Mustafa et al. Biochar (2026) 8:3
https://doi.org/10.1007/s42773-025-00521-8

Biochar

REVIEW

Open Access

Beyond one-size-fits-all: tailoring engineered biochar for purpose-specific rhizosphere engineering in crop production, protection, and soil remediation

Adnan Mustafa[1,2†], Qudsia Saeed[1,2†], Xiankai Lu[1,2*], Zia Ur Rahman Farooqi[3,4], Usman Arshad[5], Jiri Holatko[6], Wentao Wei[1,2], Mohsin Mahmood[7], Martin Brtnicky[6,8], Weibin Chen[1,2], Ansa Rebi[9], Muhammad Amjad Ali[10], Muhammad Naveed[11], Jiri Kucerik[6] and Abdul Ghafoor[12]

Abstract

Engineered biochar has emerged as a versatile tool for purpose-specific rhizosphere engineering, offering tailored solutions for enhancing crop production, crop protection, and environmental remediation. Yet, its effectiveness depends on optimizing application for specific functional goals rather than adopting a one-size-fits-all approach. This review explores how engineered biochar shapes rhizosphere processes to support crop production, crop protection, and soil remediation. It examines key mechanisms including enhanced nutrient availability, stimulation of beneficial microbial communities, pathogen suppression, and soil contaminant immobilization, and how different biochar modifications, such as nutrient enrichment, antimicrobial functionalization, and surface engineering, drive these outcomes. The review highlights important trade-offs, such as the competing demands of nutrient availability for crop growth versus contaminant immobilization for remediation, and accounts for the spatial and temporal variability of biochar effects in the rhizosphere. While biochar presents clear synergistic benefits (e.g., improving soil structure, enhancing water retention, reducing greenhouse gas emissions, and enabling carbon sequestration), its practical application faces challenges related to competing objectives, rhizosphere complexity, and economic constraints. Emerging innovations such as nanocomposite biochars, bioprimed biochars, and biochar-microbe synergies offer new avenues for precision agriculture and sustainable land management. Finally, the review emphasizes the importance of long-term field studies to evaluate sustainability, and outlines opportunities for biochar in climate change mitigation, waste valorization, and agroecological resilience. By integrating the latest research on biochar's mechanisms, challenges, and opportunities, this review provides a comprehensive framework for leveraging engineered biochar to address the pressing challenges of modern agriculture and environmental management.

Highlights

- Engineered biochars are tailored to modify rhizosphere interactions, optimizing nutrient cycling, microbial activity, and soil structure.

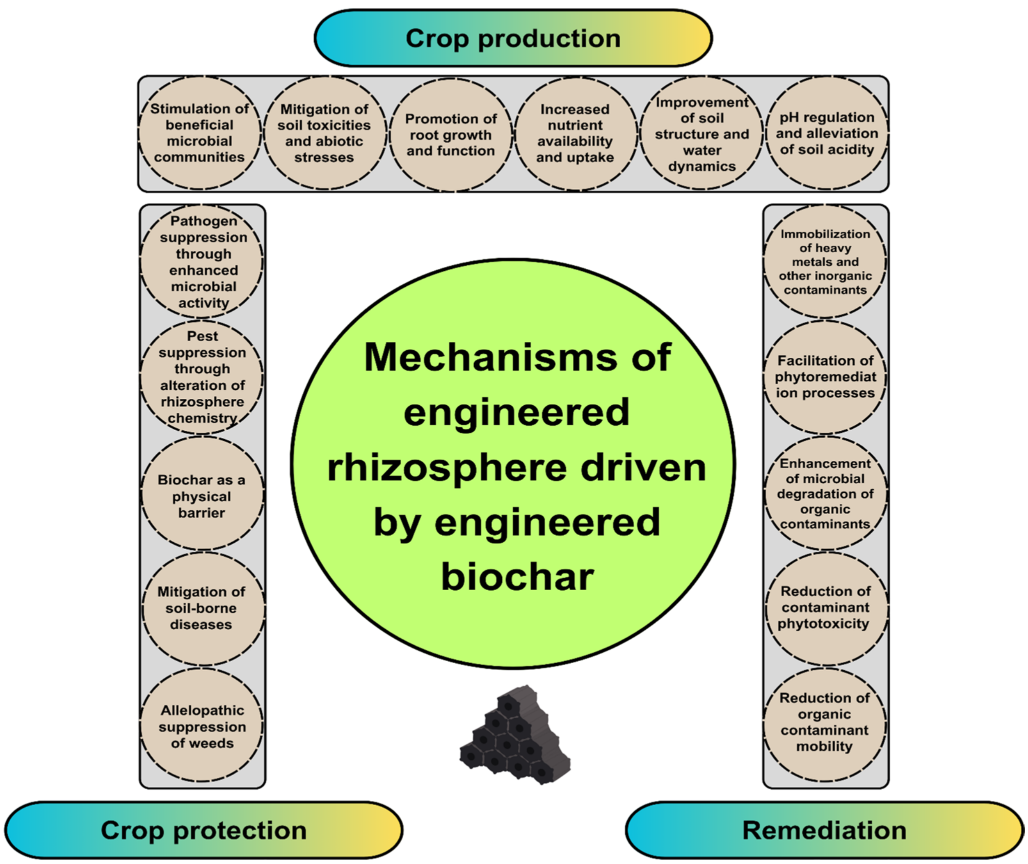
[†]Adnan Mustafa and Qudsia Saeed have contributed equally to this work.

*Correspondence:
Xiankai Lu
luxiankai@scbg.ac.cn
Full list of author information is available at the end of the article

- A one-size-fits-all approach is ineffective, and biochar must be customized for crop production, crop protection, and remediation.
- Biochar effects evolve over time, requiring precise application strategies to maintain long-term soil and plant benefits.
- Balancing yield enhancement, pathogen suppression, and contaminant stabilization demands careful biochar formulation and dosage adjustment.
- Integrating biochar engineering with precision agriculture and climate resilience strategies is key for sustainability.

Keywords Engineered biochar, Rhizosphere engineering, Microbial communities, Pathogen suppression, Biochar challenges, Innovative biochar applications

Graphical Abstract



1 Introduction

The growing demands of a rapidly expanding global population, coupled with the escalating impacts of climate change, have placed unprecedented pressure on agricultural systems and natural ecosystems. Sustainable solutions that enhance crop productivity, protect plants from pests and diseases, and remediate contaminated soils are urgently needed. Among these, engineered biochar-based rhizosphere engineering (strategic manipulation of root-associated soil zone) has emerged as a transformative approach to optimizing soil functions and addressing the tripartite nexus of crop production, protection, and environmental remediation. Engineered biochar, a carbon-rich material derived from the pyrolysis of organic biomass and modified for specific applications, offers superior physicochemical properties compared to conventional biochar, including high surface area, porosity, tailored nutrient retention, and enhanced contaminant sorption capacities (Ravindiran et al. 2024; Yu et al. 2015). Recent advancements, such as nano-enabled biochar with reduced particle size and enhanced reactivity, have demonstrated potential for improving soil structure, increasing nutrient availability, and immobilizing pollutants (Chhipa 2016; Chausali et al. 2021). However, despite its promise, the spatial and temporal variability of biochar effects, trade-offs between nutrient availability and contaminant sorption, and limited field-scale validation remain critical research gaps.

The rhizosphere represents one of Earth's most biologically active interfaces, where root exudates create a dynamic microenvironment facilitating intricate chemical signaling and nutrient exchange between plants and soil biota (Saeed et al. 2021; Wang and Kuzyakov 2024). Recent advances reveal that biochar's most profound impacts occur precisely within this critical zone through a process now termed rhizosphere engineering, the deliberate modification of root-soil-microbe interactions through targeted biochar applications (Zhang et al. 2023). This paradigm shift recognizes that biochar's benefits (nutrient retention, pathogen suppression, contaminant immobilization) manifest only when its physicochemical properties are precisely aligned with rhizospheric conditions, through four key mechanisms: Firstly biochar alters the composition and quantity of root exudates (organic acids, flavonoids, strigolactones), which subsequently reshape microbial recruitment and nutrient mobilization (Sun et al. 2020). Secondly, the pore architecture of biochar (10–100 µm) provides ideal refuge for beneficial microbes (Wong et al. 2022), increasing their abundance 3–5-fold compared to bulk soil. This creates a "microbial hotspot" where nitrogen (N) fixation and phytohormone production are amplified. Thirdly, biochar stabilizes rhizospheric pH fluctuations and maintains optimal moisture even under drought (Joseph et al. 2021). Lastly, in polluted soils, biochar forms a protective zone around roots, reducing heavy metal uptake by permitting essential nutrient flow (Antonangelo et al. 2025). This selective filtration is mediated by surface functional groups (–COOH, –OH) that preferentially bind contaminants. This advanced understanding transforms biochar from a passive amendment to an active rhizospheric architect, as illustrated in Fig. 1. However, this tripartite framework must be carefully designed and strategically deployed to optimize root zone processes for sustainable agriculture.

Engineered biochar has shown promise in modulating these interactions, yet critical knowledge gaps persist regarding its effects on microbial communities, pathogen suppression, and contaminant immobilization (Sarma et al. 2024; Yang et al. 2025). For instance, how does biochar influence the balance between beneficial and pathogenic microbes in the rhizosphere? Can biochar be engineered to simultaneously enhance crop productivity and protect plants from soil-borne diseases? Addressing these questions is essential for developing purpose-specific biochars that optimize microbial interactions and nutrient dynamics. Unlike conventional biochar applications, rhizosphere engineering with engineered biochar enables precise manipulation of soil microbial networks, root exudate dynamics, and biogeochemical cycles to achieve targeted agronomic and environmental benefits (Luthra et al. 2024). Nutrient-enriched biochars improve soil fertility by providing a controlled release of essential nutrients like N, phosphorus (P), and potassium (K) (Kizito et al. 2019). Bioprimed biochars inoculated with plant growth-promoting rhizobacteria (PGPR) or arbuscular mycorrhizal fungi (AMF) facilitate nutrient uptake and enhance plant resilience against environmental stresses (Sun et al. 2016; Sani et al. 2020). Additionally, high porosity biochars improve water retention, which is crucial for crop production in arid or degraded soils (Chen et al. 2023a, b). Beyond crop productivity, engineered biochars represent a sustainable alternative to chemical pesticides. Functionalized biochars with antimicrobial properties suppress soil-borne pathogens (Ratnadass et al. 2023; Mahmoud et al. 2024), while biochars enriched with plant defense elicitors can trigger induced systemic resistance (ISR: plant's enhanced defensive capacity triggered by specific environmental stimuli and microbes etc.,) enhancing plant immunity (Wang et al. 2021a, b, c; Ahmad et al. 2024). Similarly, nanocomposite biochars, incorporating nanoparticles such as silver or copper, have demonstrated effectiveness in pathogen suppression, offering a promising tool for integrated pest management (Pavlicevic et al. 2023). In the context of environmental remediation, biochars with contaminant-immobilizing properties facilitate the detoxification of heavy metals and organic pollutants, restoring soil health and functionality (Sha et al. 2023; Li et al. 2024). Despite this potential, widespread adoption of engineered biochar faces several challenges. The economic feasibility of large-scale application is constrained by feedstock availability, production costs, post-modification techniques, and logistical barriers. Additionally, the long-term stability and transformation of engineered biochar in different soil environments remain poorly understood, raising concerns about unintended ecological impacts. Addressing these challenges requires a multidisciplinary approach integrating advancements in biochar engineering, precision agriculture, and supportive policy frameworks.

This review addresses these limitations by providing a comprehensive analysis of engineered biochar-based rhizosphere engineering, integrating its applications

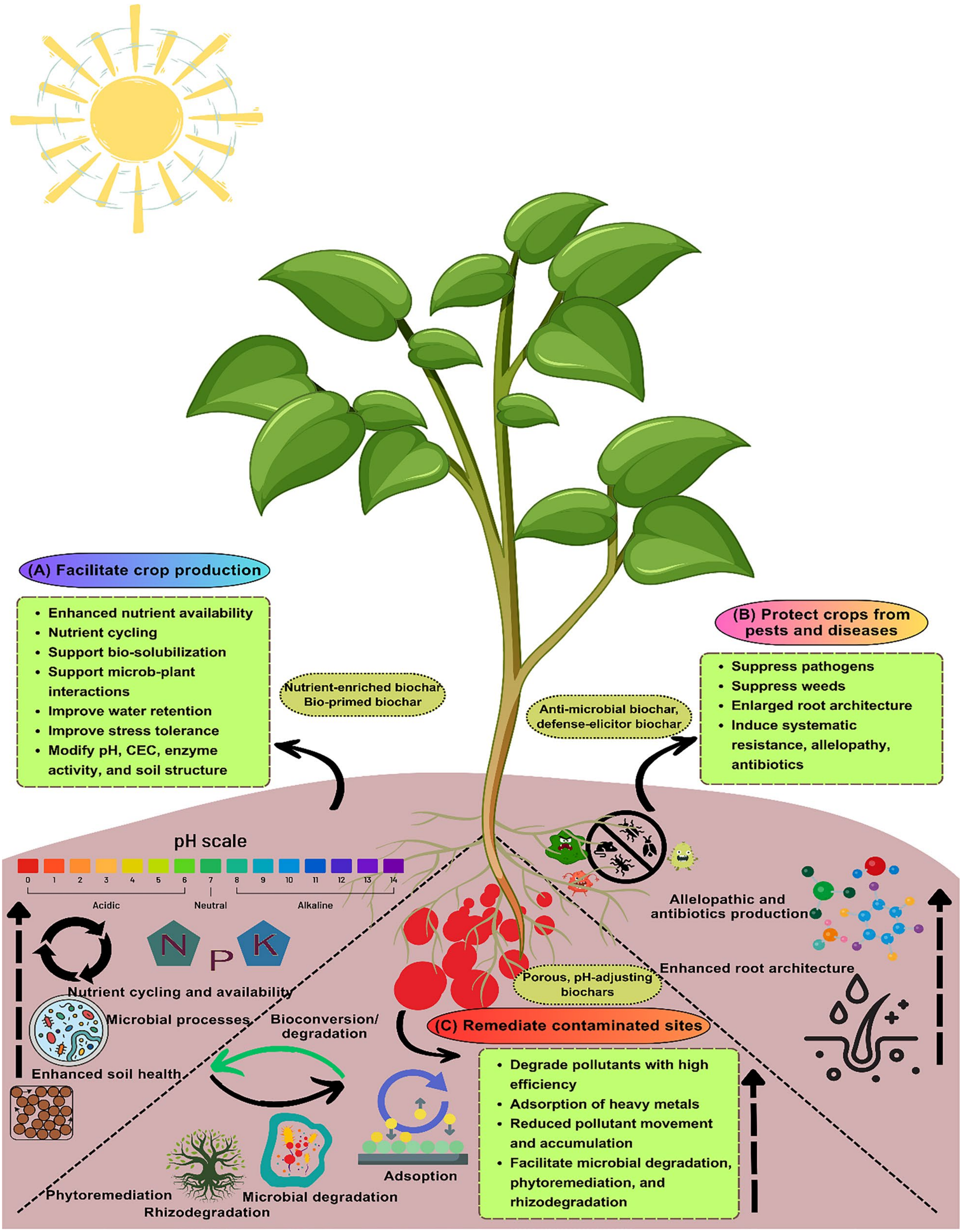


Fig. 1 Biochar as rhizosphere architect: schematic showing how engineered biochar simultaneously transforms **A** crop productivity (nutrient cycling/water retention), **B** plant defense (pathogen suppression/root immunity), and **C** soil detoxification (metal immobilization/pollutant degradation) through tailored physicochemical interactions in the root zone, highlighting biochar's role in rhizosphere engineering

across three core areas: crop production, crop protection, and environmental remediation. We explore the purpose-specific engineering of biochar for targeted outcomes and propose a practical framework for selection and application, an aspect that is critically missing in the existing literature (Table 1). We hypothesize that engineered biochars, when tailored for specific rhizosphere functions, can achieve synergistic outcomes across crop production, crop protection, and soil remediation, provided that trade-offs and soil-specific factors are carefully accounted for. Unlike previous reviews that often focus on single aspects such as biochar's role in soil fertility or pollutant removal, this work presents a holistic framework that categorizes engineered biochars based on their tailored functionalities and mechanisms in the rhizosphere (Table 1). A key novelty of this review is the systematic classification of engineered biochars into different functional types, including nutrient-enriched, bioprimed, porous, antimicrobial, ISR-inducing, adsorptive, and catalytic biochars, linking each to specific rhizosphere processes and targeted applications. Additionally, this review provides detailed mechanistic insights into how engineered biochar influences nutrient dynamics, microbial interactions, soil structure, pathogen suppression, and contaminant remediation, aspects that are often overlooked in previous reviews. Another unique contribution of this review is its integrated approach to the tripartite nexus, synthesizing the roles of engineered biochar in crop productivity, plant protection, and environmental remediation, while highlighting synergistic effects and trade-offs. Finally, this work critically assesses the economic feasibility, scalability, and long-term stability of engineered biochars, identifying research gaps and future directions for optimizing their role in climate change mitigation, sustainable soil management, and enhanced crop resilience. By bridging these gaps, this review provides a scientifically informed roadmap for leveraging engineered biochar-based rhizosphere engineering to achieve sustainable agriculture, environmental restoration, and global food security.

2 Review methodology

This review was conducted following a structured literature survey and thematic synthesis approach. We searched major scientific databases including Web of Science, Scopus, PubMed, Google Scholar, ScienceDirect, and AGRICOLA and Agris: databases with a focus on agriculture, using combinations of keywords such as "engineered biochar," "biochar modification", "rhizosphere engineering," "nanocomposite biochar," "bioprimed biochar," "ISR biochar," "microbial biochar," "crop production," "crop protection," "remediation," "soil contaminants," "soil microbiome," and "biochar mechanisms." All results were considered, and additional hand-searching was performed. Additionally, targeted manual searches were performed on the websites of agricultural research institutes, environmental agencies, and biochar-related organizations to capture relevant grey literature and policy reports not indexed in conventional databases. The search covered literature published between 2010 and 2025, with a strong focus on the most recent and high-impact studies from 2018 to 2025. Only peer-reviewed journal articles, authoritative reviews, and experimental studies were included. Conference papers, opinion pieces, and non-English language publications were excluded. Inclusion criteria were: (i) peer-reviewed original research or reviews; (ii) studies reporting experimental evidence of biochar modification and its effects on rhizosphere processes; (iii) publications detailing mechanisms, challenges, or applications of engineered biochar in at least one of the three key areas: crop production, crop protection, or soil remediation. Exclusion criteria included: (i) purely theoretical papers without data; (ii) studies focused solely on unmodified or conventional biochar unless they provided mechanistic insights relevant to engineered biochar; (iii) duplicated studies or those lacking methodological rigor, (iv) studies evaluating biochar under hydroponic conditions without soil–rhizosphere relevance. To minimize selection bias, studies were screened independently by at least two authors, and any discrepancies were resolved through discussion and cross-validation. A critical reading of each selected study was conducted to assess limitations, methodologies, and replicability. Data were synthesized and organized thematically under sections for crop production, crop protection, and remediation. Critical insights, gaps, limitations, and recommendations were extracted and tabulated.

3 Engineered biochar and classification for tailored application

3.1 Engineered biochar for crop production

3.1.1 Nutrient-enriched biochar

Nutrient-enriched biochar is engineered to enhance nutrient retention and release, making it a valuable soil amendment for improving fertility in degraded or nutrient-poor soils. Nutrient-enriched biochar is produced through three main approaches: (i) natural feedstock enrichment via increased nutrient uptake (Yao et al. 2013b), (ii) pre-pyrolytic blending of feedstock with nutrient-rich materials or compounds (Khajavi-Shojaei et al. 2020), and (iii) post-pyrolytic soaking or impregnation with liquid or gaseous nutrient sources. Among these, post-pyrolytic modification offers better control over nutrient composition and loading efficiency, although it often incurs higher production costs

Table 1 Comparison of present review and other top-notch reviews published hitherto on engineered biochar-based improvements in soil–plant system

Review	Production method	BC-engineering	Tailored classification			BC-rhizo-engineering	Engineered BC mechanism	Engineered BC application			Challenge	Opportunity
			Production	Protection	Remediation			Production	Protection	Remediation		
Present review	+	√**	√**	√**	√**	√**	√**	√**	√**	√**	√**	√**
Fan et al. (2023)	+	√**	+	+	+	√**	√*	+	+	√**	+	b
Sarma et al. (2024)	√*	√**	+	+	+	b	√**	√**	+	√**	√*	√*
Liu et al. (2021)	√**	√**	+	+	+	√*	√*	√*	+	√*	+	+
Poveda et al. (2021a, b)	+	+	+	+	+	+	+	+	√**	+	+	√*
Ravindiran et al. (2024)	√**	√**	+	+	+	+	√**	√**	+	√**	√**	√**
Wang et al. (2017)	√**	√**	√**	+	√**	+	√*	√**	√*	√**	√*	√*
Panahi et al. (2020)	+	√**	a	+	a	√*	+	√**	+	√**	+	√*
Wang et al. (2021a, b, c)	+	+	√**	+	√**	+	√**	+	+	√**	√**	√**
Bhatt et al. (2024)	√*	√*	+	+	+	√*	√**	√*	√**	+	√*	√*
Xiang et al. 2022	+	+	+	+	√*	√**	√*	√**	√*	√**	√**	√**
Antonangelo et al. (2025)	√*	+	√**	+	+	√*	+	√**	√*	√*	√**	+

√**Comprehensively discussed

√*Briefly discussed

+ Not discussed

a Referred to reference

b Specific on one topic (e.g., remediation or microbial responses) compared to feedstock-based enrichment. A wide range of materials are used for engineering nutrient-enriched biochar, including (i) organic materials such as manure, slurries, digestate (Kizito et al. 2019), compost, and wastewater (Zheng et al. 2019); (ii) mineral raw materials like rock phosphate (Moradi et al. 2019), apatite, struvite, and dolomite (Li et al. 2018a, b); (iii) chemical compounds including P salts (Nardis et al. 2020), N salts (Khajavi-Shojaei et al. 2020), and trace metals. Notably, chemical nutrient enrichment tends to provide higher nutrient concentrations but may pose risks of leaching or toxicity under certain soil conditions. In contrast, organically enriched biochars provide more gradual nutrient release and improved microbial compatibility, though often with lower immediate availability (Table 2).

The nutrients in enriched biochars are stabilized within the recalcitrant structures of pyrolyzed material (Suwanree et al. 2022), which consists of slow-degrading carbon forms (Rajput et al. 2024) and insoluble compounds like silicates (Sornhiran et al. 2022). These structures enable mineral bonding and gradual mineralization of organic macronutrients, preventing nutrient losses through leaching (Peng et al. 2021) or volatilization (Puga et al. 2020). This slow-release mechanism aligns nutrient availability with plant demand, contrasting with the rapid nutrient release and lower long-term efficiency of mineral fertilizers, which can negatively impact soil microflora. As shown in Table 2, nutrient-enriched biochars have been widely studied for their capacity to reduce dependency on synthetic fertilizers and recycle nutrients from waste streams such as digestate (Zheng et al. 2025), wastewater (Zheng et al. 2019), and stormwater (Marcińczyk et al. 2022). These applications not only support circular nutrient economies but also contribute to climate change mitigation by reducing greenhouse gas emissions associated with N loss (Osman et al. 2022). However, field performance remains inconsistent, partly due to soil-specific responses and differences in biochar composition. Despite their benefits, several challenges limit widespread adoption. These include soil acidification risks (Das et al. 2020), occasional suppression of crop root development (Anyanwu et al. 2018), and simultaneous promotion of both crop and weed growth (Safaei Khorram et al. 2018). The effectiveness of nutrient-enriched biochar is highly dependent on soil type and crop species, making broad recommendations difficult (Zhu et al. 2015). Financial barriers such as high activation costs (Alhashimi and Aktas 2017) and expenses for added nutrients (Mosa et al. 2018) further limit their widespread adoption (Li et al. 2023d). To improve feasibility, the use of low-cost enrichment strategies, such as nutrient capture from wastewater, is recommended over energy-intensive regeneration methods (Harussani and Sapuan 2022; Almanassra et al. 2021). In this regard, Latawiec et al. (2021) reported that biochar application up to 60 Mg ha^{-1} yielded economic benefits, reaching break-even point after three years. Overall, nutrient-enriched biochar holds strong potential for low-fertility and weathered upland soils (Palansooriya et al. 2019), but future work should focus on standardizing enrichment techniques, evaluating long-term field efficacy, and developing integrated strategies that balance crop nutrition with weed and soil microbiome management.

3.1.2 Bioprimed biochar

Bioprimed biochar is engineered through the activity or enrichment of soil macrobiota, such as earthworms (Yuvaraj et al. 2021), or microbes, including bacteria (Blanco-Vargas et al. 2022) and fungi (Iacomino et al. 2023). Earthworms-bioprimed biochar is modified by association with exoenzymes, either through the addition of biochar to vermicomposting (Yuvaraj et al. 2021) or earthworm-enriched soil (Sanchez-Hernandez 2018). It can also be treated with vermicompost extracts, containing exoenzymes and associated microbes. These modifications enhance nutrient transformation and availability (Carril et al. 2024) while improving the biochar´s specific surface area. Such biochar has demonstrated improved plant growth, leaf area, and net assimilation rates, even under reduced irrigation (Jahan et al. 2023). Microbially bioprimed biochar is prepared by inoculating biochar with defined microbial isolates (Azeem et al. 2021; Ortiz-Liébana et al. 2022) or colonizing it with microbial communities from sources such as compost (Edenborn et al. 2017), or slurry (Ferdous 2024). The biochar is either soaked in microbial suspension (Azeem et al. 2021; Guerena et al. 2019) or co-cultivated with cell cultures (Hale et al. 2014; Lebrun et al. 2021). This process enriches the biochar surface with plant growth-promoting bacteria (PGPB) including phosphate solubilizers (Azeem et al. 2021; Kari et al. 2021) or N_2 fixators (Kari et al. 2021). These microbes enhance nutrient transformation, increase soil fertility and protect plants against environmental stressors like potentially toxic elements (PTE) (Yuvaraj et al. 2021). Similarly, fungal biopriming protects plants from pathogenic moulds (da Silva et al. 2022; Muter 2017) and increases maize germination and growth (Muter 2017).

PGPB-bioprimed biochar enhances plant nutrition and crop yields as evidenced in beans (Guerena et al. 2019) and mung beans (Azeem et al. 2021), offering a sustainable alternative to conventional fertilizers derived from non-renewable resources. Comparatively, fungal-primed biochars show greater promise in pathogen suppression, while bacterial-primed variants are more effective in nutrient solubilization, suggesting that

Table 2 Summary of studies using engineered BC for crop production with a special focus on engineered BC-based rhizosphere engineering

Biochar feedstock type	Host crop	Engineering strategy	Rhizosphere mechanism, properties	Finding/production outcome	Challenge/limitation	Recommendation	Soil type	Reference
Nutrient-Enriched Biochar								
Mg-enriched tomato leaves	Brown Top Millot	Surface deposition of P on Mg	Slow release of bioavailable P	Increased grass seed germination	Slow kinetics of P sorption	Address slow P sorption kinetics	–	Yao et al. (2013a, b)
Metal contaminated water hyacinth	Maize seedlings	Phosphate sorption by metal ions	Slow release of P, micronutrients	Increased maize P content	Disposal of metal-contaminated biomass	Optimize metal-contaminated biomass disposal	Sandy soil (typic torripsamment)	(Mosa et al. (2018)
$MgCl_2$ impregnated corn straw	Maize (*Zea mays*)	Soaking in 3 M ammonium nitrate	Slow ammonium and nitrate release	Increased crop yield (by 44%) and height (by 37%)	Nutrient leaching risk	Use in sandy soils to boost NUE	Typic Haplocalcid (silty sand)	Khajavi-Shojaei et al. (2020)
$MgCl_2$ impregnated organic wastes	Maize (*Zea mays*)	P precipitation with cations	Higher P uptake compared to superphosphate	Accumulation of P in maize	Disposed litter, manure, sewage sludge	Supply 200 mg of P·kg^{-1} organic waste	Oxisol (Rhodic Hapludox	Nardis et al. (2020)
Bacterial biomass fermented waste	Lettuce	*E. coli* biomass supplied with P	P release to hydroculture	Increased early lettuce growth	Limitations for toxicity	Pyrolysis for valorizing waste bacterial biomass	–	Kim et al. (2018)
Poultry manure	Lettuce	Triple superphosphate TSP	Increased N, P, K content in plant	Increased crop yield (7.8-fold)	Micronutrient dilution	Supplement with micronutrients in low OM soils	Clay loam (low organic matter)	Gunes et al. (2014)
$MgCl_2$ impregnated cow dung	Lettuce	Surface deposition of P on Mg	Increased soil available P, soil moisture	Better seed germination, growth	Upscaling of the pyrolysis stage	Use PE sorbent biochar bags for P reclamation	Acidic sandy soil	Chen et al. (2018)
$AlCl_3$ impregnated hickory wood	Mung bean	Waste water P sorbed on biochar	P-promoted photosynthesis, root development	Better seed germination, growth	Not found	Use for P recovery from wastewater	Not specified	Zheng et al. (2019)
Corn stalk	Not found	Soaking in $AlCl_3$ and $FeCl_3$	Reduced Olsen-P, leaching of soil total P	Enhanced P precipitated by Ca^{2+}	Limited P adsorption by pristine biochar	Apply Fe/Al-modified biochar for P control in calcareous soils	Calcareous silt soil	Peng et al. (2021)
Oilseed rape straw residues	*Sedum alfredii*, SA	Soaking in $KMnO_4$ solution	Improved root architecture, Cd phytoextraction	Reduced shoot and root biomass SA (by 24%)	Low biomass of SA	Intercrop SA with celery for Cd accumulation	Silty Fluvisol	Chen et al. (2023a, b)
Cereal husks, sunflower peels	Barley	Co-composting with cattle manure	Increased soil enzyme activity (i.e., urease)	Increased early phase crop yield (by 50% compared to variant with no biochar)	Longer termed benefit was negligible	Verification by upscaling to field level	Silty clay loam Haplic Luvisol	Holatko et al. (2023)
Corn cob, fig tree prunings	Yellow sweet maize	2-day incubation with digestate	Increased N and P uptake to roots	Higher maize biomass yield (by 34% compared to no biochar)	< 70% of digestate recycled back	Tool to increase soil organic matter, nutrients	Clay silty low fertility subsoil	Kizito et al. (2019)
Jarrah wood	Tomato	24 h co-incubation with digestate	Biochar-induced inhibition of nitrification	Increased dry shoot & root mass (by 5% & 25%)	Low digestate dose reduced plant growth	Adjust food-waste digestate for fertilizing	Potting soil (moderate organic matter)	Mickan et al. (2022)

Table 2 (continued)

Biochar feedstock type	Host crop	Engineering strategy	Rhizosphere mechanism, properties	Finding/production outcome	Challenge/limitation	Recommendation	Soil type	Reference
Grape pruning	Not found	Rock phosphate	Increased access of Ca, Mg, K, P, Fe, Zn, Mn	Lowered Na concentration of soil	Salinity stress harms plant's growth, yield	Use biochar to reduce soil Na^+	Sandy loam poorly fertile, artificially saline	Moradi et al. (2019)
Chinese herb medicine residues	Cabbage mustard	$Fe_3(PO_4)_2$-biochar nanocomposite	Decreased translocation capacity of Cd	Reduced Fe uptake to seedlings	Over-aggregation limits the application	Effective in situ remediation of Cd in soil	not specified	Xu et al. (2016)
Corn stalks	Pak choi	Struvite crystallization on biochar	Struvite reprecipitation, antioxidation barrier	Nutrient retention, pH regulation	Time-limited demonstrated consistency	Slow-release fertilizer, minimizes N, P loss	Silty loam	Li et al. (2024)
Swine manure	Chinese cabbage	$Ca(H_2PO_4)_2$-amended swine manure	Reduced absorption of toxic metals	Increased plant biomass (1.27-fold)	Environment-save disposal of swine man	Increased available P, lower acid-soluble Cd, Pb	Two sandy loam soils (alkaline, neutral)	Ren et al. (2020)
Poplar tree wood sawdust	Chinese brassica	Dolomite powder co-pyrolysis	Not found	Improved plant growth	Low P bioavailability	Use dolomite–sawdust biochar to boost P uptake	Alkalic soil (low organic matter)	Li et al. (2018a, b)
Cereal husks, sunflower peels	Lettuce	Soaking in mineral fertilizer	Increased N, P, K content in soil pore water	Increased lettuce biomass (sixfold compared to variant with no biochar)	Reproducibility at a field scale	Activation of biochar by pre-mixing with NPK	Silty clay loam Haplic Luvisol	Brtnicky et al. (2023)
Rice husk	Rice (*Oryza sativa*)	Coating, grafting (NH_3-, HS-, Se)	Increased organic matter, available P, K	Increased N, P, K in leaves	Hg contamination risk	Apply 0.2% modified biochar for fertility improvement in polluted soils	Paddy purple soil (low organic matter)	Li et al. (2023a)
Eucalypt wood chips	Millet and maize	Blending, coating TSP + biochar	Increased P uptake by plant than from TSP	Increased yield of both crops (by 10% and 18%)	Ephemeral advantage compared to TSP	Use for short-term applications < 60 days	Two Oxisols (clayey soil, sandy-loam soil)	Pogorzelski et al. (2020)
Wood chips, wheat straw pellets	Durum wheat	Soaking in Hoagland solution	Changed α-diversity of rhizospheric bacteria	Decreased Zn available for plants	Reduced Zn availability	Test straw biochar with Marco Aurelio wheat in field trials	Alluvial gleyic Fluvisol	Latini et al. (2019)
Pinewood	Maize (*Zea mays*)	Worm tea vacuum infiltration	Increased population of *Gammaproteobacteria*	Improved plant growth in saline soil	Needed field studies to confirm results	Nutrient supplement unaffected shelf life	Sandy loam agriculture soil	Sun et al. (2016)
Corn straw, pomelo peel, eggshell	Soybean	Biochar + eggshell co-pyrolysis	Immobilization of P in soil microbial biomass	Increased crop height (by 14% compared to variant with no biochar) and P uptake	Needed field studies to confirm results	Suitable to enhance P immobilization/utilization	Silty loam topsoil (low organic matter)	Li et al. (2023b)
Mixed coniferous wood	Highbush blueberry	Mixing with bokashi (4:1 v/v)	Increased root colonization by ericoid mycorrhiza	Greater leaf area and total dry weight (70% more compared to no biochar)	No effect on root rot	Use with bokashi to enhance root colonization and growth in blueberries	Sandy loam (sandy, mixed, mesic Typic Haplorthods)	Sales et al. (2020)

Table 2 (continued)

Biochar feedstock type	Host crop	Engineering strategy	Rhizosphere mechanism, properties	Finding/ production outcome	Challenge/ limitation	Recommendation	Soil type	Reference
Citrus peel	Citrus orchard	Pre-pyrolysis mixing with 1 M $MgCl_2$	Enhanced soil enzymes, less mineralized organic C	Not found	Metagenomic analyses + mechanistic study	Use Mg-biochar for C sequestration effect in acid soils	Acidic silty loam (low organic matter)	Hu et al. (2023)
Southern yellow pine	Muscadine grape	Compost and biochar blend	Improved root architecture, decreased diameter	Increased plant root growth	Poor soil structure	Compost–biochar blend improves water retention in sandy soils	Acidic sandy Ultisol	Chang et al. (2021)
Porous and High Surface Area Biochar								
Pinewood	Quinoa	High surface area engineering	Biochar-coupled prevailing action of *Paraglomus*	Quinoa associates with variable AMF	Variable AMF response	Use biochar to selectively enrich Paraglomus-AMF colonization	Dark gray Luvisol, two orthic brown and one orthic black Chernozems	Neuberger et al. (2024)
Beech and oak wood	Ryegrass	Hot water steam activation	Enhanced availability of N, P nutrients	Reduced N, P leaching losses	more extensive testing schemes are required	Steam activated biochar prevents eutrophication	Silty Haplic Luvisol, sandy Haplic Fluvisol	Borchard et al. (2012)
Wood	*Vitis vinifera*, cover crops	Citric or tartaric acid dipping	C- and N-mineralizing enzyme activities differed in time scheme of activation	Biochar activation changed carbon content and C:N	Unclear biological pathways	Use acid treatment to simulate aged biochar effects	sandy loam vineyard soil	Ameur et al. (2018)
Not found	Mint	Chemicals (H_2O_2, KOH, H_3PO_4)	Increased pH, decreased toxicity availability	Increased leaf area, plant biomass (up to 21%)	Treatment-dependent efficacy	Prefer H_3PO_4-treated biochar for anti-toxicity effects	Silty loam (low organic matter)	Ghassemi-Golezani and Farhangi-Abriz (2023)
Softwood biochar from charcoal pile	*Andropogon gerardii*	Chemicals (H_2O_2) activation	Biochar interfered with root P uptake	Biochar decreased growth, nutrition	Species-specific response	Test biochar on diverse species before field use	Acid soil (Switzerland, pH 6.5), alkaline soil (Czechia, pH 7.8)	Paymaneh et al. (2018)
Sugarcane bagasse	Mash bean, wheat	Crushing to powder < 2 mm	Increased soil microbial biomass carbon	Enhanced microbial biomass, activity	Seasonal fluctuation in MBC	Use bagasse biochar for microbial enhancement in alkaline soils	Sandy loam with pH 8.5	Azeem et al. (2019)
Branches, peanut shells, cow dung	Rapeseed	Crushing to powder < 2 mm	Increased microbial community diversity	Lower plant stress, promoted growth	Reduced mineral-bonded organic C fraction	New potential strategy for acidified soil improvement	Acidified brown soil (pH 4.0)	Geng et al. (2022)
Corn biomass	Paddy soil plants	Crushing to powder < 2 mm	Exudation of indole acetic acid, abscisic acid	Effect of CO_2 + biochar on amino acids	Decreased cytokinin	Combine CO_2 + biochar to enhance C storage and rhizosphere signaling	Not specified	Pei et al. (2020)
Bioprimed biochar								
Pinewood	Maize (*Zea mays*)	Inoculation *Psedomonas putida*	Increased population of *Gammaproteobacteria*	Improved plant growth in saline soil	Shelf life unaffected	Conduct field trials for validation	Sandy loam agriculture soil	Sun et al. (2016)

