pH, nutrient availability, and carbon content, favoring specific microbial taxa. Microbes colonize in biochar pores and form biofilms, which could protect them from environmental stressors. However, the existing local microbes could compete with the added functional microbes for both nutrients and biochar sites. In addition, possible agricultural practices, wet-dry and freeze-thaw cycles, are all unknown challenges for functional microbes in BIMs. Future research should prioritize more field-scale studies to provide more understanding of BIMs in real farmland.

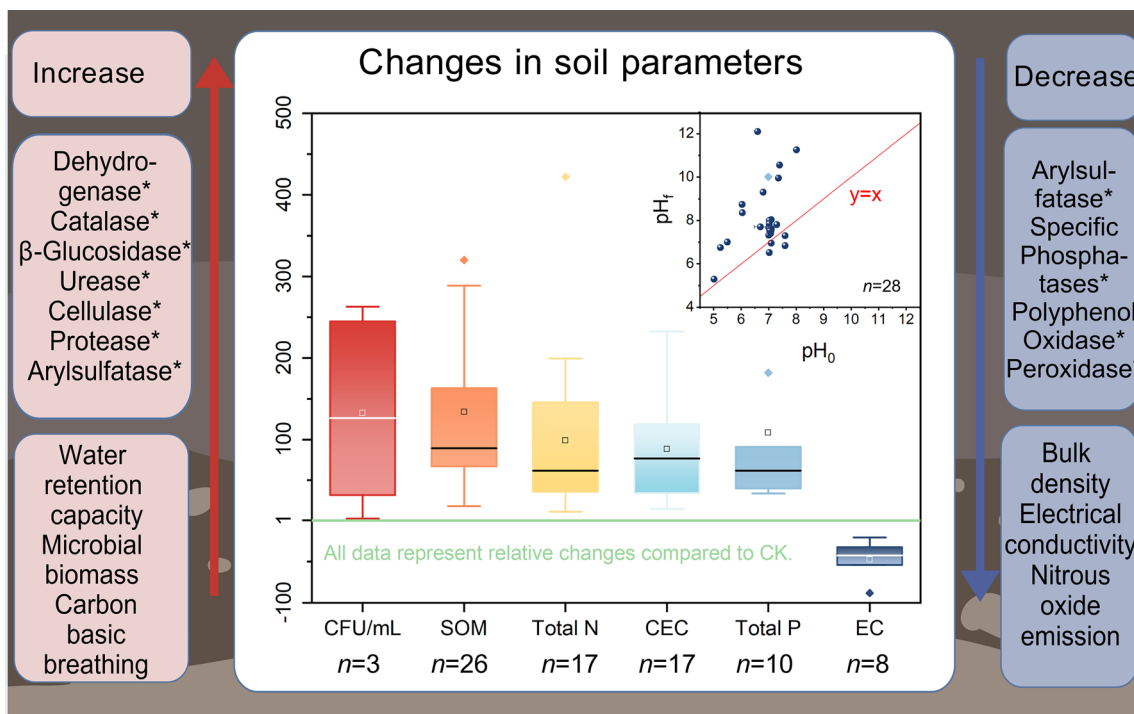
#### 4.2 Effects of BIMs on soil properties

BIM application significantly enhances soil physicochemical and biological properties, improving soil health and plant growth (Fig. 7). Documented positive effects include elevated enzyme activities (urease, dehydrogenase, and phosphatase) and improved aeration/water retention capacity. The overall soil pH increased in most of the cases we reviewed (inset in Fig. 7, as 76.3% of the points appear above the  $y=x$  line). Some other important biochemical parameters, such as CFU/mL, SOM, total

N/P, and CEC, all increased after BIM application, while soil EC dropped.

**Soil pH and buffering capacity.** BIMs are particularly effective in neutralizing acid soils because the carbonates and silicates in the biochar ash release alkaline ions (e.g.,  $Ca^{2+}$ ,  $Mg^{2+}$ ) to neutralize  $H^+$ . In the cases we reviewed, the soil pH increases by 1–2 units (Fig. 7) after application of BIMs. In addition, the activity of acid-producing bacteria (e.g., nitrifying bacteria) is suppressed (Ma et al. 2021). At the same time, the activity of alkali-producing bacteria (e.g., some actinomycetes) is increased (Azeem et al. 2021). In neutral soils, changes in pH are slight, but the inherent buffering capacity of biochar and microbes can stabilize the soil and prevent acidification. In the cases we reviewed, application of 10 tons/ha of BIMs (rice husk biochar; pH 9.2) to neutral paddy soil (initial pH 7.1) slightly increased soil pH to 7.4 after 3 years (Wang et al. 2021).

**Cation exchange capacity (CEC) and nutrient retention.** Soil CEC can be significantly increased by 23.4–118% after adding BIMs (Fig. 7). The high value of CEC of biochar can also help stabilize essential nutrients, such as nitrogen, phosphorus, and potassium (Shyam et al. 2025b). Biochar itself contains a certain amount of organic matter, nitrogen, phosphorus, and potassium, which can be used as a slow-release fertilizer source to provide a continuous supply of nutrients to



**Fig. 7** Effects of BIMs on soil properties (Specific enzyme activity is indicated; the circle represents the sample case. The horizontal line within the box denotes the median.)

microorganisms and plants. For example, straw biochar released soluble organic carbon (DOC) during decomposition, which promoted a 37.7% increase in the soil carbon pool management index and enhanced microbial utilization of persistent organic matter (Chen et al. 2012). In a study utilizing a BIM (biochar loaded with *Bacillus aryabhatai*), Huang et al. observed an associated increase in soil CEC from 8.77 to 24.42 cmol kg<sup>-1</sup>, underscoring the soil-amendment potential of biochar-based composites (Huang et al. 2024). The negatively charged functional groups on biochar (such as carboxyl and hydroxyl) can effectively attract cations. Organic acids and other substances produced by microorganisms can further increase the negative surface charge of BIMs. Microbial metabolism promotes nutrient cycling, enzyme secretion, and contaminant transformation. Concurrently, BIMs reduce nutrient leaching via adsorption of NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>, and PO<sub>4</sub><sup>3-</sup> on biochar, while microbial mineralization converts insoluble nutrients into plant-available forms. For example, BIMs (biochar composites with immobilized *Bacillus lysimachiae*) effectively degraded petroleum hydrocarbons while significantly increasing reactive soil phosphorus and potassium levels (Chen et al. 2012).

**Water retention capacity and soil structure.** Biochar, with its inherent high porosity and large specific surface area, effectively adsorbs moisture and expands capillary pores in soil, thereby directly enhancing soil water-holding capacity. Simultaneously, extracellular polysaccharides secreted by microorganisms immobilized on biochar act as natural biocementing agents, promoting soil particle aggregation and optimizing soil aggregate structure (Sher et al. 2020). This structural improvement not only enhances soil stability and permeability but also indirectly yet significantly boosts water retention by creating more stable pore spaces. These microbial-mediated soil structure improvements are supported by relevant research. Thus, within the BIM system, biochar's physical water retention and microbial biochemical soil modification complement each other, jointly enhancing the soil's water-holding capacity.

