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REVIEW

Biochar as a Rhizosphere Modulator: Enhancing Root Resilience to Multifaceted Environmental Stresses for Sustainable Agriculture

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Abstract
Biochar, a carbon-rich material derived from organic biomass through pyrolysis, has emerged as a promising soil amendment for enhancing plant root resilience under diverse environmental stressors. This review is novel in its emphasis on biochar's modulation of the rhizosphere under multiple simultaneous stresses. It synthesizes the multifaceted role of biochar in mitigating drought, salinity, heavy metal toxicity, organic pollutants, and pathogen-induced stresses on root systems. Biochar's unique physicochemical properties, including high porosity, surface area, and cation-exchange capacity, improve soil water retention, nutrient availability, and microbial activity, fostering robust root development. Under drought conditions, biochar enhances root elongation and branching by optimizing soil moisture dynamics and reducing oxidative stress. In saline soils, it alleviates ion toxicity and osmotic stress, promoting root growth and nutrient uptake. Biochar immobilizes heavy metals, reducing their bioavailability and protecting root tissues, while its adsorptive capacity mitigates organic pollutant toxicity. Furthermore, biochar suppresses soil-borne pathogens by modulating the rhizosphere microbiome and inducing systemic resistance in plants. The efficacy of biochar is influenced by feedstock type, pyrolysis temperature, application rate, soil characteristics, and plant species-specific responses. Despite its benefits, challenges such as nutrient imbalances, pH alterations, and long-term impacts necessitate careful optimization of biochar use. Future research should prioritize the customization of biochar properties to address specific environmental stressors, explore its synergistic integration with other soil amendments, and deepen the understanding of its role in advancing sustainable agricultural practices. By elucidating biochar's rhizosphere-modulating mechanisms and interactions under concurrent stresses, this review highlights its potential to enhance crop resilience and productivity amidst escalating environmental pressures.

Keywords Biochar · Multifaceted environmental stresses · Sustainable agriculture · Rhizosphere modulation · Root resilience

1 Introduction

Root systems are vital for plant health, performing essential roles in anchorage, water and nutrient acquisition, and interactions with soil microbiota. Crucially, roots are the first plant organ to sense environmental stress and initiate adaptive responses, making them central to agricultural productivity and ecosystem stability (Kalra et al. 2024; Shoaib et al. 2022; Karlova et al. 2021). However, global agriculture faces escalating challenges from environmental stressors like drought, soil salinity, heavy metal contamination, organic pollutants, and pathogenic infections (Yuan et al. 2024; Fróna et al. 2021). These stresses collectively impair root development, disrupt nutrient uptake, and reduce crop

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yields, posing significant risks to food security (Karlova et al. 2021; Teh and Koh 2016). Enhancing root resilience—the capacity of roots to withstand, adapt to, and recover from these multifaceted stresses—is therefore critical. This resilience encompasses morphological changes (e.g., root elongation and branching), enhanced stress signaling, improved antioxidant protection against oxidative damage, and strengthened symbiotic relationships with beneficial microbes.

In this context, biochar, a carbon-rich material produced by pyrolyzing organic biomass, has emerged as a promising sustainable soil amendment (Brassard et al. 2019; Lehmann and Joseph 2024; Zheng et al. 2010). Its unique properties, including high porosity, surface area, and cation-exchange capacity, improve soil structure, water retention, nutrient availability, and microbial activity (Lehmann et al. 2011; Kabir et al. 2023; Hossain et al. 2020) (Fig. 1). Biochar also adsorbs contaminants, aiding the remediation of polluted soils (Shaaban and Abid 2021; Zhang et al. 2013a). Collectively, these properties create a more favorable rhizosphere environment for root development and function (Agegnehu et al. 2017; Yadav et al. 2023; Yu et al. 2019). While biochar's agronomic benefits are increasingly recognized, a comprehensive synthesis focusing specifically on its role in enhancing **root resilience** under *simultaneous* multifactorial stresses remains limited. Previous reviews have often addressed biochar's broader impacts on plant growth or soil properties. This review systematically evaluates how biochar modulates root growth and resilience under combined abiotic (drought, salinity, heavy metals, and organic pollutants) and biotic (pathogen) stresses. We integrate recent mechanistic insights to clarify how biochar's physicochemical properties interact with roots to enhance stress tolerance. Specifically, we explore biochar's influence on root architecture, function, and associated microbial communities, discussing implications for sustainable agriculture. By identifying research gaps and proposing future directions, this review aims to provide a framework for leveraging biochar to build resilient agricultural systems amidst climate change and resource scarcity.

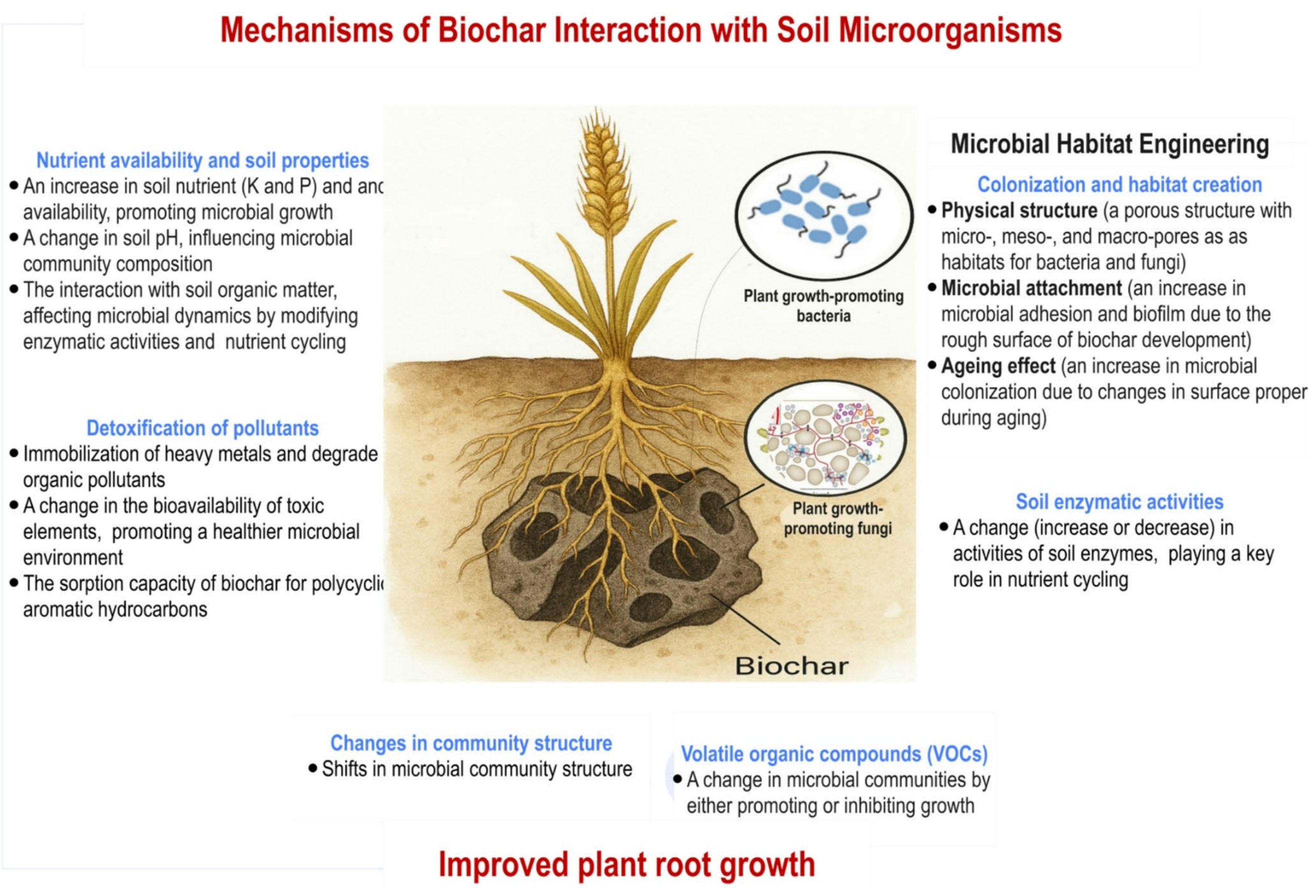

Fig. 1 A detailed overview of the mechanisms by which biochar influences soil microorganisms and their interactions with the rhizosphere environment

2 Roots as Key Players in Plant Resilience to Environmental Stresses

Roots are fundamental to plant resilience against environmental stresses, serving as the primary interface between the plant and its surrounding soil environment (Shoaib et al. 2022; Balestrini et al. 2024; Karlova et al. 2021; Kalra et al. 2024). They play a critical role in the uptake, storage, and transport of minerals and water, anchoring the plant, and responding dynamically to various abiotic and biotic stressors such as drought, salinity, heavy metals, and pathogen attacks (Lynch 1995; Comas et al. 2013a; Karlova et al. 2021; Chen and Palta 2024; Kalra et al. 2024). Roots facilitate communication and interaction with the soil microbiome and neighboring plants. This interaction is crucial for nutrient exchange and defense against pathogens (Koevoets et al. 2016; Karlova et al. 2021). Roots exhibit remarkable developmental plasticity, allowing them to adapt their growth patterns in response to environmental cues (Karlova et al. 2021). The spatial and temporal configurations of roots are collectively referred to as root system architecture (RSA), which has been defined as the geometric description of the shape (topology and distribution) of the root system (Lynch 1995). Roots undergo significant morphological and physiological adaptations under various environmental conditions. For example, under drought stress conditions, roots may deepen their architecture to access deeper water reserves or increase root hair density to enhance water absorption (Comas et al. 2013b; Kalra et al. 2024). In saline environments, roots play a crucial role in regulating ion homeostasis by excluding excess sodium while accumulating compatible solutes such as proline and glycine betaine. These solutes help maintain cellular osmotic balance, thereby supporting plant survival under stress (Munns and Tester 2008). Additionally, roots also form symbiotic relationships with mycorrhizal fungi, which extend their reach into the soil and significantly improve nutrient acquisition—particularly phosphorus—under nutrient-deficient conditions (Smith and Read 2008; Balestrini et al. 2024). This symbiosis not only enhances nutrient uptake but also contributes to soil health by improving soil structure. In addition to their structural roles, roots produce and exude a variety of secondary metabolites such as flavonoids and strigolactones. These compounds can deter pathogens, attract beneficial microbes, and modulate plant-microbe interactions (Bais et al. 2006; Bouwmeester et al. 2007). Furthermore, roots are capable of sensing mechanical stresses—such as soil compaction—and respond by altering growth patterns or secreting mucilage that reduces friction and improves soil structure (Bengough et al. 2006). The plasticity of root systems is driven by both genetic and epigenetic mechanisms that enable plants to adapt to fluctuating environmental conditions. This adaptability is essential for plant survival and productivity in challenging environments (Hodge 2004; Giehl and von Wirén 2014). In summary, these "hidden heroes" of plant life not only anchor plants but also act as nutrient detectives. They employ diverse strategies to ensure essential element uptake while underscoring their foundational role in growth, adaptation, and long-term survival. Through these mechanisms, roots emerge as indispensable components in the quest for sustainable agricultural practices amidst evolving environmental pressures. Their ability to adapt to stressors is vital for maintaining ecosystem balance and ensuring food security in a changing climate.