Table 2 (continued)

Biochar feedstock type	Host crop	Engineering strategy	Rhizosphere mechanism, properties	Finding/ production outcome	Challenge/ limitation	Recommendation	Soil type	Reference
Timbe waste	Wheat 'Glaxay 2013'	PGPR *Agrobacterium, Bacillus*	PGPR solubilized P and K, produced ACC	Better root growth, nutrient uptake	No photosynthesis gain	Evaluate long-term field performance	Sandy clay loam	Zafar-ul-Hye et al. (2019)
Tea leaves	Mung bean	Inoculation with *Bacillus cereus*	Increased soil available P and microbial biomass P	Enhanced crop growth and yield (by 113% compared to control)	Not found	Assess optimal biochar temperature range	Silty loam neutral soil	Azeem et al. (2021)
Pinewood	Cucumber	Inoculation *Enterobacter cloacae*	Biochar did not interfere with root colonization	Increased root biomass and branching	Future work to evaluate the results is needed	Evaluate long-term colonization effects	Formerly agriculture sandy loam	Hale et al. (2014)
Coffee grounds, coffee and bean husks, soursop waste	Cassava	Inoculation of *Trichoderma aureoviride*	Decreased severity of *Fusarium solani* URM 8425 i.e. root rot disease on both root and shoot induced root rot in cassava plants	Improved crop growth due to increased soil enzymes (i.e. urease)	Biological control of cassava root rot aims to sustainable and integrative agriculture	Amendment of soursop waste biochar + *T. aureoviride* was the most beneficial	Not specified	da Silva et al. (2022)
Timber waste	Tomato cv. BARI 14	Inoculation of *Trichod. harzianum*	Increased nutrients absorption, root architecture	Increased root biomass, fruit quality	Environment-save maximized production	Promote integrated biochar-Trichoderma application	Silty clay loam, shallow red brown Terrace soil	Sani et al. (2020)
Caribbean pine sawdust	Onion (*Allium cepa*)	*Serratia* sp., *Pseudomonas* sp.	Mobilization of nutrients, mainly P in rhizosphere	Increased plant dry shoot, bulb weight (1.2-fold)	P limitation in various stages of onion growth	Apply biochar with microbial consortia	Not specified	Blanco-Vargas et al. (2022)
Oil mallee extraction residues	Wheat, clover	PGPR, AMF inoculum + NPK fertiliz	Mycorrhizal colonization in plant roots	Wheat yield increased by 18% (compared to control)	Mycorrhiza did not improve P uptake	Integrate biochar with AMF inoculum	Acidic sand over gravel Tenosol	Solaiman et al. (2010)
Eucalyptus wood	Not found	Crushing into smaller particles	Not found	Hyphal colonization of biochar	Habitable space (pores, surfaces) of biochar	Optimize particle size for colonization	Agriculture loamy sand soil (Australia)	Jaafar et al. (2014)
Mixed woods, *Miscanthus* chips	Not found	Inoculation with *Agaricus bisporus*	Better microbial colonization on wood biochar	Colonization by gram-positive bacteria	Better habitat quality in *Miscanthus* biochar	Colonization unpredictable from physical description	Ferralsols, Oxisols, Ultisols	Schnee et al. (2016)
P-rich wastewater, banana peduncles	Not found	Cultivation colonization of biochar	Not found	P solubilization by *Ps. aeruginosa*	P laden biochar + microbes for soil + plant	Promote *Pseudomonas* for biochar enrichment	Not specified	Ray et al. (2024)
Acacia stem, wheat straw, manure	Maize (*Zea mays*)	Inoculation with *Bacillus* sp. ZM20	Improved maize growth, plant uptake of N, P, K	Increased maize fresh, dry biomass (by 26%)	Not found	Use combined biochar-bacteria treatment	Slightly alkalic sandy loam (poor organic matter)	Ahmad et al. (2020)

Table 2 (continued)

Biochar feedstock type	Host crop	Engineering strategy	Rhizosphere mechanism, properties	Finding/production outcome	Challenge/limitation	Recommendation	Soil type	Reference
Pruning residues' woodchips	Not found	Soaking liquid vermicompost extract	Increased C-related soil bio-fertility, enzymes	Positive in low-, medium-fertile soils	Respiration tests needed	Promote biochar activation with vermicompost	Sandy soils: very low (1.0%) and moderate (2.2%) soil organic matter	Carril et al. (2024)
Hardwood lumber scraps	Eggplant	Compost tea mixed with biochar	Biochar + compost tea changed soil microbial activity, community composition	Enhanced eggplant growth with biochar + vermicompost tea microbiome	Isolating strains: compost tea, rhizosphere	Match vermicompost tea to soil	Neutral Hazleton loamy-skeletal, siliceous, mesic, Typic Dystrudrepts; slightly acidic (pH 6.2) Rainsboro silt loam	Edenborn et al. (2017)
Ripped vines' wood	Melon, pepper	Mixing with bacterial suspension	More rhizospheric *Bacillus*, changed microbiome	A 47% yield increase for melon and 28% for pepper at high inoculum dose	Phytohormone influence unclear	Reduce NPK and compost doses	Clayey sand alkalic soil	Ortiz-Liébana et al. (2022)
Grain husk and paper fiber sludge	Maize cultivar Mv 277	Cultivation colonization of biochar	Higher PGPR and nitrogen content in rhizosphere	Increased in above-ground plant biomass (3.2-folds)	Lack of field validation	Open-field and long-term study needed	Acidic sandy lamellic arenosol	Kari et al. (2021)

NUE: Nitrogen use efficiency, *M*: molar, SA: surface area, EPA: environmental protection agency, AMF: arbuscular mycorrhizal fungi, MBC: microbial biomass carbon, PGPR: plant growth promoting rhizobacteria the biochar–microbe pairing should be selected based on the dominant crop constraint (Table 2). Bioprimed biochar contributes to sustainable agriculture (Kari et al. 2021) and environmental pollution remediation (Bolan et al. 2023b). Using renewable feedstock (Kari et al. 2021; Sun et al. 2016) and leveraging the benefits provided by symbiotic microbes underscore its importance in sustainable agricultural practices (Iacomino et al. 2023). Limitations of bioprimed biochar include challenges in microbial inoculation efficacy, which depends on efficient colonization and adherence to the biochar surface (Bolan et al. 2023b; Jaafar et al. 2014), durability of the inoculum (microbial viability during storage) (Azeem et al. 2021; Husna et al. 2019), and soil performance (microbial proliferation and activity) (Wang et al. 2021a). In contrast to direct soil inoculation, biochar provides a protective microsite that can enhance microbial survival; yet the biochar-microbe-soil interaction is highly context-dependent. While the porous structure of biochar and microbial extracellular polymers facilitate colonization (Carril et al. 2024), microbial consortia may undergo compositional shifts over time (Carril et al. 2024), raising concerns about long-term efficacy. Encouragingly, strong microbial adherence to the biochar surface (Tao et al. 2018) does not hinder root colonization (Douds Jr et al. 2014; Hale et al. 2014), and biochar-introduced strains do not outcompete native soil microbes (Solaiman et al. 2010). Biochar feedstock and pyrolysis temperature significantly influence microbial compatibility. Hardwood-derived biochars (e.g., from acacia or coconut shell) have been shown to support higher microbial viability during storage compared to softer or more fibrous materials (Husna et al. 2019; Kuppusamy et al. 2011). Biochars produced at 600 °C outperform those made at 350 °C in terms of microbial stability and colonization efficiency (Azeem et al. 2021). Additionally, adding nutrients (e.g., glucose, phosphate) to the microbial inoculation suspension can enhance microbial activity and storage viability (Sun et al. 2016), particularly for commercial-scale applications. Future studies should focus on long-term field validation, optimization of microbe-biochar pairings for specific crops or stresses, and cost-effective scale-up strategies to ensure widespread adoption of this promising technology.

3.1.3 Porous and high surface area biochar

Porous and high surface area biochars are engineered using physical methods such as steam (Borchard et al. 2012; Sajjadi et al. 2019) and microwave irradiation (Sajjadi et al. 2019), as well as chemical methods involving gaseous phase such as O_3 (Huff et al. 2018) and H_2 in air (Díaz et al. 2024; Sajjadi et al. 2019) and liquid phases such as acids (Ameur et al. 2018), alkalis (Ghassemi-Golezani and Farhangi-Abriz 2023), oxidative agents (Paymaneh et al. 2018), arylation at acidic pH (Snoussi et al. 2022), and surfactants (Hua et al. 2018). These post-pyrolytic treatments alter the surface structure of pristine biochar by disrupting or enlarging cavities and pores. Biochars from feedstocks, such as wood (Ameur et al. 2018; Neuberger et al. 2024), and oilseed rape straw residues (Chen et al. 2023a, b) are commonly modified using chemicals like KOH, H_2SO_4, HNO_3 (Vikrant et al. 2018) or HCl (Ameur et al. 2018; Vikrant et al. 2018). KOH modifies the biochar through releasing volatiles and forming micropores through redox reaction and gasification (Huang et al. 2017). H_2SO_4 and HNO_3 remove the impurities and introduce sulfonic and nitro groups, respectively, while HCl increases the surface area through removing inorganic ash and impurities, thus increasing porosity (Lin et al. 2024; Yan et al. 2024). The resulting biochar exhibits enhanced porosity and specific surface area (SSA), enabling higher adsorption capacity for nutrients (Borchard et al. 2012; Paymaneh et al. 2018) and potentially toxic elements (Yang et al. 2021a, b). In comparison to unmodified or low-temperature biochars, chemically activated variants offer superior adsorption performance but often require more energy- and input-intensive procedures (Table 2). These properties contribute to soil quality restoration (Murtaza et al. 2024), increased plant growth and yields (Antor et al. 2023), enhanced nitrification and NH_4^+ sorption (Tsang and Ok 2022). Porous biochars also improve nutrient retention, particularly gaseous nitrogen capture in composted materials (Kim et al. 2022) making co-composted biochar a promising tool for sustainable agriculture (Antonangelo et al. 2021). Moreover, their enhanced carbon reactivity facilitates greater CO_2 sorption and long-term soil carbon storage, positioning them as effective tools for climate change mitigation (Ringsby et al. 2024).

Despite their advantages, limitations of porous biochars include reduced levels of exchangeable cations due to activation with strong alkalis such as KOH (Masoumi and Dalai 2020), loss of surface functional groups and formation of less polar biochars due to gas or steam activation, which can limit nutrient interactions (Borchard et al. 2012). Acid activation (e.g., with H_2SO_4 or HNO_3) may cause carbon degradation and release of greenhouse gases (Uchimiya et al. 2012), while microwave-based activations suffer from scalability issues due to inconsistent heating and reproducibility (Zhao et al. 2010). In contrast, steam activation is gaining popularity for its simplicity, low cost, and environmental friendliness (Sajjadi et al. 2019), offering a viable alternative to CO_2 or acid-based methods for large-scale applications. Additionally, innovative approaches such as photochemical and acoustic activation with CO_2 offer promising, adjustable techniques that may bridge laboratory and field-scale applications (Chen et al. 2014). Future research should focus on optimizing activation protocols for different feedstocks and target functions, reducing environmental risks of chemical activation, and validating the performance of porous biochars in field-scale rhizosphere engineering.

3.2 Engineered biochar for crop protection

3.2.1 Antimicrobial functionalized biochar

Antimicrobial functionalized biochar has been reformed to possess antimicrobial properties, making it an effective tool for crop protection (Khan et al. 2024). The BC is typically prepared from any organic material through pyrolysis of biomass at very high temperature ranges (300 to 700 °C), followed by post-treatment with several biotic and abiotic antimicrobial agents (Jin et al. 2024). Methods for functionalization of BC comprise impregnation, adsorption or coating of antimicrobial agents onto the surface of BC (Gęca et al. 2023), with efficacy often depending on the biochar's porosity, surface chemistry, and compatibility with the antimicrobial compound. A range of biotic agents includes essential oils, chitosan, biocontrol microbes and their extracts, while abiotic agents encompass metals like silver (Ag), silicon (Si) and zinc (Zn) as well as metal oxides such as iron oxide (FeO) and zinc oxide (ZnO) (Table 3). While metal-based agents often act rapidly through cell wall disruption or ROS generation, biotic agents may provide longer-term protection by enhancing host immunity or reshaping microbial communities. Antimicrobial biochars act via multiple mechanisms: disrupting microbial membranes, interfering with ion transport, and generating oxidative stress to inhibit pathogen proliferation. In addition to pathogen suppression, these biochars can enhance soil microbial balance and reduce dependency on chemical pesticides, contributing to integrated pest management and improved soil health (Alfei et al. 2024).

Comparative studies provide insights into agent-specific effects and rhizosphere interactions. For instance, silver-functionalized biochar reduced Fusarium wilt incidence in tomato by up to 60% (Kim et al. 2023), while silicon-enriched biochar suppressed a broader range of pests and pathogens across solanaceous and gramineous crops, including aphids, cicadas, soil fungi, and nematodes (Ratnadass et al. 2023). However, Abdellatef et al. (2022) reported enhanced resistance to *Rhizoctonia solani* in rice when using biochar coated with the essential biopolymer chitosan. Moreover, Ahmed et al. (2021) reported enhanced resistance (89.04%) to *Rhizoctonia solani* in rice when using chitosan-Mg composite biochar. A study depicted the potential of three aromatic plants essential oil-based BC in stored peanut seeds and found that antifungal compound was produced after its application (Barbara et al. 2023). Studies emphasize the synergistic benefits of combining biochar with biocontrol microbes. For example, ZnO-functionalized biochar reduced downy mildew in grapevines (Ramezani et al. 2019), while FeO-enriched biochar suppressed root-knot nematode infection in tomato by enhancing plant metabolic responses (Mahmoud et al. 2024) (Table 3). A more integrative approach, combining 3% w/w rice husk derived BC combined with two microbial extracts (*Bacillus subtilis* and *Trichoderma harzianum*) profoundly reduced RKN infection by 60% by reducing number of galls, juveniles and eggs produced in root zone of tomato (Arshad et al. 2021). Likewise, 3% v/v green waste BC consortium with a biocontrol arbuscular mycorrhizal fungi (AMF) extract enhanced its colonization in the rhizosphere of soybean and thereby lowering the nutrients supply leads to mitigate the *Sclerotina sclerotiorum* development in the soil (Safaei Asadabadi et al. 2021). As highlighted in Table 3, despite their promise, antimicrobial biochars face several challenges. These include variability in field efficacy, potential toxicity to non-target soil microbes, and stability of antimicrobial agents during storage or soil interaction (Mahmoud et al. 2024). Moreover, while metal-enriched biochars may show higher pathogen suppression rates, their long-term effects on beneficial microbial communities remain underexplored (Barbara et al. 2023). Future research should emphasize the development of biochar-microbe consortia tailored for specific crops and soil conditions and investigate the compatibility of antimicrobial biochars with broader soil microbiomes and integrated pest management frameworks.

3.2.2 Induced systemic resistance (ISR)/defense elicitor biochar

Induced systemic resistance (ISR) BC, also known as defense elicitor BC, is prepared by pyrolyzing organic materials, which modifies the BC to have beneficial properties to boost plant defense mechanism (Arshad et al. 2024). During the process, antimicrobial agents both biotic and abiotic can be incorporated into the BC matrix to enhance its defensive capabilities. Biotic agents like *Bacillus* spp., *Pseudomonas* spp., and *Trichoderma* spp (Hou et al. 2022) and abiotic agents such as zinc oxide nanoparticles (ZnO-NPs) and silver nanoparticles (Ag-NPs) and 5-methoxyindole nano-biochar are commonly used to enhance the antimicrobial properties of BC (Table 3). Unlike direct antimicrobial biochars, ISR biochars do not attack pathogens directly, but rather stimulate the plant's intrinsic resistance pathways, making them a promising eco-friendly

Table 3 Summary of studies using engineered biochar for crop protection with a special focus on engineered biochar-based rhizosphere engineering

Type of biochar	Engineered agent	Biochar	Host crop	Targeted Pathogen/ Disease/Pest	Rhizosphere mechanism	Finding & Protection outcome	Challenge/ limitation	Recommendation	Reference
Antimicrobial	Essential oils	Not found	Peanut seeds	*Aspergillus* spp.	Antibiosis	Produced antifungal compounds in seed	Not found	Combine with microbes for enhanced persistence	Barbara et al. (2023)
	Chitosan	Not found	Rice	*Rhizoctonia solani*	Interfere electrical conductivity of microbial cells	Reduced fungal attack and improve resistance	Not found	Use for fungal inhibition in rice	Abdellatef et al. (2022)
	Microbial extracts	Rice husk, Green waste	Tomato, soybean	Root knot nematode, *Sclerotina sclerotiorum*	Reduced J2, Upsurge AMF colonization	Reduced RKN infection, Reduced white mold infection and colonization	Exact mechanism is unknown	Not found	Arshad et al. (2021), Safaei Asadabadi et al. (2021)
	Silver (Ag)	Not found	Tomato	*Fusarium oxysporum*	Change soil pH	Suppressed *Fusarium* wilt up to 60%	Not found	Apply in pH-sensitive disease soils	Kim et al. (2023)
	Silicon (Si)	Not found	Solanaceous crops	Bacterial wilt and Sucking insects	Enhanced beneficial microbial community	Downregulate the pathogens population	Multifactor are involved in pathogen suppression	Use for microbial-mediated pathogen control	Ratnadass et al. (2023)
	Zinc oxide (ZnO)	Wood	Grapes	Downy mildew	Not found	Suppress fungal infection	Mechanism is unknown	Investigate mode of antifungal action	Ramezani et al. (2019)
	Iron oxide (FeO)	Green magnetic	Tomato	Root knot nematode	Plant metabolites excretion	Decrease RKN infection up to 22%/ reduced chemical use	Not found	Check efficacy for nematode suppression in multi crops	Mahmoud et al. (2024)
	Trichoderma sp.	Green waste	Cucumber	*Fusarium* spp.	Enhancing organic matter, pH and ammonia concentration in the soil	Reduced the incidence of *Fusarium* wilt infection by 37.5%	Not found	Use in *Fusarium*-prone cucumber soils	Ali et al. (2023)
	Pseudomonas fluorescens	Poultry litter	Lettuce	Root knot nematode	Enhanced soil microbial diversity particularly beneficial bacteria	Lower nematode populations	No well-defined mechanism	Not found	Fosu-Nyarko et al. (2022)
	Streptomyces-enriched	Not found	Potato	*Phytophthora infestans*	Increased microbial activity and antibiotic production against pathogen	Disease incidence decreasing by 46.1%/ reduced need for pesticides	Mechanism is unknown	Promote for biocontrol in other crops	Jin et al. (2023a, b)
	Bacillus subtilis	Not found	Tomato	*Pseudomonas syringae*	Proliferation of PGPR in rhizosphere	Reduce the disease severity by 50%	Mechanism is unknown	Investigate mechanism of action at molecular level	Kumar et al. (2021)

Table 3 (continued)

Type of biochar	Engineered agent	Biochar	Host crop	Targeted Pathogen/Disease/Pest	Rhizosphere mechanism	Finding & Protection outcome	Challenge/limitation	Recommendation	Reference
	Vermicompost	Not found	Rice	*Meloidogyne graminicola*	Particularly increasing the release of organic acids	Deterred (*Meloidogyne graminicola*) population	BC kind missing	Identify suitable biochar type	Mondal et al. (2021)
	Zeolite	Spelt husk	Carrot	*Pratylenchus penetrans*	Enhanced microbial populations and altered pH	Suppressed root lesion nematode (*Pratylenchus penetrans*) infestations by 95%	Mechanism is unknown	Clarify underlying mechanisms	George et al. (2016)
	AMF + *Trichoderma asperellum*	Palm bunch	Tomato	Root knot nematode	Obstructed nematode movement	Reduced nematode infestation by 79.5%	Nematode Specie not defined	Define nematode species involved	Claudius-Cole et al. (2017)
	Caster oil cake	Mesquite	Tomato	*Meloidogyne incognita*	Boost the physiochemical properties of the soil	Reduced *Meloidogyne incognita* infestations	Assumed that Engineered BC decline J2 speed	Need to test on broad range pathogens	Ikram et al. (2024)
	Pseudomonas putida L2	Maize	Narrow-Leafed Lupin	Root rot (*Fusarium solani)*	BC elevate adsorption of fusaric acid	Reduction in root rot disease incidence	Not found	Develop cost effective products	Egamberdieva et al. (2020)
	Calcium carbonate + DAP	Sugarcane bagasse	Soybean	*Fusarium oxysporum*	Modulate soil pH	Reduced root rot infestations by 90%	Could be expensive treatment	Not found	Wachira (2020)
	Vermicompost	Not found	American ginseng	*Fusarium* root rot	Regulate microbial community (*Pseudomonas*, *Lysobacter*, and *Chryseolinea*)	Reduced the incidence of *Fusarium* root rot by 80.96%	Biochar type missing	Identify specific biochar type for specific target	Tian et al. (2021)
	Glyphosate-iso propylammonium	Not found	*Faba bean*	Broomrape weed	Diminished allelopathic effects of weed	Reducing weed biomass by up to 44.7%	Slow process	Host specificity should be enhanced	Saudy et al. (2021)
	Greenhouse compost	Pepper plant	Tomato	Egyptian broomrape	Not found	Decrease in germination percentage of Egyptian broomrape	Rhizosphere mechanism is unknown	Investigate rhizosphere mechanism	Eizenberg et al. (2017)
Defense elicitor	*Bacillus subtilis*	Rice husk	Tomato	Root knot nematode	Act as a barrier in J2 locomotion	Upregulated defensive genes PR1 and JERF3	Mechanism of strengthen biocontrol agents is unknown	Increasing self-life is needed	Arshad et al. (2021)
	Trichoderma aureoviride	Soursop waste	Cassava	Cassava root rot	Not found	Increased β-glucosidase and urease activities (109% and 200%)	Not found	Phytotoxicity should be checked	Da Silva et al. (2022)

Table 3 (continued)

Type of biochar	Engineered agent	Biochar	Host crop	Targeted Pathogen/Disease/Pest	Rhizosphere mechanism	Finding & Protection outcome	Challenge/limitation	Recommendation	Reference
	Pseudomonas chlororaphis	Plant-based (PYREG®)	Tomato	Damping off	In the rhizosphere *P. chlororaphis* had increased 4 to 100-folds	Reduced the Pythium infestation up to 95%	Short shelf-life of non-spore forming bacteria	Improve bacterial shelf-life	Postma and Nijhuis (2019)
	Klebsiella oxytoca	Green waste	Tobacco	Potato virus Y	Enhanced PGPR population in the soil	Triggered defensive genes PR1-b and Coi1	Suppress virus by indirect mean	Target direct virus suppression	Elsharkawy et al. (2022)
	5-methoxyindole	Corn stalk	*Nicotiana benthamiana*	*Phytophthora nicotianae*	Not found	Increased ROS by 20% and upregulate defensive gene PR-1a	Not found	Identify full protective mechanism	Kong et al. (2022)
	Iron bearing kaolinitic clay	Jarrah wood	Grapevine	Not found	Enhanced PGPR population in pakchoi (Brassica rapa L. ssp. chinensis) rhizosphere	Improved plant resistance	Targeted pathogen study is missing	Target specific pathogen study	Ye et al. (2016)
	Bacillus subtilis SL-44	Rice husk	Redish	*Fusarium oxysporum*	The BC-amended soil showed increased microbial activity	Suppression of disease and the induction of ISR in reddish	Targeted resistance genes study	Investigate resistance gene pathways	Chen et al. (2023a, b)
	Trichoderma harzianum	Leaf waste	Eggplant	Bacterial wilt	Enhanced activity of *Trichoderma* in soil	Triggered ISR by enhancing phenolics, flavonoids and peroxidase	Not found	Not found	Ahmad et al. (2024)
	KOH	Not found	Soybean	Root rot	Improve soil physicochemical properties and isoflavones signaling	Reduction in root rot disease incidence by 22.17%	Biochar type missing	Identify appropriate biochar type	Wang et al. (2024a, b)
	AMF	Not found	Maize	*Spodoptera frugiperda*	Altered rhizosphere pH	54.2% reduction in pest infestation and increased phenolic compounds in plant	Biochar type missing	Determine optimal biochar type	Wang et al. (2023a, b, c)
	Biocontrol-doped	Organic waste	Cotton	*Fusarium oxysporum* f. sp. *vasinfectum*	Abundance of beneficial microbes in the rhizosphere	Enhanced production of phenolics and flavonoids compounds	Mechanism is unknown	Clarify mechanism of action against broad range	Asif et al. (2023)

Table 3 (continued)

Type of biochar	Engineered agent	Biochar	Host crop	Targeted Pathogen/Disease/Pest	Rhizosphere mechanism	Finding & Protection outcome	Challenge/limitation	Recommendation	Reference
	Compost	Green waste	Tomato	*Fusarium oxysporum* f.sp. *lycopersici*	Improve root exudates and AMF bio-protective	Enhanced the production of flavonoids in the roots	Compost detail is missing	Not found	Akhter et al. (2015)
Nanocomposite	Fly ash nanoparticle	Rice husk	Pepper	Bacterial leaf spot	Not found	Reduced bacterial leaf spot of pepper by 30%	Not found	Not found	Aftab et al. (2022)
	Carbon quantum dots	Glucose	Pines	Pine wood nematode	Delayed nematodes egg laying mechanism	Reduced nematode population by direct toxicity	Can not apply on large scale	Develop large-scale application	Han et al. (2021)
	Silica nanoparticles	Not found	Tomato and watermelon	*Fusarium oxysporum*	Suppress fungus in soil	Induce resistance by activating salicylic acid pathway	Not found	Examine full resistance mechanism	Pavlicevic et al. (2023)
	Cordyceps fumosorosea	Not found	Eggplant	*Bemisia tabaci*	Not found	Toxicity against 2nd and 3rd instar larvae of *Bemisia tabaci*	Toxicity limited to 2nd and 3rd instar larvae	Expand toxicity range study	Wang et al. (2021a, b, c)
	Green-Nano	Not found	Tomato	Root knot nematode	Higher functional groups (O–H, C=C, S–H, H-C=O, C-O, and H–O–H)	Reduced root knot nematode infection by 88.65%	Can not apply on large scale	Optimize for large-scale use	Khader et al. (2023)

AMF: arbuscular mycorrhizal fungi

alternative to conventional pesticides (Poveda et al. 2021a, b). ISR-BC enhances crop protection by activating the plant's natural defense mechanisms by increasing the beneficial microbe population in the soil leading to increased resistance against various pathogens and pests (Iacomino et al. 2022).

Comparative studies across ISR biochar types demonstrate variability in efficacy, depending on the elicitor type, host crop, and target pathogen. For instance, Kong et al. (2022) investigated the nexus of 5-methoxyindole and corn stalk BC against *Phytophthora nicotianae* and reduction in lesion diameter of up to 9.26% , along with upregulation of defensive elicitors by increasing reactive oxygen species (ROS) 20% leads to activated ethylene pathway and upregulate PR-1a gene in *Nicotiana benthamiana*. Moreover, rice husk BC amended with beneficial microbes such as *Trichoderma harzianum* and *Bacillus subtilis* have been significantly shown to reduce nematode infestations in tomato plants and upregulated defensive genes PR1 and JERF3, as reported by Arshad et al. (2021) (Table 3). Similarly, soursop waste BC and *Trichoderma aureoviride* URM 5158 reportedly reduced the disease severity of cassava root rot by 75% and increased defensive enzyme β-glucosidase and urease activities by 109% and 200% respectively (da Silva et al. 2022). Another finding depicted that *Pseudomonas chlororaphis* 4.4.1 augmented plant-based BC (PYREG®) had profoundly reduced the *Pythium* infestation up to 95% in tomato plants and remarkably enhanced the population of *P. chlororaphis* in rhizosphere, resulting in improving plant vigor and defensive immunity (Postma and Nijhuis 2019). Furthermore, a combining treatment of *Klebsiella oxytoca* (PGPR) and green waste BC at 1.5% exhibited negative ELISA of potato virus Y and triggered defensive genes PR1-b and Coi1, resulting in defensive biochemical like catalase, superoxide dismutase and polyphenol oxidase in tobacco plant (Elsharkawy et al. 2022) (Table 3).

However, several challenges remain as indicated in Table 3. ISR biochars are highly context-dependent; their efficacy varies with plant species, timing, elicitor dose, and environmental conditions (Ahmad et al. 2024). Moreover, the long-term stability of defense induction and the risk of overstimulation of plant immunity potentially affecting growth, require further investigation. Additionally, a clear distinction between microbial ISR via root colonization and ISR triggered by metabolite-soaked biochars is often lacking in experimental designs, limiting mechanistic interpretations (Chen et al. 2023a, b). To address these gaps, future research should prioritize field-scale validation of ISR biochars, unravel their specificity in activating plant hormone pathways, and explore combinations with plant–microbe-biocarbon interfaces for tailored pest and disease suppression strategies.

3.2.3 Nanocomposite biochar

Nanocomposite BC is an innovative material prepared by integrating nanomaterials into BC. This composite is typically produced through methods such as co-pyrolysis where biomass is combined with nanoparticles during the thermal decomposition process or by post-pyrolysis modification where nanoparticles are added to BC after its production (Harussani and Sapuan 2024). These nanomaterials, which include metal oxides (e.g., Fe_3O_4, ZnO), carbon-based nanostructures (e.g., graphene, carbon nanotubes), quantum dots, and biopolymers, enhance the surface reactivity, porosity, and catalytic functions of biochar, making it highly effective in agricultural applications (Chakraborty et al. 2023). The use of nanocomposite BC is crucial for crop protection and sustainable agriculture as it not only enhances soil fertility and water retention but also reduces reliance on chemical inputs, thus promoting environmental sustainability and food security. Compared to conventional biochar, nanocomposite BCs allow for the controlled release of active agents, increased microbial modulation, and enhanced redox interactions (Ramadan and Abd-Elsalam 2020; Singh et al. 2023).

For instance, a study by Aftab et al. (2022) demonstrated that fly ash nanoparticle-enriched rice husk BC significantly reduced bacterial leaf spot of pepper by 30% caused by *Xanthomonas campestris pv. vesicatoria*. Similarly, Han et al. (2021) showed that glucose carbon quantum dots reduced pine wood nematode (*Bursaphelenchus xylophilus*) population, delayed the egg laying process, and caused direct toxicity to nematodes by a fatty acid degradation mechanism. Likewise, silica nanoparticle-coated BC has all been used effectively to suppress and delay the damage from *Fusarium oxysporum* infection in tomato and watermelon and to activate the salicylic acid defensive pathway (Pavlicevic et al. 2023). Additionally, *Cordyceps fumosorosea*-derived BC nanoparticles possessed toxicity against 2nd and 3rd instar larvae of *Bemisia tabaci* and inhibited the egg hatching process (Wang et al. 2021a, b, c). These studies highlight the versatility of nanomaterials: silica and carbon-based particles enhance plant immunity; metal oxide nanoparticles introduce antimicrobial or nematicidal activity; and biopolymer-based systems improve biocompatibility. However, efficacy varies based on nanoparticle type, biochar feedstock, and application rate, requiring site-specific optimization. (Table 3).

Despite their promise, nanocomposite biochars raise critical concerns. The environmental fate, bioavailability, and potential ecotoxicity of engineered nanomaterials remain largely unknown, particularly under long-term field conditions (Khader et al. 2023). Additionally, the interaction between nanoparticle-functionalized biochar and soil microbial communities requires deeper investigation (Wang et al. 2021a, b, c), as both beneficial and pathogenic microbes can be affected. Assessing the safety and persistence of nanoparticle residues in agroecosystems should thus be a critical focus of future studies in addition to exploring synergistic formulations (e.g., nanocomposite BC with ISR-inducing microbes) for integrated plant protection.

3.3 Engineered biochar for remediation of contaminated sites

3.3.1 Adsorptive biochar

Adsorptive biochar is engineered to trap and immobilize contaminants through its high surface area, porosity, and surface functionality. It is produced through pyrolysis, where biomass (e.g., agricultural residues, wood) is thermally decomposed in oxygen-limited conditions, creating a carbon-rich material with high adsorptive properties (Chemerys et al. 2020). The efficiency of adsorptive biochar is heavily influenced by the pyrolysis parameters (e.g., temperature, residence time), which control the development of micropores and surface chemistry (Wang et al. 2017). To further enhance performance, biochars undergo activation processes, such as chemical activation with potassium hydroxide (KOH) or physical activation using steam, which further increase micropores and surface area, improving the biochar's ability to adsorb heavy metals and organic pollutants like pesticides (Gabhane et al. 2020). The incorporation of specific functional groups, such as thiols (–SH) and carboxyls (–COOH), is introduced to target specific contaminants, such as mercury (Hg) and lead (Pb), through electrostatic attraction and covalent bonding (Dai et al. 2021).

Hybrid strategies that incorporate materials like iron oxides, bentonite, or activated carbon further enhance contaminant removal. For example, Fe-enriched biochar shows higher affinity for arsenic (As), while bentonite-modified biochars effectively adsorb hydrophobic pesticides (Zhang et al. 2019). Biochar amended with activated carbon also captures volatile organic compounds (VOCs) effectively (Mukhopadhyay et al. 2021). Adsorptive biochar immobilizes pollutants in soil, reducing their bioavailability and plant uptake. For example, KOH-activated biochar reduces lead bioavailability by over 70%, protecting crops from toxicity (El-Naggar et al. 2021). It also minimizes pesticide leaching, as seen with rice husk biochar, safeguarding groundwater and supporting healthier crop growth (Choi et al. 2023). Beyond pollutant immobilization, adsorptive biochar improves soil health by retaining nutrients like N and P, reducing leaching, and promoting crop growth (Dietrich et al. 2020). It also aids carbon sequestration, supporting climate change mitigation (Smith 2016). Advantages include high adsorption capacity for diverse contaminants and improved soil quality through nutrient retention (Sadhu et al. 2022). However, several limitations constrain the broader application of adsorptive biochars. Chemically activated biochars often incur high production costs and may require additional post-treatment to ensure environmental safety (Kamali et al. 2022). Moreover, the performance of adsorptive biochar is highly variable depending on the feedstock type, pyrolysis conditions, and local soil chemistry (Table 4). There is also limited consistency in field-scale outcomes due to soil heterogeneity and fluctuating contaminant loads. Developing low-cost, feedstock-optimized activation strategies, evaluating the long-term stability of sorbed pollutants under varying environmental conditions, and coupling adsorptive biochar with microbial or phytoremediation techniques for enhanced multifunctionality should thus be the key research areas in the future.

3.3.2 Catalytic and redox reactive biochar/metal-impregnated biochar

Metal-impregnated biochar is synthesized by incorporating specific metals such as iron (Fe), zinc (Zn), manganese (Mn), or copper (Cu) into the biochar matrix either during the pyrolysis process or through post-treatment methods. Typically, metal salts like ferric chloride ($FeCl_3$) or zinc nitrate are used to impregnate the biomass feedstock prior to pyrolysis, embedding the metal ions into the carbon structure and enhancing the surface reactivity and binding sites of the resulting biochar (Yang et al. 2021b). Alternatively, post-pyrolysis treatments with metal nanoparticles, such as nano-zero valent iron (nZVI), can increase the affinity of biochar for inorganic contaminants, particularly heavy metals and metalloids like arsenic and lead (Pinisakul et al. 2023). The addition of iron and manganese oxides is known to enhance redox properties, enabling the transformation of toxic contaminants such as hexavalent chromium (Cr(VI)) to less harmful trivalent chromium (Cr(III)), thereby reducing their bioavailability and environmental impact (Yang et al. 2021b).