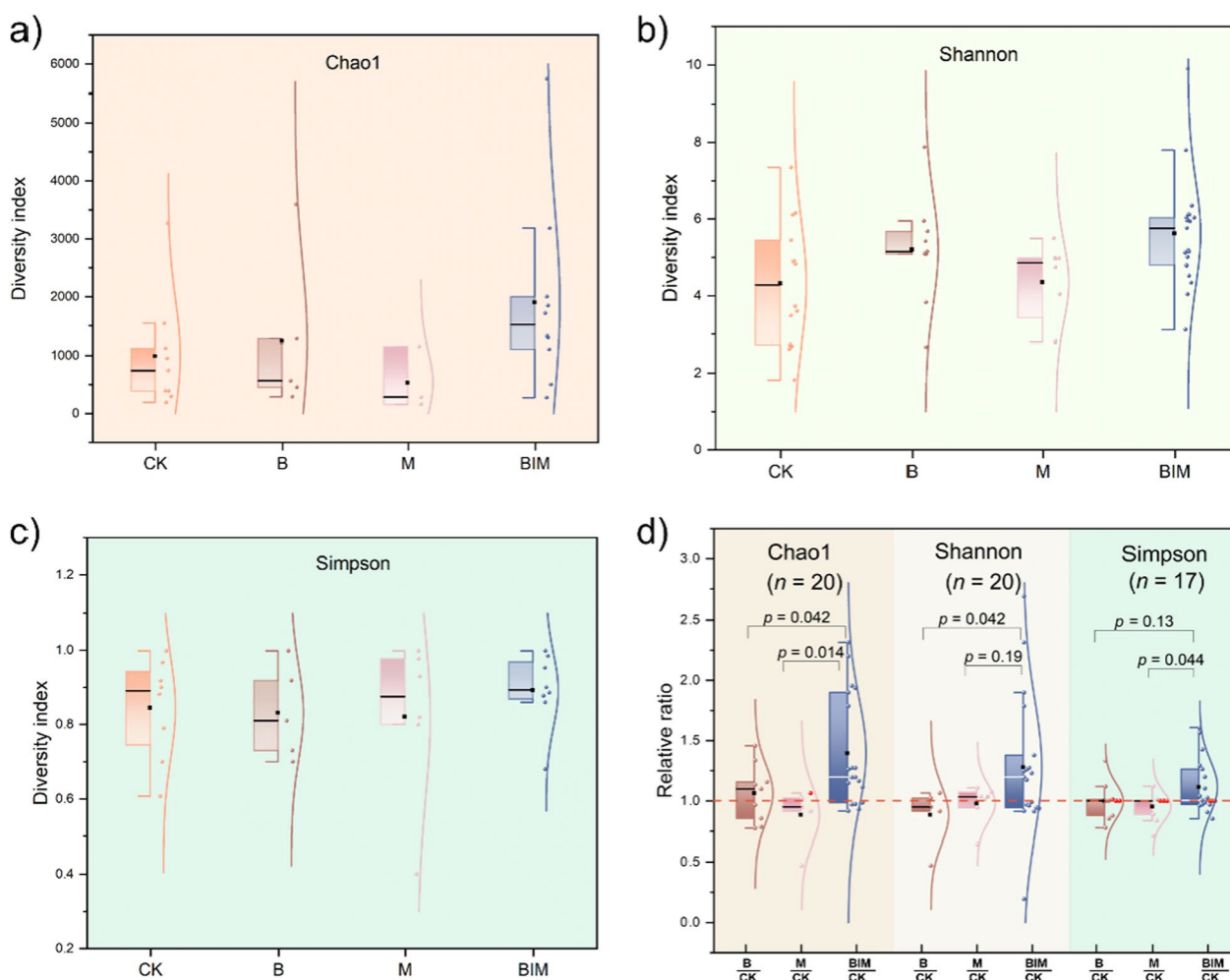
**Enzyme activity and microbial diversity.** Many soil enzymes (e.g., dehydrogenase, urease, and phosphatase) are enhanced by BIMs since the biochar surface can stabilize enzyme molecules and improve enzymatic reactions. In addition, the organic carbon absorbed on biochar can act as a carbon source for microorganisms and stimulate their secretion of enzymes (Ren et al. 2022b). For example, increased urease activity may be associated with microbial demand for nitrogen conversion. The alkalinity of biochar neutralizes acidic soils and optimizes the neutral environment for enzyme function. Microbial diversity index increases as discussed in Sect. 3.3. Biochar

pores provide differentiated microhabitats for various microorganisms and support the coexistence of diverse flora. Carbon, nitrogen, and phosphorus in biochar can provide substrates for nutritive microorganisms. Meanwhile, biochar inhibits excessive competition from indigenous microorganisms and promotes the colonization of functional microbes (e.g., phosphorus-solubilizing bacteria) (Yu et al. 2025). In addition, biochar-mediated electron transfer processes (e.g., redox reactions) (Wu et al. 2022) can activate soil enzymes (e.g., dehydrogenases, peroxidases) and accelerate the transformation of contaminants (Zhang et al. 2019).

#### 4.3 Effects of BIMs on soil microbial community structure

Adding BIMs into soil could be considered a microbial invasion into the native soil microbial communities. Use of biochar could significantly enhance the survival of functional microorganisms in soil environments and promote plant growth (Kamyab et al. 2025; Mei et al. 2022). In polluted soil, microorganisms in BIMs migrate into biochar pores for protection or encapsulate themselves within biochar particles to maintain their population against toxic substances. BIMs can also buffer soil pH and positively influence the soil microbial community. For instance, *Bacillus thuringiensis* HC-2 can secrete NH<sup>+</sup> to increase soil pH (Li et al. 2019). For acidic soils, an increase in pH can reduce the solubility and mobility of heavy metals, thereby mitigating their toxic effects on soil microorganisms (Wang et al. 2024). Thereby, BIMs could potentially increase the diversity of the soil microbial community and stimulate the beneficial microbial species.

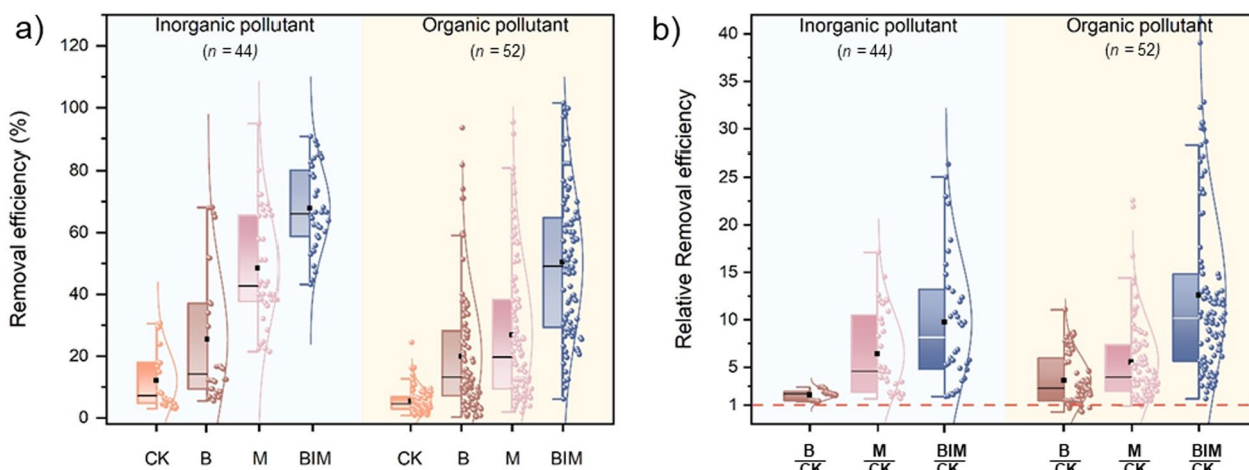
To quantify the effects of BIMs on soil microbial communities, we compared the alpha diversity indices of soil microbial communities (Chao1, Shannon, and Simpson index) across control (CK), biochar (B), microbe (M), and BIM group (Fig. 8a–c). Biochar (Group B) or microbes (Group M) alone did not increase the diversity significantly. Yet the combination of biochar and microbes (Group BIM) markedly increased alpha diversity in the Chao1 index (from 990.29 to 1900.22), Shannon index (from 4.31 to 5.62), and Simpson index (from 0.84 to 0.89). To demonstrate the increased extent, relative ratios of B/CK, M/CK, and BIM/CK (data extracted from each case) were plotted (Fig. 8d). Again, the introduction of biochar (B/CK) or microbes (M/CK) only induced a negligible increase in diversity in the Chao1 index, Shannon index, and Simpson index. However, BIMs (BIM/CK) drove significant microbe diversity increases, with the Shannon index rising by 30.85% on average. Specifically, corn straw biochar inoculated with *Klebsiella jilinsis* 2N3 significantly enhanced the  $\alpha$ -diversity of soil microbial communities, with



**Fig. 8** Effects of BIMs on soil microbe community diversity demonstrated by: **a** Chao1 Index, **b** Shannon Index, **c** Simpson index, and **d** relative ratios of the indexes. CK control, B biochar treatment, M microbe treatment, BIMs BIMs treatment

increases of 19.59%, 24.05%, and 41.07% in the Chao1, Shannon, and Simpson indices, respectively (Zhai et al. 2023). Sun et al. demonstrated that biochar-immobilized *Alcaligenes faecalis* WZ-2 enhanced tebuconazole degradation and promoted soil microbial community restoration (Sun et al. 2020). While microbe amendment alone only partially recovered richness (Chao1 only dropped by 17.1% compared to uncontaminated soil), biochar alone and BIMs restored both diversity and richness. BIM treatment performed best, restoring the Shannon and Chao1 indices to 98.6% and 93.1% of CK levels, respectively, indicating a synergistic recovery effect. To better visualize the collected experimental data, field trial results were highlighted in red (Fig. 8d). Interestingly, pot experiments exhibited a broader distribution, whereas field trial data clustered predominantly around 1.0. It is noteworthy that BIMs in pot experiments significantly enhanced all three diversity

indices; however, this positive effect was weaker under field conditions. For field tests, Zou et al. observed that biochar or microbes alone increased the bacterial community Chao1 index by 10.13% and 6.86%, respectively, but BIMs resulted in a lower enhancement (4.35%) (Zou et al. 2024). This discrepancy may be attributed to the well-controlled environmental conditions in pot experiments, such as those found in greenhouses or laboratory settings. Pot experiments exhibited a broader distribution, whereas field trial data clustered predominantly around 1.0. Field trials are subject to multiple uncontrolled factors, including rainfall, extreme weather events, and pest infestations, all of which may destabilize microbial community structures. Despite these challenges, the scarcity of existing field studies underscores the need for more comprehensive investigations to elucidate the impacts of BIM on soil microbial diversity. Future research should prioritize the



**Fig. 9** Comparison of **a** removal efficiency and **b** relative removal efficiency for inorganic and organic pollutants by varied treatment groups. CK control, B biochar treatment, M microbe treatment, BIMs BIMs treatment

design of systematic field practices that account for the complex interplay of environmental variables.