3 Multifaceted Impacts of Environmental Stressors on Root Growth

Environmental stresses—including drought, salinity, heavy metals, organic pollutants, and pathogens—profoundly suppress root growth through both convergent and stressor-specific mechanisms (Figs. 2, 3, 4, 5 and 6). A key convergent response is the induction of oxidative stress, leading to the accumulation of reactive oxygen species (ROS) that damage cellular components and impair meristematic activity (Sharma et al. 2012). Similarly, hormonal imbalances, particularly elevated abscisic acid (ABA) and ethylene, frequently disrupt auxin signaling and inhibit cell wall loosening, thereby suppressing root elongation and branching (Julkowska and Testerink 2015). Stresses like drought, salinity, and heavy metals also converge on causing osmotic stress and ionic toxicity, which reduce water uptake and disrupt ion homeostasis to limit cell expansion (Munns and Tester 2008). These stressors impose significant metabolic costs by disrupting carbon partitioning to roots while demanding energy for defense processes like antioxidant production and ion exclusion (e.g., via *SOS1* and *NHX* genes), thereby diverting resources away from growth (Poorter et al. 2012; Huot et al. 2014). This resource reallocation is governed by the modulation of transcription factors, which leads to the downregulation of growth-related genes and the upregulation of stress-responsive pathways (Nakashima et al. 2014; Munns et al. 2020). Furthermore, a common ecological impact is the disruption of symbiotic interactions with soil microorganisms, which compromises nutrient acquisition (Naylor and Coleman-Derr 2018). In addition to these shared pathways, specific stressors inflict unique damage. Heavy metals and organic pollutants can cause direct cellular ultrastructure damage and DNA lesions, directly interfering with mitosis (Adamakis et al. 2013; Goyal et al. 2020). Pathogens, conversely, inflict physical damage and manipulate host signaling to induce abnormal growths that impair root function (Jones and Goto 2011).

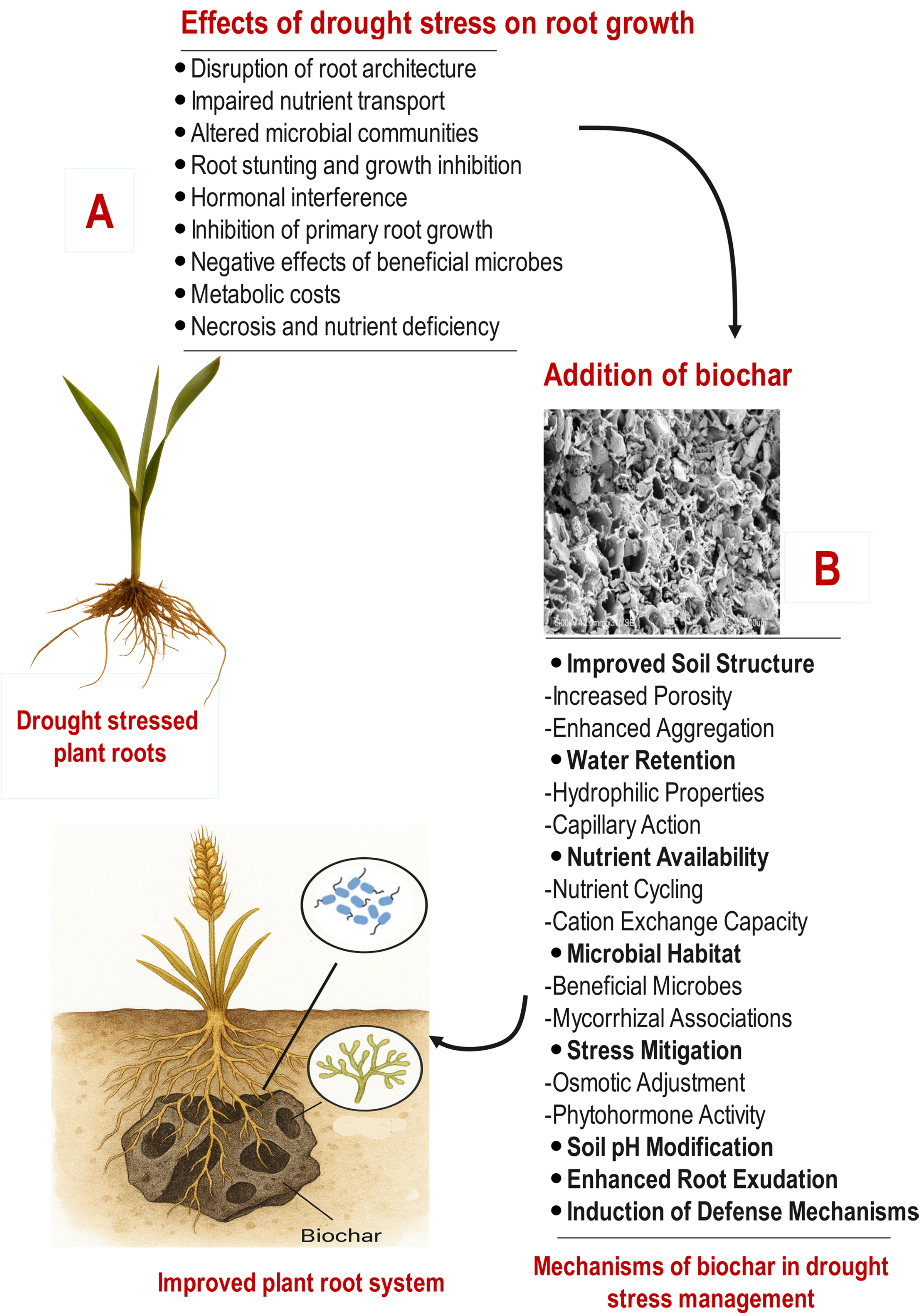
Effects of drought stress on root growth
• Disruption of root architecture
• Impaired nutrient transport
• Altered microbial communities
• Root stunting and growth inhibition
• Hormonal interference
• Inhibition of primary root growth
• Negative effects of beneficial microbes
• Metabolic costs
• Necrosis and nutrient deficiency
A
Drought stressed plant roots
Addition of biochar
B
• Improved Soil Structure
-Increased Porosity
-Enhanced Aggregation
• Water Retention
-Hydrophilic Properties
-Capillary Action
• Nutrient Availability
-Nutrient Cycling
-Cation Exchange Capacity
• Microbial Habitat
-Beneficial Microbes
-Mycorrhizal Associations
• Stress Mitigation
-Osmotic Adjustment
-Phytohormone Activity
• Soil pH Modification
• Enhanced Root Exudation
• Induction of Defense Mechanisms
Biochar
Improved plant root system
Mechanisms of biochar in drought stress management

Fig. 2 Effects of drought stress on root growth (**A**). Drought stress impairs root growth through multiple mechanisms, including the disruption of root architecture, reduced nutrient uptake, and altered interactions with beneficial soil microbes. It inhibits primary root elongation, promotes root stunting, and causes hormonal imbalances that interfere with growth regulation. Prolonged stress increases metabolic costs, leading to energy deficits, while necrosis and nutrient deficiencies further compromise root health and functionality. These effects highlight the complex challenges drought poses to root system development and plant resilience. Effect of biochar on improved plant root system under drought stress (**B**). Biochar improves soil structure by increasing porosity and aggregation, while enhancing water retention and hydrophilic properties to support root hydration. It boosts nutrient availability and cycling through improved cation exchange capacity and facilitates better microbial habitats, fostering beneficial microbes and mycorrhizal associations. Additionally, biochar aids in stress mitigation by enabling osmotic adjustment, modifying soil pH, and promoting root exudation and defense mechanisms, collectively contributing to a healthier and more resilient root system

4 Biochar as a Promising Rhizosphere Soil Amendment

Biochar, a carbon-rich material produced through the pyrolysis of organic biomass, has gained significant attention as a soil amendment with the potential to alleviate various environmental stresses in agriculture (Lehmann and Joseph 2024). By enhancing soil physical, chemical, and biological properties, biochar improves soil structure, boosts water retention, reduces nutrient leaching, adsorbs heavy metals and organic pollutants, stabilizes soil pH, increases cation exchange capacity, promotes beneficial microbial activity, and suppresses soil-borne pathogens (Major et al. 2012; Lehmann et al. 2011; Lehmann and Joseph 2024; Nepal et al. 2023; Shaaban and Abid 2021; Razzaghi et al. 2020; de Medeiros et al. 2021). These combined effects mitigate environmental stresses and collectively enhance plant resilience to both abiotic and biotic challenges. By alleviating these diverse stressors, biochar creates a more favorable rhizosphere environment, enabling roots to allocate more resources toward growth and development, ultimately enhancing plant vigor and crop productivity under challenging agricultural conditions (Figs. 2, 3, 4, 5 and 6; Table 1).

5 Biochar's Role in Root Development Under Stress

5.1 Soil Structural Improvement and Hydraulic Regulation

Biochar mitigates drought and salinity stress by enhancing soil physical properties critical for root growth through three primary mechanisms: (1) porosity and bulk density modification, (2) water retention optimization, and (3) structural stabilization. Its porous structure reduces bulk density (e.g., from 1.52 to 1.33 g cm^{-3} in silty soils) while increasing total porosity and saturated hydraulic conductivity, facilitating root penetration and subsoil water access (Zhang et al. 2021; Edeh and Mašek 2022; Major et al. 2012). Under drought, biochar's hydrophilic surface and large specific area significantly improve water retention—especially in coarse-textured soils where field capacity increases by 51% and plant-available water (AW) by 45%, enabling deeper root proliferation during dry periods (Razzaghi et al. 2020; Aller 2017). In saline conditions, calcium-rich biochars (e.g., from bone meal or poultry litter) reduce exchangeable sodium percentage (ESP) by displacing Na^+ ions and strengthening aggregates through Ca^{2+} bridging, concurrently increasing hydraulic conductivity by 40% and alleviating osmotic stress (Chaganti and Crohn 2015; Clark et al. 2007). Biochar further stabilizes soil structure via recalcitrant organic carbon that binds clay particles and forms water-stable aggregates (25% increase), resisting re-compaction and maintaining pore connectivity for gas exchange and root oxygenation (Bhaduri et al. 2016; Kim et al. 2016; Amini et al. 2016). Efficacy depends on biochar properties: high-temperature (450–600 °C) and larger-particle (0.5–2 mm) biochars optimize porosity and moisture retention under drought, while Ca-enriched feedstocks (> 500 °C) maximize salinity mitigation at 2–5% (w/w) application rates (Chen et al. 2018a; Ndede et al. 2022; McBeath et al. 2014). These structural improvements create resilient root zones that sustain hydration, reduce compaction, and enhance exploration efficiency across abiotic stresses (Figs. 2B and 3B).