The incorporation of copper and zinc oxides into biochar improves its ability to absorb both organic pollutants, such as pesticides and pharmaceuticals, and heavy metals like cadmium (Cd), by forming stable metal–organic complexes and enhancing surface polarity (Sutton et al. 2019). These modifications increase the diversity of applications for metal-impregnated biochars, particularly in treating industrial wastewater and remediating polluted soils (Table 4). The presence of metal

Table 4 Summary of studies using engineered biochars for remediation of contaminated sites with a special focus on engineered biochar-based rhizosphere engineering

Biochar type	Contaminant type	Engineering strategy	Rhizosphere mechanism	Findings & remediation outcome	Challenge/limitation	Recommendation	Reference
K_2HPO_4-modified biochar	Cd, Pb, Zn and Cu	Impregnation with K_2HPO_4	Immobilization, precipitation, electrostatic attraction, complexation	Removal up to 94.43% (Cd > Zn > Pb > Cu)	The immobilization mechanism are still unclear	Study bacteria-contaminant co-occurrence deeply	Sha et al. (2023)
MgO flake-modified biochar	Cd, Cu, Zn, Cr	Treatment of biochar with $MgCl_2$	Complexation, ion exchange, precipitation, immobilization via precipitation, complexation and pore filling	Up to 70% remediation efficiency	In-depth removal mechanism for each metal is unknown	Investigate remediation mechanism in detail	Li et al. (2022)
Fe-MnO-modified biochar	Cd	Treatment of biochar with $Fe(NO_3)_3$ and $KMnO_4$	Precipitation, cation exchange, and complexation, immobilization	Up to 77.8% Cd removal	Not reported	Key role of Fe and Mn in Cd immobilization	Tan et al. (2023)
β-cyclodextrin modified biochar	Cd, Pb	Mixing of biochar with β-cyclodextrin, EDTA and polyethylene glycol	Electrostatic attraction, complexation, pore filling	Up to 59 and 50% Cd and Pb removal, respectively	Need field scale studies	Test biochar modifications for efficacy	Qu et al. (2022)
Acid and alkali-modified biochars	Zn	Impregnation with HCL-HF and KOH	Increased soil pH and organic carbon contents	Up to 36.86% Zn removal	Not reported	Use alkaline modified biochar	Liu et al. (2021)
H_3PO_4-modified biochar	Cr(VI)	Biochar treatment with H_3PO_4	Cr(VI) reduction, co-precipitation, pore filling, and electrostatic attractions	Up to 78.38% Cr removal Exchangeable and carbonates bound Cr was reduced by 96.77 and 83.60%, respectively	Limited active sites and electrostatic repulsion between Cr(VI) anions exist in solution and on adsorbent surface, which reduce the removal efficacy	Overcome electrostatic repulsion for efficacy	Li et al. (2024)
Fe-modified biochar	Cd	Treatment with $FeCl_2$	Enhanced soil pH, introduction of ligands, precipitation, and increased SOM which binds Cd through adsorption	Up to 39.5% Cd removal	Long-term studies needed to explore the interactions between biochar, soil microbes, and Cd	Conduct long-term biochar-Cd studies	Moradi and Karimi (2021)
Phosphate-modified biochars	Cd	Biochar treatment with KH_2PO_4, $K_2HPO_4{\cdot}3H_2O$, and $K_3PO_4{\cdot}3H_2O$ treatment	Higher CEC between Cd(II) and K^+ enhanced Cd adsorption and precipitation	Up to 99.98% Cd removal was achieved	Field-scale validation lacking	Optimize phosphate modification for Cd	Wang et al. (2022)
Ochrobactrum EEELCW01-loaded Fe-modified biochar	Pb, Cd, Zn, As	Biochar treatment with $FeCl_3$ solution	Adsorption, Fe-oxidizing bacteria-mediated biomineralization, and precipitation	Removal efficacies were; Pb = 96.99%, Cd = 74.03%, Zn = 66.87%, and As = 51.94	Long-term field efficacy unknown	Develop synergistic multi-metal stabilization method	Huang et al. (2025)

Table 4 (continued)

Biochar type	Contaminant type	Engineering strategy	Rhizosphere mechanism	Findings & remediation outcome	Challenge/limitation	Recommendation	Reference
PSB + $KMnO_4$-modified biochar	Cd	Biochar treatment with $KMnO_4$ solution	Adsorption, cation exchange with K, Na, Ca, Mg, Mn, complexation, and precipitation	Up to 90.84% Cd was removed	Competitive ion adsorption	Enhance P availability for Cd removal	Zhang et al. (2023)
Fe–MnO modified biochar	Cd	Biochar treatment with $Fe(NO)_3{\cdot}9H_2O$ and $MnSO_4{\cdot}H_2O$	Complexation and precipitation	Up to 37.73% Cd removal	Modification enhanced Cd adsorption potential	Should be tested in multiple metals contaminated environments during long-term studies	Yang et al. (2022)
Silicate-modified biochar	Cd	Biochar treatment with $Na_2SiO_3{\cdot}9H_2O$	Ion exchange, precipitation, and complexation	Improved porosity and functional groups	Not field-tested	Explore waste-derived Si biochar for field Cd remediation	Cai et al. (2021)
$KMnO_4$- modified biochar	As, Cd	Biochar treatment with $KMnO_4$	Type-A and B ternary complex, synergy mechanisms, electrostatic adsorption, π-π interactions, and sorption	Sorption of As and Cd up to 141.1 and 224.4 mg g^{-1}, respectively	As–Cd synergy not fully understood	Further study co-contaminant dynamics in field	Liang et al. (2023)
Fe–Mg modified biochar	Sb, As	Treatment of biochar with $KHCO_3$ solution	Ligand exchange, inner-sphere complexation, electrostatic attraction and, H-bonding	Up to 296.9 and 195.4 mg g^{-1} removal of Sb and As, respectively	Not reported	Field validation for Sb–As removal using Fe–Mg biochar	Jiao et al. (2022)
Alkali and magnetic composite modified biochar	PAHs	Treatment with HCl, NaBC, $FeCl_3 0.6\ H_2O$, and $FeCl_2 0.4\ H_2O$	Urease and dehydrogenase activity promoted PAH degrading bacteria (*Massilia*)	PAHs degradation efficacy up to 90% in 40 days	Long-term stability untested	Validate PAH degradation across soil types and time	Zheng et al. (2023)
Fe_3O_4-modified biochar	As	Biochar treatment with HNO_3	Fe-plaque formation	Up to 51.2% As removed	Not reported	Effective strategy for brown rice production	Yao et al. (2021)
Alkali-modified biochar	Atrazine, Pb	NaOH impregnation method	Photogenerated electron transfer pathway via π-π stacking structure, sorption	Atrazine degradation and Pb removal rates up to 94.70% and 47.75%, respectively	Field performance unknown	Test alkali-modified biochar in multi-contaminated field sites	Qie et al. (2023)
FeO-modified biochar	Pb, Cd	Treatment of biochar with $FeCl_3$	Humic acid production, adsorption	Pb and Cd were removed up to 151 and 82.3 mg g^{-1}, respectively	Work more effectively where SOM is present	Develop systematic Pb and Cd remediation	Wang et al. (2023a, b, c)
KOH/$KMnO_4$ modified biochar	Tetracycline	Mixing of biochars with respective solution	Pore filling, π-π interaction, H-bonding, metal complexation	Adsorption capacity up to 584.19 mg g^{-1}	Limited sites on biochar and/or formation of complexes	Suitable candidate for tetracyclines removal	Xu et al. (2022)
MnO_2-coated composites	Cd	Hydrothermal impregnation	Complexation, adsorption	Up to 115.04 mg g^{-1} adsorption	Not reported	Effective strategy for Cd in soil and water	Zhang et al. (2023)

Table 4 (continued)

Biochar type	Contaminant type	Engineering strategy	Rhizosphere mechanism	Findings & remediation outcome	Challenge/limitation	Recommendation	Reference
Rhamnolipid-modified biochar	Crude oil	Mixing with biochar suspension	Adsorption, pore-filling, electrostatic interaction, H-bonding	Up to 32.9% crude oil was remediated in 90 days	Field validation missing	Test rhamnolipid-BC in large-scale oil-contaminated soils	Zhen et al. (2021)
Activated biochar	Ciprofloxacin	Ball-milling	ROS species, non-radical species and electron transfer mechanism	Up to 96.06% or 126.15 mg kg^{-1} remediation efficacy	Sludge formation, low efficiency	Develop safer, cleaner BC treatments for organics	Al Masud et al. (2023)
Fe-rich Biochar	VOCs	Blending biochar with Fe	Adsorption and retention	Up to 76% emissions reduction	Not reported	Enhance Fe-biochar VOCs removal	Mousavi et al. (2023)

Cd: cadmium, Pb: lead, Cu: copper, Fe: iron, Cr: chromium, As: arsenic, PAHs: polycyclic aromatic hydrocarbons, Sb: antimony, SOM: soil organic matter, VOCs: volatile organic compounds oxides also facilitates catalytic reactions, contributing to the degradation of organic contaminants and the inactivation of soil-borne pathogens, suggesting a role in rhizosphere detoxification and disease control. Agronomically, metal-impregnated biochars help stabilize contaminated soils, reduce leaching of hazardous elements, and improve crop health. For example, iron-loaded biochar has been shown to decrease arsenic mobility by more than 90%, thus improving plant health and reducing risks to food safety (Bhatt et al. 2023). In addition to its contaminant immobilization potential, metal-impregnated biochar enhances nutrient availability by participating in chemical exchanges that liberate bound nutrients or buffer soil pH, facilitating greater nutrient solubility and accessibility to plant roots (Zhou et al. 2018). These properties make it an ideal amendment for rehabilitating degraded or polluted soils, enabling safe crop cultivation and reducing the risk of groundwater contamination. Studies by Liu et al. (2022) confirm the benefits of metal-impregnated biochar in restoring soil functionality and supporting sustainable land use in industrial and peri-urban landscapes. Key advantages of metal-impregnated biochar include its enhanced adsorption capacity for a range of environmental pollutants and its improved reusability, particularly in aqueous environments, due to increased material density from metal loading (Verma et al. 2024). This added weight facilitates sedimentation and separation in water treatment systems, making recovery and reuse more feasible. Nevertheless, the production of metal-impregnated biochar involves higher costs and technical complexity. Additionally, concerns remain regarding the potential leaching of the impregnated metals, which could cause secondary pollution under specific soil or water conditions (Liang et al. 2021). Therefore, careful assessment of environmental stability, leaching behavior, and ecological risks is critical before large-scale implementation. In addition, the long-term stability of metal-impregnated biochar in soils with differing pH, texture, redox potential, and microbial communities remains poorly understood (Table 4). Soil type can influence not only the persistence of functional groups and redox activity, but also the potential for unintended metal remobilization over time (Rinklebe et al. 2020). For example, acidic sandy soils may accelerate desorption and metal leaching, whereas high-clay or alkaline soils may enhance stability but reduce the mobility of beneficial elements (Singh et al. 2023). This highlights the need for tailored formulations and testing protocols across diverse agroecological contexts. Ongoing research is needed to refine synthesis protocols and ensure the environmental safety of metal-impregnated biochars in diverse field conditions, as well as to develop hybrid systems that combine redox-active biochars with microbial remediation. Nevertheless, the potential of field-based application of engineered biochars is mentioned in various studies as shown in Table 5. Conducting long-term, soil-type-specific field trials to assess persistence, sorption behavior, and leaching risks under realistic environmental fluctuations and performing their cost–benefit analyses to guide region-specific adoption are required.

3.3.3 Microbial functionalized biochar

Microbial-functionalized biochar (MFB), also known as biologically enhanced biochar (BEB), is biochar that has been modified to enhance microbial activity (Bolan et al. 2023a). MFBs play dual roles: improving plant–microbe interactions in the rhizosphere and enhancing biochar's pollutant-remediation capabilities. Evidence shows that it supports microbial colonization through moisture retention and functional groups (e.g., hydroxyl, carboxyl) that aid adhesion (Ajeng et al. 2020), enabling it to harbor microbes, release enzymes, and shield them from stressors (Dai et al. 2019). The production of microbial-enhanced biochar primarily involves pyrolysis, a cost-effective thermochemical process that decomposes biomass in an oxygen-limited environment, optimizing its porous structure and nutrient content for microbial activity (Cho et al. 2024; Saif et al. 2021). Techniques like slow and fast pyrolysis allow the tailoring of biochar properties, such as surface area and pore size, which are essential for supporting microbial communities (Osman et al. 2022). Recent advancements show that adjusting particle size and surface chemistry enhances bacterial loading and the adsorption of pesticides and microbes, improving biochar's role as a microbial carrier and environmental remediator (Xu et al. 2021).

Implications include replacing peat, remediating soils, and sequestering carbon (Liu et al. 2016). It also boosts methane oxidation in landfill covers, cutting emissions (Zhang et al. 2023). It is also expected that microbial biochar in coming years will be an effective tool to overcome water stress among crops (UN-Water 2020) Advantages of microbial-enhanced biochar include its effective microbial carrier properties, such as high porosity, which enhance crop yields and soil health (Murtaza et al. 2023). Disadvantages involved in microbial inoculation success can vary depending on biochar feedstock, pyrolysis temperature, and post-treatment conditions. There are inconsistent yields (negative to over two fold) depending on biochar type and soil conditions (Chen et al. 2022a, b), uncertain metal ion effects on microbial activity, and high production costs that hinder scalability (Breunig et al. 2019). Unlike activated carbon, biochar selectively adsorbs microbial precursors, with *E. coli* biofilms underscoring its habitat role, while microbial fuel cells achieve 95% COD removal and 73–88%

Table 5 Summary of field-based studies demonstrating the practical application of engineered biochar for crop production, crop protection, and environmental remediation

Purpose	Biochar type	Target	Performance/efficacy in field	Rhizosphere mechanism	Reference
Crop production	N-loaded biochar	Enhancement of NUE in rice	Up to 8.1%	Controlled release of N retained in porous matrix of engineered biochar and reduced ammonia volatilization	Xiang et al. (2020)
Crop production	Biochar produced through microwave-assisted catalytic pyrolysis	Enhance WHC and CEC	WHC = 98% CEC = 220%	Increased microporosity	Mohamed et al. (2016)
Crop production	HCl-modified biochar	Enhanced P availability in maize	P availability = 40% Biomass = 110.7%	Liberation of bound P due to acid modification	Qayyum et al. (2021)
Crop production	H_2SO_4-modified biochar	Abiotic stress mitigation, maize and wheat yield enhancement	ESP = 20.95% CEC = 11.49% SOC = 11.51% Maize yield = 34.15% Wheat = 25.11%	Enhanced soil health attributes and reduced abiotic stress	El-Sharkawy et al. (2022)
Soil remediation	$Ca(H_2PO_4)_2$-engineered swine manure biochar	Cd, Pb removal	Cd = 47.73% Pb = 24.58%	Formation of stable phosphate precipitates with metals	Ren et al. (2020)
Soil remediation	MgFe-LDH engineered biochar	Sulfamethoxazole remediation	91%	OH and O_2-mediated oxidation	Chen et al. (2022a, b)
Soil remediation	Goethite modified biochar	Cd, As removal	Cd = 135% As = 6,279% Roxarsone = 961%	Electrostatic interaction, physical adsorption, π-π interaction, surface complexation, ion exchange	Zhu et al. (2020)
Soil remediation	Biochar co-composted with FYM	Cd remediation in wheat	Up to 54%	Increased soil pH reduced Cd availability	Bashir et al. (2020)
Soil remediation	Red mud modified biochar	As removal	Decreased extractable As by 27%	Enhanced microbial reduction in Fe-oxides	Zou et al. (2018)
Soil remediation	MnO-biochar	As	Adsorption of 0.5 g kg^{-1} As	Adsorption	Yu et al. (2015)
Disease management	*Bacillus subtilis* + green waste biochar	Suppression of *Alternaria solani*	Disease suppression up to 80% in vivo conditions	Enhanced tomato plant physiological functions	Rasool et al. (2021)
Disease management	PGPB + biochar (SYBB)	Suppression of *Fusarium oxysporum*	Supress fungal prevalence in the rhizosphere	Increased the carbohydrates, fatty acids and plant hormones and soil beneficial microbe signalling	Wu et al. 2022a, b)
Disease management	*Streptomyces*-based biochar	Suppression of *Phytophthora infestans*	Decrease disease index by 10–26% in two years field trial	Improve plant and soil health	Jin et al. 2023a, b)

WHC: water holding capacity, CEC: cation exchange capacity, FYM: farmyard manure, Cd: cadmium, Pb: lead, As: arsenic, PGPB: Plant growth promoting bacteria nutrient reductions. The longevity of microbial activity post-application also remains uncertain in field settings, with microbial desiccation and competition from native soil biota posing additional hurdles (UN-Water 2020). Furthermore, MFBs' field performance in different soils (acidic, saline, or contaminated) is still underexplored, and scalability remains a challenge due to high production and formulation costs. There is a growing need to establish standardized protocols for microbial loading, biochar pre-conditioning, and evaluation of functional stability under diverse environmental conditions. Moreover, assessing interactions with native soil microbial communities to avoid ecological disruption should be the focus of future studies.

4 Biochar based rhizosphere engineering for crop production, crop protection and remediation

Engineered biochar is increasingly being used in rhizosphere engineering to enhance crop productivity, protect plants from environmental stressors, and remediate contaminated soils. Unlike conventional biochar, engineered biochar is tailored with specific properties to optimize its interactions with plant roots, soil microbiota, and environmental pollutants. These engineered traits allow for context-specific outcomes depending on the soil type, crop system, and stress environment. The integration of biochar in rhizosphere engineering leads to improved soil structure, enhanced microbial activity, and increased nutrient availability, ultimately supporting sustainable agriculture and environmental restoration (Pathak et al. 2024). For instance, in sandy soils, engineered biochar improves water retention and microbial colonization due to increased porosity and surface roughness (Li et al. 2021a, b). In clayey soils, it modifies aggregation and ion exchange, mitigating compaction and improving aeration (Wong et al. 2022). In acidic soils, alkaline biochar raises pH and fosters microbial consortia favorable to nutrient cycling and metal detoxification (Lu et al. 2020). In calcareous soils, biochar functionalized with organic acids can chelate nutrients and promote their availability to plants (Mihoub et al. 2022; Lonappan et al. 2020).

Figure 2 compares a normal rhizosphere to an engineered rhizosphere, highlighting the benefits of biochar-based interventions for three key focus areas: crop production, crop

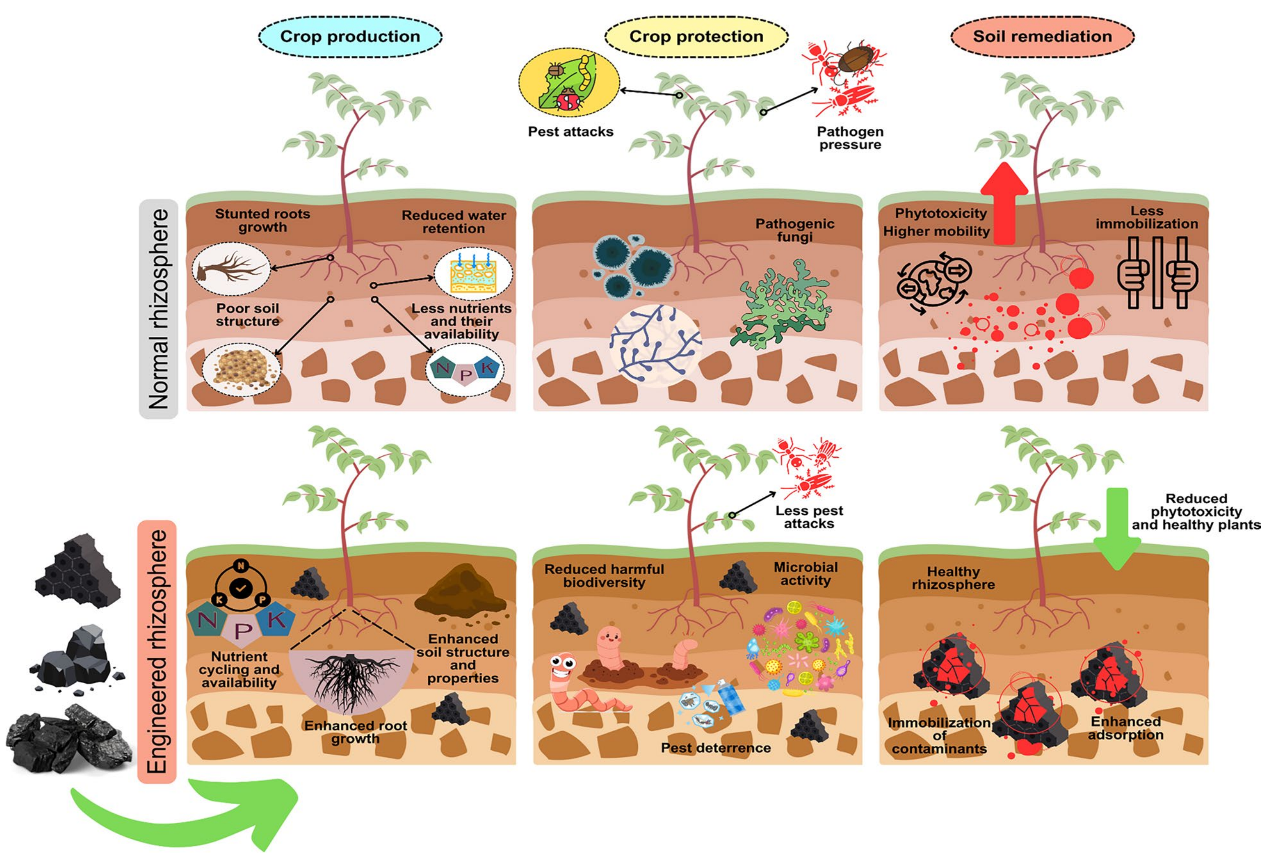


Fig. 2 Comparison of a normal and engineered rhizosphere under biochar application. While the normal rhizosphere suffers from poor soil structure, low nutrient availability, pest pressure, and pollutant toxicity, the engineered rhizosphere enhances nutrient cycling, root growth, microbial activity, pest suppression, and contaminant immobilization, ultimately improving crop yield and soil health

protection, and soil remediation. In the normal rhizosphere, poor soil structure, reduced nutrient availability, and low water retention negatively affect plant performance. Additionally, pathogen pressure and contaminant mobility further disrupt root function. In contrast, the engineered rhizosphere fosters better root growth, improves nutrient cycling, enhances microbial activity, reduces pest attacks, and immobilize contaminants, leading to a healthier and more productive plant system. The illustration also highlights reduced harmful biodiversity, indicating a shift toward a more balanced microbial community that supports plant health, supported by biochar's ability to suppress soil-borne pathogens through the activation of systemic resistance and the promotion of antagonistic microorganisms (Dorjee et al. 2024). A critical component of these improvements lies in the regulation of the microbial community. Biochar modulates microbial structure by altering the physicochemical environment of the rhizosphere affecting pH, moisture, nutrient gradients, and redox conditions (Palansooriya et al. 2019; Wang et al. 2024a, b). These shifts stimulate the growth of beneficial taxa such as phosphate-solubilizing bacteria, nitrogen-fixing microbes, and antagonists of soil-borne pathogens (Yan et al. 2024; Chang et al. 2025). Moreover, root exudates in the presence of biochar are differentially released, activating signaling pathways such as the jasmonic acid (JA) and salicylic acid (SA) pathways that regulate systemic acquired resistance (SAR) and induced systemic resistance (ISR) (Pei et al. 2020; Arshad 2024). Engineered biochar, when combined with plant growth-promoting rhizobacteria (PGPR), enhances quorum sensing and biofilm formation, further stabilizing beneficial microbial populations (Yan et al. 2024; Wang et al. 2024a, b). Through these mechanisms, biochar fosters a more stable and productive rhizosphere, making it a key component in sustainable agriculture and soil remediation. For instance, long-term field studies have shown that biochar application can increase crop yields by an average of 16% over extended periods, with benefits persisting even after six years, largely due to enhanced soil organic carbon and nutrient availability (Jiang et al. 2024). However, to fully realize these benefits, it is necessary to tailor biochar formulations according to specific soil types, crop needs, and target functions whether productivity, protection, or remediation. Figure 2 visually demonstrates these differences, emphasizing how engineered biochar transforms the limitations of a conventional rhizosphere into a functionally enhanced, biologically optimized environment capable of supporting long-term agroecosystem resilience.

5 Mechanisms of engineered biochar-based rhizosphere engineering for crop production

Engineered biochar-based rhizosphere mechanisms contributing to enhanced crop productivity are illustrated in Fig. 3. Engineered biochars specifically those modified through nutrient enrichment, biopriming, or surface area enhancement interact with the rhizosphere via three primary mechanistic pathways: modulation of microbial activity, improvement of soil properties, and stimulation of root architecture and plant physiological traits. Biochar-modulated microbial activity includes nutrient bio solubilization (P, K), N-fixation, siderophore and enzyme production, and the release of phytohormones such as IAA. These microbial processes improve nutrient availability and suppress soil pathogens. Simultaneously, biochar improves the soil environment by enhancing structure, porosity, pH buffering, water retention, and organic matter stabilization creating a favorable habitat for microbes and roots. In turn, these changes stimulate root and shoot responses, including greater root biomass, exudation, leaf area, and photosynthetic efficiency. These improvements collectively lead to better plant vigor, stress resilience, and yield.

5.1 Nutrient availability and uptake enhancement

Enhanced nutrient availability and uptake in plants can be achieved through nutrient enrichment (Brtnicky et al. 2023), retention (Borchard et al. 2012) and transformation (Blanco-Vargas et al. 2022) as illustrated in Fig. 3.

5.1.1 Supplementation of mineral and utilizable nutrient forms

Biochar engineered through soaking in nutrient solutions (Brtnicky et al. 2023; Latini et al. 2019) or surface coating (Li et al. 2023b; Pogorzelski et al. 2020) increases the availability of nitrogen, phosphorus, potassium, and trace elements in the rhizosphere. These nutrients are slowly released over time (Brtnicky et al. 2023), eventually transforming from organic to mineral forms as evidenced by enhanced enzyme activities (Ameur et al. 2018; Ducey et al. 2013)). This reduces leaching (Ducey et al. 2013), promotes efficient nutrient uptake by roots, and enhances plant growth and vigor, as demonstrated by increased lettuce shoot and root dry biomass (Brtnicky et al. 2023). Similarly, (Latini et al. 2019) reported biochar-mediated increases in microbiota richness, nutrient availability and early-stage wheat growth.

5.1.2 Nutrient retention and slow release

Porous biochars activated via oxidation agents exhibit higher cation (CEC) and anion (AEC) exchange capacities, enhancing nutrient binding and reducing leaching (Borchard et al. 2012; Dey et al. 2023). For example, eggshell-enriched biochar immobilized soil microbial P, retained N in the soybean rhizosphere, and increased plant height and biomass P (Li et al. 2023c). Thus, soil nutrients are not leached, which decreases their uptake by plant roots (Borchard et al. 2012; Paymaneh et al.

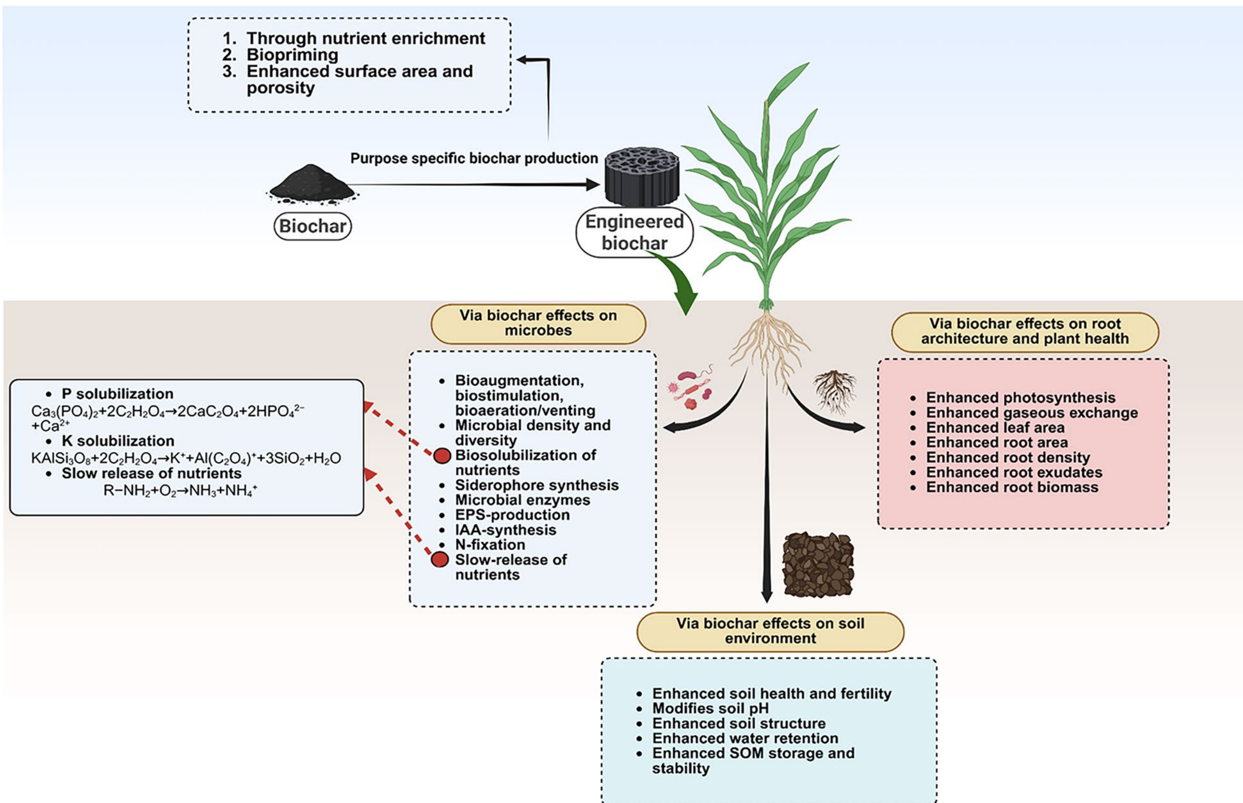


Fig. 3 Multifunctional rhizosphere mechanisms driven by engineered biochar for improved crop productivity. Purpose-specific biochars enhanced via nutrient enrichment, biopriming, or increased porosity activate soil microbial processes, improve soil health, and stimulate root architecture, resulting in enhanced nutrient availability, stress tolerance, and overall plant vigor

2018). Conversely, steam-activated biochar increased soil phosphorus and nitrogen availability but did not translate into higher plant biomass yield (Borchard et al. 2012).

5.1.3 Increased cation exchange capacity

Oxidation-activated biochars increase soil CEC by introducing charged groups or aromatic organic compounds, which reduce hydrophobicity (Khan et al. 2023). These changes occur naturally as biochar ages in soil and are also achieved through co-composting with additives like seafood shell powder, peanut shell, or commercial humates (Luo et al. 2017). Enhanced CEC neutralizes rhizospheric pH, improves N availability (e.g. reduced nitrate and increased ammonium), and supports root architecture, but without an increase in plant biomass yield (Luo et al. 2017). For instance, biochars activated with H_2O_2, KOH, or H_3PO_4 improved rhizospheric traits (increased pH) and increased photosynthetic efficiency, leaf area and biomass of mint (*Mentha crispa* L.) (Ghassemi-Golezani and Farhangi-Abriz 2023).

5.1.4 Phosphorus availability

Phosphorus retention and improved use efficiency in the rhizosphere are mediated through surface complexation (i.e. chemisorption via –OH and C=O groups), ligand exchange, and controlled diffusion (Nardis et al. 2022). Digestate-soaked corncob or wood biochar enriched with P through surface chemisorption (Kizito et al. 2017) showed higher availability of P and N, leading to increased maize biomass (Kizito et al. 2019). However, Mg-complexed phosphorus in engineered poultry litter biochar reduced P solubilization in the maize root system, but still improved P and Mg uptake and shoot biomass compared to triple superphosphate fertilizer (Nardis et al. 2020). Additionally, biochar derived from metal-enriched feedstock (Mg, Fe, Cu, and Zn) enhanced grass growth and seed germination rates (Yao et al. 2013a).

5.2 Improvement of soil structure and water dynamics

The application of engineered biochar significantly enhances soil physical properties, particularly soil structure, porosity, and water dynamics, as illustrated in Fig. 3.

Modified biochars contribute to increased macro- and microporosity, improved soil aggregation, and enhanced water-holding capacity, all of which are crucial for maintaining soil health and optimizing plant growth (Duan et al. 2021). These improvements also support better aeration, reduced compaction, and greater resilience to erosion, ultimately fostering a more favorable rhizosphere environment (Table 2).

5.2.1 Enhanced soil aggregation

Engineered biochars improve soil aggregation through their influence on soil organic matter stabilization, microbial activity, and physicochemical interactions. Specifically, porous and high-surface-area biochars such as those treated with sulfuric acid or finely ground to increase reactivity enhance aggregate stability by increasing cation exchange capacity (CEC) and promoting the formation of oxygen-containing surface functional groups that bind soil particles together (Duan et al. 2021; Liu et al. 2020; Yakout et al. 2015).

These structural improvements also support carbon sequestration through the physical occlusion of organic carbon in microaggregates, thereby reducing carbon mineralization and shifting microbial communities toward taxa associated with recalcitrant carbon processing (Liu et al. 2020). For instance, particle-size optimized biochar has been shown to reduce soil bulk density, enhance aggregate stability, and improve plant-available water, leading to enhanced root proliferation and increased crop productivity (Obia et al. 2016).

5.2.2 Water-holding capacity

Improving soil WHC is achieved through reduction in saturated hydraulic conductivity, soil bulk density, and alterations in pore size distribution. Porous, chemically modified biochars (H_2O_2, KOH, H_3PO_4) significantly increase WHC (Ghassemi-Golezani and Farhangi-Abriz 2022). Biochar with coarser particles enhances water retention, root biomass and OC content in soil aggregates, as demonstrated in maize and soybeans trials (Obia et al. 2016). Similarly, PGPB-bioprimed biochar has shown improved WHC, enhanced nutrient transformation in the rhizosphere, increased root growth and greater nutrient uptake (Zafar-ul-Hye et al. 2019). By retaining more water in the rhizosphere, biochar reduces nutrient leaching, supports root growth and activity, prevents anaerobic root respiration, and boosts plant biomass yield (Ghazouani et al. 2023; Kumar et al. 2022).

5.2.3 Improved soil aeration

Biochar amendments improve soil aeration by reducing compaction and increasing porosity under field applications (Karhu et al. 2011), decreasing soil bulk density thereby allowing better gas exchange (Ghassemi-Golezani and Farhangi-Abriz 2022). This leads to higher oxygen saturation, which supports root respiration, growth, and the proliferation of the beneficial rhizobiome (Tang et al. 2023). For instance, the application of 4% acid-modified porous biochar reduced bulk density in saline soils, enhancing spinach yield and quality (Wang et al. 2023a, b, c). Improved aeration also fosters optimal conditions for root development and overall plant health.

5.3 Stimulation of beneficial microbial communities

Engineered biochar stimulates beneficial soil microbial communities by providing spatial niches within interpores and inner pores of biochar particles (Neuberger et al. 2024; Solaiman et al. 2010) or by supplying rhizospheric microbes with essential nutrients for growth (Carril et al. 2024; Sales et al. 2020) (Table 2). In acidic soils, microbial communities are shaped by low pH, aluminum toxicity, and limited nutrient availability. Therefore acid-tolerant taxa, such as certain fungi and acidophilic bacteria, dominate through stress-response genes, proton efflux systems, and organic acid production to maintain pH homeostasis and support survival under harsh conditions (Wan et al. 2022). Alkaline soils favor microbial taxa adapted to high pH, reduced metal solubility, and limited P availability (*Bacillus*, *Actinobacteria*) through the regulation of alkaline phosphatase activity, ion transporters, and biosynthesis of siderophores for nutrient acquisition.

5.3.1 Habitat for beneficial microbes

Plant roots naturally offer a complex habitat for soil beneficial microbes, partly due to nutrient availability. Biochar surfaces mimic these conditions, particularly porous and high surface area biochars (Neuberger et al. 2024; Paymaneh et al. 2018) or nutrient-enriched biochars (Sales et al. 2020; Sun et al. 2016). These biochars provide improved habitats for microbial colonization compared to pristine biochars by increasing surface area and nutrient availability. This leads to the proliferation of introduced beneficial microbes such as *Pseudomonas putida* UW4 (Sun et al. 2016), AMF inocula (Solaiman et al. 2010) or soil-acquired taxa like ericoid mycorrhiza (Sales et al. 2020). Bioprimed biochars further enhance microbial habitability when enriched with organic matter (Edenborn et al. 2017; Sales et al. 2020). Such increases in microbial population enhance rhizospheric nutrient fluxes, soil fertility (Azeem et al. 2021) and root and plant growth, resulting in greater shoot and root biomass (Sales et al. 2020) and higher crop yield (Azeem et al. 2021; Solaiman et al. 2010; Sun et al. 2016).

5.3.2 Enhanced symbiotic relationships

Bioprimed biochars serve as inoculum carriers for plant-beneficial microbes, such as PGPB, which perform vital soil functions such as nitrification (Ortiz-Liébana et al. 2022; Sun et al. 2016) and P solubilization (Azeem et al. 2021; Ray et al. 2024). These microbes increase nutrient availability and foster positive interactions with plant roots. Key mechanisms include the production of microbial products such as indole-3-acetic acid (IAA) (Azeem et al. 2021; Ortiz-Liébana et al. 2022) or 1-aminocyclopropane-1-carboxylate deaminase (ACC deaminase) (Ortiz-Liébana et al. 2022; Sun et al. 2016), which promote root development (Pantoja-Guerra et al. 2023) and enhance resilience to environmental stresses such as drought or salinity (Sun et al. 2016). Moreover, several PGPB synthesize auxins, further stimulating plant growth (Kudoyarova et al. 2017). For instance, biochar bioprimed with *Bacillus cereus* enhanced crop growth and yield, increased soil P availability and microbial biomass P, and demonstrated high phosphate solubilization and IAA production (Azeem et al. 2021).

5.3.3 Increased microbial activity

By providing habitat and nutrients, biochar supports bacterial and fungal proliferation, increasing soil microbial activity and nutrient transformation. Nutrient retention in biochar (Ameur et al. 2018) induces microbial exoenzymes production, enhancing soil fertility (Azeem et al. 2019; Sanchez-Hernandez 2018). For example, biochar activated with liquid vermicompost extracts increased soil microbial enzyme activity by 38% and improved biological fertility index by 32% over a 21-day incubation period (Carril et al. 2024).

5.4 pH regulation and alleviation of soil acidity

Biochar is widely reported to increase soil pH (Shi et al. 2019), with most types of pristine biochar effectively alleviating soil acidity upon amendment (Dai et al. 2014).

5.4.1 Soil pH buffering

Biochar buffers acidic soil pH through interactions with its negatively charged surface, particularly in biochars engineered via activation with alkalic materials (Hu et al. 2023; Wang et al. 2021b). For example, rice husk-derived biochar modified with NaOH not only increased soil pH and enzyme activity, but also reduced bioavailability of heavy metals. This mitigated their harmful effect on plant roots, ultimately improving plant growth (Wang et al. 2021b). Similarly (Geng et al. 2022) reported the alkalizing effect of modified (crashed and sieved) biochar, which enhanced soil organic carbon availability by reducing the mineral-bonded organic C fraction. This modification also increased microbial community diversity, positively impacted the rhizosphere, and promoted rapeseed growth.

5.4.2 Liming effect

Biochar´s liming effect in soil is primarily attributed to surface sorption and proton capture during the transformation of carbon, nitrogen and sulphur compounds (Bolan et al. 2023a), such as decarboxylation reactions (Manso 2017). The most effective liming effects are observed in biochars pyrolyzed at high temperatures, as these possess multiple functional surface groups ($-COO^-$, and $-O^-$) (Yuan et al. 2011), high CEC (Hu et al. 2023), and smaller particle sizes (Wang et al. 2014). For instance, corn cob biochar charred at 700 °C demonstrated a liming effect comparable to conventional lime ($CaCO_3$), increasing the pH of acidic soil planted with soybeans by up to 1.0 within six weeks (Manso 2017). Mg-enriched biochar also exhibits strong liming potential (Hu et al. 2023). The amendment neutralized soil acidity, enhanced enzyme activities, and increased soil organic carbon content, demonstrating potential for carbon sequestration in a citrus orchard.