Research has shown that the BIMs can provide an optimal micro-ecological environment for the proliferation of beneficial bacteria in the soil. This favorable environment enables beneficial microbes to reproduce rapidly and establish a dominant presence within the community. For example, Wang et al. found that pig manure biochar loaded with *Bacillus subtilis* promoted the growth and reproduction of native microorganisms (Wang et al. 2017). Biochar is inherently rich in essential nutrients (Wu et al. 2021); thus, BIMs could not only support microbial growth but also enhance their metabolic activities (Bolan et al. 2023). Furthermore, the presence of biochar affords protection to microorganisms, thereby promoting their growth and reproduction (Liu et al. 2023).

#### 4.4 Performance of BIMs for soil remediation

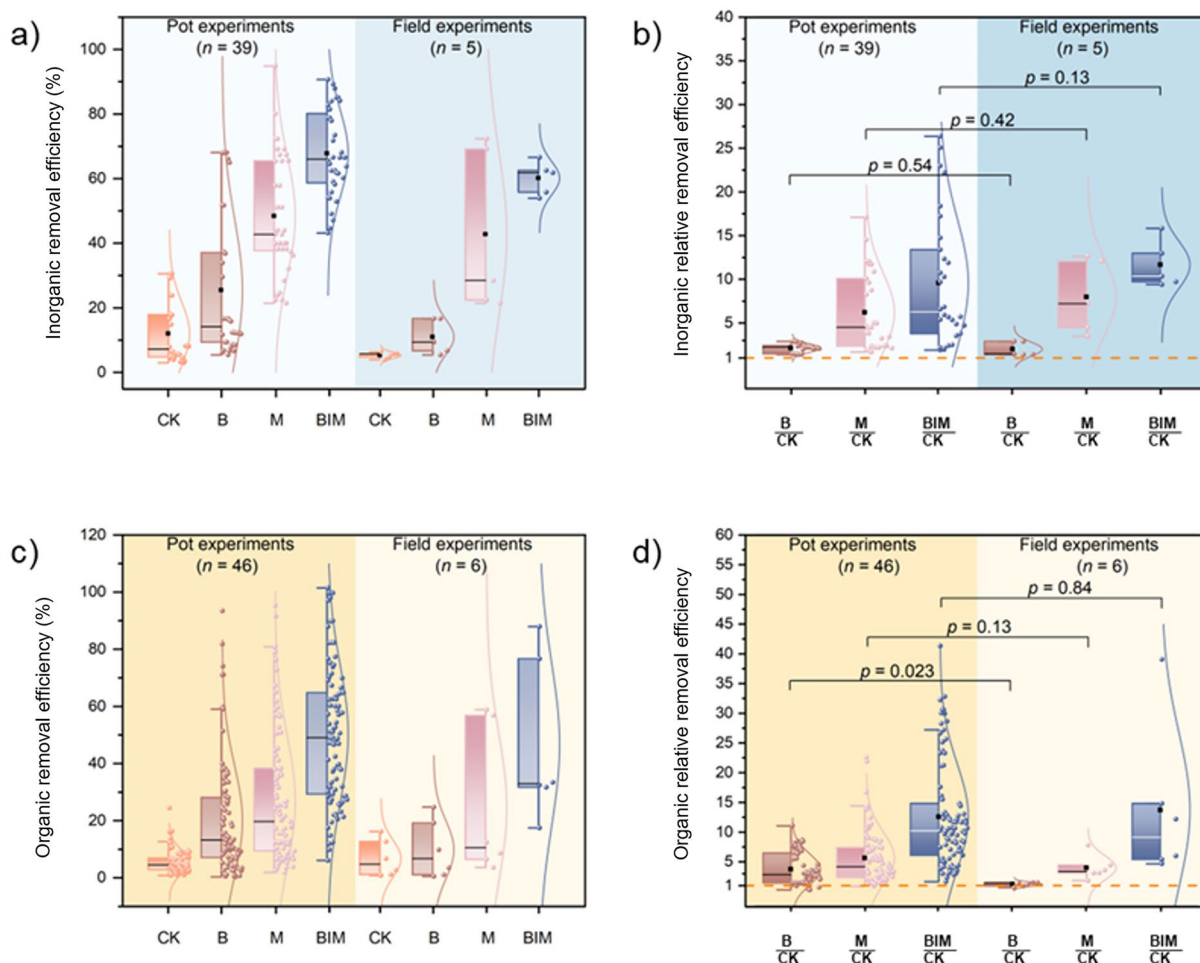
BIMs can effectively remediate diverse soil pollutants, categorized as organic and inorganic contaminants. In the cases we reviewed, typical organic pollutants include polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides, and other organic pollutants, which are primarily remediated through adsorption-enriched biodegradation facilitated by BIMs. For the inorganic pollutants, BIMs mainly immobilize heavy metals, including lead (Pb), chromium (Cr), cadmium (Cd), nickel (Ni), arsenic (As), and copper (Cu) (Saravanan et al. 2023).

Comparative analysis of soil remediation efficiency across treatment groups (Fig. 9a) consistently demonstrated the order: BIMs > B > M > CK. For inorganic pollutants (left part in Fig. 9a), the control group (CK) exhibited a natural immobilization with an average

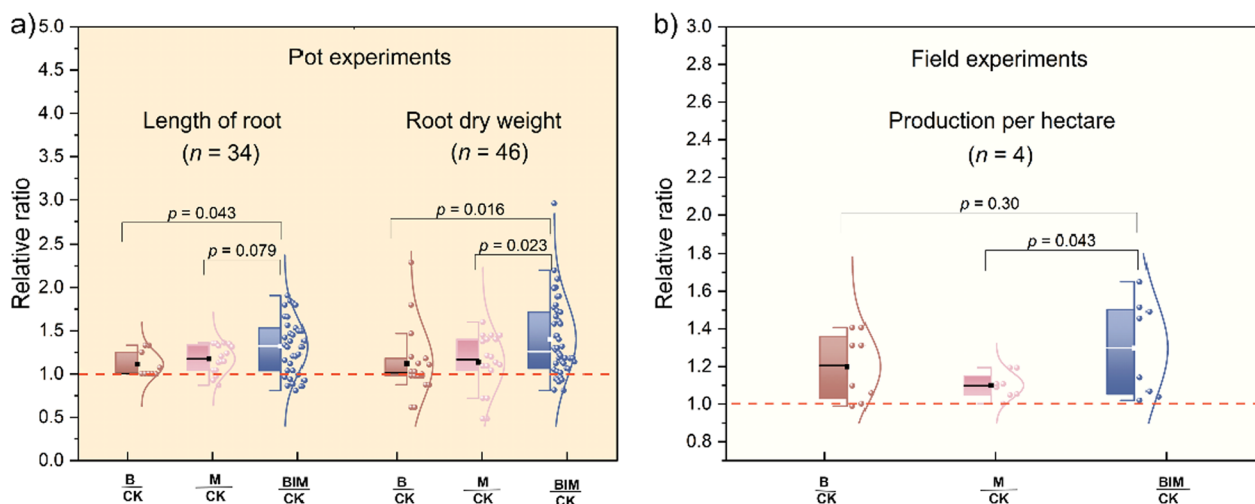
removal efficiency of 14.3%. Similarly, natural decay of organic pollutants was found (right part in Fig. 9a). For inorganic pollutants, introduction of biochar alone (B) and microbe alone (M) can greatly increase the removal efficiency to 26.2% and 42.4%, respectively. However, the BIM group was able to further increase the removal rate to 94.7%. In the case we studied, the highest removal rate of 95% was achieved with the BCXZM complex (*Bacillus* XZM immobilized on rice husk biochar) (Irshad et al. 2021). A similar trend can be found for organic pollutants, and up to 97.64% degradation was found (right part in Fig. 9a). For example, Eman H et al. found that biochar and bacterial community complexes derived from sunflower seed husk and rice straw were able to further increase the removal rate to 97.64% (El-Gamal et al. 2023). Again, to highlight the relative increase of removal efficiency of target pollutants by adding biochar, microbes, or BIMs, the normalized relative ratio of removal efficiency was also plotted (Fig. 9b). The BIM group demonstrated the highest pollutant relative removal ratio (82.6% for inorganic and 94.7% for organic pollutants), while biochar alone (B) was not as effective at immobilizing heavy metals Pb(II) as it was at removing organic pollutants phenol (El-Gamal et al. 2023). The superior performance of BIMs compared to M or B alone suggests that biochar not only serves as an effective sorbent but also enhances microbial survival, thereby establishing synergistic mechanisms for sustainable pollutant removal. In the pepper study (Zhang et al. 2023), treatments were CK (no amendments), TF (chemical fertilizer only), TFP (PGPR only, as M), TPB (biochar only, as B), TFPB1 (PGPR+biochar, as BIM), and TFPB2 (double-dosed BIM). Significant outcomes ( $p < 0.05$ ) showed that BIM treatments (both TFPB1 and TFPB2) yielded the