5.2 Morphological Modifications in Root Systems

Biochar drives critical morphological adaptations in plant root systems, optimizing their architecture to overcome drought stress and maximize nutrient acquisition—key factors for sustaining plant growth under water scarcity. By enhancing root length, surface area, and branching, biochar enables plants to exploit deeper soil layers and improve resilience to arid conditions (Akram et al. 2024; Han et al. 2023). Biochar application induces profound structural changes in roots, favoring traits that enhance drought tolerance. A meta-analysis by Xiang et al. (2017) demonstrated that biochar-amended soils increased root biomass by 32%, root volume by 29%, and root surface area by 39%. Notably, root length surged by 52%, far outpacing increases in root diameter (+ 9.9%), indicating preferential investment in exploratory root growth (Xiang et al. 2017). This elongation enables roots to reach water and nutrients in deeper soil layers, providing a crucial advantage during drought conditions (Eissenstat and Yanai 1997). For example, biochar-treated wheat exhibited 1.4× greater root length and 1.8× higher

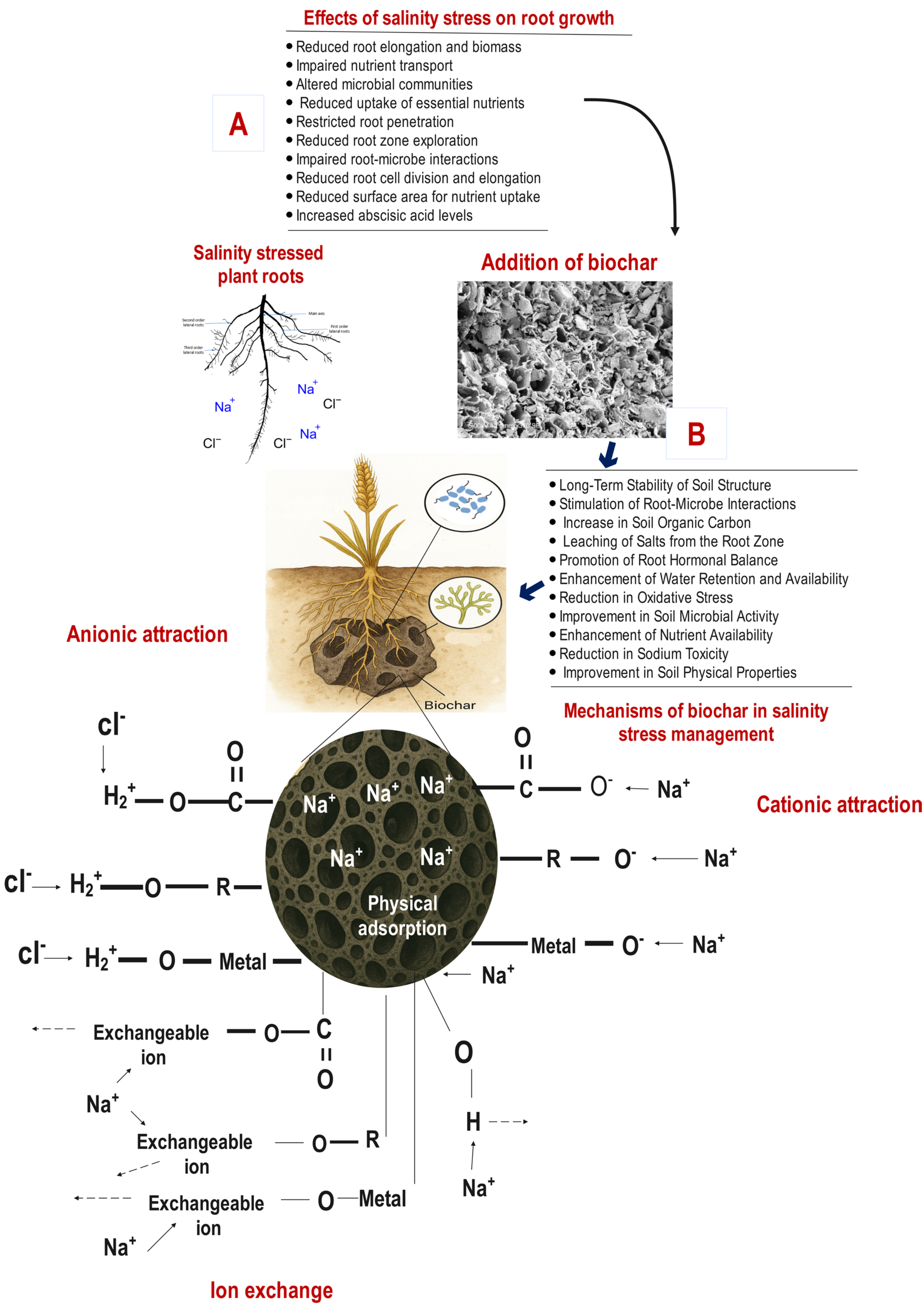
Effects of salinity stress on root growth
• Reduced root elongation and biomass
• Impaired nutrient transport
• Altered microbial communities
• Reduced uptake of essential nutrients
• Restricted root penetration
• Reduced root zone exploration
• Impaired root-microbe interactions
• Reduced root cell division and elongation
• Reduced surface area for nutrient uptake
• Increased abscisic acid levels
A
Salinity stressed plant roots
Na+
Cl−
Na+
Cl−
Cl−
Na+
Addition of biochar
B
• Long-Term Stability of Soil Structure
• Stimulation of Root-Microbe Interactions
• Increase in Soil Organic Carbon
• Leaching of Salts from the Root Zone
• Promotion of Root Hormonal Balance
• Enhancement of Water Retention and Availability
• Reduction in Oxidative Stress
• Improvement in Soil Microbial Activity
• Enhancement of Nutrient Availability
• Reduction in Sodium Toxicity
• Improvement in Soil Physical Properties
Biochar
Mechanisms of biochar in salinity stress management
Anionic attraction
Cationic attraction
Physical adsorption
Ion exchange
Exchangeable ion
Metal
Na+
Cl-
H2+
O
C
R
O-
H

Fig. 3 Effects of salinity stress on plant root growth (**A**). Salinity stress can lead to reduced root elongation and biomass, impaired nutrient transport, altered microbial communities, and decreased uptake of essential nutrients. Mechanisms of biochar in improving root growth under salinity stress (**B**). Postulated mechanisms of biochar interactions with inorganic contaminants. Mechanisms include: (I) Ion exchange; (II) Electrostatic repulsion of anions; (III) Physical adsorption; and (IV) Electrostatic attraction of cations. Biochar properties (pyrolysis temperature, pH, dissolved organic carbon, and functional groups) determine the dominant mechanism(s) for a given contaminant. Biochar mitigates salinity stress on root growth through multiple mechanisms: (1) improving soil structure and porosity, enhancing root penetration; (2) adsorbing Na^+ ions and reducing ion toxicity; (3) increasing nutrient availability, particularly K^+ and Ca^{2+}, for optimal root function; (4) enhancing microbial activity, which promotes root growth and stress tolerance; (5) reducing oxidative stress by lowering reactive oxygen species levels; (6) improving water retention and availability, ensuring steady water supply to roots; (7) regulating phytohormones like abscisic acid to promote root elongation; (8) facilitating salt leaching from the root zone; (9) increasing soil organic carbon, which enhances soil health; (10) stimulating root-microbe interactions, particularly with mycorrhizal fungi; (11) reducing soil pH in alkaline saline soils, improving nutrient solubility; and (12) providing long-term stability to soil structure. These combined effects enable robust root growth and improved plant resilience under saline conditions

surface area, correlating with improved water uptake and yield stability in arid regions (Schmidt et al. 2021; Sui et al. 2022; Yu et al. 2019).

Biochar enhances nutrient cycling, directly stimulating root proliferation. By elevating soil pH and cation-exchange capacity (CEC), biochar improves phosphorus (P) solubility, increasing root P concentrations by 22% (Cui et al. 2011; Graber et al. 2010). This is pivotal for root elongation, as P is essential for cell division and energy metabolism (Vitousek et al. 2010). Enhanced P availability, combined with biochar's porous structure, promotes finer root growth, expanding the absorptive surface area and enabling plants to scavenge scarce resources efficiently (Prendergast-Miller et al. 2014; Glaser and Lehr 2019). Biochar fosters beneficial root-microbe interactions, amplifying nutrient acquisition (Saleem et al. 2022). It increases root nodulation by 25% in legumes, boosting biological nitrogen fixation (Rondon et al. 2007). This symbiosis is critical in drought-stressed soils, where nitrogen scarcity limits growth. Biochar also enriches populations of auxin-producing bacteria (e.g., *Pseudomonas* spp.), which enhance root architectural plasticity by stimulating lateral root formation and root hair density (Etesami and Glick 2024; Xu et al. 2016, 2021; Saleem et al. 2022). These microbes maintain root vitality during critical growth stages. In maize, biochar extended root longevity during grain filling, preventing a 21–34% decline in root length observed in untreated soils (Han et al. 2023). The magnitude of root morphological benefits depends on biochar's physicochemical properties. High pyrolysis temperatures (450–600 °C) yield biochars with greater porosity and surface area, which enhance soil aeration and water retention, indirectly promoting root elongation (Sohi et al. 2010). Larger particle sizes (0.5–2 mm) improve moisture retention in drought conditions, while finer particles optimize nutrient release (Chen et al. 2018a). Combined applications with fertilizers synergistically enhance root traits: for instance, biochar-compost blends increased plant root length by 1.8× compared to controls (Steiner et al. 2008). However, excessive application rates (e.g., >10% *v/v*) can compact soil pores, underscoring the need for calibrated dosing (Ndede et al. 2022). Biochar's ability to remodel root morphology—boosting length, surface area, and microbial partnerships—positions it as a cornerstone for drought-resilient agriculture. By enabling roots to exploit deeper soil moisture, retain hydraulic conductivity, and sustain nutrient uptake under stress, biochar ensures robust plant growth even in water-limited environments. Future research should prioritize biochar customization (feedstock and particle size) and field-scale validation to optimize root-focused drought adaptation strategies.

5.3 Physiological and Biochemical Adaptations in Root Systems

Biochar application triggers physiological and biochemical adaptations that enhance root development and vitality, enabling plants to mitigate drought-induced cellular and metabolic stresses. By modulating osmotic regulation, hormonal signaling, antioxidant defenses, and nutrient dynamics, biochar fosters root systems capable of sustaining growth under water scarcity (Wu et al. 2023; Murtaza et al. 2024; Agbna et al. 2017). Biochar enhances osmotic adjustment in roots by promoting the accumulation of osmolytes like proline, which stabilizes cellular turgor and membrane integrity during dehydration. For instance, biochar-amended soils in drought-stressed plants increased proline synthesis, enabling roots to maintain elongation and function under severe water deficits (Murtaza et al. 2024). Similarly, maize straw biochar (100 t ha^{-1}) reduced root osmolality and malonaldehyde (a lipid peroxidation marker) while improving root water potential and ascorbate peroxidase activity, directly supporting root growth and biomass retention during drought (Ruan et al. 2024). Biochar influences hormonal balance, particularly ABA, which regulates stomatal closure and root growth under stress. In soybean seedlings, biochar reduced ABA concentrations by improving soil moisture retention, delaying stomatal closure, and prolonging photosynthesis. This moderation of ABA signals allows roots to prioritize growth over premature stress responses, fostering deeper root penetration during intermittent dry periods (Gullap et al. 2024).