5.5 Promotion of root growth and function

Biochar improves soil structure through increased porosity, aggregation, and reduced bulk density, thereby promoting plant root growth and function (Ren et al. 2020; Simiele et al. 2022). These benefits arise from enhanced water retention (Ma et al. 2020) and physico-chemical mechanisms such as the stimulation of growth-promoting root exudates (Pei et al. 2020), adsorption of phytostatic compounds and promotion of biostimulants (Bonanomi et al. 2023).

5.5.1 Root architecture enhancement

Root architecture is strongly influenced by soil permeability and bulk density. Biochar amendments enhance these traits by supporting soil structure and aggregate stability (Amendola et al. 2017). For example, (Chang et al. 2021) demonstrated that engineered biochar increased soil porosity by 50%, reduced bulk density by 40% and improved WHC by 1.9 times compared to sand soil. These changes facilitated greater soil permeability, promoting muscadine root development, including increased fine root length and branching (Fig. 3). In vineyard soil, biochar derived from orchard pruning residues enhanced macroaggregate formation, leading to increased radial growth, fine root diameter and annual biomass, which ultimately boosted wine grape production (Amendola et al. 2017). Furthermore, this root architecture improvement influenced soil nutrient content with higher ammonium availability (+84%), organic carbon content (+21%), and available water content (+12%) compared to the control soils.

5.5.2 Stimulation of root exudation

Root exudation serves as a source of organic nutrients and soil-conditioning compounds, facilitating the recruitment of microbial symbionts such as *Pseudomonas* sp. that enhance plant nutrient uptake such as P (Hao et al. 2022). Symbiotic microorganisms stimulate root exudation through bilateral host-plant quorum sensing within the rhizosphere, mediated by signalling molecules (Majdura et al. 2023). This enhanced exudation not only recruits beneficial microbes but also leads to rhizodeposition (Pausch et al. 2013), which can account for up to 21% of photosynthetically fixed C (Canarini et al. 2019). The combined effect of biochar amendment and elevated CO_2 levels have been shown to enhance root exudation, stimulating root growth and formation in rice paddy (Pei et al. 2020).

Microbial signal molecules, such as auxin-like substances (Kudoyarova et al. 2017) and biostimulants for root development (Bartolini et al. 2023) are produced by PGPB and mycorrhizal fungi. These molecules also help plants respond to environmental stresses. Bioprimed biochar serves as a delivery mechanism for such organisms, enhancing resilience against harmful agents like *Fusarium* wilt disease. Biochar-induced signalling between plant and the rhizobium has been shown to reduce disease severity by stimulating root exudate production (Jin et al. 2022).

5.6 Mitigation of soil toxicities and abiotic stresses

Biochar's high surface area and sorption properties enable it to mitigate soil toxicities caused by potentially toxic elements such as heavy metals, pesticides, organic pollutants as well as abiotic stress like heat, salinity and drought (Arshad et al. 2024). Figure 4 shows the intricate interactions between engineered biochar and rhizosphere engineering for stress tolerance by modulating root

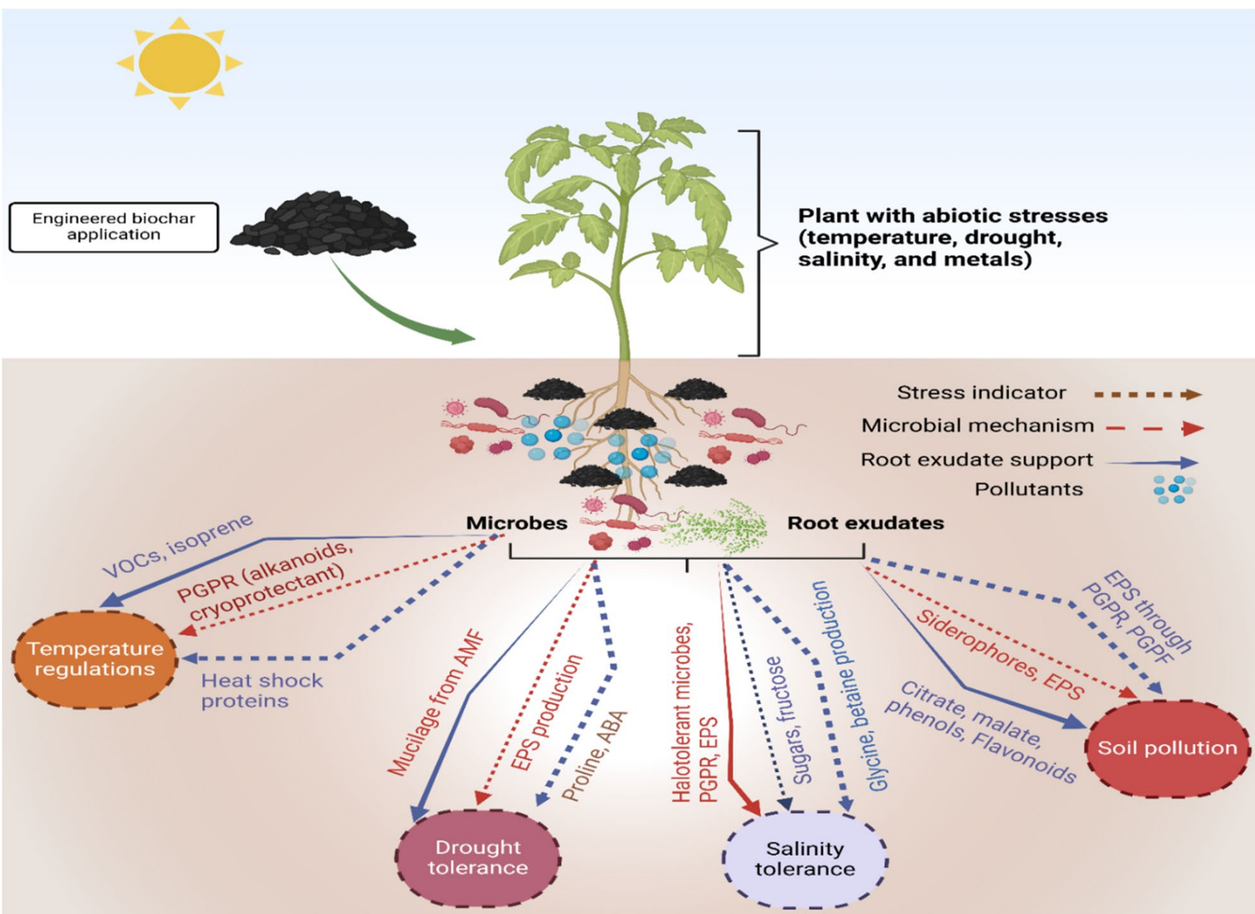


Fig. 4 Schematic showing the intricate interactions between engineered biochar and rhizosphere engineering for stress tolerance by modulating root exudates and boosting microbial candidates for enhanced functions ultimately conferring resistance to soil toxicities

exudates and boosting microbial candidates for enhanced functions ultimately conferring resistance to soil toxicities. The illustration clearly differentiates direct effects of biochar (e.g., adsorption, thermal buffering) and indirect effects (e.g., stimulation of root exudation, microbial shifts, and rhizosphere remodeling), aligning closely with current understanding of biochar-rhizosphere interactions under abiotic stress.

5.6.1 Immobilization of heavy metals

Biochar immobilizes HM in soil by adsorption onto its high surface area (Chen et al. 2023a, b), increased CEC through charged functional groups (Duwiejuah et al. 2020), and complexation with nutrient-enriched biochar components such as N, S, and P (Serrano et al. 2024). Additionally, biochar-induced soil pH increases promote HM precipitation (Schmidt et al. 2016). PGPB-bioprimed biochar can further stabilize HM via microbial interactions (Han et al. 2020) or by enhancing plant tolerance and resistance to HM uptake (Pramanik et al. 2018). For instance, P-loaded activated sugarcane leaf biochar combined with ryegrass (*Lolium perenne*) improved soil pH and electrical conductivity, reducing the bioavailability of Cd, Cr, and Pb to levels below 1 mg kg^{-1} (Serrano et al. 2024).

5.6.2 Reduction of salinity stress

Engineered biochars with enhanced CEC, porosity, and WHC effectively alleviate salinity stress in plants (Huang et al. 2023). They mitigate salinity toxicity by boosting antioxidant responses (e.g. reduced ROS formation), photosynthetic efficiency, osmolytes accumulation, and the production of hormones and secondary metabolites (Parkash and Singh 2020) (Fig. 4). For example, Chinese cabbage grown in saline-alkali soil exhibited improved germination (83%) and increased chlorophyll and soluble protein content with the application of 5% humic acid–magnetic biochar, which restored soil permeability and water absorption (Li et al. 2023a). Similarly, *Pseudomonas* UW4 inoculated biochar relieved salinity stress in maize by synthesizing of ACC deaminase, enhancing root establishment and plant growth (Sun et al. 2016).

5.6.3 Drought mitigation

Biochar mitigates drought by enhancing WHC, aggregate stability, and reducing bulk density, protecting soil from water losses and desiccation (Ali et al. 2017; Paetsch et al. 2018). Mycorrhiza and PGPB further strengthen plant drought resilience, especially when delivered via bioprimed biochar (Hashem et al. 2019). For example, co-application of biochar and *Bacillus amyloliquefaciens* increased wheat grain yield (+77%), straw yield (+75%), and above- and below-ground biomasses (77%) compared to the control (Zafar-ul-Hye et al. 2019). Similarly, biochar combined with AMF improved nitrogen fixation in chickpea by increasing nodulation, leghemoglobin and nitrate reductase activity under drought conditions (Hashem et al. 2019). Algal biochar and PGPB *Serratia odorifera* further enhanced maize growth, increasing fresh and dry shoot and root weights and root length under drought stress (Ullah et al. 2019).

5.6.4 Temperature regulation

Biochar regulates soil temperature by influencing CH_4 and CO_2 emissions, soil organic carbon, dissolved organic caron, and microbial biomass carbon content, and water saturation (Qi et al. 2020). While biochar mitigates drought effects on soil microorganisms under warming conditions, its amendment can also initiate fungal decomposition. As shown in Fig. 3, eengineered biochar supports rhizosphere mechanisms that aid in temperature regulation through a combination of physical, chemical, and biological interactions in the soil environment. For instance, temperature stress is mitigated by VOCs and isoprene from microbes, as well as increased microbial thermotolerance via biochar (Pathak et al. 2024).

6 Mechanisms of biochar-based rhizosphere engineering for crop protection

Figure 5 illustrates biochar-based rhizosphere engineering that enhances crop protection through a combination of direct and indirect mechanisms, including the suppression of soilborne pathogens, induction of plant systemic resistance, modulation of root exudates, and stimulation of beneficial microbial communities that collectively strengthen plant defense against biotic stressors.

6.1 Pathogen suppression through enhanced microbial activity

6.1.1 Promotion of beneficial microbes

Engineered BC enhances soil microbial activity leading to increased competition among soil micro-organisms and the production of antimicrobial compounds which collectively suppresses soil-borne pathogens (Chauhan et al. 2023). This suppression is primarily due to the BC-induced shift in the microbial community composition and its impact on microbial functions (Wang et al. 2021a, b, c; Chen et al. 2023a, b). As illustrated in Fig. 5, BC provides a habitat for beneficial microbes and enhances soil properties such as pH, water retention, and nutrient availability, which together foster a more robust microbial community capable of suppressing pathogens (Gorovtsov et al. 2020). In a study by Ali et al. (2023), it was validated that BC amended with *Trichoderma* spp. enhanced organic matter, pH, and ammonia concentration in the

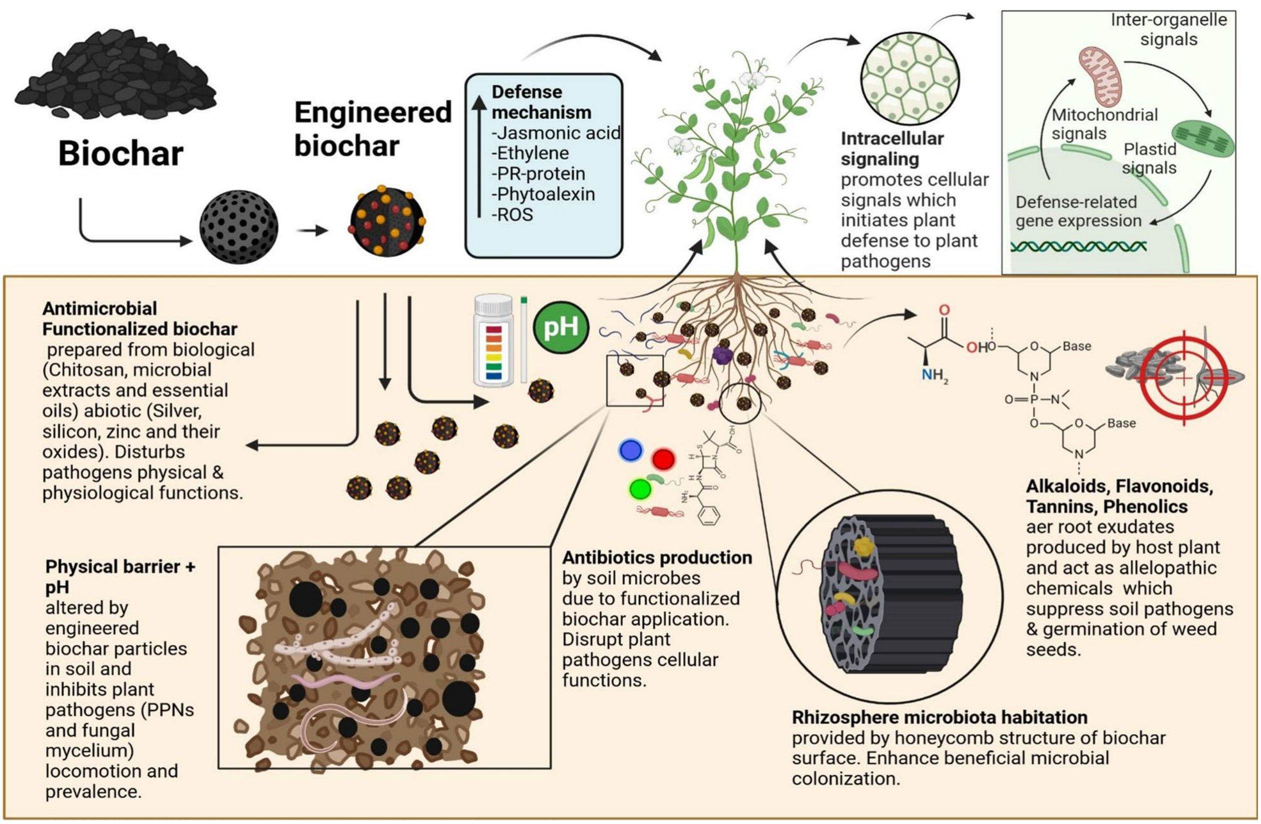


Fig. 5 Engineered biochar-based rhizosphere mechanisms outcome in improved crop protection notably via its direct and indirect effects on rhizosphere chemistry, providing shelter to rhizosphere microbes and antibiosis

soil, resulting in an effective reduction in the incidence of *Fusarium* wilt infection by 37.5% in cucumber and enhanced colonization of (*Bacillus* spp., *Pseudoxanthomonas* spp., *Flavobacterium* spp., *Flavisolibacter* spp., and *Arthrobacter* spp.) and (*Trichoderma* spp., *Chaetomium* spp., *Cladosporium* spp., *Psathyrella* spp. and *Westerdykella*) genera which were likely the potential antagonists for various plant pathogens. Another study concluded a significant decrease in the incidence of powdery mildew on grapevines following the application of BC engineered with phosphorus coating. This amendment was found to enhance microbial activity and diversity in the rhizosphere, leading to increased production of natural antifungal compounds (Chen et al. 2023a, b) (Table 3).

6.1.2 Induction of systemic resistance

Pathogen suppression via enhanced microbial activity occurs when engineered BC is added to the soil, fostering beneficial microbial communities that compete with or inhibit harmful pathogens (Bolan et al. 2023c). This microbial boost can lead to the induction of systemic resistance (ISR) in plants by salicylic acid production stimulated by ethylene and jasmonic acid pathways which are responsible for inducing resistance and upregulation of defensive genes in a plant system, a state where plants are primed to respond more effectively to pathogen attacks by activating their immune responses including the production of antimicrobial compounds and strengthening of cell walls (Das et al. 2022). Engineered BC supports these mechanisms by providing a conducive habitat for beneficial microorganisms due to its porous structure high surface area and ability to retain nutrients (Fig. 5). This environment enhances microbial diversity and activity, promoting the suppression of pathogens and the induction of systemic resistance in plants (Zheng et al. 2022). Chen et al. (2023a, b) demonstrated that the application of engineered BC, derived from rice husks and enriched with *Bacillus subtilis* SL-44, significantly reduced the incidence of *Fusarium* wilt in radish plants. The BC-amended soil showed increased microbial activity, leading to the suppression of disease and the induction of ISR in radish, resulting in healthier plants with lower disease symptoms. In a study by Fosu-Nyarko et al. (2022) lettuce plants grown in soil amended with BC derived from poultry litter and engineered with

Pseudomonas fluorescens exhibited reduced infestations of root-knot nematodes and enhanced soil microbial diversity particularly beneficial bacteria that antagonize nematodes leading to lower nematode populations and healthier plant roots. Research by Ahmad et al. (2024) explored the effects of leaf waste BC engineered with *Trichoderma harzianum* on eggplants and found that the BC-treated soil significantly reduced the severity of bacterial wilt disease. This was attributed to the enhanced activity of *Trichoderma*, which not only suppressed the pathogen but also triggered ISR by enhancing the production of phenolics, flavonoids, and peroxidase activity in the eggplant resulting in increased resistance to the disease (Table 3).

6.1.3 Antibiotic production

Pathogen suppression through enhanced microbial activity involves the stimulation of beneficial soil microbes which outcompete or directly inhibit harmful pathogens (Fig. 5). This is achieved through mechanisms like the production of antibiotic compounds and the enhancement of plant immune responses (Niu et al. 2020). Engineered BC provides a porous habitat that enhances microbial colonization and activity. It also adsorbs organic compounds which can serve as nutrients or signals for beneficial microbes further enhancing their ability to suppress pathogens by releasing various antibiotic compounds in the rhizosphere as well as in plants (de Medeiros et al. 2021; Poveda et al. 2021a, b; Awasthi 2022). A study by Jin et al. (2023a, b) investigated the use of Streptomyces-enriched BC in potato which enhanced the activity of *Rhizobium* spp., a bacteria known for its nitrogen fixation properties and a significant reduction in Potato late blight (PLB) caused by *Phytophthora infestans* due to increased microbial activity and antibiotic production against the pathogen, with *Streptomyces*-doped BC amendment reducing disease incidence by 46.1%. Kumar et al. (2021) explored that *Bacillus subtilis* enriched BC facilitated the proliferation of PGPR in the rhizosphere which produce antibiotics that target *Pseudomonas syringae* a pathogen responsible for bacterial speck in tomato and reduce the disease severity by 50% (Table 3).

6.2 Pest suppression through alteration of rhizosphere chemistry

6.2.1 Changes in root exudation patterns

The addition of engineered BC to soil can alter rhizosphere chemistry leading to changes in root exudation patterns that enhance the plant's ability to suppress pathogens. These alterations in exudate composition could inhibit pathogen growth by enhancing the beneficial microbial community that outcompete plant pathogens by directly producing antimicrobial compounds (Sharma et al. 2021). Engineered BC provides a porous structure and surface chemistry that adsorbs organic molecules, modulates soil pH, and acts as a habitat for beneficial microbes. This enhances microbial activity and diversity, which, in turn, influences root exudation patterns and supports pest suppression (Palansooriya et al. 2019; Zhao et al. 2022a, b). A study by Wang et al. (2024a, b) demonstrated that the application of KOH modified BC in soybean fields led to a 22.17% reduction in root rot disease incidence caused by *Fusarium* species. The BC-modified rhizosphere chemistry increased soil physicochemical properties and isoflavones signaling to rhizosphere beneficial bacteria and increased their community, enhancing plant defense mechanisms. Mondal et al. (2021) reported that 1.2% BC and 5% vermicompost could alter root exudation patterns in rice crops particularly increasing the release of organic acids that deterred (*Meloidogyne graminicola*) and fostered a microbiome hostile to nematodes. In a study by Wang et al. (2023a, b, c), AMF and BC application in maize fields resulted in a 54.2% reduction in pest infestation by *Spodoptera frugiperda*. The treated soils showed altered rhizosphere pH, leading to increased exudation of phenolic compounds, which are known for their pest-deterrent properties (Table 3).

6.2.2 Enhancement of plant secondary metabolites

Modified BC alters rhizosphere chemistry by modulating soil pH, nutrient availability, and microbial communities leading to changes in root exudation patterns. This process enhances the production of plant secondary metabolites which act as chemical defense against pathogens reducing their ability to multiply or infect the plant (Cheng et al. 2018; Yang et al. 2024). BC provides a conducive environment for beneficial soil microbes, increases nutrient retention, and adsorbs harmful substances (Kocsis et al. 2022). These properties facilitate the optimal production and release of root exudates, including secondary metabolites, which suppress pathogenic activity in the soil (Gorovtsov et al. 2020). A study demonstrated that biocontrol-doped organic waste BC increased the abundance of beneficial microbes such as *Pseudomonas* spp. and *Trichoderma* spp. in the rhizosphere of cotton plants. These microbes were linked to enhanced production of phenolics and flavonoids compounds that led to a reduction in Fusarium wilt incidence caused by *Fusarium oxysporum* f. sp. *vasinfectum* (Asif et al. 2023). In a field trial, plants treated with compost-enriched green waste BC enhanced the production of flavonoids in the roots of tomato resulting in a significant decrease in *Fusarium oxysporum* sp. *lycopersici* infestations. The BC's ability to improve root exudates and AMF bio-protective potential of mycorrhization was evident in treated plants (Akhter et al. 2015) (Table 3).

6.2.3 Modulation of soil pH

The addition of engineered BC to soil alters rhizosphere chemistry, primarily by modulating soil pH (Fig. 1), which can inhibit pathogen growth and enhance plant health (Das et al. 2022). This alteration in pH affects the availability of nutrients and the activity of beneficial microbes, ultimately suppressing pests and diseases through induced systemic resistance and the production of plant secondary metabolites (Bolan et al. 2023b). Engineered BC supports this mechanism by providing a stable matrix that adsorbs and releases ions thereby stabilizing soil pH. The surface chemistry and porous structure enhance microbial habitat promoting beneficial microbial activity and reducing the availability of nutrients that pathogens rely on (Gao et al. 2022). A study found that the application of organic amendments and BC altered soil EC, pH, C: N, N and NO_3 and reduced the severity of *Fusarium oxysporum* f. sp. *lactucae* in lettuce by 37%, The BC amendment led to increased phosphorus availability enhancing plant defenses against the pathogen (Bonanomi et al. 2022). A previous study demonstrated that Zeolite-enriched spelt husk BC 5% (v/v) altered soil pH and microbial activity which suppressed root lesion nematode (*Pratylenchus penetrans*) infestations by 95% and enhanced microbial populations that outcompeted nematodes for nutrients and space leading to reduced infestations rate in carrot (George et al. 2016). Another study showed that Green-Nano BC amended soils had a higher pH and functional groups (such as O–H, C=C, S–H, H-C=O, C-O, and H–O–H) which reduced root knot nematode infection by 88.65% per 250 cm^3 soil in tomato. The elevated pH and functional group levels were toxic to the nematodes and inhibited them from invading in roots while promoting plant growth (Khader et al. 2023) (Table 3).

6.3 Biochar acts as a physical barrier

6.3.1 Reduction of pathogens and pest movement

BC acts as a physical barrier in soil impeding the movement of pathogens and pests by creating a more porous and heterogeneous soil structure. This barrier effect reduces the ability of pathogens to spread and pests to reach plant roots thereby dropping infection rates (Zheng et al. 2022; Zhao et al. 2024). The porous structure and high surface area of BC enhanced soil physical structure improving its ability to trap and immobilize pathogens and pests. Additionally, BC can upsurge soil microbial communities, resulting from suppressing pathogen proliferation and movement (Graber and Kookana 2015). A study by Cao et al. (2018) demonstrated that BC enriched compost had significantly altered soil structure, minimized the potential leaching of nutrients and reduced plant-parasitic nematodes infections in cucumber plants. The BC physical structure combined with manure antimicrobial properties created a barrier that prevented the nematodes from spreading through the soil. Likewise, AMF and *Trichoderma asperellum* consortium with palm bunch BC applied to tomato fields effectively reduced nematode infestation by 79.5%. The BC physical properties, coupled with the antagonistic nature of biocontrol fungi obstructed nematode movement by colonizing thick mycelia in the rhizosphere thereby protecting the cucumber roots from invading J_2 (Claudius-Cole and Ajayi-Choco 2017). Mesquite (*Prosopis juliflora*) BC infused with castor oil cake reduced *Meloidogyne incognita* infestations in tomato fields. This might be attributed to increased surface area, acting as a barrier and boosting the physiochemical properties of the soil which could resist the root-knot nematode locomotion (Ikram et al. 2024).

6.3.2 Root system protection

BC protects root systems from soil borne pathogens by enhancing antagonistic microbial diversity creating unfavorable conditions for pathogens to survive and multiply and adsorbing allelopathic compounds produced by pathogens. This improves soil health and plant resilience effectively reducing pathogen colonization (de Medeiros et al. 2021). BC supports these protective measures by providing a porous structure that is capable of adsorbing toxic compounds and keeping the soil detoxifyed (Anae et al. 2021). The application of *Pseudomonas putida* L2 and *Stenotrophomonas pavanii* L8 along with maize BC to Narrow-Leafed Lupin plants led to a reduction in root rot disease incidence caused by *Fusarium solani*, The BC elevated adsorption of fusaric acid produced by *F. solani* and increases PGPR diversity and reduced pathogen invasion through roots (Egamberdieva et al. 2020) (Table 3). Wachira (2020) demonstrated that this sugarcane bagasse-derived BC functionalized with pure calcium carbonate and DAP significantly reduced root rot (*Fusarium oxysporum*) infestations in soybean crops by 90%. The functionalization with calcium carbonate helped modulate soil pH making the environment less conducive to fungi mycelia growth thereby protecting the roots from damage.

6.4 Mitigation of soil-borne diseases

6.4.1 Reduction of phytotoxicity

BC mitigates soil-borne diseases by altering the soil physiochemical attributes and improving soil beneficial microbial diversity which reduces the stress on plants and enhances immune responses. It also neutralizes harmful substances in the soil decreasing the incidence of diseases by limiting pathogen activity (Tikoria et al. 2023). BC's porous structure and large surface area allow it to sorb allelopathic and phytotoxic metal pollutant like arsenic (As), nickel (Ni), cadmium (Cd), lead (Pb) chemicals in the rhizosphere, while its ability to enhance soil pH and nutrient availability creates a more favorable environment for antagonistic microbes that suppress pathogens (Kammann and Graber 2015; Mansoor et al. 2021; Pathak et al. 2024). In a study on American ginseng, the application of vermicompost impregnated BC (VBC) significantly reduced the incidence of *Fusarium* root rot by 80.96% compared to the control. The VBC regulated the adsorbing potential of phenolic acid produced by the friendly microbial community (*Pseudomonas*, *Lysobacter*, and *Chryseolinea*) was highlighted as the primary mechanism (Tian et al. 2021). Similarly, the use of vermicompost enriched BC in bean crops led to a 60% reduction in the occurrence of root rot caused by (*Fusarium solani*). BC improved soil pH and nutrient cycling which promoted the growth of disease-suppressive microorganisms (*Trichoderma* and *Paecilomyces lilacinus*) thus mitigating the disease (Were et al. 2021).

6.5 Allelopathic suppression of weeds

6.5.1 Biochar and allelochemicals

Engineered biochar, through its tailored physicochemical properties can suppress weed growth through allelopathic effects, where it releases bioactive compounds that inhibit the germination and growth of weed seeds (Fig. 6). Additionally, BC modifies soil pH and nutrient availability, which can further affect weed seed viability and growth (Eizenberg et al. 2017). Plant-derived allelochemicals, such as phenolic acids (e.g., ferulic acid, caffeic acid) and terpenoids (e.g., sorgoleone), are exuded by crops and can be adsorbed and stabilized by biochar, thereby prolonging their bioavailability for weed suppression (Fig. 6). It also enhances soil properties such as increased cation exchange capacity (CEC), water holding capacity, functional group, C content, specific surface area (SSA) and boosted potential of chemical herbicide

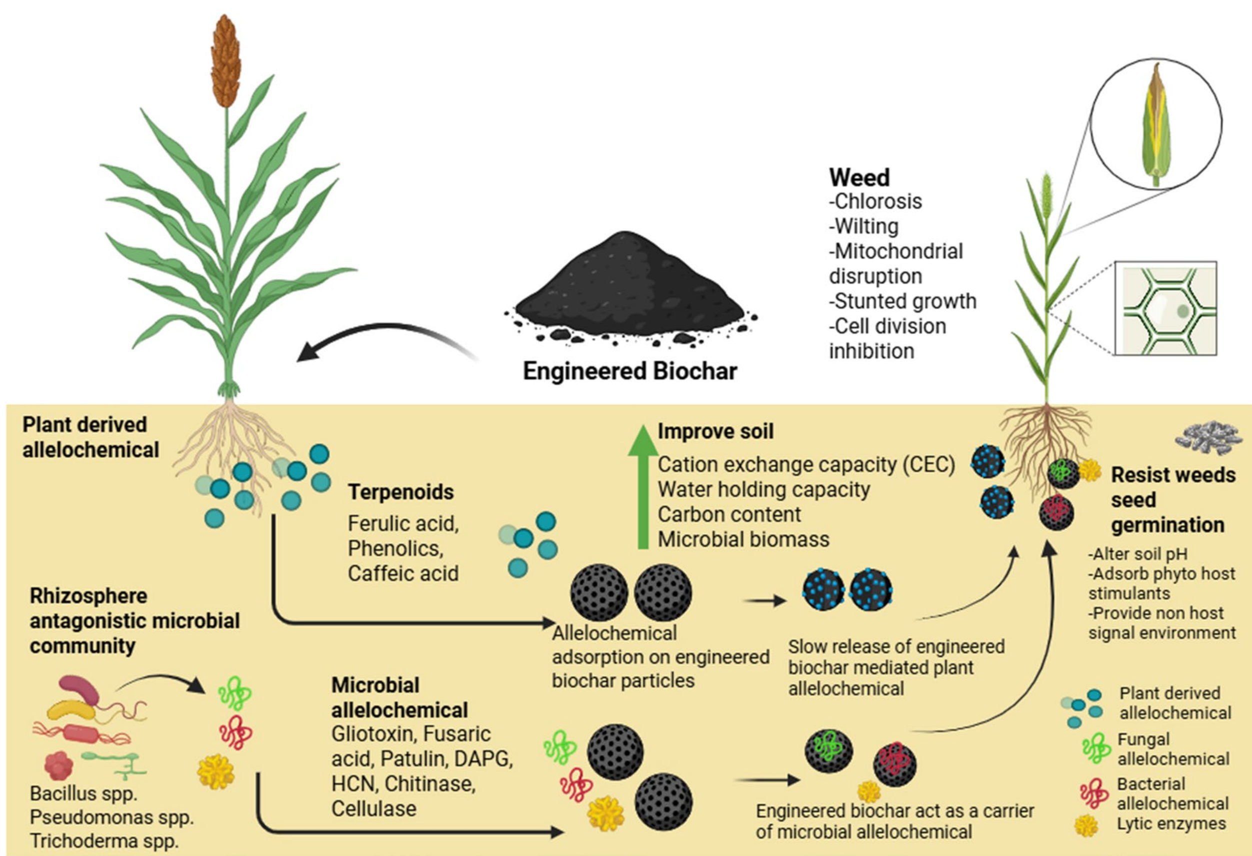


Fig. 6 Mechanistic representation of engineered biochar in weed suppression through rhizosphere-mediated allelopathy. Engineered biochar acts as a carrier for plant- and microbe-derived allelochemicals (e.g., terpenoids, phenolics, fusaric acid, DAPG, HCN) and supports antagonistic microbial communities (e.g., *Bacillus*, *Pseudomonas*, *Trichoderma* spp.). By adsorbing and slowly releasing allelochemicals, biochar improves soil properties and creates a non-host signaling environment. This leads to impaired weed growth and seed germination via altered soil pH, disruption of mitochondria, reduced cell division, and stunted growth, ultimately strengthening crop competitiveness

which can create less favorable conditions for weed growth (da Silva Amaral et al. 2022). A previous study investigated the use of glyphosate-isopropylammonium and BC in suppressing broomrape weed (*Orobanche crenata* Forsk.) growth in faba bean (*Vicia faba* L.) fields. The engineered BC significantly diminished allelopathic effects, reducing weed biomass by up to 44.7% compared to control plots (Saudy et al. 2021).

El–Bially et al. (2023) assessed the impact of AMF and peanut husk BC on broomrape weed management in a two-year trial of faba bean crops. The engineered BC showed a noticeable reduction in weed density and improved faba bean upper and lower ground growth. The study highlighted the role of AMF-BC in altering soil nutrition and raising the tolerance degree of the crop against weed, resulting in suppressing weed germination. Green waste-derived BC had significantly enhanced soil dehydrogenase activity, reduction in Hydrolytic enzyme activity and decreased the *Parthenium hysterophorus* weed growth in a maize field. The study emphasized the capacity of BC to increase active microbial biomass carbon and modify soil conditions creating an environment less conducive to weed growth (Kumar et al. 2013) (Table 3).

6.5.2 Weed seed germination inhibition

BC inhibits weed seed germination primarily through physical and chemical mechanisms (Fig. 6). It creates a physical barrier by occupying the soil surface which can prevent seed-to-soil contact necessary for germination. Additionally, BC can alter soil pH and adsorb phyto-host chemicals (such as flavonoids, sesquiterpenes, and strigolactones) that stimulate weed seed germination and growth (Eizenberg et al. 2017; Joseph et al. 2021). BC could support this mechanism by providing a nutrient deficit and lack of host signaling environment for weed seeds that physically obstructs seedling emergence. It also affects soil chemistry by buffering pH changes and adsorbing signaling compounds that may inhibit weed seed germination (Thies et al. 2015). It was found that the use of greenhouse compost with pepper-BC decreased the root parasitic weed Egyptian broomrape (*Phelipanche aegyptiaca*) seed germination percentage in the BC-treated root and reduced weed biomass in a tomato field and adsorbed synthetic weed seed stimulant GR-24 *in-vitro* conditions. Particularly, the reason for the decrease in germination percentage could be physical adsorption of the stimulant molecule by the BC (Eizenberg et al. 2017) (Table 3, Fig. 6).

7 Mechanisms of biochar-based rhizosphere engineering for remediation

Biochar-rhizosphere mechanisms for the remediation of contaminated sites involve using biochar to transform the rhizosphere into a more favorable environment for detoxifying pollutants and enhancing plant growth. These mechanisms target the immobilization of contaminants, enhancement of microbial degradation, and improvement of plant resilience, all within the engineered rhizosphere (Table 4). These mechanisms with a focus on rhizosphere engineering using biochar are described in detail below.

7.1 Immobilization of heavy metals and other inorganic contaminants

7.1.1 Adsorption and complexation

Engineered biochars adsorb the pollutants through H-bonding, pore filling, electrostatic attraction, hydrophobic interaction, and van der Waals forces (Islam et al. 2021) as illustrated in Fig. 7. The high aromaticity and porosity of activated biochars are essential for the sorption of these contaminants, along with enlarged surface areas and pore structures facilitate these interactions, enhancing their adsorption capacity for pollutants (Braghiroli et al. 2018), i.e., clay-biochar composites have shown good efficiency in removing antibiotics and dyes from contaminated water (Murtaza et al. 2024). Heavy metals are also remediated through ion exchange, precipitation, electrostatic attraction, and complexation (Islam et al. 2021). The presence of O-containing functional groups and optimum pH conditions also play a major role in the sorption of heavy metals (Braghiroli et al. 2018; Zhang et al. 2024). Viglašová et al. (2020) compared pristine biochar with Fe- and Mg-biochar for nitrate removal and reported that Mg- and Fe-biochar had more efficacy (9.13 and 10.35 mg g^{-1}, respectively) than pristine biochar (4.41 mg g^{-1}). Similarly, biochar composites also show promising results i.e., Wang et al. (2015) reported that manganese-oxide/biochar increased the lead(II) removal efficacy to 98.9%. Similarly, complexation primarily involves the formation of stable complexes between the pollutants and the biochar functional groups located on the biochar surface, facilitated through increased surface area and the presence of specific functional groups, such as C=O, -COOH, -OH, and $-NH_2$ (Islam et al. 2021; Chen et al. 2022a, b; Murtaza et al. 2024). Engineered biochars remediate organic pollutants through hydrogen bonding, π-π electron donor–acceptor (EDA) interactions, and hydrophobic interactions (Islam et al. 2021). The engineered biochars have increased aromaticity and specific functional groups, providing higher pollutant removal efficiency (Qiu et al. 2022).