highest fresh and dry pepper yields compared to CK, B, and M treatments, with TFPB2 being superior. Fruit quality parameters (e.g., reducing sugar, and vitamin C) were significantly enhanced in BIM treatments, and NPK accumulation, fertilizer use efficiency, and net income were also significantly higher in BIM groups than in the single-amendment treatments. Scaling effects from laboratory (pot tests,  $n=39$ ) to field practices ( $n=5$ ) were evaluated (Fig. 10). Despite disparities in sample size, environmental exposure, and soil heterogeneity between field and pot experiments, a consistent trend was observed across treatment groups for the removal efficiency of both inorganic (Fig. 10a and b) and organic (Fig. 10c and d) pollutants: BIM>M>B>CK. (Both median and mean values followed the same trend) This trend suggests that BIMs exhibit synergistic remediation efficiency stably across environmental scales. It is worth noting that the efficiency of the field BIMs (70.2% for inorganic contaminants; 80.1% for organic contaminants)

was moderately lower compared to the pot trials (93.2% for inorganic; 94.7% for organic) (Li et al. 2024c), likely due to climatic variability and competition from indigenous microorganisms. Nevertheless, treatment with B only demonstrated a limited efficiency (<30%), confirming that adsorptive immobilization alone was insufficient for complete pollutant removal. Microbial treatment (M) exhibited moderate efficiency. A study on cadmium immobilization by rice straw biochar and *Bacillus cereus* RC-1 revealed that only the microbial group demonstrated cadmium immobilization of 38.82%. In contrast, the biochar group exhibited a lower immobilization efficiency (11.77%) (Mei et al. 2022). To quantify plant growth enhancement by BIMs, we extracted the experimental data of root length, root dry weight, and crop production to evaluate in various treatment groups (Fig. 11). The application of BIMs in soil significantly enhanced root ( $p<0.05$ ), compared to CK, B, and M, with BIMs showing the highest yield in both seasons. Soil properties



**Fig. 10** Comparison of **a** and **c** removal efficiency and **b** and **d** relative removal efficiency for inorganic and organic pollutants by various treatment groups in field and pot experiments. CK control, B biochar treatment, M microbe treatment, BIMs BIMs treatment



**Fig. 11** Comparison of **a** length and dry weight of root, and **b** crop production among various treatment groups (CK control, B biochar treatment, M microbe treatment, BIMs BIMs treatment). Data for root parameters **a** are derived from pot experiments under controlled conditions, while data for crop production **b** are derived from field experiments under controlled conditions

(e.g., organic matter and available potassium) and beneficial microbial abundance (e.g., *Bacillus*, *Pseudomonas*) were also significantly improved in BIM treatments.

The synergy in BIMs addresses fundamental limitations: biochar alone can adsorb contaminants, but it lacks microbial degradation capacity. As a result, the adsorbed pollutants could be released/desorbed back to the soil matrix, resulting in limited and unstable remediation. Microorganisms are susceptible to environmental stressors (e.g., pH changes, nutrient deficiencies), leading to possible low survival rates and inhibited activity, especially in contaminated sites. Combining biochar with microbial degradation in BIMs can create an “adsorption-degradation-regeneration” cycle to significantly improve remediation efficiency and long-term stability. For instance, BIMs outperformed biochar or microbial treatments in petroleum hydrocarbon remediation by 32–51% (Bekchanova et al. 2024). In heavy metal-contaminated soils, the BIM group synergistically reduced heavy metal bioavailability through microbial metabolism and biochar immobilization (Shan et al. 2025). The great efficiency enhancement by BIMs is mainly attributed to: (1) pollutant adsorption and microbial enrichment within the porous matrix of biochar, creating localized high-concentration zones for metal immobilization/organic complexation; and (2) biochar-mediated stabilization of soil pH and moisture, buffering environmental fluctuations that inhibit microbial activity.

#### 4.5 Performance of BIMs for plant growth enhancement

To quantify plant growth enhancement by BIMs, we extracted the experimental data of root length, root dry

weight, and crop production across various treatment groups (Fig. 11). The application of BIMs in soil significantly enhanced root length, dry root weight, and even crop production, compared to the use of B or M alone (Fig. 11). The addition of B showed a slight increase of 11.23% and 11.89% in root length and dry root, respectively. The introduction of functional M significantly increased root length and dry root by 17.51% and 13.48%, respectively. BIMs further increased root length and dry root by 32.10% and 40.05%, respectively. Noureen et al. found that drought stress significantly inhibited wheat morphogenesis, resulting in reductions of root length and shoot length by 21% and 10%, respectively (Noureen et al. 2024). All individual amendment measures demonstrated positive mitigative effects: the application of biochar alone increased root length and shoot length by 17–30% and 30–42%, respectively, relative to the drought-stressed control. Inoculation with efficient PGPR strains alone, such as *Bacillus subtilis* DTS-21, exhibited even stronger biostimulatory potential, promoting increases in root length and plant height by 32.1% and 46.4%, respectively. Notably, the combined treatment of PGPR consortia and biochar revealed a significant synergistic effect, enhancing root length and shoot length by 70% and 82%, respectively, compared to the drought control—markedly outperforming any individual treatment. For crop yield, B and M showed limited increase, with average gains of 19.88% and 9.97% on a per-hectare basis. However, treatment of BIMs demonstrated the most significant effect, achieving a 29.76% yield increase. For example, Zhang et al. demonstrated that soil amendment with BIMs (grain-derived biochar with *Bacillus*

*amyloliquefaciens* and *Paenibacillus polymyxa*) significantly enhanced chili pepper yield by 66.86% compared to the control group (Zhang et al. 2023).

Early plant growth critically determines crop yield, as stressors during this phase can cause irreversible damage (Carril et al. 2025; Wen et al. 2022). Roots play a central role in nutrient uptake, and their health directly correlates with overall plant vitality (Jafri et al. 2018). Roots can directly interact with added biochar, microbes, or BIMs. Notably, thirty days after application of BIMs (cotton straw biochar immobilized with PSB), the root length of tomato increased by 375%, and root dry weight increased by 80% (Bai et al. 2024a). PSB is a widely used biofertilizer that converts insoluble phosphorus into plant-available forms. Biochar enhances the colonization of PSB in the plant root zone and boosts the acid production capacity of PSB (Chen et al. 2023a). Additionally, functional groups on the biochar surface can help improve phosphorus solubility (Tallur et al. 2015). These synergistic interactions significantly enhance phosphorus dissolution efficiency and increase the abundance of available phosphorus in the soil (Qu et al. 2024).

BIMs offer a suite of benefits for plant growth by improving the soil CEC to enhance nutrient retention and provide a more favorable growth environment for crops. Immobilized microorganisms in BIMs exhibit higher stability, prolonged efficacy, and improved resistance to adverse environmental stressors (Tallur et al. 2015). For example, the application of BIMs in Cd-contaminated soil significantly enhanced the growth performance of ryegrass, particularly with improved shoot elongation and root system development (Liu et al. 2025).

In addition to promoting nutrient availability, certain microorganisms can produce beneficial compounds such as amino acids, amines, and plant growth-promoting hormones (e.g., polyamines, indole acetic acid, or indole-3-acetic acid) that further support plant growth (Wang et al. 2022). Indole-3-acetic acid (IAA), a primary natural auxin, plays a crucial role in regulating plant growth and development. It enhances the absorption efficiency of mineral elements by optimizing root system structure, including improving root hair density and lateral root formation. In addition, IAA boosts pathogen defense by inducing systemic resistance. For instance, *Arthrobacter creatinolyticus* can secrete both IAA (up to 68.9 mg mL<sup>-1</sup>) and ammonium nitrogen, concurrently promoting plant growth and nitrogen nutrition (Prum et al. 2018). Amino acids and amine compounds (like glutamine and putrescine) can act as nitrogen reserves, alleviating nitrogen limitation stress. Some microorganisms also secrete siderophores to increase iron bioavailability, synergistically enhancing IAA-mediated growth promotion and plant health (Egamberdieva et al. 2019).

BIM application in soil also enhances pathogen control and disease suppression for crops. Biochar inhibits pathogen proliferation by modulating soil pH, stabilizing soil nutrients, and exerting inherent antimicrobial effects. For example, Russi et al. applied BIMs (grape bagasse biochar combined with *Bacillus velezensis* S26) to inhibit grape diseases (Russi et al. 2024). Similarly, Chen et al. found that BIMs (biochar combined with *Bacillus subtilis* SL-44) could reduce the incidence of fusarium wilt in radish by 59.88% (Chen et al. 2023b). Jia et al. found that BIMs (biochar-loaded *Bacillus subtilis* Tbp55) achieved 79.60% efficacy against tobacco disease (Jia et al. 2022). Similarly, Rasool et al. found that BIMs (biochar combined with *Bacillus subtilis*) significantly enhanced the disease resistance of tomatoes. Biochar can absorb nutrients and increase soil pH to inhibit certain pathogen growth (Rasool et al. 2021). Moreover, biochar, along with the fixed microorganisms, exhibits antibacterial effects for some bacteria, thereby reducing the incidence of soil-borne diseases (Jaiswal et al. 2020). PGPB are common inoculants that can fix nitrogen, solubilize phosphorus and potassium, and produce antibiotics. PGPB can greatly help to decrease pathogen populations and improve overall soil health (Kong et al. 2022). Through antagonistic interactions, either by secreting bioactive compounds (e.g., by producing organic acids, gibberellins, cytokinins, etc.) or inducing plant resistance (Liu et al. 2022), PGPB play a vital role in enhancing soil quality and crop resilience.