Reactive oxygen species (ROS) generated under drought disrupt root cell membranes, impairing growth. Biochar

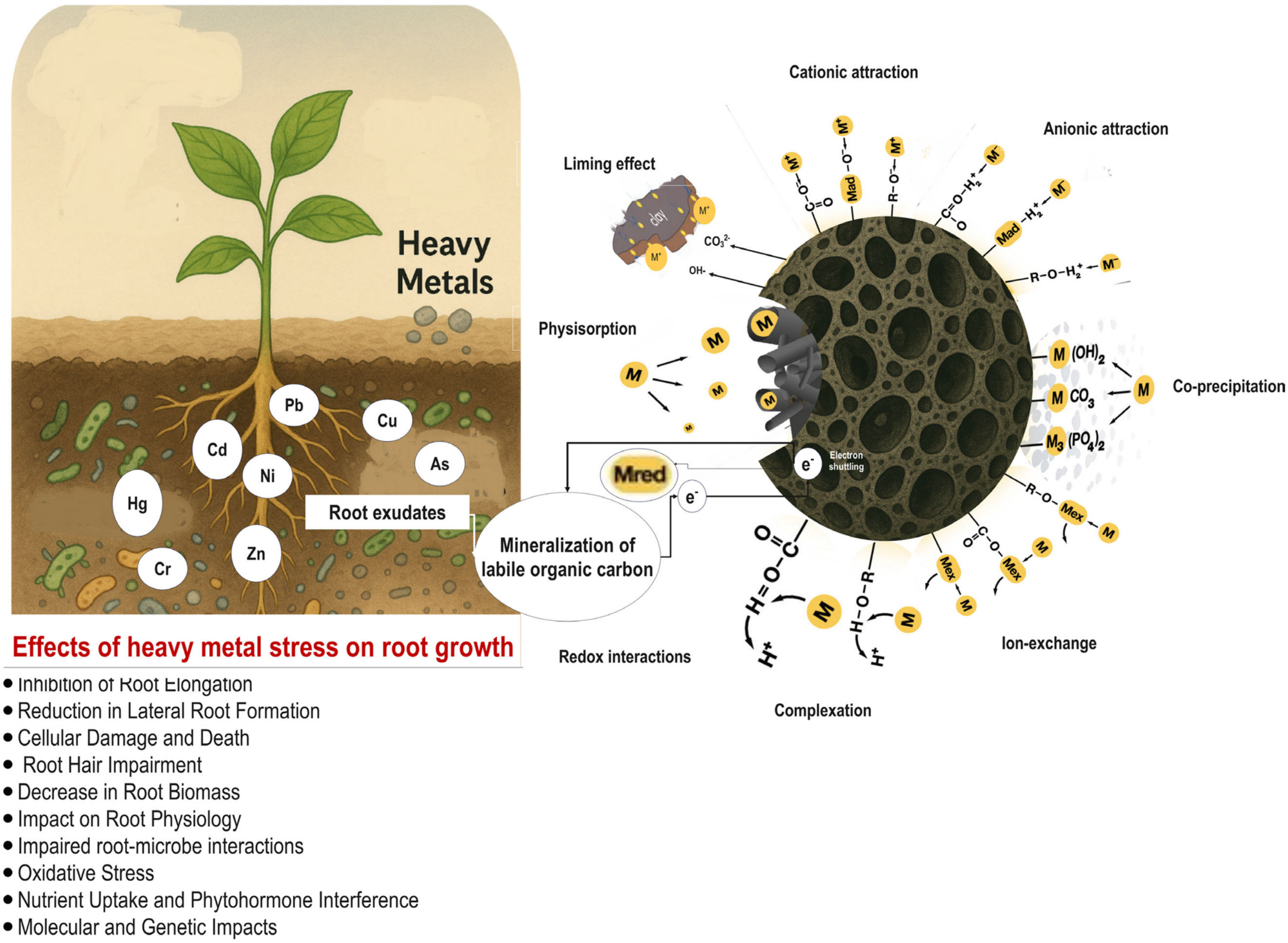

Fig. 4 Effect of heavy metals on root growth. Toxic elements such as lead (Pb), cadmium (Cd), and arsenic (As) exhibit toxicity to plant cells, which can result in reduced root elongation and overall growth. These metals disrupt essential cellular processes like photosynthesis and respiration, vital for root development. Additionally, they interfere with the uptake of essential nutrients, such as nitrogen and phosphorus, causing deficiencies that further hinder root growth. The presence of heavy metals can also induce oxidative stress, damaging root cells and impairing their function. This exposure often leads to altered root morphology, characterized by shorter roots, fewer root hairs, and stunted systems. Moreover, heavy metals can negatively affect microbial communities in the rhizosphere, which play a crucial role in nutrient availability and root health. Biochar alleviates heavy metal stress on root growth by immobilizing toxic elements, improving soil structure and nutrient availability, fostering beneficial microbial communities, and reducing oxidative damage—synergistically enhancing root resilience and plant health. Effect of biochar on root growth under heavy metals stress. Biochar interacts with heavy metals through multiple mechanisms: precipitation/coprecipitation with minerals (e.g., carbonates, phosphates, and silicates) in biochar; ion exchange with cationic metals on biochar's negatively charged surfaces; complexation via surface functional groups (e.g., carboxyl, hydroxyl, and phenolic); electrostatic attraction to charged surfaces; and physical adsorption within its porous structure. The dominant mechanism(s) depend on biochar properties (pH, ash/mineral content, surface charge, functional groups, and porosity) and soil/solution conditions (pH, redox, ionic strength, and competing ions). Biochar's alkalinity often raises soil pH, promoting metal precipitation and reducing bioavailability. Surface oxidation or mineral enhancement can further increase complexation capacity for cationic metals (e.g., Cd^{2+} and Pb^{2+}), while anionic metals (e.g., CrO_4^{2-} and AsO_4^{3-}) may be retained via ligand exchange or electrostatic interactions with metal oxides

counters this by boosting antioxidant enzyme activity. In rapeseed, biochar increased superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) activities by 63%, 48%, and 62%, respectively, reducing oxidative damage and preserving root tip viability—critical for maintaining meristematic activity and lateral root formation (Khan et al. 2021). Similarly, hazelnut shell biochar enhanced antioxidant enzyme levels in soybean roots, mitigating ROS-induced growth inhibition (Gullap et al. 2024). Biochar enhances nutrient retention (N, P, K, and Ca) through its CEC and reduces nutrient fixation, ensuring sustained availability under drought. For example, biochar increased nitrate-N concentrations in the rhizosphere of fine roots (<2 mm diameter), stimulating root branching and active absorption zones (Feng et al. 2021). In maize, biochar promoted longer, thinner roots with more tips, enhancing soil exploration and nutrient uptake (Sun et al. 2020). This morphological shift was linked to biochar-induced organic acid exudation (e.g., citrate), which solubilizes soil nutrients, and upregulated expression of genes like *ZmMATE1*, facilitating root exudate release. Biochar-enhanced root exudates (sugars, amino acids) stimulate microbial activity, improving nutrient cycling. Increased ammonia-oxidizing bacteria (AOB) abundance in biochar-amended soils boosts nitrogen availability, supporting root proliferation (Feng et al. 2021). Additionally, biochar's alkaline nature mitigates P fixation in acidic soils, ensuring P availability for root elongation and branching (Rathinapriya et al. 2025; Murtaza et al. 2023).

By improving water potential, nutrient uptake, and oxidative stress management, biochar allows plants to allocate resources toward root growth rather than stress mitigation. This results in deeper, more branched root systems with higher surface area for water/nutrient absorption. For instance, tomato residue biochar (15 t ha^{-1}) enhanced barley and wheat root growth by increasing soil water retention and N-P-K availability (Albalasmeh et al. 2023). Similarly, biochar-amended soils boosted K^+ uptake in sugar beet roots, improving water-use efficiency and sustaining root function during drought (Durukan et al. 2020). Biochar orchestrates a synergistic interplay of osmotic adjustment, hormonal balance, antioxidant activity, and nutrient optimization to transform root systems into dynamic hubs of drought resilience. These adaptations not only enhance immediate root survival but also prime plants for rapid post-stress recovery, ensuring sustained productivity in water-limited environments.

5.4 Adsorption and Surface Complexation of Heavy Metals

Biochar mitigates heavy metal toxicity in plant roots by immobilizing metals through adsorption and surface complexation, directly reducing their bioavailability and uptake (Fig. 4). Its porous structure and large surface area provide abundant binding sites for heavy metal ions like Cd, Pb, Cu, and Zn, while oxygenated functional groups (e.g., carboxyl and hydroxyl) form stable complexes with metal cations, sequestering them and limiting their mobility (Ahmad et al. 2014; Beesley et al. 2011; Park et al. 2011). Biochar interacts with heavy metals via multiple pathways, including complexation (e.g., Hg^{2+} binding), surface precipitation (e.g., Cu^{2+} forming hydroxides), reduction-precipitation (e.g., Cr^{6+} to Cr^{3+}), pore filling, ion exchange, and electrostatic attraction (Bandara et al. 2021; Qiu et al. 2022). These mechanisms, along with the formation of binary/ternary chelates enabled by biochar's 3D porous structure, reduce metal bioavailability and alleviate metal-induced inhibition of root elongation, branching, and biomass accumulation (Wu et al. 2021). For instance, dehydrated potentially toxic elements react with biochar's functional groups, while inorganic minerals like carbonates and phosphates promote metal precipitation (Lian and Xing 2017). However, excessive metal sorption can cause biochar matrix swelling or collapse, potentially affecting its long-term efficacy (Wang et al. 2021a). Key factors influencing biochar's performance include feedstock and pyrolysis temperature, which dictate functional group density, pH, and ash content. Manure-derived biochars excel in immobilizing Cd and Pb through ion exchange and precipitation, while wood-derived biochars favor direct complexation with Cu and Zn (Chen et al. 2018b). Soil conditions also play a role, as biochar's alkaline nature raises soil pH in acidic soils, promoting metal hydroxide/carbonate formation and reducing soluble metal fractions that damage root tissues (Beesley et al. 2011). Additionally, biochar increases soil organic carbon (SOC), introducing low-molecular-weight organics that chelate metals and indirectly protect roots from toxicity (Smebye et al. 2016). By immobilizing metals, biochar alleviates oxidative stress and membrane damage in roots, enabling enhanced root biomass, length, and architecture. Studies demonstrate significant reductions in metal uptake, such as a 38%, 39%, 25%, and 17% decrease in Cd, Pb, Cu, and Zn, respectively, correlating with improved root elongation and lateral root formation (Chen et al. 2018b). Chicken manure biochar reduced NH_4NO_3-extractable Cd and Pb by 88.4% and 93.5%, resulting in a 572% increase in root biomass of *Brassica juncea* (Park et al. 2011). Similarly, biochar decreased Cu, Pb, and Zn accumulation in the rhizosphere, shifting metals to less bioavailable fractions and improving nutrient uptake (Medyńska-Juraszek et al. 2020). Mechanistically, biochar's pH modulation converts toxic forms of Al^{3+} and Mn^{2+} into stable ones, while enhanced CEC preserves essential nutrients like K^+, Ca^{2+}, and Mg^{2+} critical for root cell division and elongation. Biochar also fosters microbial communities that produce phytohormones stimulating root growth (Meier et al. 2021). In coarse-textured soils with low native metal retention, biochar compensates for weak adsorption, shielding roots from Pb-induced stunting (Chen et al. 2018b). Practically, tailoring biochar properties—such as using high-temperature biochars for electrostatic adsorption in alkaline soils or low-temperature biochars for complexation in acidic soils—can maximize root protection. Future research should focus on the long-term stability of biochar-metal complexes and field-scale validation of root growth outcomes. By reducing metal bioavailability and fostering a healthier rhizosphere, biochar enables plants to develop robust root systems, enhancing stress resilience and productivity in contaminated environments, making it a promising tool for sustainable agriculture.