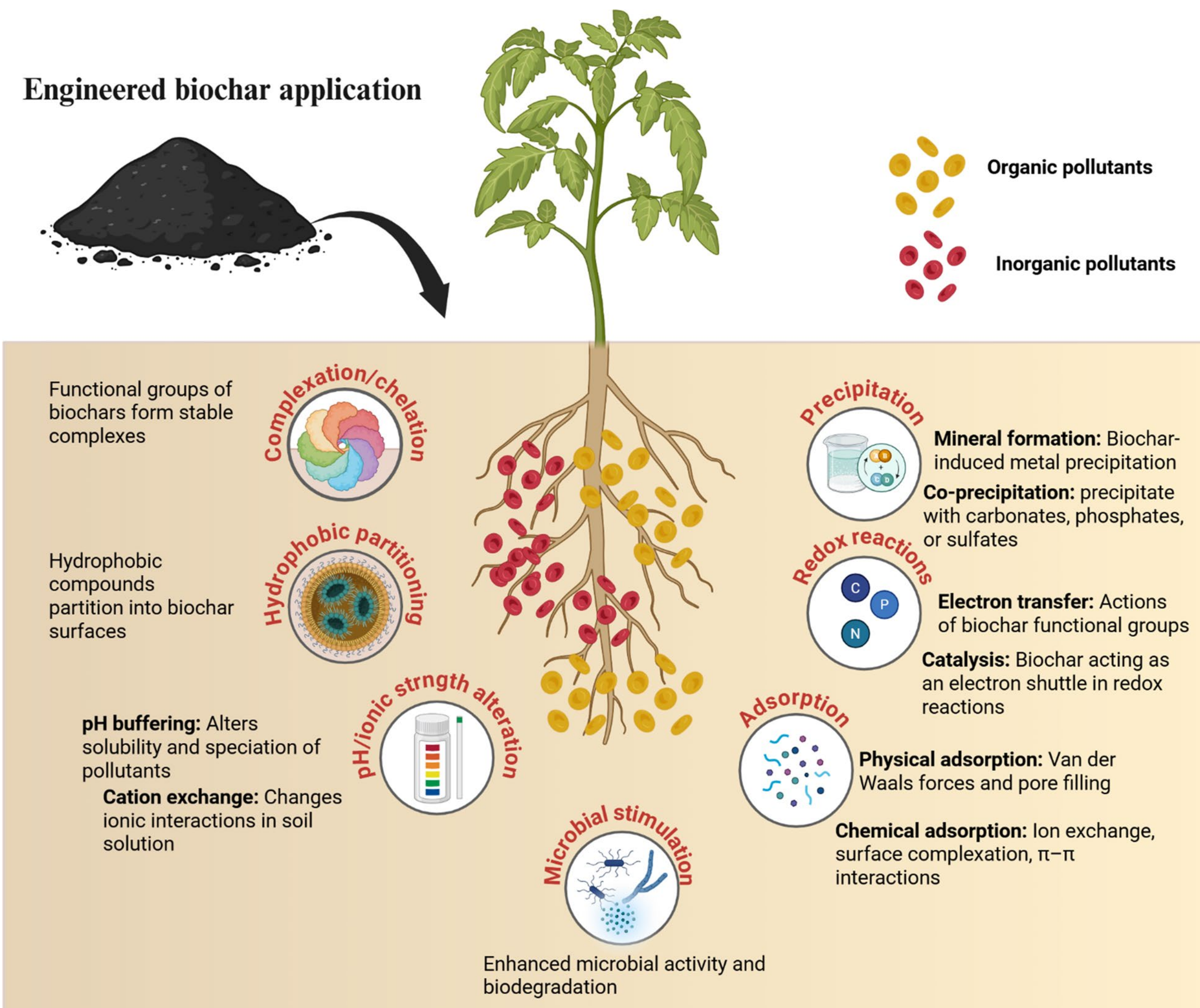


Fig. 7 Rhizospheric mechanisms are driven by engineered biochar for soil remediation. Engineered biochar immobilizes heavy metals and organic pollutants through surface adsorption, ion exchange, and redox reactions, reducing their bioavailability to plants. Simultaneously, it enhances root exudation and supports pollutant-degrading microbial communities, accelerating bioremediation processes

For example, tetracycline remediation is accomplished through the formation of bonds between the functional groups on the engineered biochar surface and the polar groups of tetracycline molecules (Xiong and Bi 2023). Yang et al. (2024) reported Fe–Mn modified biochar remediated Cd and Pb with an efficacy of 73.73% and 69.87%, respectively. Similarly, Ke et al. (2023) reported up to 80% stabilization efficiency of magnetic biochar for As and Pb.

7.1.2 pH modification and precipitation

Through pH modification, the solubility and mobility of organic and inorganic pollutants are altered and facilitated their precipitation and effective immobilization (Qiu et al. 2022; Zhang et al. 2024). As engineered biochars have alkaline pH, they increase the pH of the contaminated environment, leading to higher availability and subsequent precipitation of heavy metals in the form of metal hydroxides or carbonates (Zhang et al. 2024). For example, As interacts with higher pH engineered biochar to promote the formation of less soluble arsenic species, reducing their mobility in soil and water (Zhang et al. 2024). This precipitation mechanism is further enhanced by the presence of carbonates and phosphates in the ash content of engineered biochars, which can form stable precipitates with heavy metals (Guo et al. 2020). Hussain et al. (2022) reported an effective remediation strategy of rock phosphate loaded green coconut shell biochar for heavy metals contaminated sites. Sun et al. (2021) reported Fe-modified biochar restricted Cd entry (up to 76.64%) into maize crop due to increasing its pH increasing and subsequent precipitation. Surface complexation is another crucial mechanism for inorganic pollutant remediation, which is significantly influenced by pH. Engineered biochars with abundant oxygen-containing functional groups i.e., -COOH, and -OH can form strong complexes with metal ions, especially at higher pH levels where these functional groups become deprotonated and more reactive (Qiu et al. 2022). The efficiency of this process depends on the cation exchange capacity (CEC) of the applied biochar type, which is often improved through modification techniques (Guo et al. 2020). Lee and Shin (2021) reported an effective strategy of Zn, Cd, and Pb removal through MgO-impregnated biochar up to > 9.15 mg g^{-1}. Li et al. (2022) reported that Mg–Al modified biochar application remediated As, Pb and Cd contaminated soils up to 100%. Similarly, Wang et al. (2021a, b, c) reported that H_2O_2 and 3-mercapto-propyltrimethoxysilane thiolated pig manure biochar effectively remediated Cd and Pb through enhanced surface complexation of metals with biochar.

7.1.3 Formation of stable metal-biochar complexes

The remediation of heavy metals through stable metal-biochar complexes is accomplished through ion exchange, precipitation, electrostatic attraction, and complexation due to higher surface area and functional groups (Murtaza et al. 2024). For example, phosphate-solubilizing bacteria (PSB)-modified biochar has been shown promising results in enhancing the immobilization of Pb^{2+} (Chen et al. 2019). The addition of PSB to biochar increased Pb^{2+} removal efficiency up to 60.85% as PSB-biochar significantly enhanced the formation of stable pyromorphite on the surface of PSB-biochar, due to increased P release and regulated pH on the biochar surface (Enaime et al. 2020). Dissolved organic matter (DOM) released from biochars plays a significant role in biochar-metals complexation, e.g., Liu et al. (2019) reported > 99% of Hg removal through metal-biochar complexation through thiol groups in DOM. Amorphous MnO-coated biochar also has the potential to remediate heavy metals through metal-biochar complexation e.g., Trakal et al. (2018) reported that MnO-biochar composite removed 99%, 91% and 51% of Pb, As and Cd, respectively.

7.2 Enhancement of microbial degradation of organic contaminants

Engineered biochars provide a suitable habitat for microbial colonization due to their higher surface area and porosity (Fig. 7). Moreover, they adsorb organic pollutants, making them more bioavailable to microorganisms for degradation. In addition, these biochars act as electron shuttles, facilitating direct interspecies electron transfer and promoting microbial metabolism (Kong et al. 2024; Liu et al. 2020).

7.2.1 Habitat for degrading microorganisms

The improved properties of engineered biochars, such as increased specific surface area and uniform distribution of pores, contribute to their effectiveness in supporting microbial degradation of contaminants (Akhil et al. 2021). These characteristics provide a larger surface area for microbial colonization and create a more favorable environment for microbial growth and activity. Furthermore, engineered biochars can introduce exogenous microorganisms to the soil, further diversifying the microbial community and potentially introducing specialized degraders for specific contaminants (Fan et al. 2023). This introduction of new microbial species can enhance the overall degradation capacity of the soil microbial community. The presence of O_2-containing groups (OCGs), imperfections, and persistent free radicals (PFRs) on the biochar surface also contributes to its catalytic activity in advanced oxidation processes (AOPs) (Kong et al. 2024). These reactive sites can generate active radical species, leading to the enhanced degradation of organic contaminants through both radical and non-radical pathways. Engineered biochars can also influence the biodegradation of organic pollutants by altering soil properties e.g., biochar amendment increased the surface area, pH, total organic carbon, and dissolved organic carbon (DOC) of paddy and red soils (Zhang et al. 2021). The immobilization of microorganisms on engineered biochars further enhances their potential for organic contaminant degradation. Zeng et al. (2023) used Fe_3O_4 nanomaterial-modified pharmaceutical residue biochar to immobilize Alcaligenes faecalis strains for phenol removal. Similarly, Chang et al. (2021) used Fe-MnO-modified biochar for the remediation of phthalate-contaminated soils and reported that the addition of Fe-MnO-modified biochar enhanced the relative abundance of *Firmicutes sp.* Moreover, the abundance of *Sphenodons* and *Pseudomonas* effectively degraded phthalates. Ma et al. (2023) reported that nanoparticles synthesized from wood and rice straw biochar resulted in significant remediation capacity of naphthalene, pyrene, trimethoprim, and ciprofloxacin in sandy soil.

Furthermore, application of engineered biochars significantly alter the soil microbial communities, enhancing the relative abundances of beneficial microorganisms e.g., biochar addition increases the presence of *Acidobacteriota*, *Firmicutes*, *Basidiomycota*, and *Mortierellomycota* (Lei et al. 2023). These changes in microbial community composition can have profound effects on the degradation of soil contaminants, as certain microorganisms are known to be more efficient in breaking down specific pollutants. Engineered biochars also promote the growth of potentially beneficial microbes, such as *Gemmatimonadetes*, *Microtrichales*, *Candidatus_Kaiserbacteria*, and *Pyrinomonadales*, which are associated with improved plant growth and enhanced soil nutrient cycling (Lei et al. 2023). This enrichment of beneficial microorganisms can contribute to the overall health of the soil ecosystem and support the natural attenuation of contaminants. Gregory et al. (2015) reported that low- and high-temperature biochar treatments resulted in a significant increase in soil microbial activity during 60 days of treatment compared to the controls. Engineered biochars can also alleviate the stress caused by co-contaminants, allowing native soil microbial communities to thrive and degrade pollutants more effectively. The same study also reported that biochar addition led to a short-term reduction in soluble As concentration, which allowed native soil microbial communities to overcome As-related stress (Gregory et al. 2015).

7.2.2 Co-metabolism and synergy

Engineered biochars support co-metabolism and synergistic microbial degradation by enhancing microbial activity and diversity in contaminated soils (Fig. 7). Biochar addition alter the composition, diversity, and structure of microbial communities through nutrient supply, provision of colonization sites, immobilization of heavy metal(loid)s, and introduction of exogenous microorganisms (Fan et al. 2023). This enhanced microbial diversity, and activity can lead to more efficient degradation of contaminants through co-metabolic processes. The application of low-temperature (300 °C) biochar has been found to promote the biodegradation of organic contaminants such as neonicotinoid insecticides by 11.3–41.9% (Zhang et al. 2020). This enhancement is attributed to the biochar's ability to provide more dissolved organic carbon (DOC) and available nitrogen for microorganisms, creating favorable conditions for co-metabolic processes. The increased availability of carbon and nitrogen sources allows microorganisms to grow and maintain their metabolic activities, which in turn supports the degradation of contaminants that may not serve as primary substrates for growth. Engineered biochars can also influence the metabolic patterns of microbial communities, accelerating the utilization of various carbon sources, including amino acids, carboxylic acids, polymers, and other plant chemical compounds (Xu et al. 2021). Zhang et al. (2020) used Fe–Mn–Ce modified biochar composite for arsenic remediation in paddy soil. They reported increased urease, catalase, alkaline phosphatase, and peroxidase enzymes activity along with higher relative abundance of *Proteobacteria*, *Acidobacteria*, and *Gemmatimonadetes*, which play a crucial role in inducing heavy metal remediation. This enhanced metabolic activity, and diversity can lead to more efficient co-metabolic degradation of contaminants, as microorganisms are better equipped to break down a wider range of compounds simultaneously. The synergistic effects of engineered biochars on microbial degradation are further supported by their ability to modify soil properties. Zhou et al. (2023) used PSB-biochar combination to remediate Pb and reported 71.30% efficacy. It was suggested that Pb remediation was done through the action of strain combined with biochar which regulated the microenvironment of the biochar surface, enhanced phosphate release, and promoted stable pyroxite generation.

Biochar amendment has been shown to increase soil pH, which can create more favorable conditions for certain microbial populations (Xu et al. 2021). Additionally, the improved water holding capacity (WHC) and nutrient retention properties of engineered biochars-amended soils can support sustained microbial activity, leading to more effective long-term degradation of contaminants (Egamberdieva et al. 2021). Engineered biochars can also enhance the interactions between microorganisms and root exudates in the rhizosphere, which plays a crucial role in the degradation of soil contaminants. Biochar provides electron transfer support between microorganisms and exudates, regulates the secretion of enzymes to resist oxidative stress stimulated by heavy metal(loid)s, and promotes the activity of soil enzymes (Fan et al. 2023). These interactions can lead to synergistic effects in the degradation of contaminants, as plant–microbe-biochar interactions create a more efficient and resilient remediation system.

7.2.3 Electron donor/acceptor provision

Engineered biochars possess enhanced electron storage capacity (ESC), allowing them to serve as both electron donors and acceptors in redox reactions (Xin et al. 2023). This property is particularly important in anaerobic environments, where biochar can act as an alternative electron acceptor, suppressing methanogenesis and promoting the oxidation of organic pollutants. For instance, air-oxidized biochar has been shown to support anaerobic oxidation of organic substrates, outcompeting methanogens and reducing methane production (Xin et al. 2023). Souza et al. (2024) used MnO-impregnated sugarcane bagasse for the removal of 2,4-dichlorophenoxyacetic acid and reported 57.19 mg g^{-1} adsorption due to the action of hydrogen bonding. Zhao et al. (2022a, b) used CuO-biochar for peroxydisulfate removal from soil and reported that the pollutant was removed through the formation of surface-bonding active complexes via an outer-sphere interaction between CuO-biochar contaminant as well as the continuous generation of $^1O_2$ through the cycling of the Cu(I)/Cu(II) redox couple. Engineered biochars can also be designed to generate reactive oxygen species (ROS) upon exposure to light, which can contribute to the degradation of organic pollutants (Wan et al. 2021). These ROS can rapidly degrade organic pollutants through various oxidation mechanisms. The activation of persulfate by biochar-supported catalysts represents another mechanism for pollutant degradation. Tao et al. (2022) reported that application of wood chips biochar coated with *Sphingobium yanoikuyae* B1 effectively removed naphthalene, phenanthrene, and pyrene. The suggested mechanisms proposed for this was that extracellular OH^- was produced through a Fenton-like reaction involved siderophore, H_2O_2, and Fe ions, which significantly enhanced pollutants removal. Tian et al. (2020) reported that Ferrate biochar removed sulfamethoxazole effectively through the action of intermediate Fe species during the oxidation process. This approach shows high selectivity towards electron-rich pollutants and effectively inhibits the formation of toxic byproducts (Guo et al. 2020).

7.3 Reduction of contaminant phytotoxicity

Engineered biochars reduce contaminants phytotoxicity through their immobilization or decreasing their bioavailability to plants (Guo et al. 2020; Akhil et al. 2021; Yu et al. 2019). For instance, engineered biochars can significantly alleviate cadmium damage to plants by reducing its uptake and migration in the soil–plant system (Jiang et al. 2022). This is accomplished through the alleviation of phytotoxicity, increased support for plant vigor, and stimulation of plant defense mechanisms against pollutants (Guo et al. 2020; Wang et al. 2020).

7.3.1 Alleviation of phytotoxic effects

The mechanisms by which engineered biochars alleviate metal phytotoxicity include surface complexation, electrostatic attraction, ion exchange, adsorption, and co-precipitation. For instance, acid-modified biochar effectively reduces soil pH and CEC, which can help in immobilization of heavy metals (Pan et al. 2022). In another study, $ZnCl_2$ and thiourea co-modified biochar was used for the removal of quinclorac and reported an adsorption capacity of 235.9 mg g^{-1} along with plant growth promotion due to less phytotoxicity in Tobacco plants (Ouyang et al. 2024). Similarly, Rafique et al. (2022) reported that Cr toxicity was alleviated after the application of polymer-modified biochar in wheat. The shoot length was increased up to 150%, while dry biomass was increased by 250%. Similarly, Dai et al. (2022) used magnetic *Enteromorpha prolifera* biochar for the alleviation of Cr phytotoxicity and reported that Cr uptake in barley plant was reduced up to 53.22%. Naeem et al. (2022) used FeO nanoparticles doped biochar for reducing metals toxicity in tomato. It was reported that As, Cr, Pb, and Cd availability in soil was reduced up to 78%, 58%, 46%, and 50%, thereby reduceding phytotoxicity chances to tomato plants. Similarly, Naeem et al. (2024) also used silicon-nanoparticles loaded biochar for As immobilization in soil during Barley production. It was reported that up to 71% reduced As movement was recorded in barley shoots, due to which, 94% higher yield was achieved. Wen et al. (2021) reported up to 60% increase in rice grain yield through Fe-modified biochar application in As, Cd and Pb contaminated soil, while Kang et al. (2024) reported that Cd and Zn uptake by foxtail millet decreased by 96.44% and 32.08% due to $KMnO_4$-hematite modified biochar application. A summary of such studies with specific mechanisms is given in (Table 4).

7.3.2 Retrieval of plant vigor

The application of engineered biochars improve retrieval of plant vigor in soils polluted with metals and organic contaminants. This adjustment in the soil environment not only reduces the metal's mobility and availability but also enhances the overall soil health through synthesizing a more favorable environment for plant growth. As a result, plants grown in engineered biochars amended soils often exhibit improved growth, increased biomass, and reduced metal accumulation in their tissues (Zhang et al. 2021). For example, the application of Fe-modified biochar improved the wheat crop growth and productivity. It was reported that dry matter production of roots, shoots, husk and grains were enhanced by 148.2%, 53.2%, 64.2% and 148%, respectively. It was noted that Cd levels were decreased in roots, shoots, husk, and grains by 23.7%, 44.5%, 33.2%, and 76.3%, respectively. The reason behind the improvements came out as soil enzymes modulation and increased nutrients availability e.g., soil urease, CAT and acid phosphatase activities were enhanced by 48.4%, 74.4% and 117.3%, respectively. Similarly, the soil nutrients availability e.g., N, P, K, and Fe to plants increased up to 22%, 25%, 7.3%, and 13.3%, respectively (Algethami et al. 2023). Han et al. (2023) reported that application of phosphorus-modified biochar to lettuce crop caused significant reduction in Pb and Cd uptake to lettuce plants along with improvements in lettuce productivity. It was reported that Lettuce biomass production was increased by 53.3%, while Pb and Cd concentrations were reduced by 56.79% and 44.56%, respectively. Ajmal et al. (2023) used magnetite nano-rods-modified biochar for Pb mobility and its transfer to soil and rice. It was reported that the application of magnetite nano-rods modified biochar reduced Pb toxicity in roots and shoots by 48.6% and 60.2%, respectively. It was noted that magnetite nano-rods modified biochar application to crop increased plant physiological attributes i.e., photosynthetic rate increased by 65.9%, while stomatal conductance by 138.7% due to chlorophyll contents increased up to 71.5%.

7.3.3 Stimulation of plant defense mechanisms

The application of engineered biochars significantly improves the plant tolerance to metal stress by strengthening the plant's antioxidant defense system e.g., upregulation of genes, increased activity of the glyoxalate system, and antioxidant enzymes (Zhou et al. 2023). This enhanced antioxidant capacity protects membrane lipids from oxidative stress caused by heavy metals. Additionally, engineered biochars can increase the expression of genes related to proline metabolism, such as P5CR and PRP5, which helps in maintaining osmotic balance and protecting cellular structures under metal stress (Zhou et al. 2023). Furthermore, engineered biochars also play a crucial role in improving photosynthetic efficiency in plants exposed to metal stress. By increasing the expression of Rubisco-S and Rubisco-L genes, they also help maintain higher levels of photosynthetic pigments and protect the photosynthetic apparatus (Zhou et al. 2023). This protective effect minimizes the negative impact of toxic metals on leaf function and overall plant growth. The immobilization of heavy metals in soil is another key mechanism through which engineered biochars alleviate phytotoxicity. They also effectively reduce the bioavailability of metals through various processes, including ion exchange, precipitation, electrostatic attraction, and complexation (Islam et al. 2021; Zhang et al. 2021). Razzaq et al. (2022) used nanoscale zerovalent-Fe-enriched biochar for Cd removal in maize contaminated soil. They reported enhanced maize growth (57%), chlorophyll contents (65%), intracellular permeability (61%), and plant biomass production (76%) through reducing Cd uptake through regulating Cd homeostasis in soil by 92%. The plant defense against Cd toxicity was regulated by 11.4% higher catalase, 10.7% SOD, and ascorbate peroxidase activity up to 31% in nanoscale zerovalent-Fe-enriched biochar. Irshad et al. (2022) used goethite-modified biochar to reduce As toxicity in rice crop. This treatment restricted the As movement to plants by 174% through promoting soil enzyme activities e.g., peroxidase (POD) and catalase (CAT) by 90% and 40%, respectively. Huang et al. (2023) also reported that ammonium polyphosphate modified biochar also reduced 2.57-fold Cd contents in soybean grains. Ghassemi-Golezani and Farhangi-Abriz (2023) reported that chemically modified biochar application in mint plants reduced Zn, Fe, Mg, and Ca concentrations in plants through the biochar addition triggered-activation of reduced pollutant entry in plant root cells via blocking apoplastic pathways. Biochar treatment increased the root cells viability and reduced fluoride (F), Cd contents, and oxidative damage.

7.4 Reduction of organic contaminant mobility

Engineered biochars reduce organic contaminant's mobility through enhanced adsorption mechanisms due to their higher surface area, improved pore structure, and modified surface chemistry (Akhil et al. 2021; Panwar and Pawar 2022). The primary mechanisms include pore-filling, partition, hydrophobic effects, H-bonding, and electrostatic attraction, and promotion of microbial activity (Guo et al. 2020).

7.4.1 Adsorption of organic pollutants

Engineered biochars exhibit enhanced adsorption capacity for organic contaminants due to their improved physicochemical properties, enhanced surface areas of more than 400 cm^3 g^{-1} to 1215 m^2 g^{-1} (Grimm et al. 2024) provides more adsorption sites for organic contaminants, enhancing the overall removal efficiency. The adsorption of organic contaminants by engineered biochars is influenced by several factors, including the biochar's surface chemistry, pore structure, and the nature of the contaminant. Nonpolar organic compounds are primarily adsorbed through pore-filling, partition, and hydrophobic effects, while polar organic compounds are adsorbed via H-bonding, electrostatic attraction, specific interaction, and surface precipitation (Guo et al. 2020). The high aromaticity and porosity of engineered biochars are essential for the sorption of organic contaminants (Braghiroli et al. 2018). The effectiveness of engineered biochars in reducing organic contaminant mobility is demonstrated by their high adsorption capacities. For example, activated biochar derived from hardwood spent mushroom substrate showed a maximum adsorption capacity of 236.8 mg g^{-1} for acetaminophen (Grimm et al. 2024). Similarly, reed-based biochar activated with KOH exhibited a significant improvement in tetracycline adsorption capacity, increasing by more than 20 times compared to non-activated biochar (Zhao et al. 2020).

The adsorption process of organic contaminants on engineered biochars typically follows pseudo-second-order kinetics and can be well-represented by models such as the Freundlich isotherm (Zhao et al. 2020). This indicates that the adsorption is primarily driven by chemical interactions between the contaminant and the biochar surface. Engineered biochars also demonstrate the ability to adsorb a wide range of organic contaminants simultaneously. A study on GO-functionalized biochars showed removal rates of 39.9–98.3% for six different organic micro-pollutants in water and treated wastewater (Regkouzas et al. 2023). This versatility makes engineered biochars particularly useful for addressing complex contamination scenarios. The effectiveness of engineered biochars in reducing organic contaminant mobility can be further enhanced by tailoring the activation process to target specific pollutants. For instance, the presence of oxygen-containing functional groups on the biochar surface can be optimized to improve the adsorption of certain organic contaminants (Xiong and Bi 2023). Chen et al. (2023a, b) reported > 95% removal efficacy of malachite green, bisphenol A, methylene blue, sulfamethoxazole, tetracycline, and thiacloprid from contaminated environments through $MnFe_2O_4$ modified biochar. It was revealed that contaminants were adsorbed on biochar doping sites, which were created after biochar treatment with Peroxymonosulfate activation using $MnFe_2O_4$. Song et al. (2022) used H_3PO_4-modified TiO_2 nanoparticles anchored on biochar for dyes removal and reported similar results. Similarly, Liang et al. (2022) used Fe–Mn-modified biochar for atrazine removal in soil and reported 79.5% efficacy due to the formation of oxygen functional groups (OH, C = C, and C = O) and Fe_3O_4, Mn_3O_4, and $FeMnO_3$ on modified biochar which facilitated that enhanced atrazine removal.

7.4.2 Hydrophobic interaction

Engineered hydrophobic biochars demonstrate a higher affinity for organic pollutants. The addition of engineered biochars significantly increased the adsorption of organic pollutants through the hydrophobic interactions, i.e., hydrophobic surfaces of engineered biochars attract and retain organic contaminants, effectively removing them from the soil solution (Islam et al. 2021). Similarly, the increased porosity and specific surface area of engineered biochars allow for the physical entrapment of organic pollutants within their pore structures (Guo et al. 2020; Islam et al. 2021). Partitioning is another mechanism, while weak intermolecular forces contribute to the adsorption of organic pollutants onto the hydrophobic biochar surfaces (Islam et al. 2021). Qiu et al. (2022) used biochar-based asymmetric membrane for mixed organic pollutants remediation through hydrophobic interaction and reported 78.85% removal efficacy. Le and Hwang (2023) reported that alkali-activated rice husk biochar usage in soil polluted with multiple organic contaminants through hydrophobicity activated sorption mechanism. Similarly, Fe–MnO modified biochar was used by Gao et al. (2021) for phthalate pollution remediation in wheat cultivated soil and reported its effectiveness for phthalate entry into the wheat plant along with improving its grain yield by 208.7%. Gao et al. (2023) used carboxymethyl cellulose-modified FeO-biochar for PAHs removal form soil and reported up to 100% pyrene removal, while total pollutants removal rate was achieved up to 61.1%.

7.5 Facilitation of phytoremediation processes

Engineered biochars can effectively reduce the bioavailability of heavy metals and organic pollutants in soil, thereby decreasing their uptake by plants. For instance, UV-modified biochars have shown significant reductions in $CaCl_2$-extractable Cd and plant Cd uptake (Zhang et al. 2021). Additionally, engineered biochars can enhance soil pH and electrical conductivity, promotion of phytoextraction, phytostabilization, and enhanced roots growth (Zhang et al. 2021).

7.5.1 Promotion of phytoextraction

Phytoextraction is a key mechanism of phytoremediation in which plants uptake contaminants from the soil and accumulate them in above and belowground biomass. Engineered biochars facilitate this process by improving contaminant bioavailability, enhancing plant growth, and modulating soil microbial activity to optimize heavy metal and organic pollutants uptake (Murtaza et al. 2024). Moreover, through modulation of soil pH and redox conditions, biochars also influence metal speciation, such as FeO-enriched biochars facilitated conversion of As into its more mobile form As(III), i.e., up to 7.72 mg g^{-1} As(III), thereby improving its uptake and subsequent removal from contaminated soil (Xu et al. 2021). Similar results were reported by Zhang et al. (2021) when they used UV-modified biochar for Cd remediation in *Coriandrum sativum* L. cultivated soil. They reported up to 51.4% Cd remediation efficacy during the plant life cycle. Similarly, phosphorus-loaded biochar was used by Serrano et al. (2024) and they reported that up to 11.6% of the metals (Cd, Cr, and Pb) were extracted in the plant tissues after biochar application than respective control.

Additionally, biochars doped with nitrogen and phosphorus compounds supply essential nutrients, promoting root elongation and increasing root surface contact with contaminants, thereby facilitating additional capacity of pollutants translocation from soil to plant tissues (Zhang et al. 2021). Ding et al. (2022) also reported that phosphorus loaded biochar application enhanced phytoextraction by restricting Cd, Pb, Zn, and Cu entry in tomato fruit and soil by 58% and 72%, respectively. Some biochars are infused with plant growth-promoting bacteria (PGPB) or mycorrhizal fungi, which enhance nutrient acquisition and stress resilience, enabling plants to accumulate higher contaminant loads. Moreover, biochar-mediated changes in soil microbial diversity further enhance contaminant breakdown and mobilization. Moreover, functionalized biochars can host microbial consortia capable of degrading organic pollutants or mobilizing metals through biosurfactant production, improving phytoextraction efficiency. Shi et al. (2023) reported that biochar loaded with bacteria (*Burkholderia contaminans* ZCC) enhanced the potential of Cd and Zn accumulation in the plant *Sedum alfredii* by 230.13% and 381.27%, respectively. Song et al. (2022) reported that biochar-immobilized *Bacillus sp.* KSB7 application effectively immobilized the PAHs and metals (Zn, Pb, Cr, Cu) by 94.17%, 58.46%, 53.42%, 84.94%, and 83.15% in polluted soil of coking plant. PGPR-augmented biochar also remediated Cd stress on sunflowers (*Helianthus annuus* L.) in saline-alkali soil. It was reported that biochar application enhanced soil enzyme activities which in turn reduced soil EC which reduced Cd in plant by 92.5%.

7.5.2 Support for phytostabilization

Engineered biochars facilitate phytostabilization through enhancing soil structure, adsorbing and stabilizing contaminants, modulating microbial communities, and improving plant stress tolerance (Zhang et al. 2021). Naveed et al. (2021) reported that co-composted biochar helped in the stabilization of Cr in *Brassica* grown on Cr-contaminated soil. It was reported that brassica plant growth was enhanced i.e., plant height (75.3%), root length (151.0%), shoot dry weight (139.4%), root dry weight (158.5%), and photosynthetic rate (151.0%) along with reduced Cr accumulation in grain, shoot, and roots by 4.12, 2.27, and 2.17 folds, while enhanced Cr accumulation in soil by 1.52-fold. Zhang et al. (2021) studied the effects of applying *Enterobacter* sp. YG-14 combined with sludge biochar on *Robinia pseudoacacia* L. growth in Cd contaminated soils. It was reported that Cd pollution was reduced by 69.01%, while phytostabilization capacity of the system was recorded as 81.42% and 72.73% reduction in Cd movement from to root–shoot system. Similarly, engineered biochars enriched with minerals, i.e., Ca, Mg, and Fe promote the formation of stable metal precipitates, such as carbonates and oxides, further reducing contaminant mobility. Chelator-modified biochar was used in a field experiment to evaluate the stabilization effects by different plants (*Achnatherum splendens*, *Puccinellia chinampoensis*, and *Chinese small iris*). It was reported that up to 49.8% stabilization effect was recorded for As, Cu, Pb, and Zn after biochar application (Liu et al. 2022). Zanganeh et al. (2022) also reported similar results after use of cyanobacteria and biochar inoculation with up to 90% phytostabilization efficiency of purslane (*Portulaca oleracea* L.). Similarly, engineered biochars inoculation with beneficial microbial consortia capable of producing extracellular polymeric substances (EPS) further stabilize heavy metals by forming insoluble complexes in the rhizosphere. Additionally, biochars doped with phosphate-solubilizing bacteria (PSB) facilitate the precipitation of toxic metals as metal-phosphate complexes, reducing their bioavailability. Biochar synergized with *Bacillus cereus* PSB-2 was used to remediate Pb and Cd. It was reported that Pb and Cd extractable forms were decreased up to 65.06 and 71.26%, indicating their stabilization in soil (Zhang et al. 2025). Anbuganesan et al. (2024) reported that biochar augmented with PGPR *Bacillus pseudomycoides* strain ARN7 during maize growth in Ni and Zn contaminated soil maize growth, physiology and yield after PGPR augmented biochar was applied. It was recorded that up to 58% Ni and Zn concentrations were reduced in plant tissues compared to control.

7.5.3 Enhanced root growth and function

Engineered biochars facilitate roots growth and their functioning through augmenting soil properties for their growth i.e., reducing bulk density, loosening the soil matrix and allowing roots to penetrate deeper and spread more extensively (Naveed et al. 2021). The enhanced porosity also improves oxygen diffusion in the rhizosphere, which is essential for root respiration and microbial activity. Han et al. (2023) reported that enhanced soil porosity and WHC due to P-modified biochar addition, which promoted roots growth and functions in Pb and Cd contaminated soils. Additionally, biochars enriched with essential macronutrients such as N, P, and K, as well as micronutrients like Fe, Zn, and Mg, enhance root growth by providing readily available nutrients that support cell division, elongation, and overall plant vigor (Zhang et al. 2021), which mitigates nutrient deficiencies commonly found in contaminated or degraded soils, ensuring that plants establish robust root systems capable of sustaining high biomass for phytoremediation. Wang et al. (2023a, b, c) reported that P-modified biochar addition to Cd contaminated soil under wheat production. It was reported that P-modified biochar addition increased the roots growth and diameter (0.338 mm), which promoted higher Cd remediation through EPS secretion and Cd stabilization in soil.

Additionally, engineered biochars enhance root exudation, which stimulate the production of organic acids, chelating agents, and signaling molecules that mobilize metals, degrade organic pollutants, or recruit beneficial microbes (Naveed et al. 2021). El-Desouki et al. (2025) reported that P-laden biochar addition in aluminum contaminated soil under Pakchoi (*Brassica chinensis* L.) and reported up to 83.88% reduced aluminum toxicity, which was attributed to soil enzymes activities enhancement due to biochar addition and root exudates secretion. Thus, through integration of engineered biochars with phytoremediation strategies, contaminated sites can be restored through an efficient way, making this a valuable tool for sustainable soil remediation and rhizosphere engineering.

8 Challenges and opportunities in the tripartite nexus

The application of engineered biochar in the tripartite nexus of crop production, crop protection, and environmental remediation presents a unique set of challenges and opportunities (Table 6). While biochar offers immense potential to address multiple agricultural and environmental issues, its implementation is often hindered by technical, economic, and practical constraints. At the same time, the synergistic effects of biochar, innovative applications, and its role in climate change mitigation provide significant opportunities for sustainable development.

8.1 Challenges

8.1.1 Balancing multiple objectives

One of the primary challenges in using biochar for the tripartite nexus is achieving synergy across diverse objectives of enhancing crop productivity, suppressing pests and pathogens, and remediating contaminated soils (Table 6). Biochar must simultaneously enhance crop productivity, protect crops from pests and diseases, and remediate contaminated soils. Biochar's efficacy in these roles depends on competing physicochemical properties, necessitating careful trade-off management. However, the properties of biochar that benefit one objective may not always align with those required for another. For example, highly adsorptive or metal-impregnated biochars optimized for heavy metal immobilization may limit nutrient bioavailability, adversely affecting crop growth (Lwin et al. 2018). Similarly, optimizing biochar for crop production may prioritize nutrient availability, while remediation might require immobilization of contaminants, potentially limiting nutrient accessibility. While biochar enhances nutrient retention (e.g., NH_4^+, PO_4^{3-}) through cation exchange and surface adsorption (Dey et al. 2023), its efficacy in immobilizing contaminants (e.g., heavy metals, organic pollutants) depends on feedstock and pyrolysis conditions. For instance, high-temperature biochars (> 600 °C) exhibit greater aromaticity and surface area, favoring contaminant sorption, but may reduce nutrient availability due to decreased functional groups (e.g., -COOH, -OH). As recently reviewed by Wang et al. (2020) that biochars pyrolyzed at 400–500 °C retained ~ 60–80% of cationic nutrients while immobilizing > 50% of Cd/Pb, whereas 700 °C biochars sequestered > 90% of metals but retained < 40% of NH_4^+. This necessitates a tailored approach to biochar engineering, where specific modifications are made to address the unique needs of each application and prevailing site conditions. Balancing these objectives requires a deep understanding of the interactions between biochar, soil, plants, and microorganisms. The amount of biochar required to effectively remediate a contaminated site might differ from what is optimal for crop production or protection. High biochar concentrations could immobilize contaminants effectively but might also alter soil pH or nutrient dynamics, leading to potential nutrient deficiencies or imbalances (Hossain et al. 2020). Furthermore, the effects of biochar in the rhizosphere are not uniform over time or space. For example, biochar might initially enhance nutrient availability but later reduce it as its sorption sites become saturated with contaminants or nutrients (Ahmad et al. 2017). This variability makes it challenging to design a one-size-fits-all approach for the tripartite nexus. Furthermore, biochar stability varies significantly by soil type. In sandy or acidic soils, biochar may degrade faster or leach metals, while in alkaline or clay-rich soils, it may persist longer but alter microbial composition (Hossain et al. 2020). These soil-specific responses complicate standardization and highlight the need for long-term field trials to evaluate biochar persistence and effectiveness under real-world conditions (Wang et al. 2021a, b, c). To mitigate conflicts between functions, systems-based solutions such as the co-application of multiple engineered biochars (e.g., microbial-enhanced + adsorptive biochar) or composite biochars (e.g., nanocomposite ISR biochars) can be used. These combinations can align agronomic and environmental goals more effectively than single-function biochars. Finally, a practical decision-making framework, such as that presented in Fig. 8 and Table 6, can aid in selecting suitable biochar types for specific objectives and site conditions.