The application of BIMs in soil enhances the photosynthetic efficiency of plants. Bai et al. observed that under phosphorus deficiency conditions, the total chlorophyll content in tomatoes increased significantly by 63% compared to the control group after 30 days of BIM treatment (Bai et al. 2024a). In contaminated soil, BIMs not only effectively mitigate soil fertility loss but also regulate nutrient cycling to support chlorophyll synthesis. Concurrently, microorganisms immobilized on BIMs protect plants from stress through mechanisms such as cellular adhesion and signal transduction (Shi et al. 2023), further promoting chlorophyll accumulation. Additionally, BIM application modulates the functionality of photosystem II (PSII), including electron transport and energy dissipation (Woo et al. 2025). These findings highlight multifaceted roles of BIMs in optimizing plant photosynthetic performance under abiotic stress.

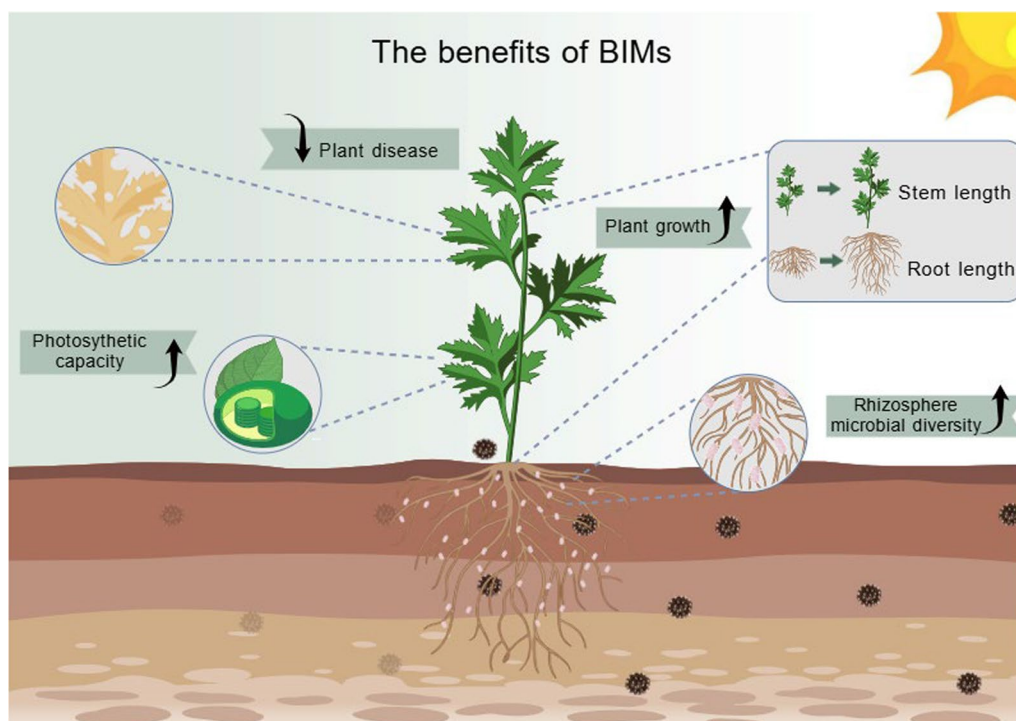
Regarding monitoring strategies, future research should establish a real-time dynamic monitoring database centered on the abundance of microbial functional genes (e.g., the nitrogen-fixing gene *nifH*, the denitrification gene *nosZ*), integrated with soil physicochemical properties and contaminant residues. This will enable precise assessment of the field colonization and activity

of functional microorganisms. Secondly, for microbial protection, the porous structure of biochar should be fully utilized to provide physical refuge for microorganisms. Furthermore, advanced delivery technologies such as microencapsulation and sodium alginate/chitosan embedding should be further developed to enhance microbial resistance to stressors like drought and UV radiation, thereby ensuring their viability in the field. Additionally, it is essential to establish a proactive risk assessment and management framework to systematically evaluate potential ecological risks, such as microbial escape and horizontal gene transfer. Dose–response relationships and application guidelines should be formulated based on long-term field data to prevent potential adverse effects, such as nutrient imbalance or negative ecological impacts resulting from prolonged application. Therefore, conducting more long-term and systematic field monitoring studies and integrating the tripartite technical safeguard system of "monitoring–protection–assessment" are crucial for reducing uncertainties in the application of BIM technology and achieving its scalable and sustainable implementation.

To address these translational challenges and bridge the lab-to-field gap, future research on BIMs should prioritize the establishment of an integrated "monitoring–protection–assessment" framework to advance the field applicability and ecological safety of this

technology. Monitoring strategies must incorporate real-time, dynamic tracking of functional microbial genes coupled with soil physicochemical and contaminant data to accurately evaluate microbial colonization and metabolic activity. Concurrently, biochar properties should be optimized through surface modification, porosity engineering, and composite design to enhance microbial habitat quality and stress resilience. Microencapsulation and biofilm-based delivery systems can further improve microbial survival under environmental stressors. A proactive risk-assessment protocol is also essential to address potential ecological concerns, such as microbial dispersal and horizontal gene transfer, with guidelines informed by long-term field studies. Additionally, the integration of synthetic biology—for instance, CRISPR-engineered microbial strains—with tailored biocarriers could lead to advanced remediation systems with enhanced functionality. Ultimately, the sustainable implementation of BIM technology should align with broader environmental and agricultural sustainability goals, supported by life-cycle assessments, stakeholder engagement, and science-informed policy frameworks.

In summary, the integration of BIMs in soil has multiple beneficial effects: promoting early plant growth and improving root health to enhance disease resistance and nutrient acquisition (Fig. 12). Through these various



**Fig. 12** Plant response to BIMs application in soil

functions, a significant increase in crop yield is expected. Beyond yield, BIMs can also improve crop/fruit quality, as evidenced by elevated free amino acids and vitamin C in pepper fruits (Zhang et al. 2023). Researchers concluded that BIMs improved fruit quality mainly by boosting the nutrient transformation by beneficial rhizosphere microorganisms, increasing plant photosynthetic rate, and promoting photosynthate transformation (Luo et al. 2025).

## 5 Conclusions and perspectives

In this review, we systematically summarize the mechanisms and outcomes associated with BIMs, elucidating their roles in soil remediation and sustainable agriculture. Key conclusions and perspectives are as follows:

- 1) Synergistic efficacy of BIMs: The integration of biochar and functional microbes creates a synergistic system, enhancing pollutant adsorption and microbial degradation while improving soil health.
- 2) Enhanced pollutant remediation: BIMs significantly outperform standalone biochar or microbial treatments by 32–51% in immobilizing heavy metals and degrading organics, attributed to adsorption-metabolism coupling. (Both median and mean values followed the same trend)
- 3) Soil and crop benefits: BIMs elevate soil enzyme activities (urease, dehydrogenase), nutrient retention, and microbial diversity. By enhancing root development and stress resistance, BIMs increased root length (by 32.10%) and root dry weight (by 40.05%), as well as crop yield (up to 53%).
- 4) Field scalability challenges: Despite high efficiency in lab/pot trials, field applications face variability in microbial survival and efficacy due to environmental stressors. Unfortunately, only 11 out of 92 reviewed studies involved field tests. These data gaps and field trial scarcity greatly limited the scaling-up of this technology.
- 5) Dose and cost optimization: Current research lacks comprehensive dose–effect relationships for BIMs in farmland, with most studies relying on empirically determined dosages from lab-scale experiments. Cost–benefit analyses remain scarce, yet both factors are critical for farmers and policy decisions.
- 6) Further modifications on both biochar and microbes: Future research should focus on optimizing the surface characteristics of biochar to improve its microbial immobilization capacity. Moreover, genetically engineered microorganisms show promise for target pollutant remediation.
- 7) Alignment with sustainability goals: BIMs offer a scalable solution for soil degradation and food secu-

urity, aligning with the UN Sustainable Development Goals. Successful implementation requires farmer-centric strategies, lifecycle assessments, and policy support.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1007/s42773-026-00613-z>.

Supplementary material 1.

## Acknowledgements

We appreciated the support from the National Key R&D Program of China (2022YFD1700700), National Natural Science Foundation of China (No.52279051), China Agriculture Research System of MOF and MARA (CARS-23-B12), and 2115 Talent Development Program of China Agricultural University (No. 109018).