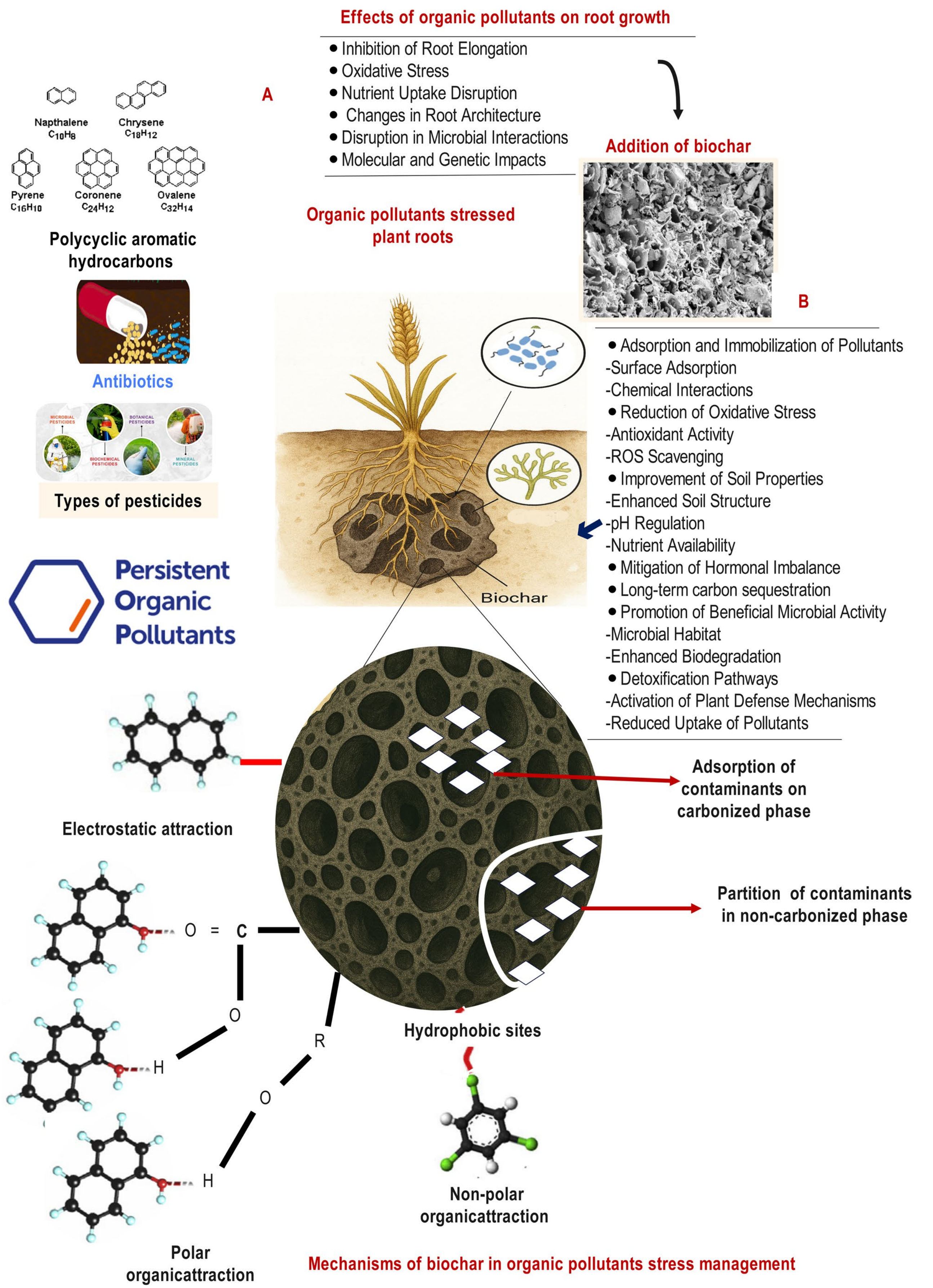
Effects of organic pollutants on root growth
• Inhibition of Root Elongation
• Oxidative Stress
• Nutrient Uptake Disruption
• Changes in Root Architecture
• Disruption in Microbial Interactions
• Molecular and Genetic Impacts
A
Napthalene $C_{10}H_8$
Chrysene $C_{18}H_{12}$
Pyrene $C_{16}H_{10}$
Coronene $C_{24}H_{12}$
Ovalene $C_{32}H_{14}$
Polycyclic aromatic hydrocarbons
Antibiotics
Types of pesticides
Persistent Organic Pollutants
Organic pollutants stressed plant roots
Addition of biochar
B
• Adsorption and Immobilization of Pollutants
-Surface Adsorption
-Chemical Interactions
• Reduction of Oxidative Stress
-Antioxidant Activity
-ROS Scavenging
• Improvement of Soil Properties
-Enhanced Soil Structure
-pH Regulation
-Nutrient Availability
• Mitigation of Hormonal Imbalance
• Long-term carbon sequestration
• Promotion of Beneficial Microbial Activity
-Microbial Habitat
-Enhanced Biodegradation
• Detoxification Pathways
-Activation of Plant Defense Mechanisms
-Reduced Uptake of Pollutants
Biochar
Electrostatic attraction
Adsorption of contaminants on carbonized phase
Partition of contaminants in non-carbonized phase
Hydrophobic sites
O = C
O
H
R
O
H
Non-polar organicattraction
Polar organicattraction
Mechanisms of biochar in organic pollutants stress management

Fig. 5 Effects of organic pollutants on root growth (**A**). Organic pollutants, such as pesticides, polycyclic aromatic hydrocarbons, and industrial chemicals, significantly impair root growth through various mechanisms: (1) Inhibition of root elongation by disrupting cell division and hormonal balance; (2) Induction of oxidative stress, leading to cellular damage from reactive oxygen species (ROS); (3) Disruption of nutrient uptake, causing deficiencies in essential elements like nitrogen, phosphorus, and potassium; (4) Alteration of root architecture, including reduced lateral root formation and changes in root hair density; (5) Disturbance of microbial interactions, affecting symbiotic relationships with beneficial soil microbes; and (6) Activation of detoxification pathways, which diverts energy away from growth. These effects collectively hinder root development, reduce plant health, and impact overall ecosystem stability. Mechanisms of biochar in organic pollutants stress management (**B**). Biochar interacts with organic pollutants through multiple mechanisms, primarily driven by its properties (especially pyrolysis temperature) and contaminant characteristics. Key interactions include: partitioning into non-carbonized fractions at low temperatures and adsorption onto carbonized, microporous surfaces at high temperatures; electrostatic attraction for cationic contaminants or repulsion (sometimes overcome by other mechanisms) for anionic contaminants; hydrogen bonding between polar contaminants and O-containing biochar functional groups; and π–π electron donor-acceptor interactions involving aromatic structures in both biochar and contaminants. The dominant mechanism depends on biochar surface area, porosity, aromaticity, polarity, and charge, as well as the contaminant's polarity, charge, and functional groups

5.5 pH Modulation and Precipitation of Heavy Metals

Biochar's capacity to elevate soil pH, particularly when derived from alkaline feedstocks, plays a pivotal role in mitigating heavy metal toxicity and fostering root growth. By inducing the precipitation of heavy metals as hydroxides or carbonates, biochar reduces their bioavailability, thereby alleviating inhibitory effects on root development. The liming effect of biochar, driven by its alkaline nature and functional groups (e.g., hydroxyl and carboxyl) and mineral content (e.g., carbonates and silicates), transforms soluble, exchangeable metal ions into stable hydroxyl-complexed phases (Bolan et al. 2023a; Wang et al. 2019a, b). This shift diminishes ion-solvation interactions, enhancing metal adsorption onto soil particles and biochar surfaces. For instance, long-term field studies demonstrate that biochar-induced pH elevation significantly reduces bioavailable Cd, Pb, Zn, and Mn, directly lowering their phytotoxic impacts on root systems (Wang et al. 2019a, b).

The precipitation of metals reduces their solubility, curtailing direct damage to root cell membranes and meristematic tissues, which are critical for elongation and branching. By lowering metal bioavailability, biochar mitigates oxidative stress and cellular dysfunction in roots, enabling unimpeded nutrient uptake and metabolic activity. Furthermore, pH modulation enhances the availability of essential nutrients like phosphorus and potassium, while alleviating aluminum toxicity—a common constraint on root growth in acidic soils. For example, Park et al. (2011) observed that chicken manure-derived biochar increased soil pH, precipitating Cd, Cu, and Pb into less soluble forms, which correlated with improved plant biomass and root architecture. Enhanced nutrient availability and reduced metal stress collectively promote robust root systems, characterized by increased biomass, length, and lateral root proliferation.

The efficacy of biochar in supporting root growth hinges on feedstock selection and pyrolysis conditions. High-temperature biochars (>400 °C) typically exhibit greater alkalinity and persistence in soil, amplifying long-term pH stabilization (Mukherjee et al. 2011; Yuan et al. 2011). Feedstocks rich in carbonates (e.g., poultry litter and manure) enhance acid-neutralizing capacity, while optimized pore structure and surface area improve soil aeration and water retention—critical for root respiration and expansion. Notably, biochar's physical properties also foster a healthier rhizosphere microbiome, indirectly supporting root development through symbiotic interactions (Lehmann et al. 2011). By modulating soil pH and precipitating heavy metals, biochar creates a conducive environment for root growth under metal stress. This dual action reduces metal uptake, enhances nutrient availability, and improves soil structure, collectively enabling plants to develop deeper, more extensive root systems. Future research should prioritize direct measurements of root morphological responses to biochar amendments, further elucidating its role in sustainable phytomanagement of heavy metal-contaminated soils.