8.1.2 Complexity of rhizosphere interactions

The introduction of biochar into the rhizosphere can have unpredictable effects on microbial communities. For instance, while biochar can enhance microbial activity in some soils, it may suppress beneficial microbes in others due to changes in pH or nutrient availability (Palansooriya

Table 6 Trade-offs and considerations in biochar application for crop production, crop protection, and soil remediation

Area of focus	Target	Trade-off	Consideration for balancing goal	Reference
Crop production	Enhance crop growth and yield	Biochar designed for nutrient enhancement may not be suitable for contaminant immobilization	Adjust biochar dose based on crop needs and soil characteristics	Lwin et al. (2018)
		Different crops and soil types require varying amounts of biochar for optimal results	Regularly assess soil nutrient levels and biochar's impact, adjusting application as necessary	Joseph et al. (2021) Streubel et al. (2011)
		Initial benefits may diminish as biochar's sorption sites become saturated	Consider long-term effects of biochar on soil fertility and nutrient availability	Ahmad et al. (2017)
Crop protection	Improve resistance to pests and diseases	Biochar may affect both harmful and beneficial microbes, leading to unpredictable pest control outcomes	Combine biochar with other pest control methods to enhance effectiveness	Palansooriya et al. (2019) Brtnicky et al. (2021)
		Biochar's pest protection efficacy might vary with soil type and pest pressure	Continuously monitor pest populations and adjust biochar application to maintain optimal protection	Gao et al. (2018) Bonanomi et al. (2021)
		Effectiveness can fluctuate over time as biochar interacts with soil and pest dynamics	Use biochar with properties that support beneficial microbes and enhance pest resistance	Iacomino et al. (2022)
Remediation	Remove or reduce contaminants from soil	Biochar optimized for contaminant removal may limit nutrient availability for crops	Design biochar specifically for the type and level of contamination	Hossain et al. (2020)
		Effective remediation may require higher or lower biochar rates compared to those used for crop production	Adjust biochar application rates and types based on contamination levels and monitoring results	O'Connor et al. (2018) Beesley et al. (2011)
		Biochar may become saturated with contaminants, reducing its effectiveness over time	Regularly evaluate biochar's performance in remediation and adjust as needed to maintain effectiveness	Ahmad et al. (2017) Anae et al. (2021)

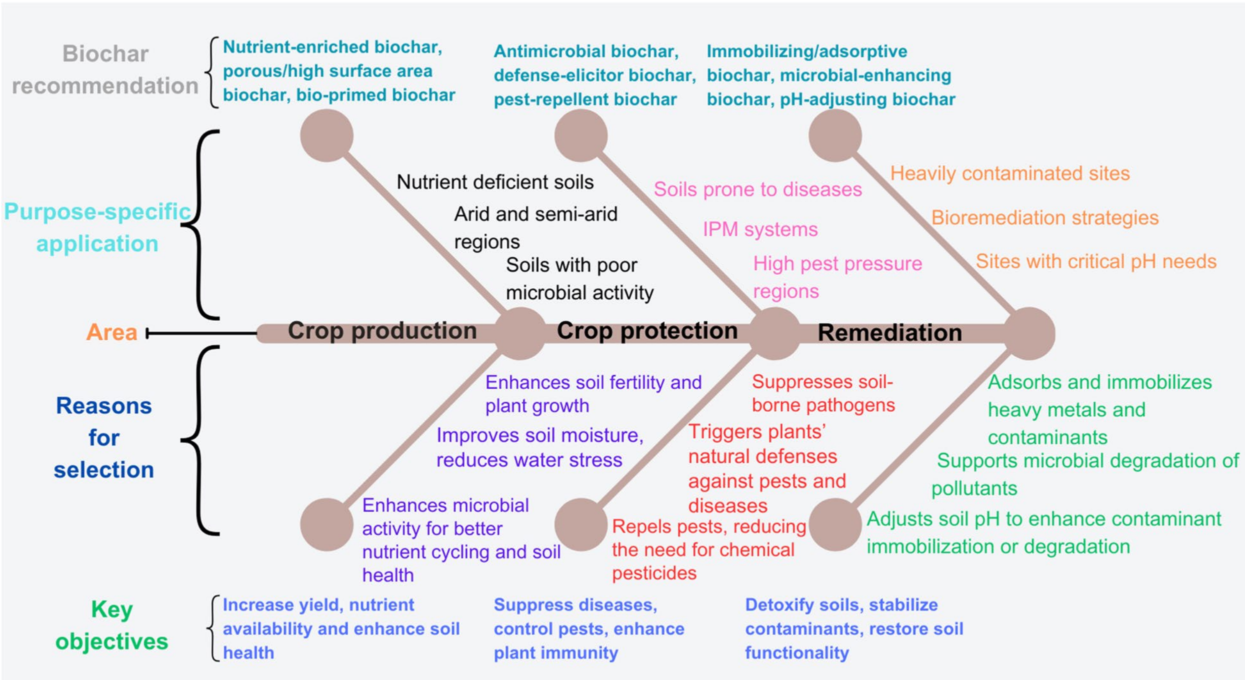


Fig. 8 Purpose-specific engineering and application of biochar: a practical guide for crop production, protection, and soil remediation

et al. 2019). While some microbes may thrive, others could be inhibited, leading to changes in nutrient cycling, disease suppression, or contaminant degradation that are difficult to predict and manage (Table 6). Understanding these complex interactions is critical for optimizing biochar applications, but it remains a major research gap. Moreover, the presence of mixed contaminants in soils, such as heavy metals, organic pollutants, and salts, adds complexity to remediation efforts (Chirakkara et al. 2016). Biochar's ability to simultaneously immobilize multiple contaminants while supporting plant growth and protection may be limited by these complex interactions.

8.1.3 Economic constraints, policy implications and socio-economic factors

Producing and applying biochar at scales large enough to impact all three goals can be cost-prohibitive (Pierson, et al. 2024). As shown in Table S1, the cost of biochar production can be high, particularly for engineered biochar with specific properties (e.g., nutrient-enriched or nanocomposite biochar). While biochar's economic viability is often debated (Campion et al. 2023; Meyer et al. 2011), our study focuses on the functional potential of engineered biochar in the rhizosphere for tripartite benefits (crop production, protection, and remediation). Existing analyses highlight that profitability depends on highly variable factors (e.g., feedstock, scale, and local policy frameworks), making generalized cost–benefit assessments challenging. For instance, Campion et al. (2023) note that private investment is hindered by case-specific uncertainties, while Meyer et al. (2011) emphasizes the lack of standardized profitability comparisons across technologies. However, these broader economic considerations, though critical for large-scale adoption, are secondary to our goal of demonstrating engineered biochar's agronomic and environmental efficacy. Therefore, the cost and benefit ratio of engineered biochar usage is the least discussed here due to several earlier works such as (Campion et al. 2023). Additionally, the scalability of biochar applications is often limited by logistical challenges, such as the availability of feedstock, transportation costs, and the need for specialized equipment (Pierson et al. 2024). Strategies such as co-utilization of agricultural waste, low-cost biochar engineering techniques, and public–private partnerships could help scale adoption sustainably. Farmers and stakeholders may also lack the knowledge or resources to implement biochar-based solutions effectively, further hindering their adoption. Policy support is thus critical to promote biochar integration into climate-smart agriculture and circular bioeconomy frameworks. For example, biochar can be integrated into carbon credit schemes or incentivized through subsidies for sustainable soil amendments. However, clear regulatory guidelines are often lacking, particularly concerning biochar classification, quality assurance, and application rates, which hinders farmer confidence and market growth. Furthermore, the economic benefits of using biochar for crop production and protection may not immediately offset the costs associated with remediation, particularly in low-value agricultural lands. It has been estimated that biochar production cost ranges from 448 to 1847 Mg^{-1} but can be reduced if a circular bioeconomy has been set up. Moreover, to cure the production costs, biochar production and use should be at the nearest to avoid its transportation costs. The nearness of the place with ample supply of biomass for biochars production is also a plus (Nematian et al. 2021). Furthermore, considering its zero global warming potential and reducing greenhouse gas emissions up to 54%, it could earn economic return through carbon credits (Saharudin et al. 2024). Furthermore, increase in yield, decreased input costs in terms of fertilizers, pesticides, and water also yield good economic returns. But the long-term impact of biochar on soil health and its effectiveness in maintaining the balance between crop production, protection, and remediation under long-term studies are needed to assess the sustainability of biochar-based interventions.

8.2 Opportunities

8.2.1 Synergistic effects

Despite these challenges, biochar offers synergistic effects that can simultaneously address multiple objectives in the tripartite nexus (Table S1). Biochar can be used as part of an integrated management strategy that simultaneously addresses crop production, protection, and remediation. For example, biochar's ability to improve soil structure and water retention can benefit all three areas by enhancing root growth, reducing erosion, and facilitating contaminant immobilization (Kamali et al. 2022; Qian et al. 2023). The use of biochar to create favorable conditions for beneficial microbes offers the potential to simultaneously improve crop productivity, protect against soil-borne diseases, and enhance the degradation of organic contaminants (Abid et al. 2023; Shanmugaraj et al. 2024). Leveraging these microbial synergies can lead to more effective and efficient management practices. Moreover, advances in biochar production techniques could lead to the development of biochars with tailored properties that address multiple objectives simultaneously. For example, biochars engineered with specific functional groups could enhance nutrient availability for crops while immobilizing heavy metals and promoting microbial degradation of organic pollutants (Xiang et al. 2022).

8.2.2 Innovative applications

The development of innovative applications for biochar further expands its potential in the tripartite nexus. The use of precision agriculture technologies, such as targeted biochar application and real-time monitoring of soil conditions (Fan et al. 2022), offers opportunities to optimize biochar use for achieving multiple goals. Developing biochar blends or composites with other soil amendments, such as compost, lime, or fertilizers, could enhance their multifunctionality. These composites could be designed to simultaneously improve soil fertility, reduce pathogen loads, and immobilize contaminants, offering a more holistic approach to soil management. Similarly, bioprimed biochar, which is enriched with beneficial microbes, can improve crop productivity and protection by enhancing symbiotic relationships and inducing systemic resistance in plants (Singh et al. 2015). These innovative applications demonstrate the potential for biochar to address complex agricultural and environmental challenges.

8.2.3 Climate change mitigation

The use of biochar for soil improvement also contributes to carbon sequestration, offering an additional benefit of mitigating climate change (Mekuria and Noble 2013). This dual role of biochar in both improving soil health and sequestering carbon provides an opportunity to align agricultural practices with broader environmental goals (Wang et al. 2023a, b, c). The stable carbon structure of biochar makes it resistant to decomposition, allowing it to store carbon for hundreds to thousands of years (Spokas 2010; Chen et al. 2019). Biochar's ability to improve soil water retention and nutrient availability can enhance the resilience of crops to climate-induced stresses, such as drought and extreme temperatures (Murtaza et al. 2025). This resilience is particularly important in contaminated sites, where stress factors are often exacerbated. Additionally, biochar can reduce emissions of nitrous oxide (N_2O) and methane (CH_4) from agricultural soils, further contributing to climate change mitigation (Kammann et al. 2017). These climate benefits, combined with the potential for carbon credits, provide economic incentives for biochar adoption.

9 Practical guides to biochar selection

Based on the discussions above, a practical guide for selecting, engineering, and applying biochar in crop production, crop protection, and remediation is presented (Fig. 8). This section emphasizes the need for a tailored, context-specific approach, as applying a one-size-fits-all biochar often leads to suboptimal or even counterproductive outcomes.

Despite the broad recognition of biochar's benefits, applying a single biochar formulation across different agricultural and environmental contexts often fails to optimize its potential. The amount, type, and modification of biochar must be carefully designed for specific functional goals, as trade-offs exist between maximizing nutrient availability for crops, suppressing pathogens, and remediating contaminated soils. For example, crop production requires biochar that enhances nutrient availability (e.g., nutrient-enriched or microbial-activating biochar), while remediation often demands biochar with strong contaminant immobilization properties, which may reduce nutrient bioavailability (Li et al. 2019; Beesley et al. 2011). Nutrient-enriched biochar may be unsuitable for remediation sites, where nutrient solubilization could increase contaminant mobility rather than reduce it. Similarly, water-retaining biochar is essential in arid regions but may contribute to waterlogging in high-rainfall areas, adversely affecting plant growth (Li et al. 2021a, b) Its applications should thus be avoided in poorly drained or flood-prone regions, as it may exacerbate waterlogging and root diseases. Additionally, antimicrobial biochar designed for crop protection against pathogens may also reduce beneficial microbial communities, leading to unintended soil fertility issues (Tsang and Ok 2022). Thus, one should be cautious to use antimicrobial biochar in soils where beneficial microbial diversity is crucial for nutrient cycling or symbiotic root interactions, as it may suppress both harmful and helpful organisms.

Such trade-offs must be carefully managed. For example, while metal-rich biochars are effective in immobilizing contaminants, they may also limit nutrient bioavailability. Similarly, disease-suppressing biochars may disrupt plant-beneficial microbial populations. Integrating different biochar types such as combining adsorptive with microbial biochar can help balance competing goals. Therefore, a tailored approach is required, considering biochar properties, application rates, soil conditions, and intended outcomes for long-term sustainability and effectiveness. In conclusion, the selection of purpose-specific biochar is essential for achieving optimal outcomes in crop production, crop protection, and environmental remediation. The key to successful implementation lies in matching biochar properties with specific agro-environmental goals nutrient supply, disease resistance, or pollutant immobilization while considering local soil characteristics, climate, crop type, and management constraints. Figure 8 serves as a visual tool for guiding biochar selection and application in a goal-oriented and site-specific manner.

10 Conclusion

Engineered biochar has emerged as a multifunctional, purpose-specific amendment that plays a transformative role in rhizosphere engineering by enhancing crop production, crop protection, and environmental remediation. Unlike conventional biochar, engineered biochars are tailored through nutrient enrichment, microbial priming, nanoparticle incorporation, or surface activation to optimize specific soil–plant-microbe interactions. In crop production, engineered biochar enhances nutrient availability, water retention, and microbial activity, leading to increased plant productivity. It stimulates beneficial microbial communities, such as mycorrhizal fungi and plant growth promoting rhizobacteria, which improve nitrogen fixation, phosphorus solubilization, and organic matter decomposition. The rhizosphere engineering potential of nutrient-enriched and microbial-activating biochars ensures that crops receive sustained nutrient supply, optimizing plant health and yield via multifaceted mechanisms. In crop protection, biochar-based rhizosphere engineering suppresses soil-borne pathogens, enhances plant immunity, and repels pests. Antimicrobial biochars enriched with functionalized nanoparticles or natural plant defense compounds create a rhizosphere that is less hospitable to pathogens. Additionally, defense-elicitor biochars can activate plant immune responses, reducing dependency on chemical pesticides. This approach reinforces plant resilience against diseases while minimizing environmental risks. In soil remediation, biochar-based rhizosphere engineering facilitates contaminant immobilization, microbial degradation, and pH regulation. Contaminant-immobilizing biochars effectively bind heavy metals and organic pollutants, reducing their bioavailability. Additionally, microbial enhancing biochars support degrading consortia, which can accelerate the breakdown of contaminants in polluted soils. This ensures the long-term restoration of soil health and functionality.

This review consolidates current advances, illustrating how engineered biochar enhances nutrient availability, stimulates beneficial microbial communities, suppresses pathogens, and immobilizes contaminants through finely tuned rhizospheric mechanisms. However, one-size-fits-all applications remain ineffective due to inherent trade-offs such as nutrient availability and contaminant immobilization, and the strike between the balance of harmful and beneficial soil microbes. These complexities are further compounded by biochar's variable performance across soil types, temporal shifts in effectiveness due to aging, and microbial adaptation in the rhizosphere. Therefore, the widespread application of biochar requires a nuanced, context-specific approach rather than a universal prescription. Practical implementation must consider soil pH, texture, crop demand, local environmental stressors, and socio-economic viability. While the benefits of engineered biochar are well documented, yet, challenges remain, including: (i) the need for long-term field studies across agroecological zones, (ii) mechanistic insights into rhizosphere modulation, (iii) economic and logistical barriers to large-scale adoption, (iv) the development of policy frameworks to regulate and support engineered biochar applications, and (v) the development of predictive models to match biochar types with intended functions. Moving forward, a systems-based approach integrating biochar engineering with precision agriculture, microbial biotechnology, and climate-resilient cropping systems, alongside supportive policy frameworks, will be critical to unlocking biochar's full potential. As agriculture faces mounting pressure from climate change, resource limitations, and pollution, engineered biochar offers a promising pathway to sustainably manage soils, secure yields, and restore degraded ecosystems.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-025-00521-8.

Additional file1 (DOCX 19 kb)

Author contributions

Conceptualization: Adnan Mustafa, Muhammad Naveed, Qudsia Saeed, Xiankai Lu; Data curation: Jiri Holatko, Zia Ur Rahman Farooqi, Adnan Mustafa, Usman Arshad, Ansa Rebi; Formal analysis: Mohsin Mahmood, Qudsia Saeed, Weibin Chen, Wentao Wei, Adnan Mustafa, Usman Arshad, Muhammad Amjad Ali; Funding acquisition: Abdul Ghafoor, Xiankai Lu, Martin Brtnicky; Investigation: Muhammad Naveed, Jiri Holatko; Methodology: Muhammad Naveed, Ansa Rebi, Adnan Mustafa; Project administration: Muhammad Naveed, Writing—original draft: Adnan Mustafa, Qudsia Saeed, Zia Ur Rahman Farooqi, Usman Arshad, Jiri Holatko; and Writing—review & editing: Jiri Kucerik, Xiankai Lu, Martin Brtnicky, Muhammad Amjad Ali, Muhammad Naveed.

Funding

This study was supported by National Key R&D Program of China (No. 2024YFF1306600), Key Research and Development Program of Guangdong Province (No. 2022B1111230001), and National Natural Science Foundation of China (No. 32271687), Guangdong Science and Technology Plan Project (2023B1212060046), Guangzhou Science and Technology Plan Project (2024A04J6441), and by Horizon Europe project EMBEDED under grant agreement ID 101182442. This work was also financed by the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia [Project No. KFU253165].

Data availability

All data generated or analyzed during this study are included in this published article (article and supplementary materials).

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.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Author details

[1]Guangdong Provincial Key Laboratory of Applied Botany, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China. [2]Key Laboratory of National Forestry and Grassland Administration on Plant Conservation and Utilization in Southern China, Guangzhou 510650, Guangdong, China. [3]Yunnan Provincial Key Lab of Soil Carbon Sequestration and Pollution Control, Faculty of Environmental Science and Engineering, Kunming University of Science and Technology, Kunming 650500, China. [4]Yunnan International Joint Laboratory for Emission Reduction and Carbon Sequestration in Agricultural Soils, Kunming 650500, China. [5]Key Laboratory of Tobacco Pest Monitoring and Integrated Management, Tobacco Research Institute of Chinese Academy of Agricultural Sciences, Qingdao 266000, China. [6]Department of Agrochemistry, Soil Science, Microbiology and Plant Nutrition, Faculty of AgriSciences, Mendel University in Brno, 613 00 Brno, Czech Republic. [7]Key Laboratory of Grassland Ecology, School of Ecology and Environment, Inner Mongolia University, Hohhot 010020, China. [8]Department of Landscape Ecology, Landscape Research Institute, Lidicka 25/27, 60200 Brno, Czech Republic. [9]Jianshui Research Station, School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, People's Republic of China. [10]Department of Plant Pathology, University of Agriculture Faisalabad, Faisalabad 38000, Pakistan. [11]Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad 38040, Pakistan. [12]Center for Water and Environmental Studies, King Faisal University, 31982 Al-Ahsa, Saudi Arabia.

Received: 17 April 2025 Revised: 8 September 2025 Accepted: 11 September 2025
Published online: 03 January 2026

References

Abdellatef MA, Elagamey E, Kamel SM (2022) Chitosan is the ideal resource for plant disease management under sustainable agriculture. InChitin and Chitosan-isolation, properties, and applications IntechOpen https://doi.org/10.5772/intechopen.107958

Abid F, Naz R, Asif T (2023) Biochar for crop protection from soil borne diseases. Sustainable agriculture reviews 61: biochar to improve crop production and decrease plant stress under a changing climate. Springer, Cham, pp 231–246

Aftab ZE, Aslam W, Aftab A, Shah AN, Akhter A, Fakhar U, Siddiqui I, Ahmed W, Majid F, Wróbel J, Ali MD (2022) Incorporation of engineered nanoparticles of biochar and fly ash against bacterial leaf spot of pepper. Sci Rep 12(1):8561

Ahmad CA, Akhter A, Haider MS, Abbas MT, Hashem A, Avila-Quezada GD, Abd Allah EF (2024) Demonstration of the synergistic effect of biochar and Trichoderma harzianum on the development of Ralstonia solanacearum in eggplant. Front Microbiol 15:1360703

Ahmad M, Wang XK, Hilger TH, Luqman M, Nazli F, Hussain A et al (2020) Evaluating biochar-microbe synergies for improved growth, yield of maize, and post-harvest soil characteristics in a semi-arid climate. Agronomy-Basel 10(7):19

Ahmad M, Lee SS, Lee SE, Al-Wabel MI, Tsang DCW, Ok YS (2017) Biochar-induced changes in soil properties affected immobilization/mobilization of metals/metalloids in contaminated soils. J Soils Sediments 17:717–730

Ahmed T, Noman M, Luo J, Muhammad S, Shahid M, Ali MA, Zhang M, Li B (2021) Bioengineered chitosan-magnesium nanocomposite: a novel agricultural antimicrobial agent against *Acidovorax oryzae* and *Rhizoctonia solani* for sustainable rice production. Int J Biol Macromol 168:834–845

Ajeng AA, Abdullah R, Ling TC, Ismail S, Lau BF, Ong HC, Chew KW, Show PL, Chang JS (2020) Bioformulation of biochar as a potential inoculant carrier for sustainable agriculture. Environ Technol Innov 20:101168

Ajmal Z, Kashif Irshad M, Qadeer A, Zia Ul Haq M, Ullah R, Aqeel Sarwar M et al (2023) Novel magnetite nano-rods-modified biochar: a promising strategy to control lead mobility and transfer in soil-rice system. Int J Environ Sci Technol 20(7):7543–7558

Akhil D, Arun J, Lakshmi D et al (2021) Production, characterization, activation and environmental applications of engineered biochar: a review. Environ Chem Lett 19:2261–2297. https://doi.org/10.1007/s10311-020-01167-7

Akhter A, Hage-Ahmed K, Soja G, Steinkellner S (2015) Compost and biochar alter mycorrhization, tomato root exudation, and development of Fusarium oxysporum f. sp. lycopersici. Front Plant Sci 6:529

Alfei S, Schito GC, Schito AM, Zuccari G (2024) Reactive oxygen species (ROS)-mediated antibacterial oxidative therapies: available methods to generate ROS and a novel option proposal. Int J Mol Sci 25(13):7182

Algethami JS, Irshad MK, Javed W, Alhamami MA, Ibrahim M (2023) Iron-modified biochar improves plant physiology, soil nutritional status and mitigates Pb and Cd-hazard in wheat (Triticum aestivum L.). Front Plant Sci 14:1221434
Alhashimi HA, Aktas CB (2017) Life cycle environmental and economic performance of biochar compared with activated carbon: a meta-analysis. Resour Conserv Recycling 118:13–26
Ali A, Elrys AS, Liu L, Xia Q, Wang B, Li Y, Dan X, Iqbal M, Zhao J, Huang X, Cai Z (2023) Deciphering the synergies of reductive soil disinfestation combined with biochar and antagonistic microbial inoculation in cucumber fusarium wilt suppression through rhizosphere microbiota structure. Microb Ecol 85(3):980–997
Almanassra IW, McKay G, Kochkodan V, Ali Atieh M, Al-Ansari T (2021) A state of the art review on phosphate removal from water by biochars. Chem Eng J 409:128211
Al Masud MA, Annamalai S, Shin WS (2023) Remediation of ciprofloxacin in soil using peroxymonosulfate activated by ball-milled seaweed kelp biochar: performance, mechanism, and phytotoxicity. Chem Eng J 465:142908
Amendola C, Montagnoli A, Terzaghi M, Trupiano D, Oliva F, Baronti S, Miglietta F, Chiatante D, Scippa GS (2017) Short-term effects of biochar on grapevine fine root dynamics and arbuscular mycorrhizae production. Agric Ecosyst Environ 239:236–245
Ameur D, Zehetner F, Johnen S, Jochlinger L, Pardeller G, Wimmer B et al (2018) Activated biochar alters activities of carbon and nitrogen acquiring soil enzymes. Pedobiologia 69:1–10
Anae J, Ahmad N, Kumar V, Thakur VK, Gutierrez T, Yang XJ, Cai C, Yang Z, Coulon F (2021) Recent advances in biochar engineering for soil contaminated with complex chemical mixtures: remediation strategies and future perspectives. SciTotal Env 767:144351
Anbuganesan V, Vishnupradeep R, Bruno LB, Sharmila K, Freitas H, Rajkumar M (2024) Combined application of biochar and plant growth-promoting rhizobacteria improves heavy metal and drought stress tolerance in Zea mays. Plants 13(8):1143
Antonangelo JA, Sun X, Eufrade-Junior HDJ (2025) Biochar impact on soil health and tree-based crops: a review. Biochar 7(1):51
Antonangelo JA, Sun X, Zhang H (2021) The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. J Environ Manage 277:111443
Antor NH, Mia S, Hasan MM, Lipi NJ, Jindo K, Sanchez-Monedero MA, Rashid MH (2023) Chemically and biologically activated biochars slow down urea hydrolysis and improve nitrogen use efficiency. Pedosphere 33(4):659–669
Anyanwu IN, Alo MN, Onyekwere AM, Crosse JD, Nworie O, Chamba EB (2018) Influence of biochar aged in acidic soil on ecosystem engineers and two tropical agricultural plants. Ecotoxicol Environ Saf 153:116–126
Arshad U, Altaf MT, Liaqat W, Ali M, Shah MN, Jabran M, Ali MA (2024) Biochar: black gold for sustainable agriculture and fortification against plant pathogens: a review. J of Crop Health 76(2):385–396
Arshad U, Azeem F, Mustafa G, Bakhsh A, Toktay H, McGiffen M, Nawaz MA, Naveed M, Ali MA (2021) Combined application of biochar and biocontrol agents enhances plant growth and activates resistance against *Meloidogyne incognita* in tomato. Gesu Pflan 73(4):591–601
Arshad U (2024) Biochar application: a sustainable approach for mitigating biotic and abiotic stresses in plants. Integrative Plant Biotechnol 2(1):77–98
Asif M, Haider MS, Akhter A (2023) Impact of biochar on Fusarium wilt of cotton and the dynamics of soil microbial community. Sustainability 15(17):12936
Awasthi MK (2022) Engineered biochar: a multifunctional material for energy and environment. Env Pollut 298:118831
Azeem M, Hassan TU, Tahir MI, Ali A, Jeyasundar PGSA, Hussain Q et al (2021) Tea leaves biochar as a carrier of *Bacillus cereus* improves the soil function and crop productivity. Appl Soil Ecol 157:13
Azeem M, Hayat R, Hussain Q, Tahir MI, Imran M, Abbass Z et al (2019) Effects of biochar and NPK on soil microbial biomass and enzyme activity during 2 years of application in the arid region. Arab J Geosci 12(10):13
Barbara MF, Honoré KI, Ntsoli PG, Aoudou Y (2023) Use of starch and biochar-based essential oil formulations from three aromatic plants as antifungal components to improve peanut (*Arachis hypogaea* L.) seed storage. Eur J Nutr Food Saf 15(11):153–163
Bartolini S, Pappalettere L, Toffanin A (2023) *Azospirillum baldaniorum* Sp245 induces anatomical changes in cuttings of olive (*Olea europaea* L., cultivar Leccino): preliminary results. Agronomy 13(2):301
Bashir A, Rizwan M, ur Rehman MZ, Zubair M, Riaz M, Qayyum MF, Ali S (2020) Application of co-composted farm manure and biochar increased the wheat growth and decreased cadmium accumulation in plants under different water regimes. Chemosphere 246:125809
Beesley L, Moreno-Jiménez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T (2011) A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environ Pollut 159(12):3269–3282
Bhatt B, Gupta SK, Mukherjee S, Kumar R (2024) A comprehensive review on biochar against plant pathogens: current state-of-the-art and future research perspectives. Heliyon 10(17):e37204
Bhatt N, Buddhi D, Suthar S (2023) Synthesizing biochar-based slow-releasing fertilizers using vermicompost leachate, cow dung, and plant weed biomass. J Environ Manage 326:116782
Blanco-Vargas A, Chacón-Buitrago MA, Quintero-Duque MC, Poutou-Piñales RA, Díaz-Ariza LA, Devia-Castillo CA et al (2022) Production of pine sawdust biochar supporting phosphate-solubilizing bacteria as an alternative bioinoculant in *Allium cepa* L., culture. Sci Rep 12(1):18
Bolan S, Sharma S, Mukherjee S, Kumar M, Rao CS, Nataraj KC, Singh G, Vinu A, Bhowmik A, Sharma H, El-Naggar A (2023a) Biochar modulating soil biological health: a review. Sci Total Environ 27:169585
Bolan N, Sarmah AK, Bordoloi S, Bolan S, Padhye LP, Van Zwieten L, Sooriyakumar P, Khan BA, Ahmad M, Solaiman ZM, Rinklebe J, Wang H, Singh BP, Siddique KHM (2023b) Soil acidification and the liming potential of biochar. Environ Pollut 317:120632
Bolan S, Hou D, Wang L, Hale L, Egamberdieva D, Tammeorg P, Li R, Wang B, Xu J, Wang T, Sun H, Padhye LP, Wang H, Siddique KHM, Rinklebe J, Kirkham MB, Bolan N (2023c) The potential of biochar as a microbial carrier for agricultural and environmental applications. Sci Total Environ 886(2023):163968
Bonanomi G, Zotti M, Idbella M, Cesarano G, Al-Rowaily SL, Abd-ElGawad AM (2022) Mixtures of organic amendments and biochar promote beneficial soil microbiota and affect *Fusarium oxysporum* f. sp. *lactucae*, *Rhizoctonia solani* and *Sclerotinia minor* disease suppression. Plant Pathol 71(4):818–829
Bonanomi G, Jesu G, Zotti M, Idbella M, d'Errico G, Laudonia S, Vinale F, Abd-ElGawad A (2021) Biochar-derived smoke-water exerts biological effects on nematodes, insects, and higher plants but not fungi. Sci Total Environ 750:142307
Bonanomi G, Zotti M, Abd-ElGawad AM, Iacomino G, Nappi A, Grauso L, Idbella M (2023) Plant-growth promotion by biochar-organic amendments mixtures explained by selective chemicals adsorption of inhibitory compounds. J Environ Chem Eng 11(1):109009
Borchard N, Wolf A, Laabs V, Aeckersberg R, Scherer HW, Moeller A et al (2012) Physical activation of biochar and its meaning for soil fertility and nutrient leaching: a greenhouse experiment. Soil Use Manage 28(2):177–184
Breunig HM, Amirebrahimi J, Smith S, Scown CD (2019) Role of digestate and biochar in carbon-negative bioenergy. Environ Sci Technol 53(22):12989–12998. https://doi.org/10.1021/acs.est.9b03763
Brtnicky M, Datta R, Holatko J, Bielska L, Gusiatin ZM, Kucerik J, Hammerschmiedt T, Danish S, Radziemska M, Mravcova L, Fahad S (2021) A critical review of the possible adverse effects of biochar in the soil environment. Sci Total Environ 796:148756
Brtnicky M, Mustafa A, Hammerschmiedt T, Kintl A, Trakal L, Beesley L et al (2023) Pre-activated biochar by fertilizers mitigates nutrient leaching and stimulates soil microbial activity. Chem Biol Technol Agric. https://doi.org/10.1186/s40538-023-00430-7
Braghiroli FL, Bouafif H, Neculita CM, Koubaa A (2018) Activated biochar as an effective sorbent for organic and inorganic contaminants in water. Water Air Soil Pollut 229(7):230
Campion L, Bekchanova M, Malina R, Kuppens T (2023) The costs and benefits of biochar production and use: a systematic review. J Clean Prod 408:137138
Canarini A, Kaiser C, Merchant A, Richter A, Wanek W (2019) Root exudation of primary metabolites: mechanisms and their roles in plant responses to environmental stimuli. Front Plant Sci 10:157

Cai T, Liu X, Zhang J, Tie B, Lei M, Wei X, Peng O, Du H (2021) Silicate-modified oiltea camellia shell-derived biochar: a novel and cost-effective sorbent for cadmium removal. J Clean Prod 281:125390
Cao Y, Gao Y, Qi Y, Li J (2018) Biochar-enhanced composts reduce the potential leaching of nutrients and heavy metals and suppress plant-parasitic nematodes in excessively fertilized cucumber soils. Environ Sci Pollut Res 25:7589–7599
Carril P, Becagli M, Celletti S, Fedeli R, Loppi S, Cardelli R (2024) Biofertilization with liquid vermicompost-activated biochar enhances microbial activity and soil properties. Soil Syst 8(2):54
Chakraborty R, Mukhopadhyay A, Paul S, Sarkar S, Mukhopadhyay R (2023) Nanocomposite-based smart fertilizers: a boon to agricultural and environmental sustainability. Sci Total Environ 863:160859
Chang Y, Rossi L, Zotarelli L, Gao B, Shahid MA, Sarkhosh A (2021) Biochar improves soil physical characteristics and strengthens root architecture in Muscadine grape (*Vitis rotundifolia* L.). Chem Biol Technol Agric 8(1):7
Chang Y, Lin L, Shen J, Lin Z, Deng X, Sun W, Wu X, Wang Y, Li Y, Xu Z (2025) Enhanced nitrogen fixation and Cd passivation in rhizosphere soil by biochar-loaded nitrogen-fixing bacteria: chemisorption and microbial mechanism. J Hazard Mater 481:136588
Chauhan P, Sharma N, Tapwal A, Kumar A, Verma GS, Meena M, Seth CS, Swapnil P (2023) Soil microbiome: diversity, benefits and interactions with plants. Sustainability 15(19):14643
Chausali N, Saxena J, Prasad R (2021) Nanobiochar and biochar based nanocomposites: advances and applications. J Agric Food Res 5:100191
Chemerys V, Baltrėnaitė-Gedienė E, Baltrėnas P, Dobele G (2020) Influence of H2 O2 modification on the adsorptive properties of birch-derived biochar. Polish J Environ Stud 29(1):579–588
Chen W, Wu Z, Liu C, Zhang Z, Liu X (2023a) 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
Chen L, Zhang Y, Wang L, Ruan S, Chen J, Li H, Yang J, Mechtcherine V, Tsang DCW (2022a) Biochar-augmented carbon-negative concrete. Chem Eng J 431:133946. https://doi.org/10.1016/j.cej.2021.133946
Chen Q, Qin J, Sun P, Cheng Z, Shen G (2018) Cow dung-derived engineered biochar for reclaiming phosphate from aqueous solution and its validation as slow-release fertilizer in soil-crop system. J Clean Prod 172:2009–2018
Chen W, Meng J, Han X, Lan Y, Zhang W (2019) Past, present, and future of biochar. Biochar 1:75–87
Chen WY, Mattern DL, Okinedo E, Senter JC, Mattei AA, Redwine CW (2014) Photochemical and acoustic interactions of biochar with CO_2 and H_2O: applications in power generation and CO2 capture. Aiche J 60(3):1054–1065
Chen XJ, Lin QM, Xiao HY, Muhammad R (2023b) Manganese-modified biochar promotes Cd accumulation in *Sedum alfredii* in an intercropping system. Environ Pollut 317(9):120525
Chen Q, Cheng Z, Li X, Wang C, Yan L, Shen G, Shen Z (2022b) Degradation mechanism and QSAR models of antibiotic contaminants in soil by MgFe-LDH engineered biochar activating urea-hydrogen peroxide. Appl Catal B Environ 302:120866
Cheng N, Peng Y, Kong Y, Li J, Sun C (2018) Combined effects of biochar addition and nitrogen fertilizer reduction on the rhizosphere metabolomics of maize (*Zea mays* L.) seedlings. Plant Soil 433:19–35
Chhipa H (2016) Nanofertilizers and nano pesticides for agriculture. Environ Chem Lett 15(1 15):15–22
Chirakkara RA, Cameselle C, Reddy KR (2016) Assessing the applicability of phytoremediation of soils with mixed organic and heavy metal contaminants. Rev Environ Sci Bio/technol 15:299–326
Cho SK, Igliński B, Kumar G (2024) Biomass based biochar production approaches and its applications in wastewater treatment, machine learning and microbial sensors. Bioresour Technol 391:129904
Choi SW, Hong J, Youn S, Kim I (2023) Removal of amoxicillin by coffee grounds biochar with different pretreatment methods. Environmental Advances 14:100446
Claudius-Cole AO, Ajayi-Choco O (2017) Management of *Meloidogyne javanica* on tomato (*Solanum lycopersicum*) with bio-control agents and soil amendments. Ib J Agric Res 12:47–57
da Silva JSA, de Medeiros EV, da Costa DP, de Souza CAF, de Oliveira JB, da França RF et al (2022) Biochar and Trichoderma aureoviride URM 5158 as alternatives for the management of cassava root rot. Appl Soil Ecol 172:104353
Dai H, Gao S, Lai C, He H, Han F, Pan X (2019) Biochar enhanced microbial degradation of 17β-estradiol. Environ Sci Process Impacts 21(10):1736–1744. https://doi.org/10.1039/c9em00168a
Dai L, Lu Q, Zhou H, Shen F, Liu Z, Zhu W, Huang H (2021) Tuning oxygenated functional groups on biochar for water pollution control: a critical review. J Hazard Mater 420:126547
Dai ZM, Wang YN, Muhammad N, Yu XS, Xiao KC, Meng J, Liu XM, Xu JM, Brookes PC (2014) The effects and mechanisms of soil acidity changes, following incorporation of biochars in three soils differing in initial pH. Soil Sci Soc Am J 78(5):1606–1614
Dai L, Chen Y, Liu L, Sun P, Liu J, Wang B, Yang S (2022) Effect of biochar on the uptake, translocation and phytotoxicity of chromium in a soil-barley pot system. Sci Total Environ 826:153905
Das SK, Ghosh GK (2020) Soil health management through low cost biochar technology. Biochar applications in agriculture and environment management. Springer, Cham, pp 193–206
Das SK, Ghosh GK, Avasthe R (2022) Valorizing biomass to engineered biochar and its impact on soil, plant, water, and microbial dynamics: a review. Biom Conver Bioref 9:4183–4199
Dey S, Purakayastha TJ, Sarkar B, Rinklebe J, Kumar S, Chakraborty R, Datta A, Lal K, Shivay YS (2023) Enhancing cation and anion exchange capacity of rice straw biochar by chemical modification for increased plant nutrient retention. Sci Total Environ 886:163681
de Medeiros EV, Lima NT, de Sousa Lima JR, Pinto KM, da Costa DP, Franco Junior CL, Souza RM, Hammecker C (2021) Biochar as a strategy to manage plant diseases caused by pathogens inhabiting the soil: a critical review. Phytoparas 49(4):713–726
Dietrich CC, Rahaman MA, Robles-Aguilar AA, Latif S, Intani K, Müller J, Jablonowski ND (2020) Nutrient loaded biochar doubled biomass production in juvenile maize plants (*Zea mays* L.). Agronomy 10(4):567
Ding Z, Alharbi S, Ali EF, Ghoneim AM, Hadi Al Fahd M, Wang G, Eissa MA (2022) Effect of phosphorus-loaded biochar and nitrogen-fertilization on release kinetic of toxic heavy metals and tomato growth. Int J Phytoremediation 24(2):156–165
Dorjee L, Nishmitha K, Pattanayak S, Wangmu T, Meshram S, Chongtham S, Gogoi R (2024) Biochar: a comprehensive review on a natural approach to plant disease management. J Pure Appl Microbiol 18:29–45
Douds DD Jr, Lee J, Uknalis J, Boateng AA, Ziegler-Ulsh C (2014) Pelletized biochar as a carrier for AM fungi in the on-farm system of inoculum production in compost and vermiculite mixtures. Compost Sci Util 22(4):253–262
Duan M, Liu G, Zhou B, Chen X, Wang Q, Zhu H, Li Z (2021) Effects of modified biochar on water and salt distribution and water-stable macro-aggregates in saline-alkaline soil. J Soils Sediments 21(6):2192–2202
Ducey TF, Ippolito JA, Cantrell KB, Novak JM, Lentz RD (2013) Addition of activated switchgrass biochar to an aridic subsoil increases microbial nitrogen cycling gene abundances. Appl Soil Ecol 65:65–72
Duwiejuah AB, Abubakari AH, Quainoo AK, Amadu Y (2020) Review of biochar properties and remediation of metal pollution of water and soil. J Health Pollut 10(27):200902
Díaz B, Sommer-Márquez A, Ordoñez PE, Bastardo-González E, Ricaurte M, Navas-Cárdenas C (2024) Synthesis methods, properties, and modifications of biochar-based materials for wastewater treatment: a review. Resources 13(1):8
Edenborn S, Johnson LMK, Edenborn H, Albarran-Jack M, Demetrion L (2017) Amendment of a hardwood biochar with compost tea: effects on plant growth, insect damage and the functional diversity of soil microbial communities. Biol Agric Horticulture 34:1–19
Egamberdieva D, Shurigin V, Alaylar B, Ma H, Müller ME, Wirth S, Reckling M, Bellingrath-Kimura SD (2020) The effect of biochars and endophytic bacteria on growth and root rot disease incidence of *Fusarium* infested narrow-leafed lupin (*Lupinus angustifolius* L.). Microorganisms 8(4):496
Egamberdieva D, Ma H, Alaylar B, Zoghi Z, Kistaubayeva A, Wirth S, Bellingrath-Kimura SD (2021) Biochar amendments improve licorice (*Glycyrrhiza uralensis* Fisch.) growth and nutrient uptake under salt stress. Plants 10(10):2135
Eizenberg H, Plakhine D, Ziadne H, Tsechansky L, Graber ER (2017) Non-chemical control of root parasitic weeds with biochar. Front Plant Sci 8:939