## Author contributions

Xinyi Li: Conceptualization, Visualization, Writing—original draft, Writing—review & editing. Qianyi Lv: Conceptualization, Visualization, Writing—original draft. Caiting Han: Visualization, Writing—original draft. Na Duan: Conceptualization, Supervision. Zhidan Liu: Conceptualization, Supervision. Gao Miao: Conceptualization, Visualization, Supervision, Writing—review & editing. Zhao Xiao: Conceptualization, Visualization, Supervision, Writing—review & editing, Funding acquisition. All authors read and approved the final manuscript.

## Funding

This work was supported by the National Key R&D Program of China (2022YFD1700700), National Natural Science Foundation of China (No.52279051), China Agriculture Research System of MOF and MARA (CARS-23-B12), and 2115 Talent Development Program of China Agricultural University (No. 109018).

## Data availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

## 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.

## Author details

<sup>1</sup>College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China. <sup>2</sup>Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, State Key Laboratory of Efficient Utilization of Arid and Semi-arid Arable Land in Northern China/Key Laboratory of Plant Nutrition and Fertilizer, Key Laboratory of Microbial Resources Collection and Preservation, Ministry of Agriculture and Rural Affairs, Beijing 100081, China.

Received: 29 June 2025 Revised: 18 March 2026 Accepted: 31 March 2026  
Published online: 08 June 2026

## References

- Azeem M, Ul Hassan T, Tahir MI et al (2021) Tea leaves biochar as a carrier of *Bacillus cereus* improves the soil function and crop productivity. *Appl Soil Ecol* 157:103732. <https://doi.org/10.1016/j.apsoil.2020.103732>
- Bai K, Wang W, Zhang J et al (2024a) Effects of phosphorus-solubilizing bacteria and biochar application on phosphorus availability and tomato

- growth under phosphorus stress. *BMC Biol* 22(1):211. <https://doi.org/10.1186/s12915-024-02011-y>
- Bai X, Bol R, Chen H et al (2024b) A meta-analysis on crop growth and heavy metals accumulation with PGPB inoculation in contaminated soils. *J Hazard Mater* 471:134370. <https://doi.org/10.1016/j.jhazmat.2024.134370>
- Bekchanova M, Campion L, Bruns S et al (2024) Biochar improves the nutrient cycle in sandy-textured soils and increases crop yield: a systematic review. *Environ Evid* 13(1):3. <https://doi.org/10.1186/s13750-024-00326-5>
- Bi F, Jiang Z, Wang M, Lin Q, Liu X et al (2025) Enhanced remediation of cadmium-contaminated farmland by smooth vetch (*Vicia villosa* var.) coupled with phosphorus/sulfur co-doped biochar: synergetic performance and mechanism. *J Clean Prod* 496:144986. <https://doi.org/10.1016/j.jclepro.2025.144986>
- Bolan N, Kunhikrishnan A, Thangarajan R et al (2014) Remediation of heavy metal(loid)s contaminated soils – to mobilize or to immobilize? *J Hazard Mater* 266:141–166. <https://doi.org/10.1016/j.jhazmat.2013.12.018>
- Bolan S, Hou D, Wang L et al (2023) The potential of biochar as a microbial carrier for agricultural and environmental applications. *Sci Total Environ* 886:163968. <https://doi.org/10.1016/j.scitotenv.2023.163968>
- Campion L, Bekchanova M, Malina R et al (2023) The costs and benefits of biochar production and use: a systematic review. *J Clean Prod* 408:137138137138. <https://doi.org/10.1016/j.jclepro.2023.137138>
- Carril P, Ghorbani M, Azarnejad N et al (2025) Promoting early growth in tomato (*Solanum lycopersicum* L.) by co-application of biochar and beneficial bacteria. *J Soil Sci Plant Nutr* 25(1):1493–1503. <https://doi.org/10.1007/s42729-025-02217-1>
- Chen B, Yuan M, Qian L (2012) Enhanced bioremediation of PAH-contaminated soil by immobilized bacteria with plant residue and biochar as carriers. *J Soils Sediments* 12(9):1350–1359. <https://doi.org/10.1007/s11368-012-0554-5>
- Chen H, Min F, Hu X et al (2023a) Biochar assists phosphate solubilizing bacteria to resist combined Pb and Cd stress by promoting acid secretion and extracellular electron transfer. *J Hazard Mater* 452:131176. <https://doi.org/10.1016/j.jhazmat.2023.131176>
- Chen W, Wu Z, Liu C et al (2023b) Biochar combined with *Bacillus subtilis* SL-44 as an eco-friendly strategy to improve soil fertility, reduce *Fusarium* wilt, and promote radish growth. *Ecotoxicol Environ Saf* 251:114509. <https://doi.org/10.1016/j.ecoenv.2023.114509>
- Chu CH, Zhu LZ (2024) Paving the way toward soil safety and health: current status, challenges, and potential solutions. *Front Environ Sci Eng* 18(6):74. <https://doi.org/10.1007/s11783-024-1834-1>
- Egamberdieva D, Wirth S, Bellingrath-Kimura SD et al (2019) Salt-tolerant plant growth promoting rhizobacteria for enhancing crop productivity of saline soils. *Front Microbiol* 10:2791. <https://doi.org/10.3389/fmicb.2019.02791>
- El-Gamal EH, Rashad M, Saleh ME et al (2023) Potential bioremediation of lead and phenol by sunflower seed husk and rice straw-based biochar hybridized with bacterial consortium: a kinetic study. *Sci Rep* 13(1):21901. <https://doi.org/10.1038/s41598-023-49036-x>
- Hajieghrari M, Hejazi P (2020) Enhanced biodegradation of n-Hexadecane in solid-phase of soil by employing immobilized *Pseudomonas aeruginosa* on size-optimized coconut fibers. *J Hazard Mater* 389:122134. <https://doi.org/10.1016/j.jhazmat.2020.122134>
- Hashem AM, Gamal AA, Hassan ME et al (2016) Covalent immobilization of *Enterococcus faecalis* Esawy dextranucrase and dextran synthesis. *Int J Biol Macromol* 82:905–912. <https://doi.org/10.1016/j.ijbiomac.2015.09.076>
- Huang Y, Liu T, Liu J et al (2024) Exceptional anti-toxic growth of water spinach in arsenic and cadmium co-contaminated soil remediated using biochar loaded with *Bacillus aryabhatai*. *J Hazard Mater* 469:133966. <https://doi.org/10.1016/j.jhazmat.2024.133966>
- Huang Y, Luo Y, Wu C et al (2025) Synergistic multi-metal stabilization of lead-zinc smelting contaminated soil by *Ochrobactrum* EEELCW01-loaded iron-modified biochar: performance and long-term efficacy. *Biochar* 7(1):58. <https://doi.org/10.1007/s42773-025-00441-7>
- Irshad S, Xie Z, Kamran M et al (2021) Biochar composite with microbes enhanced arsenic biosorption and phytoextraction by *Typha latifolia* in hybrid vertical subsurface flow constructed wetland. *Environ Pollut* 291:118269. <https://doi.org/10.1016/j.envpol.2021.118269>
- Jafri N, Wong WY, Doshi V et al (2018) A review on production and characterization of biochars for application in direct carbon fuel cells. *Process Saf Environ Prot* 118:152–166. <https://doi.org/10.1016/j.psep.2018.06.036>
- Jaiswal AK, Alkan N, Elad Y et al (2020) Molecular insights into biochar-mediated plant growth promotion and systemic resistance in tomato against *Fusarium* crown and root rot disease. *Sci Rep* 10(1):13934. <https://doi.org/10.1038/s41598-020-70882-6>
- Jesionowski T, Zdzarta J, Krajewska B (2014) Enzyme immobilization by adsorption: a review. *Adsorption* 20(5–6):801–821. <https://doi.org/10.1007/s10450-014-9623-y>
- Jia H, Lv X, Sohail MA et al (2022) Control efficiency of biochar loaded with *Bacillus subtilis* Tpb55 against tobacco black shank. *Processes* 10(12):2663. <https://doi.org/10.3390/pr10122663>
- Jiang Y, Yang F, Dai M et al (2022) Application of microbial immobilization technology for remediation of Cr (VI) contamination: a review. *Chemosphere* 286:131721. <https://doi.org/10.1016/j.chemosphere.2021.131721>
- Jiang S, Li H, Zhang L et al (2025) Generic diagramming platform (GDP): a comprehensive database of high-quality biomedical graphics. *Nucleic Acids Res* 53(D1):D1670–D1676. <https://doi.org/10.1093/nar/gkae973>
- Jorge P, Ángela M, Carmen F et al (2021) The use of biochar for plant pathogen control. *Phytopathology* 111(9):1490–1499. <https://doi.org/10.1094/PHYTO-06-20-0248-RVW>
- Kamyab H, Chelliapan S, Khalili E et al (2025) Biochar as a carrier for plant growth-promoting bacteria in phytoremediation of pesticides. *J Hazard Mater Adv* 18:100673. <https://doi.org/10.1016/j.hazadv.2025.100673>
- Kong Z, Liu H (2022) Modification of rhizosphere microbial communities: a possible mechanism of plant growth promoting rhizobacteria enhancing plant growth and fitness. *Front Plant Sci* 13:920813. <https://doi.org/10.3389/fpls.2022.920813>
- Lehmann J, Joseph S (2009) *Biochar for environmental management: science, technology and implementation*. Taylor and Francis, Abingdon. <https://doi.org/10.4324/9781003297673>
- Li Z, Wang P, Yue X et al (2019) Effects of *Bacillus thuringiensis* HC-2 combined with biochar on the growth and Cd and Pb accumulation of radish in a heavy metal-contaminated farmland under field conditions. *Int J Environ Res Public Health* 16(19):3676. <https://doi.org/10.3390/ijerph16193676>
- Li X, Wang Y, Luo T et al (2022) Remediation potential of immobilized bacterial strain with biochar as carrier in petroleum hydrocarbon and Ni co-contaminated soil. *Environ Technol* 43(7):1068–1081. <https://doi.org/10.1080/09593330.2020.1815858>
- Li W, Zhu Y, Li K et al (2023) Synergistic remediation of phenanthrene-cadmium co-contaminants by an immobilized acclimated bacterial-fungal consortium and its community response. *Chemosphere* 336:139234–139234. <https://doi.org/10.1016/j.chemosphere.2023.139234>
- Li J, Yang D, Zou W et al (2024a) Mechanistic insights into the synergetic remediation and amendment effects of zeolite/biochar composite on heavy metal-polluted red soil. *Front Environ Sci Eng* 18(9):114. <https://doi.org/10.1007/s11783-024-1874-6>
- Li J, Sun W, Lichtfouse E et al (2024b) Life cycle assessment of biochar for sustainable agricultural application: a review. *Sci Total Environ* 951:175448. <https://doi.org/10.1016/j.scitotenv.2024.175448>
- Li Y, Zhang M, Wang X et al (2024c) Synergistic enhancement of cadmium immobilization and soil fertility through biochar and artificial humic acid-assisted microbial-induced calcium carbonate precipitation. *J Hazard Mater* 476:135140. <https://doi.org/10.1016/j.jhazmat.2024.135140>
- Li H, Wang Y, Zhao Y et al (2025) Struvite-loaded biochar beads fertilizer for different soils: nutrient slow release, soil properties improvement and heavy metal remediation. *Front Environ Sci Eng* 19(6):73. <https://doi.org/10.1007/s11783-025-1993-8>
- Liu J, Ding Y, Ma L et al (2017) Combination of biochar and immobilized bacteria in cypermethrin-contaminated soil remediation. *Int Biodeterior Biodegrad* 120:15–20. <https://doi.org/10.1016/j.ibiod.2017.01.039>
- Liu J, Zhang J, Zhu M et al (2022) Effects of plant growth promoting rhizobacteria (PGPR) strain *Bacillus licheniformis* with biochar amendment on potato growth and water use efficiency under reduced irrigation regime. *Agronomy* 12(5):1031. <https://doi.org/10.3390/agronomy12051031>
- Liu Q, Wang Y, Sun S et al (2023) A novel chitosan-biochar immobilized microorganism strategy to enhance bioremediation of crude oil in soil. *Chemosphere* 313:137367. <https://doi.org/10.1016/j.chemosphere.2022.137367>
- Liu W, Xiao X, Li L et al (2025) Biochar-based metal tolerating plant growth promoting bacterial inoculants enhanced the ability of ryegrass for