5.6 Nutrient Retention and Availability

Biochar enhances root growth under salinity and heavy metal stress by optimizing nutrient retention, availability, and uptake while mitigating stress-induced imbalances. Its high cation exchange capacity (CEC) and porous structure enable dual functions: adsorbing toxic ions (Na^+ under salinity; Cd, Pb, Cr, etc., under metal stress) while releasing essential nutrients (K^+, Ca^{2+}, Mg^{2+}, and P) critical for root development and osmotic balance (Lashari et al. 2013; Taghavimehr 2015; Uchimiya et al. 2011; Kumar et al. 2020). In saline soils, biochar reduces Na^+ toxicity, accelerates salt leaching, and improves K^+/Na^+ ratios, directly supporting root cell turgor and enzyme function (Dahlawi et al. 2018; Ajayi and Horn 2016). It also combats phosphorus limitation by: (1) supplying bioavailable P; (2) increasing soil organic carbon to block P-adsorption sites; (3) inhibiting calcium phosphate crystallization; and (4) stimulating phosphate-solubilizing bacteria (Lashari et al. 2013; Beheshti et al. 2017; Liu et al. 2017). Under heavy metal stress, biochar enriches soil with organic matter and minerals (N, P, K, Ca, and Mg), enhancing microbial activity and reducing metal bioavailability through precipitation, adsorption, and redox transformations

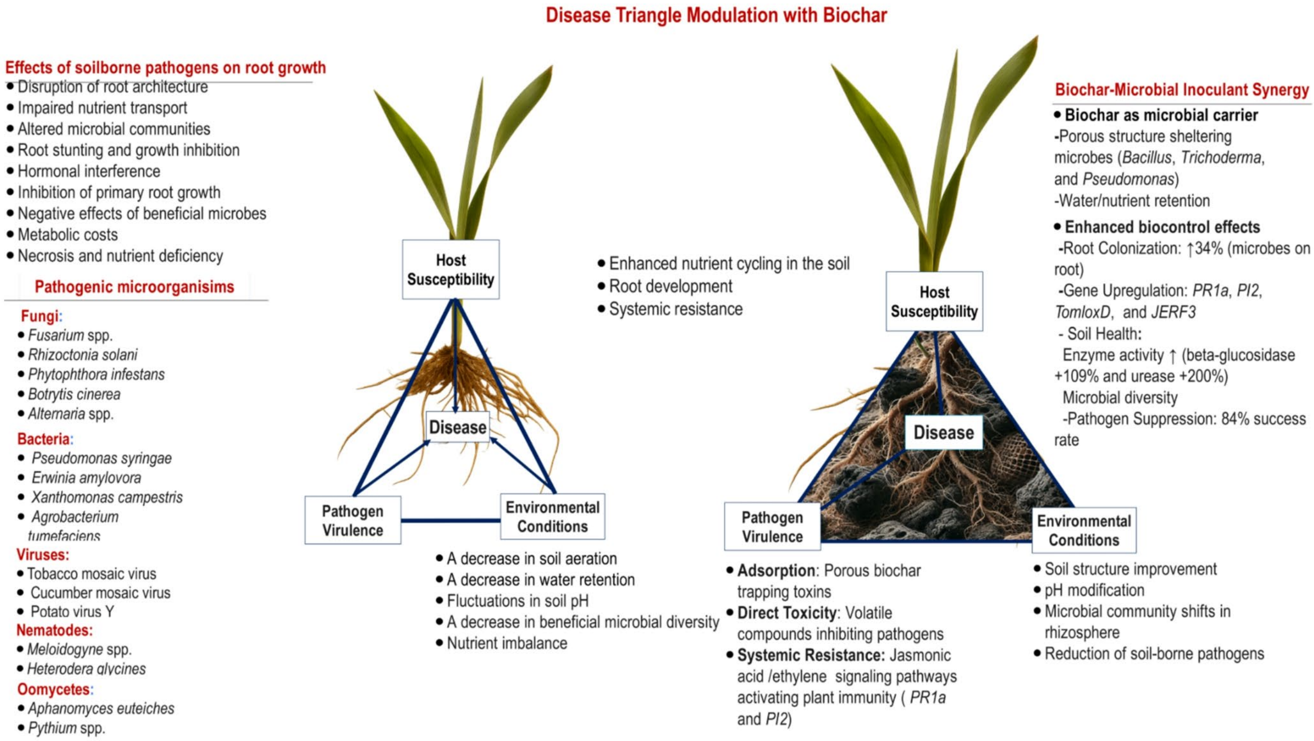

Fig. 6 Biochar-mediated disease suppression mechanisms. Biochar reduces plant diseases by modulating the disease triangle: (1) Pathogen virulence is suppressed via adsorption of pathogens/toxins in its porous structure, direct antimicrobial toxicity (e.g., volatile compounds), and chemical interference; (2) Host susceptibility decreases through enhanced nutrient availability, promoted root development, and induced systemic resistance (jasmonic acid (JA) and ethylene (ET) pathways upregulating defense genes *PR1a*/*PI2*); (3) Environmental conditions improve via soil structuring, pH buffering, and microbiome enrichment. These mechanisms collectively reshape the rhizosphere, enhancing beneficial microbes that antagonize diverse pathogens including fungi (*Fusarium* and *Botrytis*), bacteria (*Ralstonia*), viruses (TYLCV), oomycetes (*Phytophthora*), and nematodes (*Meloidogyne*). Synergy with microbial inoculants (*Bacillus*, *Trichoderma*, and *Pseudomonas*) further amplifies biocontrol: biochar acts as a nutrient-rich carrier, boosting root colonization (+34%), upregulating defense genes (*PR1a*, *PI2*, *TomloxD*, and *JERF3*), and improving soil health (↑109% β-glucosidase, ↑200% urease activity; and increased microbial diversity), achieving 84% pathogen suppression efficacy. Optimization requires pyrolysis at 300–500 °C using nutrient-rich feedstocks and screening for toxins (heavy metals/PAHs). Collectively, biochar fosters disease-suppressive soils that enhance plant resilience

(e.g., converting Cr(VI) to Cr(III) (Bian et al. 2014; Joseph et al. 2021; Sarraf et al. 2024). These processes concurrently increase nutrient accessibility—notably P, K, and Si—while decreasing toxic metal translocation to roots (Zhang et al. 2013b; Xing et al. 2020; Li et al. 2020a). Biochar's improvement of soil water retention further dilutes salt/metals and sustains nutrient mobility to roots (Ajayi and Horn 2016; Thomas et al. 2013). Collectively, these mechanisms promote robust root systems, evidenced by increased root biomass, length, and density in stressed environments (Akhtar et al. 2015a; Park et al. 2011).

5.7 Promotion of Beneficial Microbial Activity

Biochar enhances root growth and plant resilience under drought, salinity, and heavy metal stress by fostering synergistic microbial communities through multiple interconnected mechanisms. Its porous structure provides a protective habitat, buffering microbes against osmotic stress, ionic toxicity (Na^+ and heavy metals like Cd and Cu), and desiccation, while simultaneously improving soil water retention, aeration, and adsorbing stressors to reduce their bioavailability (Lehmann et al. 2011; Saleem et al. 2022; Tsolis and Barouchas 2023; Yuan et al. 2023; Batool et al. 2022; Meier et al. 2017). Biochar supplies labile carbon to stimulate microbial metabolism and recalcitrant carbon for long-term soil organic matter buildup, enhancing nutrient cycling and availability (Lehmann et al. 2011; Bolan et al. 2023b). This supports key microbial groups—including bacteria (e.g., *Pseudomonas*, *Bacillus*, *Rhizobium*, and *Burkholderia*), fungi, and arbuscular mycorrhizal fungi (AMF)—which improve soil structure (via EPS and glomalin production, enhancing aggregation and porosity under drought), increase nutrient acquisition (especially P, K, N via mineralization, solubilization, and fixation by taxa like Proteobacteria and Acidobacteria favored by biochar's pH modulation), produce root-promoting phytohormones (e.g., auxins), and mitigate stress through specific actions (Xiang

Table 1 Effect of various biochars on plant root resilience parameters under abiotic and biotic stress

Type of biochar	Test plant	Type of stress	Observed effects	References
- Source: *Morus alba* waste wood - Modification: K-enriched (2% K_2SO_4) - Pyrolysis: 550–600 °C for 2 h - Application Rate: 0.75% (*w/w*)	Canola (*Brassica napus* L.)	Drought	Under drought stress (vs. control): - ↑ Germination: 9.44% - ↑ Shoot length: 29.30% - ↑ Root dry weight: 28.79% - ↑ Chlorophyll *a*: 34.35% - ↓ Electrolyte leakage: 11.02% - ↑ Antioxidants (superoxide dismutase/peroxidase): 30–50%	Gul et al. (2024)
- Source: Fruit waste - Modification: K-enriched (2% K_2SO_4) - Pyrolysis: 550 °C for 75 min - Application Rate: 0.75% (*w/w*)	Wheat (*Triticum aestivum* L.)	Drought	Under osmotic stress (vs. control): - ↑ Germination: 9% - ↑ Shoot length: 30% - ↑ Shoot dry weight: 68.38% - ↑ Chlorophyll *b*: 20.96% - ↓ Electrolyte leakage: 11.02% - ↓ Antioxidants (superoxide dismutase/peroxidase): 7–48%	Sarwar et al. (2023)
- Source: *Parthenium hysterophorus* (whole plant) - Pyrolysis: 350–450 °C for 60 min - Application: 2.5% (w/w) + PGPR (*Serratia odorifera*)	Barley (*Hordeum vulgare* L.)	Drought	Under osmotic stress (vs. control): - ↑ Shoot length: 37.03% - ↑ Dry biomass: 62.5% - ↑ Chlorophyll *b*: 35.3% - ↑ Antioxidants: catalase (100%), superoxide dismutase (21%) - ↑ Nutrient uptake: N (39.7%), P (27.5%), and K (27%)	Gul et al. (2023)
-Source: Rice straw -Modification: Seed coating (30% biochar, 50% talcum, and 20% attapulgite) -Pyrolysis: 600 °C -Application: Seed coating (seed-to-coating ratio 1:2)	Rice (*Oryza sativa* L.)	Drought	Under drought stress (vs. drought stress without biochar): - ↑ Emergence rate: 6.7% - ↑ Shoot length: 27.4% - ↑ Root length: 33.4% - ↑ Plant height: 10.3%–19.6%, - ↑ Leaf area: 71.7%–69.8% - ↑ Plant biomass: 67.9%- 85.7% - ↑ Photosynthetic parameters - Maintained chloroplast ultrastructure - ↑ Stomatal density (adaxial/abaxial): 13.3%–33.5% - ↓ Reactive oxygen species, malondialdehyde, electrolyte leakage - ↑ Antioxidant enzymes (superoxide dismutase, peroxidases, catalase, and ascorbate peroxidase) and osmoprotectants	Zhang et al. (2024)
-Source: Oakwood -Pyrolysis: 400 °C -Application rate: 10 t ha^{-1}	Sugarcane (*Saccharum officinarum* L.)	Salinity	Under salinity stress (vs. salinity without biochar): - ↑ Stem dry biomass: 37.5% - ↑ Root dry biomass: 39.4% - ↑ Leaf dry biomass: 27.0% - ↑ Root volume: 23.5% - ↑ Fv/Fm (PSII efficiency) - ↑ Chlorophyll content - ↓ Relative ion leakage: 21.4% - ↓ Water saturation deficit: 21.9% Optimal at 10 t ha^{-1}	Vu et al. (2023)

Table 1 (continued)