El-Naggar A, Shaheen SM, Chang SX, Hou D, Ok YS, Rinklebe J (2021) Biochar surface functionality plays a vital role in (im)mobilization and phytoavailability of soil vanadium. ACS Sustain Chem Eng 9(19):6864–6874
Elsharkawy MM, Alotibi FO, Al-Askar AA, Adnan M, Kamran M, Abdelkhalek A, Behiry SI, Saleem MH, Ahmad AA, Khedr AA (2022) Systemic resistance induction of potato and tobacco plants against potato virus Y by *Klebsiella oxytoca*. Life 12(10):1521
El-Sharkawy M, El-Naggar AH, Al-Huqail AA, Ghoneim AM (2022) Acid-modified biochar impacts on soil properties and biochemical characteristics of crops grown in saline-sodic soils. Sustainability 14(13):8190
El–Bially ME, El–Metwally IM, Saudy HS, Aisa KH, Abd El–Samad GA (2023) Mycorrhiza-inoculated biochar as an eco-friendly tool improves the broomrape control efficacy in two faba bean cultivars. Rhizosph 26:100706
El-Desouki Z, Abouseif Y, Lu K, Riaz M, Abd-Elkader AM, Jiang C (2025) Phosphorus-laden biochar mitigates soil Aluminum toxicity and promotes pakchoi (*Brassica chinensis*) growth in acidic conditions. J Soil Sci Plant Nutr. https://doi.org/10.1007/s42729-025-02323-0
Enaime G, Baçaoui A, Yaacoubi A, Lübken M (2020) Biochar for wastewater treatment—conversion technologies and applications. Appl Sci 10(10):3492
Fan C, Cui Y, Zhang Q, Yin N, Cai X, Yuan X, Senadheera S, Cho Y, Ok YS (2023) A critical review of the interactions between rhizosphere and biochar during the remediation of metal (loid) contaminated soils. Biochar 5(1):87
Fan Y, Wang X, Funk T, Rashid I, Herman B, Bompoti N, Mahmud MS, Chrysochoou M, Yang M, Vadas TM, Lei Y (2022) A critical review for real-time continuous soil monitoring: advantages, challenges, and perspectives. Environ Sci Technol 56(19):13546–13564
Ferdous Z (2024) The effect of cattle slurry-activated biochar on earthworm community on arable soil in Southern Finland, Faculty of Biological and Environmental Sciences. University of Helsinki, Helsinki, Finland, p. 53
Fosu-Nyarko J, Copeland RG, Iqbal S, Jones MG (2022) Biochemical/molecular mechanisms associated with nematode management through organic amendments: a critical review. Sustainable management of nematodes in agriculture. Org Manag 1:87–115
Gabhane JW, Bhange VP, Patil PD, Bankar ST, Kumar S (2020) Recent trends in biochar production methods and its application as a soil health conditioner: a review. SN Appl Sci 2(7):1307
Gao Y, Wu P, Jeyakumar P, Bolan N, Wang H, Gao B, Wang S, Wang B (2022) Biochar as a potential strategy for remediation of contaminated mining soils: mechanisms, applications, and future perspectives. J Environ Manage 313:114973
Gao S, Doll DA, Stanghellini MS, Westerdahl BB, Wang D, Hanson BD (2018) Deep injection and the potential of biochar to reduce fumigant emissions and effects on nematode control. J Environ Manage 223:469–477
Gao M, Xu Y, Chang X, Song Z (2021) Fe–Mn oxide modified biochar decreases phthalate uptake and improves grain quality of wheat grown in phthalate-contaminated fluvo-aquic soil. Chemosphere 270:129428
Gao Y, Xue Y, Zhen K, Guo J, Tang X, Zhang P, Wang C, Sun H, Wu J (2023) Remediation of soil contaminated with PAHs and γ-HCH using Fenton oxidation activated by carboxymethyl cellulose-modified iron oxide-biochar. J Hazard Mater 453:131450
Geng N, Kang X, Yan X, Yin N, Wang H, Pan H et al (2022) Biochar mitigation of soil acidification and carbon sequestration is influenced by materials and temperature. Ecotoxicol Environ Saf 232:113241
George C, Kohler J, Rillig MC (2016) Biochars reduce infection rates of the root-lesion nematode *Pratylenchus penetrans* and associated biomass loss in carrot. Soil Biol Biochem 95:11–18
Ghassemi-Golezani K, Farhangi-Abriz S (2023) Biochar related treatments improved physiological performance, growth and productivity of *Mentha crispa* L. plants under fluoride and cadmium toxicities. Ind Crops Prod 194:116287
Ghassemi-Golezani K, Farhangi-Abriz S (2022) Improving plant available water holding capacity of soil by solid and chemically modified biochars. Rhizosphere 21:100469
Ghazouani H, Ibrahimi K, Amami R, Helaoui S, Boughattas I, Kanzari S, Milham P, Ansar S, Sher F (2023) Integrative effect of activated biochar to reduce water stress impact and enhance antioxidant capacity in crops. Sci Total Environ 905:166950
Gorovtsov AV, Minkina TM, Mandzhieva SS, Perelomov LV, Soja G, Zamulina IV, Rajput VD, Sushkova SN, Mohan D, Yao J (2020) The mechanisms of biochar interactions with microorganisms in soil. Environ Geochem Health 42:2495–2518
Graber ER, Kookana RS (2015) Biochar and retention/efficacy of pesticides. Biochem Environ Manag 20:655–678
Grimm A, dos Reis GS, Dinh VM, Larsson SH, Mikkola JP, Lima EC, Xiong S (2024) Hardwood spent mushroom substrate–based activated biochar as a sustainable bioresource for removal of emerging pollutants from wastewater. Biomass Convers Biorefinery 14(2):2293–2309
Gregory SJ, Anderson CW, Camps-Arbestain M, Biggs PJ, Ganley AR, O'Sullivan JM, McManus MT (2015) Biochar in co-contaminated soil manipulates arsenic solubility and microbiological community structure, and promotes organochlorine degradation. PLoS ONE 10(4):e0125393
Guerena DT, Lehmann J, Thies JE, Vanek S, Karanja N, Neufeldt H (2019) Nodulation of beans with inoculant carriers from pyrolyzed and non-pyrolyzed sugarcane bagasse in response to different pre-planting water availability. Appl Soil Ecol 143:126–133
Gunes A, Inal A, Taskin MB, Sahin O, Kaya EC, Atakol A (2014) Effect of phosphorus-enriched biochar and poultry manure on growth and mineral composition of lettuce (*Lactuca sativa* L. cv.) grown in alkaline soil. Soil Use Manage 30(2):182–188
Guo M, Song W, Tian J (2020) Biochar-facilitated soil remediation: mechanisms and efficacy variations. Front Environ Sci 8:521512
Gęca M, Khalil AM, Tang M, Bhakta AK, Snoussi Y, Nowicki P, Wiśniewska M, Chehimi MM (2023) Surface treatment of biochar—methods, surface analysis and potential applications: a comprehensive review. Surf 6(2):179–213
Hale L, Luth M, Kenney R, Crowley D (2014) Evaluation of pinewood biochar as a carrier of bacterial strain *Enterobacter cloacae* UW5 for soil inoculation. Appl Soil Ecol 84:192–199
Han Y, Han Y, Du G, Zhang T, Guo Q, Yang H, Li R, Xu Y (2021) Physiological effect of colloidal carbon quantum dots on *Bursaphelenchus xylophilus*. RSC Adv 11:6212–6220
Han L, Li J, Xue Q, Chen Z, Zhou Y, Poon CS (2020) Bacterial-induced mineralization (BIM) for soil solidification and heavy metal stabilization: a critical review. Sci Total Environ 746:140967
Han F, An SY, Liu L, Ma LQ, Wang Y, Yang L (2023) Simultaneous enhancement of soil properties along with water-holding and restriction of Pb–Cd mobility in a soil-plant system by the addition of a phosphorus-modified biochar to the soil. J Environ Manage 345:118827
Hao C, Dungait JA, Wei X, Ge T, Kuzyakov Y, Cui Z, Tian J, Zhang F (2022) Maize root exudate composition alters rhizosphere bacterial community to control hotspots of hydrolase activity in response to nitrogen supply. Soil Biol Biochem 170:108717
Harussani MM, Sapuan SM (2024) Carbonization of Biomass and Waste into Biosourced Carbon (BC) Nanofillers for Advanced Composite Applications. EmergSust Renew Comp (pp. 248–292). CRC Press
Harussani MM, Sapuan SM (2022) Development of Kenaf biochar in engineering and agricultural applications. Chem Afr 5(1):1–17
Hashem A, Kumar A, Al-Dbass AM, Alqarawi AA, Al-Arjani A-BF, Singh G, Farooq M, Abd Allah EF (2019) Arbuscular mycorrhizal fungi and biochar improves drought tolerance in chickpea. Saudi J Biol Sci 26(3):614–624
Holatko J, Hammerschmiedt T, Mustafa A, Kintl A, Skarpa P, Ryant P et al (2023) Time-dependent impact of co-matured manure with elemental sulfur and biochar on the soil agro-ecological properties and plant biomass. Sci Rep 13(1):4327
Hossain MZ, Bahar MM, Sarkar B, Donne SW, Ok YS, Palansooriya KN, Kirkham MB, Chowdhury S, Bolan N (2020) Biochar and its importance on nutrient dynamics in soil and plant. Biochar 2:379–420
Hou J, Pugazhendhi A, Phuong TN, Thanh NC, Brindhadevi K, Velu G, Chi NT, Yuan D (2022) Plant resistance to disease: using biochar to inhibit harmful microbes and absorb nutrients. Environ Res 214:113883
Hu L, Huang R, Zhou L, Qin R, He X, Deng H et al (2023) Effects of magnesium-modified biochar on soil organic carbon mineralization in citrus orchard. Front Microbiol 14:1109272
Hua Z, Wan S, Sun L, Yu Z, Bai X (2018) Role of non-ion surfactants in three-dimensional ordered porous biomass carbon foam derived from the liquefied eucalyptus sawdust for metronidazole adsorption. J Chem Technol Biotechnol 93(10):3044–3055

Huang H, Tang J, Gao K, He R, Zhao H, Werner D (2017) Characterization of KOH modified biochars from different pyrolysis temperatures and enhanced adsorption of antibiotics. RSC Adv 7(24):14640–14648

Huang K, Li M, Li R, Rasul F, Shahzad S, Wu C, Shao J, Huang G, Li R, Almari S, Hashem M, Aamer M (2023) Soil acidification and salinity: the importance of biochar application to agricultural soils. Front Plant Sci 14:1206820

Huang Y, Luo Y, Wu C, Xue S, Chen H, Wu Y, Li W (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

Huff M, Marshall S, Saeed H, Lee J (2018) Surface oxygenation of biochar through ozonization for dramatically enhancing cation exchange capacity. Bioresour Bioprocess. https://doi.org/10.1186/s40643-018-0205-9

Hussain T, Ahmed SR, Lahori AH, Mierzwa-Hersztek M, Vambol V, Khan AA, Rafique L, Wasia S, Shahid MF, Zengqiang Z (2022) In-situ stabilization of potentially toxic elements in two industrial polluted soils ameliorated with rock phosphate-modified biochars. Environ Pollut 309:119733

Husna N, Budianta D, Munandar M, Adipati N (2019) Evaluation of several biochar types as inoculant carrier for indigenous phosphate solubilizing microoorganism from acid sulphate soil. J Ecol Eng 20:1–8

Iacomino G, Idbella M, Laudonia S, Vinale F, Bonanomi G (2022) The suppressive effects of biochar on above-and belowground plant pathogens and pests: a review. Plants 11(22):3144

Iacomino G, Bonanomi G, Motti R, Idbella M (2023) Trick of the trade: unveiling the importance of feedstock chemistry in trichoderma-organic amendments-based bio-stimulants. Horticulturae 9(9):957

Ikram M, Singh S, Bano N, Alahmadi TA, Shariq M, Siddiqui MA, Islam J (2024) Biochar and oil cakes act as antagonists towards *Meloidogyne incognita* in tomato: a sustainable approach. Plant Str 11:1003–1020

Irshad MK, Ibrahim M, Noman A, Shang J, Mahmood A, Mubashir M, Khoo KS, Ng HS, Show PL (2022) Elucidating the impact of goethite-modified biochar on arsenic mobility, bioaccumulation in paddy rice (*Oryza sativa* L.) along with soil enzyme activities. Process Saf Environ Prot 160:958–967

Islam T, Li Y, Cheng H (2021) Biochars and engineered biochars for water and soil remediation: a review. Sustainability 13(17):9932

Jaafar NM, Clode PL, Abbott LK (2014) Microscopy observations of habitable space in biochar for colonization by fungal hyphae from soil. J Integr Agric 13(3):483–490

Jahan S, Ahmad F, Rasul F, Amir R, Shahzad S (2023) Physicochemical analysis of vermicompost-perlite based activated biochar and its influence on wheat (*Triticum aestivum* L.) growth under water stress. J Soil Sci Plant Nutr 23(3):3034–3050

Jiang W, Xu L, Liu Y, Su W, Yan J, Xu D (2022) Effect of biochar on the growth, photosynthesis, antioxidant system and cadmium content of Mentha piperita 'Chocolate'and Mentha spicata in cadmium-contaminated soil. Agronomy 12(11):2737

Jiang Y, Li T, Xu X, Sun J, Pan G, Cheng K (2024) A global assessment of the long-term effects of biochar application on crop yield. Curr Res Environ Sustain 7:100247

Jiao Y, Wang T, He M, Liu X, Lin C, Ouyang W (2022) Simultaneous stabilization of Sb and as co-contaminated soil by FeMg modified biochar. Sci Total Environ 830:154831

Jin L, Feng S, Tang S, Dong P, Li Z (2023a) Biological control of potato late blight with a combination of *Streptomyces* strains and biochar. Biol Cont 183:105248

Jin M, Zhou Q, Fu L, Wu W (2024) Application of biochar-based catalysts for soil and water pollution control. Top Catal 16:1–24

Jin X, Zhou X, Wu F, Xiang W, Pan K (2023b) BC amendment suppressed Fusarium wilt and altered the rhizosphere microbial composition of tomatoes. Agron 13(7):1811

Jin X, Bai Y, Khashi u Rahman M, Kang X, Pan K, Wu F, Pommier T, Zhou X, Wei Z (2022) Biochar stimulates tomato roots to recruit a bacterial assemblage contributing to disease resistance against Fusarium wilt. iMeta 1(3):e37

Joseph S, Cowie AL, Van Zwieten L, Bolan N, Budai A, Buss W, Cayuela ML, Graber ER, Ippolito JA, Kuzyakov Y, Luo Y, Ok YS, Palansooriya KN, Shepherd J, Stephens S, Weng Z, Lehmann J (2021) How biochar works, and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy 13(11):1731–1764

Kamali M, Sweygers N, Al-Salem S, Appels L, Aminabhavi TM, Dewil R (2022) Biochar for soil applications-sustainability aspects, challenges and future prospects. Chem Eng J 428:131189

Kammann C, Graber ER (2015) Biochar effects on plant ecophysiology. In Biochar for environmental management (pp. 391–419). Routledge

Kammann C, Ippolito J, Hagemann N, Borchard N, Cayuela ML, Estavillo JM, Fuertes-Mendizabal T, Jeffery S, Kern J, Novak J, Rasse D (2017) Biochar as a tool to reduce the agricultural greenhouse-gas burden–knowns, unknowns and future research needs. J Environ Eng Landsc Manage 25(2):114–139

Kang X, Geng N, Li Y, He W, Wang H, Pan H, Yang Q, Yang Z, Sun Y, Lou Y, Zhuge Y (2024) Biochar with KMnO4-hematite modification promoted foxtail millet growth by alleviating soil Cd and Zn biotoxicity. J Hazard Mater 477:135377

Karhu K, Mattila T, Bergström I, Regina K (2011) Biochar addition to agricultural soil increased CH4 uptake and water holding capacity—results from a short-term pilot field study. Agric Ecosyst Environ 140(1–2):309–313

Kari A, Nagymáté Z, Romsics C, Vajna B, Tóth E, Lazanyi-Kovács R, Rizó B, Kutasi J, Bernhardt B, Farkas É, Márialigeti K (2021) Evaluating the combined effect of biochar and PGPR inoculants on the bacterial community in acidic sandy soil. Appl Soil Ecol 160(10):103856

Ke W, Liu Z, Zhu F, Xie Y, Hartley W, Li X, Xue S (2023) Remediation potential of magnetic biochar in lead smelting sites: insight from the complexation of dissolved organic matter with potentially toxic elements. J Environ Manage 344:118556

Khader A, Ibrahim M, Alkhathami F, Elsawy H, El-Kader NA, Shaker E, Sedky A, Mahmoud E (2023) Properties of nano-amendments and their effect on some soil properties and root-knot nematode and yield attributes of tomato plant. Agriculture 13(2):366

Khajavi-Shojaei S, Moezzi A, Norouzi Masir M, Taghavi M (2020) Synthesis modified biochar-based slow-release nitrogen fertilizer increases nitrogen use efficiency and corn (*Zea mays* L.) growth. Biomass Convers Biorefin 13(2):593–601

Khan S, Irshad S, Mehmood K, Hasnain Z, Nawaz M, Rais A, Gul S, Wahid MA, Hashem A, Abd Allah EF, Ibrar D (2024) Biochar production and characteristics, its impacts on soil health, crop production, and yield enhancement: a review. Plants 13(2):166

Khan Z, Yang X-J, Fu Y, Joseph S, Khan MN, Khan MA, Alam I, Shen H (2023) Engineered biochar improves nitrogen use efficiency via stabilizing soil water-stable macroaggregates and enhancing nitrogen transformation. Biochar 5(1):52

Kim DY, Patel SK, Rasool K, Lone N, Bhatia SK, Seth CS, Ghodake GS (2023) Bioinspired silver nanoparticle-based nanocomposites for effective control of plant pathogens: a review. Sci Total Environ 11:168318

Kim JA, Vijayaraghavan K, Reddy DHK, Yun Y-S (2018) A phosphorus-enriched biochar fertilizer from bio-fermentation waste: a potential alternative source for phosphorus fertilizers. J Clean Prod 196:163–171

Kim M, Jeong C, Kim M, Nam J, Shim C, Shin J (2022) Evaluation of the impact of activated biochar-manure compost pellet fertilizer on volatile organic compound emissions and heavy metal saturation. Int J Environ Res Public Health. https://doi.org/10.3390/ijerph191912405

Kizito S, Luo H, Lu J, Bah H, Dong R, Wu S (2019) Role of nutrient-enriched biochar as a soil amendment during maize growth: exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand. Sustainability 11(11):3211

Kizito S, Luo H, Wu S, Ajmal Z, Lv T, Dong R (2017) Phosphate recovery from liquid fraction of anaerobic digestate using four slow pyrolyzed biochars: dynamics of adsorption, desorption and regeneration. J Environ Manage 201:260–267

Kocsis T, Ringer M, Biró B (2022) Characteristics and applications of biochar in soil–plant systems: a short review of benefits and potential drawbacks. Appl Sci 12(8):4051

Kong M, Liang J, White JC, Elmer WH, Wang Y, Xu H, He W, Shen Y, Gao X (2022) Biochar nanoparticle-induced plant immunity and its application with the elicitor methoxyindole in *Nicotiana benthamiana*. Environ Sci: Nano 9:3514–3524

Kong F, Liu J, Xiang Z, Fan W, Liu J, Wang J, Wang Y, Wang L, Xi B (2024) Degradation of water pollutants by biochar combined with advanced oxidation: a systematic review. Water 16(6):875
Kudoyarova GR, Vysotskaya LB, Arkhipova TN, Kuzmina LY, Galimsyanova NF, Sidorova LV, Gabbasova IM, Melentiev AI, Veselov SY (2017) Effect of auxin producing and phosphate solubilizing bacteria on mobility of soil phosphorus, growth rate, and P acquisition by wheat plants. Acta Physiol Plant. https://doi.org/10.1007/s11738-017-2556-9
Kumar M, Giri VP, Pandey S, Gupta A, Patel MK, Bajpai AB, Jenkins S, Siddique KH (2021) Plant-growth-promoting rhizobacteria emerging as an effective bioinoculant to improve the growth, production, and stress tolerance of vegetable crops. Int J Mol Sci 22(22):12245
Kumar S, Masto RE, Ram LC, Sarkar P, George J, Selvi VA (2013) Biochar preparation from *Parthenium hysterophorus* and its potential use in soil application. Ecol Eng 55:67–72
Kumar A, Bhattacharya T, Mukherjee S, Sarkar B (2022) A perspective on biochar for repairing damages in the soil–plant system caused by climate change-driven extreme weather events. Biochar 4(1):22
Kuppusamy S, Krishnan PS, Kumutha K, French J, Carlos GE, Toefield B (2011) Suitability of UK and Indian source Acacia wood based biochar as a best carrier material for the preparation of Azospirillum inoculum. Int J Biotechnol 4(6):582–588
Latawiec AE, Koryś A, Koryś KA, Kuboń M, Sadowska U, Gliniak M, Sikora J, Drosik A, Niemiec M, Klimek-Kopyra A, Sporysz M (2021) Economic analysis of biochar use in soybean production in Poland. Agronomy 11(11):2108
Latini A, Bacci G, Teodoro M, Gattia DM, Bevivino A, Trakal L (2019) The impact of soil-applied biochars from different vegetal feedstocks on durum wheat plant performance and rhizospheric bacterial microbiota in low metal-contaminated soil. Front Microbiol 10(20):2694
Le QTN, Hwang I (2023) Stabilization of hydrophobic organic compounds in sediment using alkali-activated rice husk biochar: Enhancement of sorption by dissolved organic matter. Chem Eng J 476:146513
Lebrun M, Miard F, Bucci A, Trupiano D, Nandillon R, Naclerio G, Scippa GS, Morabito D, Bourgerie S (2021) Evaluation of direct and biochar carrier-based inoculation of *Bacillus* sp. on As- and Pb-contaminated technosol: effect on metal(loid) availability, *Salix viminalis* growth, and soil microbial diversity/activity. Environ Sci Pollut Res 28(9):11195–11204
Lee HS, Shin HS (2021) Competitive adsorption of heavy metals onto modified biochars: comparison of biochar properties and modification methods. J Environ Manag 299:113651
Lei C, Lu T, Qian H, Liu Y (2023) Machine learning models reveal how biochar amendment affects soil microbial communities. Biochar 5(1):89
Li H, Yang L, Mao Q, Zhou H, Guo P, Agathokleous E et al (2023a) Modified biochar enhances soil fertility and nutrient uptake and yield of rice in mercury-contaminated soil. Environ Technol Innov 32:103435
Li R, Wang JJ, Zhang Z, Awasthi MK, Du D, Dang P et al (2018a) Recovery of phosphate and dissolved organic matter from aqueous solution using a novel CaO-MgO hybrid carbon composite and its feasibility in phosphorus recycling. Sci Total Environ 642:526–536
Li S, Wang N, Chen S, Sun Y, Li P, Tan J et al (2023b) Enhanced soil P immobilization and microbial biomass P by application of biochar modified with eggshell. J Environ Manage 345:118568
Li Y, Chi D, Sun Y, Wang X, Tan M, Guan Y et al (2024) Synthesis of struvite-enriched slow-release fertilizer using magnesium-modified biochar: desorption and leaching mechanisms. Sci Total Environ 926:172172
Li L, Zhang YJ, Novak A, Yang Y, Wang J (2021a) Role of biochar in improving sandy soil water retention and resilience to drought. Water 13(4):407
Li L, Zou D, Xiao Z, Zeng X, Zhang L, Jiang L, Wang A, Ge D, Zhang G, Liu F (2019) Biochar as a sorbent for emerging contaminants enables improvements in waste management and sustainable resource use. J Clean Prod 210:1324–1342
Li R, Wang JJ, Zhang Z, Awasthi MK, Du D, Dang P, Huang Q, Zhang Y, Wang L (2018b) Recovery of phosphate and dissolved organic matter from aqueous solution using a novel CaO-MgO hybrid carbon composite and its feasibility in phosphorus recycling. Sci Total Environ 642:526–536
Li S, Wang N, Chen S, Sun Y, Li P, Tan J, Jiang X (2023c) Enhanced soil P immobilization and microbial biomass P by application of biochar modified with eggshell. J Environ Manage 345:118568
Li X, Zhang J, Liu B, Su Z (2021b) A critical review on the application and recent developments of post-modified biochar in supercapacitors. J Clean Prod 310:127428
Li Q, Liang W, Liu F, Wang G, Wan J, Zhang W, Peng C, Yang J (2022) Simultaneous immobilization of arsenic, lead and cadmium by magnesium-aluminum modified biochar in mining soil. J Environ Manage 310:114792
Li Y, Gupta R, Zhang Q, You S (2023d) Review of biochar production via crop residue pyrolysis: development and perspectives. Bioresour Technol 369:128423
Liang M, Lu L, He H, Li J, Zhu Z, Zhu Y (2021) Applications of biochar and modified biochar in heavy metal contaminated soil: a descriptive review. Sustainability 13(24):14041
Liang Y, Zhao B, Yuan C (2022) Adsorption of atrazine by Fe-Mn-modified biochar: the dominant mechanism of π–π interaction and pore structure. Agronomy 12(12):3097
Liang X, Rao X, Fu Q, Zhu J, Hu H (2023) The simultaneous high-effective removal of As (III) and Cd by a modified biochar derived from rice straw. J Environ Chem Eng 11(3):109874
Lin Y, Yu C, Zhang Y, Lu L, Xu D, Peng X (2024) Biochar modification methods and mechanisms for salt-affected soil and saline-alkali soil improvement: a review. Soil Use Manage 40(1):e12992
Liu B, Guo W, Wang H, Si Q, Zhao Q, Luo H, Ren N (2020) Activation of peroxymonosulfate by cobalt-impregnated biochar for atrazine degradation: the pivotal roles of persistent free radicals and ecotoxicity assessment. J Hazard Mater. https://doi.org/10.1016/j.jhazmat.2020.122768
Liu H, Kumar V, Yadav V, Guo S, Sarsaiya S, Binod P, Sindhu R, Xu P, Zhang Z, Pandey A, Kumar Awasthi M (2021) Bioengineered biochar as smart candidate for resource recovery toward circular bio-economy: a review. Bioengineered 12(2):10269–10301
Liu S, Zhang Y, Zong Y, Hu Z, Wu S, Zhou J, Jin Y, Zou J (2016) Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. GCB Bioenergy 8(2):392–406
Liu X, Wang X, Yang W, Yuan F, Wang B, Peng Q (2022) Impregnating biochar with Fe and Cu by bioleaching for fabricating catalyst to activate H2O2. Appl Microbiol Biotechnol 106(5):2249–2262
Liu P, Ptacek CJ, Blowes DW (2019) Mercury complexation with dissolved organic matter released from thirty-six types of biochar. Bull Environ Contam Toxicol 103(1):175–180
Lu H, Wu Y, Liang P, Song Q, Zhang H, Wu J, Wu W, Liu X, Dong C (2020) Alkaline amendments improve the health of soils degraded by metal contamination and acidification: crop performance and soil bacterial community responses. Chemosphere 257:127309
Luthra N, Pathak SO, Tater A, Tewari S, Nain P, Sharma R, Kushwaha DP, Bhatt MK, Singh SK, Kaushal A (2024) Role of biochar in acidic soils amelioration. In: Biochar production for green economy (pp. 185–203). Academic Press
Luo XX, Liu GC, Xia Y, Chen L, Jiang ZX, Zheng H, Wang ZY (2017) Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China. J Soils Sediments 17(3):780–789
Lonappan L, Liu Y, Rouissi T, Brar SK, Surampalli RY (2020) Development of biochar-based green functional materials using organic acids for environmental applications. J Clean Prod 244:118841
Lwin CS, Seo BH, Kim HU, Owens G, Kim KR (2018) Application of soil amendments to contaminated soils for heavy metal immobilization and improved soil quality: a critical review. Soil Sci Plant Nutr 64(2):156–167
Ma G, Mao H, Bu Q, Han L, Shabbir A, Gao F (2020) Effect of compound biochar substrate on the root growth of cucumber plug seedlings. Agronomy 10(8):1080
Ma P, Qi Z, Wu X, Ji R, Chen W (2023) Biochar nanoparticles-mediated transport of organic contaminants in porous media: dependency on contaminant properties and effects of biochar aging. Carbon Res 2(1):4
Mahmoud NN, Khader A, Mahmoud E (2024) Green iron oxide nanoparticles and magnetic nanobc: enhancing tomato performance, phytochemicals, and root-knot nematode resistance. BMC Plant Biol 24(1):469
Majdura J, Jankiewicz U, Gałązka A, Orzechowski S (2023) The role of quorum sensing molecules in bacterial-plant interactions. Metabolites. https://doi.org/10.3390/metabo13010114

Manso E (2017) Biochar as A liming agent and phosphorus source to enhance the growth of soya bean in two acid soils. University of Ghana: Doctoral dissertation
Mansoor S, Kour N, Manhas S, Zahid S, Wani OA, Sharma V, Wijaya L, Alyemeni MN, Alsahli AA, El-Serehy HA, Paray BA (2021) Biochar as a tool for effective management of drought and heavy metal toxicity. Chemosph 271:129458
Marcińczyk M, Ok YS, Oleszczuk P (2022) From waste to fertilizer: Nutrient recovery from wastewater by pristine and engineered biochars. Chemosphere 306:135310
Masoumi S, Dalai AK (2020) Optimized production and characterization of highly porous activated carbon from algal-derived hydrochar. J Clean Prod 263:121427
Mihoub A, Amin AEEAZ, Motaghian HR, Saeed MF, Naeem A. (2022) Citric acid (CA)–modified biochar improved available phosphorus concentration and its half-life in a P-fertilized calcareous sandy soil. J. Soil Sci Plant Nutr, pp 1–10
Mekuria W, Noble A (2013) The role of biochar in ameliorating disturbed soils and sequestering soil carbon in tropical agricultural production systems. Appl Environ Soil Sci 2013(1):354965
Meyer S, Glaser B, Quicker P (2011) Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environ Sci Technol 45(22):9473-9483
Mickan BS, Ren A-T, Buhlmann CH, Ghadouani A, Solaiman ZM, Jenkins S et al (2022) Closing the circle for urban food waste anaerobic digestion: the use of digestate and biochar on plant growth in potting soil. J Clean Prod 347:131071
Mohamed BA, Ellis N, Kim CS, Bi X, Emam AER (2016) Engineered biochar from microwave-assisted catalytic pyrolysis of switchgrass for increasing water-holding capacity and fertility of sandy soil. Sci Total Environ 566:387–397
Mondal S, Ghosh S, Mukherjee A (2021) Application of biochar and vermicompost against the rice root-knot nematode (Meloidogyne graminicola): an eco-friendly approach in nematode management. J Plant Dis Protec 128:819–829
Moradi N, Karimi A (2021) Fe-modified common reed biochar reduced cadmium (Cd) mobility and enhanced microbial activity in a contaminated calcareous soil. J Soil Sci Plant Nutr. 21(1):329–340
Moradi S, Rasouli-Sadaghiani MH, Sepehr E, Khodaverdiloo H, Barin M (2019) Soil nutrients status affected by simple and enriched biochar application under salinity conditions. Environ Monit Assess 191(4):257
Mousavi M, Aldagari S, Crocker MS, Ackerman-Biegasiewicz LK, Fini EH (2023) Iron-rich biochar to adsorb volatile organic compounds emitted from asphalt-surfaced areas. ACS Sustain Chem Eng 11(7):2885–2896
Mosa A, El-Ghamry A, Tolba M (2018) Functionalized biochar derived from heavy metal rich feedstock: Phosphate recovery and reusing the exhausted biochar as an enriched soil amendment. Chemosphere 198:351–363
Mukhopadhyay R, Sarkar B, Palansooriya KN, Dar JY, Bolan NS, Parikh SJ, Sonne C, Ok YS (2021) Natural and engineered clays and clay minerals for the removal of poly- and perfluoroalkyl substances from water: state-of-the-art and future perspectives. Adv Colloid Interface Sci 297:102537
Murtaza G, Ahmed Z, Eldin SM, Ali B, Bawazeer S, Usman M, Iqbal R, Neupane D, Ullah A, Khan A, Hassan MU, Ali I, Tariq A (2023) Biochar-soil-plant interactions: a cross talk for sustainable agriculture under changing climate. Front Environ Sci 11:1059449
Murtaza G, Ahmed Z, Iqbal R, Deng G (2025) Biochar from agricultural waste as a strategic resource for promotion of crop growth and nutrient cycling of soil under drought and salinity stress conditions: a comprehensive review with context of climate change. J Plant Nutr, pp 1–52
Murtaza G, Ahmed Z, Valipour M, Ali I, Usman M, Iqbal R, Zulfiqar U, Rizwan M, Mahmood S, Ullah A, Arslan M, Rehman MHU, Ditta A, Tariq A (2024) Recent trends and economic significance of modified/functionalized biochars for remediation of environmental pollutants. Sci Rep 14(1):217
Muter O (2017) Effect of biochar and Trichoderma application on fungal diversity and growth of Zea mays in a sandy loam soil. Environ Exp Biol 15:289–296
Naeem MA, Abdullah M, Imran M, Shahid M, Abbas G, Amjad M, Shah GM, Khan WUD, Alamri S, Al-Amri AA (2022) Iron oxide nanoparticles doped biochar ameliorates trace elements induced phytotoxicity in tomato by modulation of physiological and biochemical responses: implications for human health risk. Chemosphere 289:133203
Naeem MA, Shabbir A, Imran M, Ahmad S, Shahid M, Murtaza B, Amjad M, Khan WUD (2024) Silicon-nanoparticles loaded biochar for soil arsenic immobilization and alleviation of phytotoxicity in barley: Implications for human health risk. Environ Sci Pollut Res 31(16):23591–23609
Nardis BO, Franca JR, Carneiro J, Soares JR, Guilherme LRG, Silva CA, Melo LCA (2022) Production of engineered-biochar under different pyrolysis conditions for phosphorus removal from aqueous solution. Sci Total Environ 816:151559
Nardis BO, Da Silva S, Carneiro J, Souza IMGD, Barros RGD, Azevedo Melo LC (2020) Phosphorus recovery using magnesium-enriched biochar and its potential use as fertilizer. Arch Agron Soil Sci 67(8):1017–1033
Naveed M, Tanvir B, Xiukang W, Brtnicky M, Ditta A, Kucerik J, Subhani Z, Nazir MZ, Radziemska M, Saeed Q, Mustafa A (2021) Co-composted biochar enhances growth, physiological, and phytostabilization efficiency of brassica napus and reduces associated health risks under chromium stress. Front Plant Sci 12:775785
Nematian M, Keske C, Ng'ombe JN (2021) A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. Waste Manage 135:467–477
Neuberger P, Romero C, Kim K, Hao X, A. McAllister T, Ngo S, et al. Biochar is colonized by select arbuscular mycorrhizal fungi in agricultural soils. Mycorrhiza. 2024;34(3):191–201. https://doi.org/10.1007/s00572-024-01149-5
Niu B, Wang W, Yuan Z, Sederoff RR, Sederoff H, Chiang VL, Borriss R (2020) Microbial interactions within multiple-strain biological control agents impact soil-borne plant disease. Front Microbiol 11:585404
O'Connor D, Peng T, Zhang J, Tsang DC, Alessi DS, Shen Z, Bolan NS, Hou D (2018) Biochar application for the remediation of heavy metal polluted land: a review of in situ field trials. Sci Total Environ 619:815–826
Obia A, Mulder J, Martinsen V, Cornelissen G, Børresen T (2016) In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. Soil and Tillage Res 155:35–44
Ortiz-Liébana N, Zotti M, Barquero M, González-Andrés F (2022) An organic fertilizer "doped" with a bacillus strain improves melon and pepper yield, modifying the rhizosphere microbiome with negligible changes in the bulk soil microbiome. Agronomy-Basel 12(11):23
Osman AI, Fawzy S, Farghali M, El-Azazy M, Elgarahy AM, Fahim RA, Maksoud M, Ajlan AA, Yousry M, Saleem Y, Rooney DW (2022) Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. Environ Chem Lett 20(4):2385–2485
Ouyang Y, Zhu W, Yao X, Ye C, Lei B, Rong X, Zheng J, Liu X, Wu J, Liu X, Ding C (2024) ZnCl2 and thiourea co-modified biochar for effectively removing quinclorac in water and soil: Mechanism and alleviating its phytotoxicity on tobacco plants. Sep Purif Technol 350:127865
Paetsch L, Mueller CW, Kögel-Knabner I, von Lützow M, Girardin C, Rumpel C (2018) Effect of in-situ aged and fresh biochar on soil hydraulic conditions and microbial C use under drought conditions. Sci Rep 8(1):6852
Palansooriya KN, Wong JT, Hashimoto Y, Huang L, Rinklebe J, Chang SX, Bolan N, Wang H, Ok YS (2019) Response of microbial communities to biochar-amended soils: a critical review. Bioch 1:3–22
Pan X, Shi M, Chen X, Kuang S, Ullah H, Lu H, Riaz L (2022) An investigation into biochar, acid-modified biochar, and wood vinegar on the remediation of saline– alkali soil and the growth of strawberries. Front Environ Sci 10:1057384
Panahi HKS, Dehhaghi M, Ok YS, Nizami AS, Khoshnevisan B, Mussatto SI, Aghbashlo M, Tabatabaei M, Lam SS (2020) A comprehensive review of engineered biochar: production, characteristics, and environmental applications. J Clean Prod 270:122462
Pantoja-Guerra M, Burkett-Cadena M, Cadena J, Dunlap CA, Ramírez CA (2023) Lysinibacillus spp.: an IAA-producing endospore forming-bacteria that promotes plant growth. Antonie van Leeuwenhoek. 116(7):615–630
Panwar NL, Pawar A (2022) Influence of activation conditions on the physicochemical properties of activated biochar: a review. Biomass Convers Biorefinery 12(3):925–947
Pathak HK, Chauhan PK, Seth CS, Dubey G, Upadhyay SK (2024) Mechanistic and future prospects in rhizospheric engineering for agricultural contaminants removal, soil health restoration, and management of climate change stress. Sci Total Env 3:172116