- phytostabilization. *Environ Res* 265:120389. <https://doi.org/10.1016/j.envres.2024.120389>
- Lu J, Peng W, Lv Y et al (2020) Application of cell immobilization technology in microbial cocultivation systems for biochemicals production. *Ind Eng Chem Res* 59(39):17026–17034. <https://doi.org/10.1021/acs.iecr.0c01867>
- Luo D, Huang H, Wang J et al (2025) Inoculations of phosphorus-solubilizing bacteria alter soil properties, microbial communities, and improve crop yield and fruit quality in the tomato production system. *Appl Soil Ecol* 207:105944. <https://doi.org/10.1016/j.apsoil.2025.105944>
- Ma L, Hu T, Liu Y et al (2021) Combination of biochar and immobilized bacteria accelerates polyacrylamide biodegradation in soil by both bio-augmentation and bio-stimulation strategies. *J Hazard Mater* 405:124086. <https://doi.org/10.1016/j.jhazmat.2020.124086>
- Ma Y, Zhang F, Cheng L et al (2025) Remediation potential of biochar for As and Cd by modifying soil physicochemical properties: a conceptual model elucidating stabilization mechanism based on conditional probability theory. *Biochar* 7(1):63. <https://doi.org/10.1007/s42773-025-00455-1>
- Mei C, Wang H, Cai K et al (2022) Characterization of soil microbial community activity and structure for reducing available Cd by rice straw biochar and *Bacillus cereus* RC-1. *Sci Total Environ* 839:156202. <https://doi.org/10.1016/j.scitotenv.2022.156202>
- Nguyen Thi Hai H, Nguyen Chi T, Kajitvichyanukul P (2022) Enhanced paraquat removal from contaminated water using cell-immobilized biochar. *Clean Technol Environ Policy* 24(4):1073–1085. <https://doi.org/10.1007/s10098-020-01996-8>
- Noureen S, Iqbal A, Muqet HA (2024) Potential of drought tolerant rhizobacteria amended with biochar on growth promotion in wheat. *Plants Basel* 13(9):1183. <https://doi.org/10.3390/plants13091183>
- Patel K, Amaresan N (2022) Mass multiplication, production cost analysis, and marketing of cellulase. In: Amaresan N, Dharumadurai D, Cundell DR (eds) *Industrial microbiology based entrepreneurship. Microorganisms for sustainability*. Springer, Singapore
- Pathak HK, Chauhan PK, Seth CS et al (2024) Mechanistic and future prospects in rhizospheric engineering for agricultural contaminants removal, soil health restoration, and management of climate change stress. *Sci Total Environ* 927:172116. <https://doi.org/10.1016/j.scitotenv.2024.172116>
- Peng Y, Zhang H, Li G et al (2025) Microbial inoculum improved soil aggregate formation and increased cucumber yield in a greenhouse under secondary salinization conditions. *J Environ Manag* 376:124576. <https://doi.org/10.1016/j.jenvman.2025.124576>
- Prum C, Dolphen R, Thiravetyan P (2018) Enhancing arsenic removal from arsenic-contaminated water by *Echinodorus cordifolius*–endophytic *Arthrobacter creatinolyticus* interactions. *J Environ Manag* 213:11–19. <https://doi.org/10.1016/j.jenvman.2018.02.060>
- Qi X, Gou J, Chen X et al (2021) Application of mixed bacteria-loaded biochar to enhance uranium and cadmium immobilization in a co-contaminated soil. *J Hazard Mater* 401:123823. <https://doi.org/10.1016/j.jhazmat.2020.123823>
- Qu JH, Wang SQ, Li ZW et al (2024) Highly efficient recovery of phosphate from water using Cerium Carbonate Hydroxide-decorated magnetic biochar: a slow-release phosphate fertilizer for agricultural reuse. *ACS ES T Eng* 4(12):3045–3056. <https://doi.org/10.1021/acsesteng.4c00407>
- Qu JH, Yu R, Wang MN et al (2025) Tailoring sponge-like nitrogen-enriched biochar: a green and sustainable remediation technology for Pb and Cu contaminated soil. *Chem Eng J* 522:167603. <https://doi.org/10.1016/j.cej.2025.167603>
- Rasool M, Akhter A, Haider MS (2021) Molecular and biochemical insight into biochar and *Bacillus subtilis* induced defense in tomatoes against *Alternaria solani*. *Sci Hortic* 285:110203. <https://doi.org/10.1016/j.scienta.2021.110203>
- Ren H, Deng Y, Ma L et al (2022a) Enhanced biodegradation of oil-contaminated soil oil in shale gas exploitation by biochar immobilization. *Biodegradation* 33(6):621–639. <https://doi.org/10.1007/s10532-022-09999-6>
- Ren W, Liu H, Mao T et al (2022b) Enhanced remediation of PAHs-contaminated site soil by bioaugmentation with graphene oxide immobilized bacterial pellets. *J Hazard Mater* 433:128793. <https://doi.org/10.1016/j.jhazmat.2022.128793>
- Russi A, Granada CE, Schwambach J (2024) *Bacillus velezensis* S26-loaded biochar boosts plant growth, alleviates copper stress and suppresses black foot disease in SO4 vine rootstock. *Appl Soil Ecol* 202:105550. <https://doi.org/10.1016/j.apsoil.2024.105550>
- Saravanan A, Swaminaathan P, Kumar PS et al (2023) A comprehensive review on immobilized microbes - biochar and their environmental remediation: mechanism, challenges and future perspectives. *Environ Res* 236:116723. <https://doi.org/10.1016/j.envres.2023.116723>
- Shan T, Wang B, Tu W et al (2025) Adsorption and biodegradation of butyl xanthate in mine water by *Pseudomonas* sp. immobilized on yak dung biochar. *Environ Res* 264:120300. <https://doi.org/10.1016/j.envres.2024.120300>
- Sharma L, Shukla SK, Jaiswal VP et al (2023) Novel strains of *Pseudomonas fluorescens* and *Bacillus cereus* and their integrated use with inorganic fertilizers enhancing P availability, crop growth parameters, and sugarcane yield in subtropical India. *Sugar Tech* 25(6):1467–1485. <https://doi.org/10.1007/s12355-023-01299-4>
- Sher Y, Baker NR, Herman D et al (2020) Microbial extracellular polysaccharide production and aggregate stability controlled by switchgrass (*Panicum virgatum*) root biomass and soil water potential. *Soil Biol Biochem* 143:107742. <https://doi.org/10.1016/j.soilbio.2020.107742>
- Shi A, Hu Y, Zhang X et al (2023) Biochar loaded with bacteria enhanced Cd/Zn phytoextraction by facilitating plant growth and shaping rhizospheric microbial community. *Environ Pollut* 327:121559. <https://doi.org/10.1016/j.envpol.2023.121559>
- Shyam S, Ahmed S, Joshi SJ et al (2025a) Biochar as a soil amendment: implications for soil health, carbon sequestration, and climate resilience. *Discov Soil*. <https://doi.org/10.1007/s44378-025-00041-8>
- Shyam S, Daimary M, Narayan M et al (2025b) Biochar-based electroanalytical materials: towards sustainable, high-performance electrocatalysts and sensors. *Next Mater* 8:100873. <https://doi.org/10.1016/j.nxmate.2025.100873>
- Sun T, Miao J, Saleem M et al (2020) Bacterial compatibility and immobilization with biochar improved tebuconazole degradation, soil microbiome composition and functioning. *J Hazard Mater* 398:122941. <https://doi.org/10.1016/j.jhazmat.2020.122941>
- Tallur PN, Mulla SI, Megadi VB et al (2015) Biodegradation of cypermethrin by immobilized cells of *Micrococcus* sp strain CPN 1. *Braz J Microbiol* 46(3):667–672. <https://doi.org/10.1590/s1517-838246320130557>
- Tao R, Ding W, Zhang K et al (2025) Biochar and *Bacillus subtilis* boost cut chrysanthemum growth via intensified microbial interkingdom interactions. *Biochar* 7(1):75. <https://doi.org/10.1007/s42773-025-00466-y>
- Tu C, Wei J, Guan F et al (2020) Biochar and bacteria inoculated biochar enhanced Cd and Cu immobilization and enzymatic activity in a polluted soil. *Environ Int* 137:105576. <https://doi.org/10.1016/j.envint.2020.105576>
- Wahla AQ, Anwar S, Mueller JA et al (2020) Immobilization of metribuzin degrading bacterial consortium MB3R on biochar enhances bioremediation of potato vegetated soil and restores bacterial community structure. *J Hazard Mater* 390:121493. <https://doi.org/10.1016/j.jhazmat.2019.121493>
- Wang T, Sun H, Ren X et al (2017) Evaluation of biochars from different stock materials as carriers of bacterial strain for remediation of heavy metal-contaminated soil. *Sci Rep* 7:12114. <https://doi.org/10.1038/s41598-017-12503-3>
- Wang L, Li Z, Wang Y et al (2021) Performance and mechanisms for remediation of Cd(II) and As(III) co-contamination by magnetic biochar-microbe biochemical composite: competition and synergy effects. *Sci Total Environ* 750:141672. <https://doi.org/10.1016/j.scitotenv.2020.141672>
- Wang X, Cai D, Ji M et al (2022) Isolation of heavy metal-immobilizing and plant growth-promoting bacteria and their potential in reducing Cd and Pb uptake in water spinach. *Sci Total Environ* 819:153242. <https://doi.org/10.1016/j.scitotenv.2022.153242>
- Wang N, Wang T, Chen Y et al (2024) Microbiome convergence enables siderophore-secreting-rhizobacteria to improve iron nutrition and yield of peanut intercropped with maize. *Nat Commun* 15(1):839. <https://doi.org/10.1038/s41467-024-45207-0>
- Wen M, Ma Z, Gingerich DB et al (2022) Heavy metals in agricultural soil in China: a systematic review and meta-analysis. *Eco-Environ Health* 1(4):219–228. <https://doi.org/10.1016/j.eehl.2022.10.004>
- Woo J-I, Adhikari A, Gam H-J et al (2025) Integrated role of biochar and PGPR (*Leclercia adecarboxylata* HW04) in enhancing cadmium phytoremediation and stress tolerance in *Glycine max* L. *Plant Physiol Biochem* 220:109489. <https://doi.org/10.1016/j.plaphy.2025.109489>
- Wu P, Wang Z, Bhatnagar A et al (2021) Microorganisms-carbonaceous materials immobilized complexes: synthesis, adaptability and environmental applications. *J Hazard Mater* 416:125915. <https://doi.org/10.1016/j.jhazmat.2021.125915>
- Wu C, Zhi D, Yao B et al (2022) Immobilization of microbes on biochar for water and soil remediation: a review. *Environ Res* 212:113226. <https://doi.org/10.1016/j.envres.2022.113226>