Type of biochar	Test plant	Type of stress	Observed effects	References
-Source: Municipal solid waste -Pyrolysis: 500 °C for 40 min	Alfalfa (*Medicago sativa* L.)	Salinity	Under salt stress (vs. control): - ↑ Plant height: 28% - ↑ Shoot fresh weight: 50% - ↑ Root fresh weight: 33% - ↑ Root projected area: 39% - ↑ Root surface area: 31% - ↑ Total root length: 46% - ↑ Root volume: 82% - ↑ Chlorophyll *a*: 8% - ↑ Chlorophyll *b*: 10% - ↑ Total chlorophyll: 9% - ↑ Carotenoids: 25% - ↑ Soil nutrients (N, P, and K and humus) - ↑ Soil enzyme activities (catalase and urease)	Jabborova et al. (2023)
-Source: Municipal solid waste -Pyrolysis: 500 °C for 40 min	Amaranth (*Amaranthus caudatus* L.)	Salinity	Under salt stress (vs. control): - ↑ Plant height: 24% - ↑ Shoot fresh weight: 54% - ↑ Root fresh weight: 43% - ↑ Root surface area: 24% - ↑ Root projected area: 25% - ↑ Root diameter: 27% - ↑ Root volume: 36% - ↑ Total root length: 50% - ↑ Chlorophyll b: 39% - ↑ Total chlorophyll: 21% - ↑ Carotenoids: 12% - ↑ Soil nutrients (N, P, and K and humus) - ↑ Soil enzyme activities (catalase and urease)	Jabborova et al. (2023)
-Source: Municipal solid waste -Pyrolysis: 500 °C for 40 min	Maize (*Zea mays* L.)	Salinity	Under salt stress (vs. control): - ↑ Plant height: 48% - ↑ Shoot fresh weight: 25% - ↑ Root fresh weight: 50% - ↑ Root surface area: 63% - ↑ Total root length: 24% - ↑ Root projected area: 32% - ↑ Root volume: 42% - ↑ Root diameter: 43% - ↑ Chlorophyll b: 64% - ↑ Soil nutrients (N, P, and K and humus) - ↑ Soil enzyme activities (catalase and urease)	Jabborova et al. (2023)
-Source: Groundnut shell biochar - Pyrolyzed at 400 °C for 90 min - Application rate: 5% (*w/w*) - Co-applied with PGPR (*Bacillus pseudomycoides* ARN7)	Maize (*Zea mays* L.)	Heavy metal	Under combined stress (vs. control): - ↑ Shoot length: 48% - ↑ Root length: 98% - ↑ Fresh weight: 53% - ↑ Dry weight: 45% - ↑ Chlorophyll: 64% - ↑ Soluble proteins: 65% - ↑ Relative water content: 26% - ↓ Malondialdehyde (oxidative stress): 67% - ↓ Electrolyte leakage - ↓ Ni/Zn accumulation (shoots: Ni 58% and Zn 13%) - ↑ Soil enzymes (dehydrogenase 328% and β-glucosidase 251%)	Anbuganesan et al. (2024)
-Source: Wood shavings of *Pinus roxburghii* - Pyrolysis: 300–400 °C for 15–20 min - Application rate: 50 mg kg^{-1}	Maize (*Zea mays* L.)	Heavy metals (Cd and Cr)	Under Cd/Cr stress (vs. stressed control without biochar): - ↑ Shoot length: 39% (Cd) and 30% (Cr) - ↑ Root length: 30% (Cr) - ↑ Protein content: 56% (Cd) - ↑ Chlorophyll *a*/*b*: 33% (Cd + Cr) - ↑ Carotenoid: 52% (Cd + Cr) - ↑ Antioxidant enzymes (peroxidases:45%, superoxide dismutase:40%, catalase:45%) - ↓ Cd/Cr accumulation Synergistic effect in combined stress (Cd + Cr)	Zahra et al. (2024)

Table 1 (continued)

Type of biochar	Test plant	Type of stress	Observed effects	References
-Source: Peanut shell biochar - Pyrolyzed at 500 °C - Application rates: 1–10% (w/w)	*Vetiveria zizanioides* (vetiver)	Heavy metals (Cu, Cd, and Pb)	Under heavy metal stress: - ↑ Chlorophyll *a* (196.88% max), chlorophyll *b* (241.70% max), total chlorophyll (208.87% max), and carotenoids (150.28% max) - ↓ Malondialdehyde (32.44–78.69%) and proline (4.58–71.42%) - Superoxide dismutase activity ↑ mid-late stages (37.21% max); peroxidase activity ↓ - Cu accumulation ↓ roots (12.22–65.44%), leaves (80.63% max) - Cd/Pb accumulation ↑ at 1–4% biochar, ↓ at 10% biochar	Ai et al. (2023)
-Source: Rice husk biochar (RH) - Pyrolysis: Unspecified - Application rates: 2.5–5% (w/w) - Combined with foliar salicylic acid (SA: 0.5–1 mM)	Chinese mustard (*Brassica juncea* L.)	Heavy metals (Pb, Cd, Cu, and Zn) in acidic soil	Under stress: - ↓ DTPA-extractable metals: Pb (32.16%), Cd (43.22%), Cu (49.72%), and Zn (29.54%) at 5% RH - ↑ Shoot biomass: Fresh (19-fold), dry (3-fold) with RH + SA - ↓ Shoot HM: Pb (74.72%), Cu (69.19%), Cd (54.16%), and Zn (53.86%) - ↑ Antioxidant enzymes - ↑ Chlorophyll *a* (300%), *b* (400%), and carotenoids (250%) - ↓ H_2O_2, malondialdehyde, and proline	Awad et al. (2022)
-Source: Wheat straw biochar (500 °C pyrolysis) 0.25–0.50% w/w application	Maize (*Zea mays* L.)	Organic pollutant (Chlorpyrifos)	- ↑ Shoot fresh weight: 154–175% - ↑ Root fresh weight: 4–5× - ↓ CP uptake: 76–91% (shoots) - Normalized superoxide dismutase/peroxidase/catalase enzymes - ↓ Oxidative stress	Aziz et al. (2021)
- Source: *Cyperus alternifolius* - Modification: Fe-impregnation (FeOx composite via Fe^{3+}/Fe^{2+} coprecipitation) - Application rate: 0.1% or 1.0% (*w/w*)	Welsh onion (*Alliumfistulosum* L.)	Chlorpyrifos & TCP (pesticide pollutant)	Under pesticide stress (vs. control/levels): - ↓ Uptake of chlorpyrifos & TCP in plant (dose-dependent) - Fe-biochar > pristine biochar in reducing uptake - ↑ Sorption capacity (Fe-biochar) - ↑ Root iron plaque (Fe-biochar) - ↓ Bioavailability of chlorpyrifos (both biochars) - Highest residue persistence: 1.0% pristine biochar - ↑ Chlorpyrifos degradation efficiency (Fe-biochar; via microbial shift)	Tang et al. (2017)
-Source: Forest pine wood - Pyrolysis: 650 °C for 30 min - Application rate: 1% (w/w)	Radish (*Raphanus sativus* L.)	Pharmaceutical contamination	With 1% biochar amendment (vs. unamended soil): - ↓ Uptake of 11 pharmaceuticals (acetaminophen, carbamazepine, sulfadiazine, sulfamethoxazole, lamotrigine, carbadox, trimethoprim, oxytetracycline, tylosin, estrone, and triclosan): 33.3–83.0% - ↑ Uptake of lincomycin: 36.7–48.2% - ↑ Soil sorption of all 15 pharmaceuticals - ↑ Half-lives of 7 pharmaceuticals (caffeine, sulfadiazine, sulfamethoxazole, lincomycin, estrone, 17β-estradiol, and triclosan)	Li et al. (2020a, 2020b)
-Source: *Eucalyptus* wood chips - Pyrolysis: 850 °C (BC850) - Properties: High surface area, strong sequestration capacity -Application rate (0.1, 0.5, and 1% *w/w*)	Spring onion (*Allium cepa* L.)	Insecticides: - Chlorpyrifos (50 mg kg^{-1}) - Carbofuran (50 mg kg^{-1})	-With 1% BC850 vs. control: - ↓ Pesticide loss (degradation/volatilization): - Chlorpyrifos: 44% lost (vs. 86–88% in control) - Carbofuran: 51% lost - ↑ Soil persistence but ↓ bioavailability - ↓ Plant uptake: - Chlorpyrifos: 90% reduction - Carbofuran: 75% reduction - High sequestration in soil reduces phytoavailability	Yu et al. (2009)
-Source: Olive pruning - Pyrolysis: EBC-certified (European Biochar Certificate) - Properties: Basic pH, low heavy metals/PAHs	Tomato (*Solanum lycopersicum* L.)	Systemic viral infections: - Potato spindle tuber viroid (PSTVd) - Tomato spotted wilt virus (TSWV)	-With 10–15% biochar + *Trichoderma* spp.: - ↓ PSTVd titer: Significant reduction in viroid replication - ↓ PSTVd symptoms: Mild/no symptoms vs. severe stunting in controls - ↓ TSWV infection rate: 22–33% infection (vs. 89% in controls) - ↓ TSWV titer: Up to 40,000-fold reduction - ↑ Root growth: 2–20% biochar concentrations - ↑ Rhizobacteria: Enhanced beneficial microbe populations - ↑ plant growth promoting microorganisms survival: *Trichoderma*/*Bacillus* viability maintained 90 days	Luigi et al. (2022)
- Source: Green waste biochar (GWB) at 3% and 6% *v/v*	Tomato (*Solanum lycopersicum* L.)	Early blight (*Alternaria solani*)	-↑ Disease suppression: 35.6% reduction in disease index - Moderately resistant (MR) disease response -Enhanced growth with PGPR - Improved chlorophyll and nutrient content	Rasool et al. (2021)

Table 1 (continued)

Type of biochar	Test plant	Type of stress	Observed effects	References
- Source: Green waste biochar (GWB) + compost (20% compost (Comp), 3% GWB - Pyrolysis: 500 °C - Application rate: 3% (*v/v*)	Tomato (*Solanum lycopersicum* L.)	*Fusarium* wilt (Chlamydospore infection)	Under *Fusarium* stress (vs. biochar + Comp/Comp): - ↓ Disease incidence: 20% (vs. 60–66% in other treatments) - ↓ Disease severity: 5.7 (vs. 14–87 in others) - ↓ Fungal load (CFU g^{-1} soil): 0.30×10^4 (vs. 6.78×10^4 in unamended soil) - ↑ Plant growth: 28% higher root biomass, 23% higher shoot biomass (GWBcomp + Chl) - ↑ Shoot height: 31.03 cm (vs. 18–21 cm in WCBcomp/Comp + Chl) - ↑ Photosynthetic rate: 15.67 µmol CO_2 m^{-2} s^{-1} (vs. 12.67–13.18 in other + Chl treatments) - In vitro: 31.27% inhibition of *Fusarium* radial growth (GWBcomp PDA media)	Akhter et al. (2016)
- Source: Green waste biochar -Modification: Pre-conditioned with compost (PC) - Application rate: 3% (w/w)	Tomato (*Solanum lycopersicum* L.)	Damping-off (*Pythium aphanidermatum*)	Under *Pythium* stress (vs. control): -↓ Damping-off incidence: 75% reduction with PC/biochar(3%) - ↑ Shoot dry weight: 27.3 mg $plant^{-1}$ (vs. 23.8 mg in control) - ↑ Plant height: Significant increase -↑ Beneficial microbes: Fluorescent Pseudomonas (3.86×10^5 CFU g^{-1}), *Bacillus* spp., Actinobacteria, *Trichoderma* - ↑ Bacterial diversity (Shannon index) and specific genera (*Bradyrhizobium*, *Massilia*, *Sphingomonas*, etc.) - ↓ Pathogen survival: Reduced *Pythium* CFU in soil	Jaiswal et al. (2019)
- Source: Eucalyptus wood (EUC-350, EUC-600) and green waste (GHW-350, GHW-600) biochars - Pyrolysis: 350 °C and 600 °C Application rate: 3% (*w/w*)	Tomato (*Solanum lycopersicum* L.)	Root rot (*Fusarium oxysporum* f. sp. *radicislycopersici*)	Under stress (vs. Control): - ↓ Disease severity: Score 1–2 (vs. 4–5 in control) characterized by reduced wilting/necrosis - ↓ Enzyme activity: Polygalacturonase (16–30% active) and cellulase (5–9% active) immobilized on biochar - ↑ Adsorption of polygalacturonic acid (substrate for pathogen virulence enzymes - ↓ Pathogen virulence: Reduced enzyme-driven cell wall degradation	Jaiswal et al. (2018)