Pausch J, Tian J, Riederer M, Kuzyakov Y (2013) Estimation of rhizodeposition at field scale: upscaling of a 14C labeling study. Plant Soil 364(1):273–285
Pavlicevic M, Elmer W, Zuverza-Mena N, Abdelraheem W, Patel R, Dimkpa C, O'Keefe T, Haynes CL, Pagano L, Caldara M, Marmiroli M (2023) Nanoparticles and BC with adsorbed plant growth-promoting rhizobacteria alleviate Fusarium wilt damage on tomato and watermelon. Plant Physio Biochem 203:108052
Paymaneh Z, Gryndler M, Konvalinkova T, Benada O, Borovicka J, Bukovska P, Puschel D, Rezacova V, Sarcheshmehpour M, Jansa J (2018) Soil matrix determines the outcome of interaction between mycorrhizal symbiosis and biochar for andropogon gerardii growth and nutrition. Front Microbiol 9(16):2862
Pei J, Li J, Fang C, Zhao J, Nie M, Wu J (2020) Different responses of root exudates to biochar application under elevated CO2. Agr Ecosyst Environ 301:107061
Peng YT, Sun YQ, Fan BQ, Zhang S, Bolan NS, Chen Q et al (2021) Fe/Al (hydr) oxides engineered biochar for reducing phosphorus leaching from a fertile calcareous soil. J Clean Prod 279:9
Pierson D, Anderson N, Brewen J, Clark N, Hardy MC, McCollum D, McCormick FH, Morisette J, Nicosia T, Page-Dumroese D, Rodriguez-Franco C (2024) Beyond the basics: a perspective on barriers and opportunities for scaling up biochar production from forest slash. Biochar 6(1):1
Pinisakul A, Kruatong N, Vinitnantharat S, Wilamas P, Neamchan R, Sukkhee N, Werner D, Sanghaisuk S (2023) Arsenic, iron, and manganese adsorption in single and trinary heavy metal solution systems by bamboo-derived biochars. C-Journal Carbon Res 9(2):40
Pogorzelski D, Filho JFL, Matias PC, Santos WO, Vergutz L, Melo LCA (2020) Biochar as composite of phosphate fertilizer: Characterization and agronomic effectiveness. Sci Total Environ 743:140604
Postma J, Nijhuis EH (2019) Pseudomonas chlororaphis and organic amendments controlling Pythium infection in tomato. Euro J Plant Path 154(1):91–107
Poveda J, Martínez-Gómez Á, Fenoll C, Escobar C (2021a) The use of biochar for plant pathogen control. Phytopath 111(9):1490–1499
Poveda J, Martínez-Gómez Á, Fenoll C, Escobar C (2021) The use of biochar for plant pathogen control. Phytopathology®, 111(9), pp.1490–1499
Pramanik K, Mitra S, Sarkar A, Maiti TK (2018) Alleviation of phytotoxic effects of cadmium on rice seedlings by cadmium resistant PGPR strain Enterobacter aerogenes MCC 3092. J Hazard Mater 351:317–329
Puga AP, Grutzmacher P, Cerri CEP, Ribeirinho VS, Andrade CAD (2020) Biochar-based nitrogen fertilizers: greenhouse gas emissions, use efficiency, and maize yield in tropical soils. Sci Total Environ 704:135375
Qayyum MF, Haider G, Iqbal M, Hameed S, Ahmad N, ur Rehman MZ, Ali S, (2021) Effect of alkaline and chemically engineered biochar on soil properties and phosphorus bioavailability in maize. Chemosphere 266:128980
Qi L, Pokharel P, Ni C, Gong X, Zhou P, Niu H, Wang Z, Gao M (2020) Biochar changes thermal activation of greenhouse gas emissions in a rice–lettuce rotation microcosm experiment. J Clean Prod 247:119148
Qian S, Zhou X, Fu Y, Song B, Yan H, Chen Z, Sun Q, Ye H, Qin L, Lai C (2023) Biochar-compost as a new option for soil improvement: Application in various problem soils. Sci Total Environ 870:162024
Qiu M, Liu L, Ling Q, Cai Y, Yu S, Wang S, Fu D, Hu B, Wang X (2022) Biochar for the removal of contaminants from soil and water: a review. Biochar 4(1):19
Qie H, Ren M, You C, Cui X, Tan X, Ning Y, Liu M, Hou D, Lin A, Cui J (2023) High-efficiency control of pesticide and heavy metal combined pollution in paddy soil using biochar/g-C3N4 photoresponsive soil remediation agent. Chem Eng J 452:139579
Qu J, Dong M, Bi F, Tao Y, Wang L, Jiang Z, Zhang G, Zhang B, Zhang Y (2022) Microwave-assisted one-pot synthesis of β-cyclodextrin modified biochar for stabilization of Cd and Pb in soil. J Clean Prod 346:131165
Rafique MI, Ahmad M, Al-Wabel MI, Ahmad J, Al-Farraj AS (2022) Mitigating the toxic effects of chromium on wheat (*Triticum aestivum* L.) seed germination and seedling growth by using biochar and polymer-modified biochar in contaminated soil. Sustainability 14(23):16093
Rajput NA, Laghari M, Mangio HUR, Soothar RK (2024) Enhanced phosphorus and potassium recovery through co-pyrolysis of nutrient-rich biomass feedstocks for engineered biochar production. Bioresour Technol Rep 26(7):101818
Ramezani M, Ramezani F, Gerami M (2019) Nanoparticles in pest incidences and plant disease control. Nanotech agri: crop prod prot Springer, Singapore
Ramadan MM, Abd-Elsalam KA (2020) Micro/nano biochar for sustainable plant health: present status and future prospects. Carbon nanomaterials for agri-food and environmental applications, pp 323–357
Rasool M, Akhter A, Soja G, Haider MS (2021) Role of biochar, compost and plant growth promoting rhizobacteria in the management of tomato early blight disease. Sci Rep 11(1):6092
Ratnadass A, Llandres AL, Goebel FR, Husson O, Jean J, Napoli A, Sester M, Joseph S (2023) Potential of silicon-rich biochar (Sichar) amendment to control crop pests and pathogens in agroecosystems: a review. Sci Total Env 910:168545
Ravindiran G, Rajamanickam S, Janardhan G, Hayder G, Alagumalai A, Mahian O, Lam SS, Sonne C (2024) Production and modifications of biochar to engineered materials and its application for environmental sustainability: a review. Biochar 6(1):62
Ray A, Kumar M, Biswas K, Mohanty S, Pandey S (2024) Phosphorus recycling mediated by Pseudomonas aeruginosa from eutrophic biochar. Geomicrobiol J 41(3):277–286
Razzaq S, Zhou B, Zia-ur-Rehman M, Aamer Maqsood M, Hussain S, Bakhsh G, Zhang Z, Yang Q, Altaf AR (2022) Cadmium stabilization and redox transformation mechanism in maize using nanoscale zerovalent-iron-enriched biochar in cadmium-contaminated soil. Plants 11(8):1074
Ren J, Zhao ZX, Ali A, Guan WD, Xiao R, Wang JJ et al (2020) Characterization of phosphorus engineered biochar and its impact on immobilization of Cd and Pb from smelting contaminated soils. J Soils Sediments 20(8):3041–3052
Regkouzas P, Sygellou L, Diamadopoulos E (2023) Production and characterization of graphene oxide-engineered biochars and application for organic micro-pollutant adsorption from aqueous solutions. Environ Sci Pollut Res 30(37):87810–87829
Ringsby AJ, Ross CM, Maher K (2024) Sorption of soil carbon dioxide by biochar and engineered porous carbons. Environ Sci Technol 58(19):8313–8325
Rinklebe J, Shaheen SM, El-Naggar A, Wang H, Du Laing G, Alessi DS, Ok YS (2020) Redox-induced mobilization of Ag, Sb, Sn, and Tl in the dissolved, colloidal and solid phase of a biochar-treated and un-treated mining soil. Environ Int 140:105754
Sadhu M, Bhattacharya P, Vithanage M, Padmaja Sudhakar P (2022) Adsorptive removal of fluoride using biochar: a potential application in drinking water treatment. Sep Purif Technol 278:119106
Saeed Q, Xiukang W, Haider FU, Kučerik J, Mumtaz MZ, Holatko J, Naseem M, Kintl A, Ejaz M, Naveed M, Brtnicky M (2021) Rhizosphere bacteria in plant growth promotion, biocontrol, and bioremediation of contaminated sites: a comprehensive review of effects and mechanisms. Int J Mol Sci 22(19):10529
Safaei Asadabadi R, Hage-Ahmed K, Steinkellner S (2021) Biochar, compost and arbuscular mycorrhizal fungi: a tripartite approach to combat Sclerotinia sclerotiorum in soybean. J Plant Dis Protec 128(6):1433–1445
Safaei-Khorram M, Fatemi A, Khan MA, Kiefer R, Jafarnia S (2018) Potential risk of weed outbreak by increasing biochar's application rates in slow-growth legume, lentil (Medik.). J Sci Food Agric 98(6):2080–2088
Saharudin DM, Jeswani HK, Azapagic A (2024) Biochar from agricultural wastes: Environmental sustainability, economic viability and the potential as a negative emissions technology in Malaysia. Sci Total Environ 919:170266
Saif I, Salama ES, Usman M, Lee DS, Malik K, Liu P, Li X (2021) Improved digestibility and biogas production from lignocellulosic biomass: biochar addition and microbial response. Ind Crops Prod 171:113851
Sajjadi B, Chen W-Y, Egiebor NO (2019) A comprehensive review on physical activation of biochar for energy and environmental applications. Rev Chem Eng 35(6):735–776
Sales BK, Bryla DR, Trippe KM, Weiland JE, Scagel CF, Strik BC, Sullivan DM (2020) Amending sandy soil with biochar promotes plant growth and root colonization by mycorrhizal Fungi in Highbush blueberry. HortScience 55(3):353–361
Sanchez-Hernandez JC (2018) Biochar activation with exoenzymes induced by earthworms: a novel functional strategy for soil quality promotion. J Hazard Mater 350:136–143

Sani MNH, Hasan M, Uddain J, Subramaniam S (2020) Impact of application of Trichoderma and biochar on growth, productivity and nutritional quality of tomato under reduced N-P-K fertilization. Ann Agric Sci 65(1):107–115

Sarma H, Shyam S, Zhang M, Guerriero G (2024) Nano-biochar interactions within the rhizosphere and their implications for plant-soil dynamics. Soil Environ Health, p 100095

Saudy HS, Hamed MF, El-Metwally IM, Ramadan KA, Aisa KH (2021) Assessing the effect of biochar or compost application as a spot placement on broomrape control in two cultivars of faba bean. J Soil Sci Plant Nut 21:1856–66

Schmidt HP, Bucheli T, Kammann C, Glaser B, Abiven S, Leifeld J (2016) European biochar certificate-guidelines for a sustainable production of biochar

Schnee LS, Knauth S, Hapca S, Otten W, Eickhorst T (2016) Analysis of physical pore space characteristics of two pyrolytic biochars and potential as microhabitat. Plant Soil 408(1–2):357–368

Serrano MF, Lopez JE, Henao N, Saldarriaga JF (2024) Phosphorus-loaded biochar-assisted phytoremediation to immobilize cadmium, chromium, and lead in soils. ACS Omega 9(3):3574–3587

Sha H, Li J, Wang L, Nong H, Wang G, Zeng T (2023) Preparation of phosphorus-modified biochar for the immobilization of heavy metals in typical lead-zinc contaminated mining soil: performance, mechanism and microbial community. Environ Res 218:114769

Shanmugaraj C, Jaiganesh V, Biswas MK, Akshay Kumar HM (2024) Biochar in agriculture: enhancing crop productivity and disease resistance. J Adv Biol Biotechnol 27(6):221–234

Sharma P, Sharma MM, Malik A, Vashisth M, Singh D, Kumar R, Singh B, Patra A, Mehta S, Pandey V (2021) Rhizosphere, rhizosphere biology, and rhizospheric engineering. InPlant growth-promoting microbes for sustainable biotic and abiotic stress management (pp. 577–624). Cham: Springer International Publishing

Shi R-Y, Li J-Y, Ni N, Xu R-K (2019) Understanding the biochar's role in ameliorating soil acidity. J Integr Agric 18(7):1508–1517

Shi Z, Wen M, Zhao Y, Wang C (2023) Vermitoxicity of aged biochar and exploring potential damage factors. Environ Int 172:107787

Simiele M, Argentino O, Baronti S, Scippa G, Chiatante D, Terzaghi M, Montagnoli A (2022) Biochar enhances plant growth, fruit yield, and antioxidant content of cherry tomato (Solanum lycopersicum L.) in a soilless substrate. Agriculture 12:1135

Singh R, Babu JN, Kumar R, Srivastava P, Singh P, Raghubanshi AS (2015) Multifaceted application of crop residue biochar as a tool for sustainable agriculture: an ecological perspective. Ecol Eng 77:324–347

Singh S, Luthra N, Mandal S, Kushwaha DP, Pathak SO, Datta D, Sharma R, Pramanick B (2023) Distinct behavior of biochar modulating biogeochemistry of salt-affected and acidic soil: a review. J Soil Sci Plant Nutr 23(3):2981–2997

Smith P (2016) Soil carbon sequestration and biochar as negative emission technologies. Glob Chang Biol 22(3):1315–1324

Snoussi Y, El Garah M, Khalil AM, Ammar S, Chehimi MM (2022) Immobilization of biogenic silver–copper nanoparticles over arylated biochar from sugarcane bagasse: method and catalytic performance. Appl Organomet Chem 36(12):e6885

Solaiman ZM, Blackwell P, Abbott LK, Storer P (2010) Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. Soil Res 48(7):546–554

Sornhiran N, Aramrak S, Prakongkep N, Wisawapipat W (2022) Silicate minerals control the potential uses of phosphorus-laden mineral-engineered biochar as phosphorus fertilizers. Biochar. 4(1):2

Souza TF, Lobato RLM, Camargos JB, Ferreira GMD, Ribeiro-Soares J, Ferreira GMD (2024) Influence of Mn precursor on pre-pyrolysis modification of sugarcane bagasse biochar for enhanced removal of 2, 4-dichlorophenoxyacetic acid from aqueous solutions: experimental and theoretical insights. J Environ Chem Eng 12(5):113499

Song L, Niu X, Zhou B, Xiao Y, Zou H (2022) Application of biochar-immobilized *Bacillus* sp. KSB7 to enhance the phytoremediation of PAHs and heavy metals in a coking plant. Chemosphere 307:136084

Spokas KA (2010) Review of the stability of biochar in soils: predictability of O: C molar ratios. Carbon Manag 1(2):289–303

Streubel JD, Collins HP, Garcia-Perez M, Tarara J, Granatstein D, Kruger CE (2011) Influence of contrasting biochar types on five soils at increasing rates of application. Soil Sci Soc Am J 75(4):1402–1413

Sun DQ, Hale L, Crowley D (2016) Nutrient supplementation of pinewood biochar for use as a bacterial inoculum carrier. Biol Fertil Soils 52(4):515–522

Sun C, Wang D, Shen X, Li C, Liu J, Lan T, Wang W, Xie H, Zhang Y (2020) Effects of biochar, compost and straw input on root exudation of maize (*Zea mays* L.): from function to morphology. Agric Ecosyst Environ 297:106952

Sun T, Xu Y, Sun Y, Wang L, Liang X, Zheng S (2021) Cd immobilization and soil quality under Fe–modified biochar in weakly alkaline soil. Chemosphere 280:130606

Sutton AJ, Fisher TR, Gustafson AB, Liu XX, Mao P, Li L et al (2019) An innovative biochar-amended substrate vertical flow constructed wetland for low C/N wastewater treatment: impact of influent strengths. Bioresour Technol 247:844–850

Suwanree S, Knijnenburg JTN, Kasemsiri P, Kraithong W, Chindaprasirt P, Jetsrisuparb K (2022) Engineered biochar from sugarcane leaves with slow phosphorus release kinetics. Biomass Bioenerg 156(10):106304

Tang H, Chen M, Wu P, Faheem M, Feng QW, Lee XQ, Wang SS, Wang B (2023) Engineered biochar effects on soil physicochemical properties and biota communities: a critical review. Chemosphere 311(13):137025

Tao S, Wu Z, He X, Ye B, Li C (2018) Characterization of biochar prepared from cotton stalks as efficient inoculum carriers for Bacillus subtilis SL-13. BioRes 13(1):1773–1786

Tao J, Wu W, Lin D, Yang K (2022) Microbial degradation of nondesorbable organic compounds on biochars by extracellular reactive oxygen species. J Hazard Mater 439:129625

Thies JE, Rillig MC, Graber ER (2015) Biochar effects on the abundance, activity and diversity of the soil biota. In Bio env manag (pp. 327–389). Routledge

Tian GL, Bi YM, Jiao XL, Zhang XM, Li JF, Niu FB, Gao WW (2021) Application of vermicompost and biochar suppresses Fusarium root rot of replanted American ginseng. Appl Microbio Biotech 105(18):6977–6991

Tian SQ, Wang L, Liu YL, Ma J (2020) Degradation of organic pollutants by ferrate/biochar: enhanced formation of strong intermediate oxidative iron species. Water Res 183:116054

Tikoria R, Kumar D, Sharma R, Parkirti P, Jasrotia S, Chowdhary AB, Ohri P (2023) Insights into the role of biochar as potential agent in the management of disease caused by phytopathogens: a Review. J Soil Sci Plant Nutr 4:4856–4885

Trakal L, Michálková Z, Beesley L, Vítková M, Ouředníček P, Barceló AP, Ettler V, Číhalová S, Komárek M (2018) AMOchar: amorphous manganese oxide coating of biochar improves its efficiency at removing metal (loid) s from aqueous solutions. Sci Total Environ 625:71–78

Tsang, D.C. and Ok, Y.S. eds., 2022. Biochar in agriculture for achieving sustainable development goals. Academic Press

Uchimiya M, Bannon DI, Wartelle LH (2012) Retention of heavy metals by carboxyl functional groups of biochars in small arms range soil. J Agric Food Chem 60(7):1798–1809

Ullah N, Ditta A, Khalid A, Mehmood S, Rizwan MS, Ashraf M, Mubeen F, Imtiaz M, Iqbal MM (2019) Integrated effect of algal biochar and plant growth promoting rhizobacteria on physiology and growth of maize under deficit irrigations. J Soil Sci Plant Nutr 20(2):346–356

UN-Water, 2020. UN-Water Analytical Brief on Unconventional Water Resources, United Nations

Verma A, Sharma G, Kumar A, Dhiman P, Mola GT, Shan A, Si C (2024) Microplastic pollutants in water: a comprehensive review on their remediation by adsorption using various adsorbents. Chemosphere 352:141365

Viglašová E, Galamboš M, Diviš D, Danková Z, Daňo M, Krivosudský L, Lengauer CL, Matik M, Briančin J, Soja G (2020) Engineered biochar as a tool for nitrogen pollutants removal: preparation, characterization and sorption study. Desalin Water Treat 191:318–331

Vikrant K, Kim KH, Ok YS, Tsang DCW, Tsang YF, Giri BS, Singh RS (2018) Engineered/designer biochar for the removal of phosphate in water and wastewater. Sci Total Environ 616:1242–1260

Wachira RW (2020) Effect of soil amendment with biochar, lime and compost on soil acidity and root rot in common bean *Phasoelus Vulgaris* L. In Western Kenya (Doctoral dissertation, University of Nairobi) http://erepository.uonbi.ac.ke/handle/11295/154754

Wan Z, Xu Z, Sun Y, He M, Hou D, Cao X, Tsang DC (2021) Critical impact of nitrogen vacancies in nonradical carbocatalysis on nitrogen-doped graphitic biochar. Environ Sci Technol 55(10):7004–7014
Wan S, Li Y, Cheng S, Wu G, Yang X, Wang Y, Gao L (2022) Cadmium removal by FeOOH nanoparticles accommodated in biochar: Effect of the negatively charged functional groups in host. J Hazard Mater 421:126807
Wang X, Xu J, Sun T, Ali S (2021a) Synthesis of Cordyceps fumosorosea-biochar nanoparticles and their effects on growth and survival of Bemisia tabaci (Gennadius). Fron Microbiol 12:630220
Wang Y, Liu C, Jiang J, Shi F, Wang W (2024a) Mechanism of KOH-modified biochar application under water-saving and nitrogen-reducing conditions to inhibit soybean root rot and improve quality and efficiency. J Soil Sci Plant Nutr 10:1–4
Wang B, Gao B, Fang J (2017) Recent advances in engineered biochar productions and applications. Crit Rev Environ Sci Technol 47(22):2158–2207
Wang C, Kuzyakov Y (2024) Rhizosphere engineering for soil carbon sequestration. Trends Plant Sci 29(4):447–468
Wang J, Shi D, Huang C, Zhai B, Feng S (2023) Effects of common biochar and acid-modified biochar on growth and quality of spinach in coastal saline soils. Plants (Basel) 12(18)
Wang L, Butterly CR, Wang Y, Herath H, Xi YG, Xiao XJ (2014) Effect of crop residue biochar on soil acidity amelioration in strongly acidic tea garden soils. Soil Use Manage 30(1):119–128
Wang L, Deng J, Yang X, Hou R, Hou D (2023b) Role of biochar toward carbon neutrality. Carbon Research 2(1):2
Wang L, Ok YS, Tsang DC, Alessi DS, Rinklebe J, Mašek O, Bolan NS, Hou D (2022) Biochar composites: emerging trends, field successes and sustainability implications. Soil Use Manag 38(1):14–38
Wang L, Ok YS, Tsang DC, Alessi DS, Rinklebe J, Wang H, Mašek O, Hou R, O'Connor D, Hou D (2020) New trends in biochar pyrolysis and modification strategies: feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment. Soil Use Manag 36(3):358–386
Wang Y, Li W, Du B, Li H (2021b) Effect of biochar applied with plant growth-promoting rhizobacteria (PGPR) on soil microbial community composition and nitrogen utilization in tomato. Pedosphere 31(6):872–881
Wang MC, Sheng GD, Qiu YP (2015) A novel manganese-oxide/biochar composite for efficient removal of lead (II) from aqueous solutions. Int J Environ Sci Technol 12(5):1719–1726
Wang Y, Ma C, Kong D, Lian L, Liu Y (2023c) Review on application of algae-based biochars in environmental remediation: progress, challenge and perspectives. J Environ Chem Eng 11(6):111263
Wang Y, Ren Q, Li T, Zhan W, Zheng K, Liu Y, Chen R (2021c) Influences of modified biochar on metal bioavailability, metal uptake by wheat seedlings (*Triticum aestivum* L.) and the soil bacterial community. Ecotoxicol. Environ. Safe. 220:112370
Wang YC, Ni JJ, Guo HW, Kravchenko E (2024b) Influences of phosphorus-modified biochar on bacterial community and diversity in rhizosphere soil. Environ Sci Pollut Res 31(1):1681–1691
Were SA, Narla R, Mutitu EW, Muthomi JW, Munyua LM, Roobroeck D, Valauwe B (2021) Biochar and vermicompost soil amendments reduce root rot disease of common bean (*Phaseolous Vulgaris* L.). Afr J Biol Sci 3(1):176–196
Wen E, Yang X, Chen H, Shaheen SM, Sarkar B, Xu S, Song H, Liang Y, Rinklebe J, Hou D, Li Y (2021) Iron-modified biochar and water management regime-induced changes in plant growth, enzyme activities, and phytoavailability of arsenic, cadmium and lead in a paddy soil. J Hazard Mater 407:124344
Wong JTF, Chow KL, Chen XW, Ng CWW, Wong MH (2022) Effects of biochar on soil water retention curves of compacted clay during wetting and drying. Biochar 4(1):4
Wu Y, Qi L, Chen G (2022a) A mechanical investigation of perfluorooctane acid adsorption by engineered biochar. J Clean Prod 340:130742
Wu H, Wu H, Jiao Y, Zhang Z, Rensing C, Lin W (2022b) The combination of biochar and PGPBs stimulates the differentiation in rhizosphere soil microbiome and metabolites to suppress soil-borne pathogens under consecutive monoculture regimes. GCB Bioenergy 14(1):84–103
Xiang W, Wang L, Liu T, Li S, Zhai Z, Li C (2020) Effects of biochar plus inorganic nitrogen on the greenhouse gas and nitrogen use efficiency from rice fields. Sci Agric Sin 53:4634–4645
Xiang L, Harindintwali JD, Wang F, Redmile-Gordon M, Chang SX, Fu Y, He C, Muhoza B, Brahushi F, Bolan N, Jiang X (2022) Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. Environ Sci Technol 56(23):16546–16566
Xin D, Li W, Choi J, Yu YH, Chiu PC (2023) Pyrogenic black carbon suppresses microbial methane production by serving as a terminal electron acceptor. Environ Sci Technol 57(49):20605–20614
Xiong Y, Bi E (2023) Effect of endogenetic dissolved organic matter on tetracycline adsorption by biochar. Environ Sci Pollut Res 30:77022–77031. https://doi.org/10.1007/s11356-023-27847-9
Xu Y, Fang Z, Tsang EP (2016) In situ immobilization of cadmium in soil by stabilized biochar-supported iron phosphate nanoparticles. Environ Sci Pollut Res Int 23(19):19164–19172
Xu W, Whitman WB, Gundale MJ, Chien CC, Chiu CY (2021) Functional response of the soil microbial community to biochar applications. GCB Bioenergy 13(1):269–281
Xu J, Zhang Y, Li B, Fan S, Xu H, Guan DX (2022) Improved adsorption properties of tetracycline on KOH/KMnO4 modified biochar derived from wheat straw. Chemosphere 296:133981
Yakout SM, Daifullah AEHM, El-Reefy SA (2015) Pore structure characterization of chemically modified biochar derived from rice straw. Environ Eng Manag J 14(2)
Yan W, Liu Y, Malacrinò A, Zhang J, Cheng X, Rensing C, Zhang Z, Lin W, Zhang Z, Wu H (2024) Combination of biochar and PGPBs amendment suppresses soil-borne pathogens by modifying plant-associated microbiome. Appl Soil Ecol 193:105162
Yang H, Kerner P, Liang X, Struhs E, Mirkouei A, You Y (2024) Biochar modulates wheat root metabolome and rhizosphere microbiome in a feedstock-dependent manner. bioRxiv 07
Yang J, Song Y, Yue Y, Liu W, Che Q, Chen H, Ma H (2021a) Chemically dual-modified biochar for the effective removal of Cr (VI) in solution. Polymers 14(1):39
Yang F, Chen Y, Nan H, Pei L, Huang Y, Cao X, Xu X, Zhao L (2021b) Metal chloride-loaded biochar for phosphorus recovery: Noteworthy roles of inherent minerals in precursor. Chemosphere 266:128991
Yang T, Xu Y, Huang Q, Sun Y, Liang X, Wang L (2022) Removal mechanisms of Cd from water and soil using Fe–Mn oxides modified biochar. Environ Res 212:113406
Yang Y, Li G, Yue X, Zhang K, Zhang Z, Zheng H, Zhao X, Li H, Zhou P, Wu F, Wang D (2025) Advances in biochar composites for environmental sustainability. Adv Compos Hybrid Mater 8(1):74
Yao Y, Gao B, Chen J, Yang L (2013a) Engineered biochar reclaiming phosphate from aqueous solutions: mechanisms and potential application as a slow-release fertilizer. Environ Sci Technol 47(15):8700–8708
Yao Y, Gao B, Chen J, Zhang M, Inyang M, Li Y, Alva A, Yang L (2013b) Engineered carbon (biochar) prepared by direct pyrolysis of Mg-accumulated tomato tissues: characterization and phosphate removal potential. Bioresour Technol 138:8–13
Yao Y, Zhou H, Yan XL, Yang X, Huang KW, Liu J, Li LJ, Zhang JY, Gu JF, Zhou Y, Liao BH (2021) The Fe_3O_4-modified biochar reduces arsenic availability in soil and arsenic accumulation in indica rice (*Oryza sativa* L.). Environ Sci Pollut Res 28(14):18050–18061
Ye J, Zhang R, Nielsen S, Joseph SD, Huang D, Thomas T (2016) A combination of biochar–mineral complexes and compost improves soil bacterial processes, soil quality, and plant properties. Front Microbiol 7:372
Yu H, Zou W, Chen J, Chen H, Yu Z, Huang J, Tang H, Wei X, Gao B (2019) Biochar amendment improves crop production in problem soils: a review. J Environ Manage 232:8–21
Yu Z, Zhou L, Huang Y, Song Z, Qiu W (2015) Effects of a manganese oxide-modified biochar composite on adsorption of arsenic in red soil. J Environ Manage 163:155–162
Yuan J, Xu R-K, Zhang H (2011) The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresour Technol 102:3488–3497
Yuvaraj A, Thangaraj R, Karmegam N, Ravindran B, Chang SW, Awasthi MK, Kannan S (2021) Activation of biochar through exoenzymes prompted by earthworms for vermibiochar production: a viable resource recovery option for heavy metal contaminated soils and water. Chemosphere 278:130458

Zafar-ul-Hye M, Danish S, Abbas M, Ahmad M, Munir TM (2019) ACC deaminase producing PGPR bacillus amyloliquefaciens and agrobacterium fabrum along with biochar improve wheat productivity under drought stress. Agronomy 9(7):16

Zanganeh F, Heidari A, Sepehr A, Rohani A (2022) Bioaugmentation and bioaugmentation–assisted phytoremediation of heavy metal contaminated soil by a synergistic effect of cyanobacteria inoculation, biochar, and purslane (*Portulaca oleracea* L.). Environ Sci Pollut Res 29(4):6040–6059

Zeng Z, Xiao J, Li M, Wu J, Zhang T (2023) Degradation of phenol by immobilized alcaligenes faecalis Strain JH1 in Fe_3O_4-modified biochar from pharmaceutical residues. Water 15(23):4084

Zhang Q, Keitel C, Singh B (2019) Evaluation of the influence of individual clay minerals on biochar carbon mineralization in soils. Soil Syst 3(4):79

Zhang Y, Chen Z, Chen C, Li F, Shen K (2021) Effects of UV-modified biochar derived from phytoremediation residue on Cd bioavailability and uptake in *Coriandrum sativum* L. in a Cd-contaminated soil. Environ Sci Pollut Res 28(14):17395–17404

Zhang T, Tang Y, Li H, Hu W, Cheng J, Lee X (2023) A bibliometric review of biochar for soil carbon sequestration and mitigation from 2001 to 2020. Ecotoxicol Environ Saf 264:115438

Zhang D, Lin J, Luo J, Sun S, Zhang X, Ma R, Peng J, Ji F, Zheng S, Tian Z, Ma N (2024) Rapid immobilization of arsenic in contaminated soils by microwave irradiation combined with magnetic biochar: microwave-induced electron transfer for oxidation and immobilization of arsenic (III). Sci Total Environ 919:170916

Zhang G, Liu X, Gao M, Song Z (2020) Effect of Fe–Mn–Ce modified biochar composite on microbial diversity and properties of arsenic-contaminated paddy soils. Chemosphere 250:126249

Zhang Y, Peng J, Wang Z, Zhou F, Yu J, Chi R, Xiao C (2025) Metagenomic analysis revealed the bioremediation mechanism of lead and cadmium contamination by modified biochar synergized with Bacillus cereus PSB-2 in phosphate mining wasteland. Front Microbiol 16:1529784

Zhao M, Dai Y, Zhang M, Feng C, Qin B, Zhang W, Zhao N, Li Y, Ni Z, Xu Z, Tsang DC (2020) Mechanisms of Pb and/or Zn adsorption by different biochars: biochar characteristics, stability, and binding energies. Sci Total Environ 717:136894

Zhao X, Elcin E, He L, Vithanage M, Zhang X, Wang J, Wang S, Deng Y, Niazi NK, Shaheen SM, Wang H (2024) Using biochar for the treatment of continuous cropping obstacle of herbal remedies: A review. Appl Soil Ecol 193:105127

Zhao Y, Wang X, Yao G, Lin Z, Xu L, Jiang Y, Jin Z, Shan S, Ping L (2022a) Advances in the effects of biochar on microbial ecological function in soil and crop quality. Sustain 14(16):10411

Zhao X, Song Z, Liu H, Li Z, Li L, Ma C (2010) Microwave pyrolysis of corn stalk bale: a promising method for direct utilization of large-sized biomass and syngas production. J Anal Appl Pyrolysis 89(1):87–94

Zhao Y, Li YL, Yang F (2022b) A state-of-the-art review on modeling the biochar effect: guidelines for beginners. Sci Total Environ 802:149861

Zheng X, Xu W, Dong J, Yang T, Shangguan Z, Qu J, Li X, Tan X (2022) The effects of biochar and its applications in the microbial remediation of contaminated soil: a review. J Hazard Mater 438:129557

Zheng YL, Wang B, Wester AE, Chen JJ, He F, Chen H et al (2019) Reclaiming phosphorus from secondary treated municipal wastewater with engineered biochar. Chem Eng J 362:460–468

Zheng Z, Liu W, Zhou Q, Li J, Zeb A, Wang Q, Lian Y, Shi R, Wang J (2023) Effects of co-modified biochar immobilized laccase on remediation and bacterial community of PAHs-contaminated soil. J Hazard Mater 443:130372

Zheng Y, Abbott LK, Bolan N, Hu H, Jenkins SN, Mickan BS (2025) Biochar interacted with organic compounds from digestate in controlling N2O emissions. J Environ Manage 385:125591

Zhen M, Tang J, Li C, Sun H (2021) Rhamnolipid-modified biochar-enhanced bioremediation of crude oil-contaminated soil and mediated regulation of greenhouse gas emission in soil. J Soils Sediments 21(1):123–133

Zhou Q, Lin L, Qiu W, Song Z, Liao B (2018) Supplementation with ferromanganese oxide–impregnated biochar composite reduces cadmium uptake by indica rice (*Oryza sativa* L.). J Clean Prod 184:1052–1059

Zhou Y, Zhao X, Jiang Y, Ding C, Liu J, Zhu C (2023) Synergistic remediation of lead pollution by biochar combined with phosphate solubilizing bacteria. Sci Total Environ 861:160649

Zhu Q, Peng X, Huang T (2015) Contrasted effects of biochar on maize growth and N use efficiency depending on soil conditions. Int Agrophys 29(2):257–266

Zhu S, Zhao J, Zhao N, Yang X, Chen C, Shang J (2020) Goethite modified biochar as a multifunctional amendment for cationic Cd (II), anionic As (III), roxarsone, and phosphorus in soil and water. J Clean Prod 247:119579

Zou Q, An W, Wu C, Li W, Fu A, Xiao R, Xue S (2018) Red mud-modified biochar reduces soil arsenic availability and changes bacterial composition. Environ Chem Lett 16:615–622