- Wu J, Fu X, Zhao L et al (2024) Biochar as a partner of plants and beneficial microorganisms to assist in-situ bioremediation of heavy metal contaminated soil. *Sci Total Environ* 923:171442. <https://doi.org/10.1016/j.scitotenv.2024.171442>
- Wu C, Wang Y, Clarke JL et al (2025) Biochar enhances the sorption and degradation of fluridone and its main metabolite in soil: insights into biodegradation potential and remediation of microbial communities. *Biochar* 7(1):81. <https://doi.org/10.1007/s42773-025-00469-9>
- Xiong B, Zhang Y, Hou Y et al (2017) Enhanced biodegradation of PAHs in historically contaminated soil by *M. gilvum* inoculated biochar. *Chemosphere* 182:316–324. <https://doi.org/10.1016/j.chemosphere.2017.05.020>
- Xiong X, Liu J, Xiao T et al (2025) Remediation of uranium-contaminated water and soil by biochar-based materials: a review. *Biochar* 7(1):41. <https://doi.org/10.1007/s42773-025-00438-2>
- Yang H, Kerner P, Liang X et al (2025) Biochar amendment modulates root metabolome and rhizosphere microbiome of wheat. *Biochar* 7(1):46. <https://doi.org/10.1007/s42773-025-00434-6>
- Yin C, Yan H, Cao Y et al (2023) Enhanced bioremediation performance of diesel-contaminated soil by immobilized composite fungi on rice husk biochar. *Environ Res* 226:115663. <https://doi.org/10.1016/j.envres.2023.115663>
- Yu K, Wang Z, Yang W et al (2025) Application of biochar-immobilized *Bacillus megaterium* for enhancing phosphorus uptake and growth in rice. *Plants* Basel 14(2):214. <https://doi.org/10.3390/plants14020214>
- Zeng Y, Wen M, Li S et al (2025) Role of Fe-based nanoparticles introduced into soil-plant systems or contaminated soil-plant systems: toxic substance or remediation agent? *Front Environ Sci Eng* 19(3):27. <https://doi.org/10.1007/s11783-025-1947-1>
- Zhai Q, Chen X, Zhang M et al (2023) Immobilization of *Klebsiella jilinsis* strain 2N3 by corn straw biochar enhanced the degradation of nicosulfuron and restores the soil microbiome function and composition. *Appl Soil Ecol* 189:104917. <https://doi.org/10.1016/j.apsoil.2023.104917>
- Zhang B, Zhang L, Zhang X (2019) Bioremediation of petroleum hydrocarbon-contaminated soil by petroleum-degrading bacteria immobilized on biochar. *RSC Adv* 9(60):35304–35311. <https://doi.org/10.1039/c9ra06726d>
- Zhang Z, Fan Z, Zhang G et al (2021) Application progress of microbial immobilization technology based on biomass materials. *Bioresour* 16(4):8509–8524. <https://doi.org/10.15376/biores.16.4.Zhang>
- Zhang M, Liu Y, Wei Q et al (2023) The co-application of PGPR and biochar enhances the production capacity of continuous cropping peppers in the Karst Yellow Soil Region of Southwest China. *Horticulturae* 9(10):1104. <https://doi.org/10.3390/horticulturae9101104>
- Zhang S, Shen Y, Zheng C et al (2024) Recent advances, challenges, and perspectives on carbon capture. *Front Environ Sci Eng* 18(6):2095–2201. <https://doi.org/10.1007/s11783-024-1835-0>
- Zhong JC, Xie CJ, Yan KJ et al (2025) Optimizing biochar-microbe immobilization for formaldehyde removal: synergistic adsorption and phytoremediation enhancement. *J Environ Chem Eng* 13(5):118964. <https://doi.org/10.1016/j.jece.2025.118964>
- Zou Q, Zhao L, Guan L et al (2024) The synergistic interaction effect between biochar and plant growth-promoting rhizobacteria on beneficial microbial communities in soil. *Front Plant Sci* 15:1501400. <https://doi.org/10.3389/fpls.2024.1501400>