et al. 2017; Ji et al. 2019; Ullah et al. 2021; Akram et al. 2024; Shi et al. 2023; Etesami 2018). Crucially, biochar amplifies microbial partnerships: it boosts AMF colonization (e.g., *Rhizophagus irregularis*), enabling hyphae to access water and nutrients within biochar pores and extend root reach while excluding metals, and enhances the efficacy of plant growth-promoting bacteria, which aid in nutrient solubilization, hormone synthesis, and metal chelation (e.g., via siderophores) (Hammer et al. 2015; Rummel et al. 2017; Akhtar et al. 2015b). Stress-specific benefits include improved soil aggregation and moisture retention for drought resilience; reduced Na^+ uptake, improved K^+/Na^+ ratios, and sustained microbial biomass via labile carbon under salinity; and microbial immobilization of heavy metals (reducing phytoavailability) and enrichment of resilient taxa (e.g., Proteobacteria and Chloroflexi) in contaminated soils (Lashari et al. 2013; Saifullah et al. 2018; Zhu et al. 2022; Ji et al. 2022). Outcomes depend on biochar properties (feedstock and pyrolysis temperature—e.g., wood-derived at 500–600 °C optimizes microbial habitat) and soil type (e.g., greater aggregation in clays) (Abideen et al. 2020; Baiamonte et al. 2019). Collectively, biochar shapes microbial communities that enhance soil structure, nutrient cycling, and stress mitigation, creating a positive feedback loop where robust root systems further enrich microbial activity and sustain plant performance under abiotic adversity.

5.8 Mitigation of Organic Pollutants Impact on Root Development

Biochar has demonstrated significant potential in mitigating the adverse effects of organic pollutants (OPs)—such as antibiotics, pesticides, polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (POPs)—on root growth by reducing their bioavailability in contaminated soils (Yao and Zhou 2022; Shaaban and Abid 2021) (Fig. 5). These pollutants, often resistant to degradation, impede root development by inducing oxidative stress, disrupting nutrient uptake, and altering microbial communities. Biochar counteracts these effects through multifaceted sorption mechanisms: (i) partitioning, where OPs diffuse into its non-carbonized organic matrix or pores; (ii) pore-filling, leveraging its micro-/mesoporous structure to trap polar/nonpolar contaminants; (iii) electrostatic interactions between charged pollutants and biochar surfaces, modulated by pH and ionic strength; (iv) electron donor-acceptor interactions via its graphene-like layers; and (v) hydrophobic interactions that sequester nonpolar compounds (Dai et al. 2019; Shaaban and Abid 2021; Zhu and Pignatello 2005). By immobilizing OPs, biochar alleviates phytotoxicity, enabling roots to thrive. For instance, Qin et al. (2018) reported an 88% reduction in dibutyl phthalate leaching using 1% bamboo- or pig-derived biochar (650 °C), directly lowering root exposure. Similarly, pine needle biochar (1%) reduced PAH uptake in plants by diminishing their extractability (Zhu et al. 2018), while wheat straw biochar enhanced atrazine degradation (Yang et al. 2017), fostering healthier root systems. However, efficacy depends on biochar properties (e.g., pyrolysis temperature and feedstock), pollutant type, and soil conditions. High-temperature biochars (> 500 °C) often exhibit stronger sorption due to enhanced porosity and π-electron systems (Zheng et al. 2013), yet exceptions exist, such as maize straw biochar (500 °C) inhibiting pentachlorophenol reduction (Zhu et al. 2020). Additionally, biochar stimulates soil microbes that degrade OPs, indirectly supporting root health (Yang et al. 2017). Optimizing biochar application parameters—such as dosage, particle size, and pretreatment—is thus critical to maximizing its protective role in polluted soils. By reducing OP bioavailability and fostering microbial activity, biochar creates a rhizosphere environment conducive to robust root development, offering a sustainable strategy for phytoremediation and agricultural resilience.

5.9 Mitigation of Pathogen Impact on Root Development

The application of biochar as a sustainable strategy to mitigate pathogen-induced suppression of root growth and control plant diseases has gained significant attention in recent years (Fig. 6). Research highlights its efficacy against diverse pathogens, including 20 fungal species (e.g., *Fusarium oxysporum f. sp. radicis lycopersici* and *Botrytis cinerea*), 8 bacterial species (notably *Ralstonia solanacearum*), 2 viral pathogens (e.g., Tomato yellow leaf curl virus), and pathogens from other groups such as *Phytophthora capsici* (oomycetes) and *Meloidogyne incognita* (nematodes) (Liu et al. 2023b; Alaylar et al. 2021; de Medeiros et al. 2021; Poveda et al. 2021; Hou et al. 2022; Iacomino et al. 2022; Bhatt et al. 2024). Biochar's disease-suppressive effects are attributed to its ability to modulate the three components of the disease triangle—pathogen virulence, host susceptibility, and environmental conditions—while reshaping the rhizosphere microbiome (Graber et al. 2014; Pokhrel 2021; Liu et al. 2023b). Its alkaline pH, nutrient content, and labile carbon enhance soil quality and promote beneficial microbial communities, while its porous structure adsorbs phytotoxic compounds and pathogen-derived toxins, such as organic acids and enzymes (Palansooriya et al. 2019). Additionally, volatile organic compounds in biochar exhibit direct fungitoxic properties, and its application can induce systemic plant resistance, further reducing host susceptibility. These mechanisms collectively improve soil-plant-pathogen dynamics, fostering disease-suppressive soils enriched with microbes that antagonize pathogens via antimicrobial compounds or by priming plant immunity (Jaiswal et al. 2017; Yuan et al. 2018; de Medeiros et al. 2021). The effectiveness of biochar depends on feedstock type, pyrolysis temperature (350–600 °C for straw-derived BC), and application rate, with a 3–5% soil incorporation ratio shown to reduce disease severity by up to 47% (Yang et al. 2022). By synergistically enhancing soil health, suppressing pathogen activity, and boosting plant resilience, biochar emerges as a multifaceted tool to counteract root growth inhibition caused by soilborne pathogens.

5.9.1 Improvement of the Efficiency of Biocontrol Agents

Biochar enhances the efficacy of biocontrol agents by addressing key challenges faced by microbial inoculants when applied alone, such as predation by soil microfauna, competition with native microorganisms, and rapid population decline (Liu et al. 2023b; Bashan et al. 2014). As a porous, nutrient-rich carrier with high water-holding capacity, biochar provides physical shelter and essential resources to sustain microbial inoculants survival, colonization, and activity in soil and plant rhizospheres (Ajeng et al. 2020; Quilliam et al. 2013; Yan et al. 2023). This synergy not only improves microbial inoculants persistence but also amplifies their pathogen-suppressive effects, with studies demonstrating biochar-microbial inoculants systems effectively controlling diverse plant pathogens, including six fungal, two oomycete, one nematode, and two viral strains, achieving success in 84% of experimental cases (de Medeiros et al. 2021; Liu et al. 2023b). For instance, biochar combined with *Trichoderma* or arbuscular mycorrhizal fungi enhances root colonization—up to 34% in soybean—while mitigating pathogens like *Rhizoctonia solani* and improving plant biomass (Safaei Asadabadi et al. 2021; Lewandowski et al. 2013). Furthermore, biochar-microbial inoculants interactions alter root exudates, upregulate defense-related genes (e.g., *PR1a* and *PI2*), and enhance systemic resistance via jasmonic acid and ethylene signaling pathways, bolstering plant immunity (Liu et al. 2023a; Pieterse et al. 2014). Postma et al. (2013) demonstrated that animal bone charcoal coupled with *Pseudomonas chlororaphis* 4.4.1 achieved population densities of $0.5–5 \times 10^7$ CFU g^{-1} in roots or rhizosphere soil, effectively suppressing root rot, while later work revealed its superior control of tomato *Pythium* infections compared to plant-based biochar (Postma and Nijhuis 2019). Enhanced colonization of microbial inoculants in roots—critical for their function (Raaijmakers et al. 2009)—is facilitated by biochar's ability to sustain microbial populations, as seen in Rasool et al. (2021), where green waste biochar (6% v/v) combined with *Bacillus subtilis* outperformed wood biochar in suppressing tomato early blight by upregulating defense genes (*PR1a*, *PI2*, *TomloxD*, and *PR2*), with *B. subtilis* specifically boosting *PR2* expression. Similarly, rice husk biochar paired with *B. subtilis* induced JERF3 expression to combat root-knot nematodes, an effect absent with *Trichoderma harzianum* (Arshad et al. 2021), while *Trichoderma*-loaded biochar (10% w/w) effectively managed potato spindle tuber viroids (Luigi et al. 2022). These gene expression shifts are linked to microbial inoculants-mediated systemic resistance: jasmonic acid and ethylene pathways dominate when microbial inoculants colonize roots (Pieterse et al. 2014), though some microbial inoculants activate salicylic acid -dependent responses (Yu et al. 2022).

Biochar-microbial inoculant systems enhance soil health and disease suppression by improving nutrient availability, enzymatic activity, and microbial diversity, with effects shaped by biochar's feedstock and pyrolysis conditions. For example, corn straw biochar combined with *Frankia F1* elevated soil pH, nitrogen, phosphorus, and enzyme activities in ginseng soil (Qi et al. 2021), while soursop residue biochar with *Trichoderma* spp. boosted beta-glucosidase (109%) and urease (200%) activities to combat cassava root rot (da Silva et al. 2022). Biochar produced at lower temperatures (e.g., 300 °C) optimized nutrient release and pathogen control when paired with *Bacillus subtilis* (Jia et al. 2022). Microbial activity on biochar surfaces accelerates aging through oxidation and organic acid secretion, increasing oxygen-containing functional groups and cation exchange capacity, which enhance water retention and nutrient retention (K^+, Mg^{2+}, and Ca^{2+}) (Wang et al. 2020; Cheng et al. 2006). Aged biochar integrates into soil aggregates, stabilizing carbon and microbial products, while fostering antifungal microbes like *Papiliotrema flavescens* (Liu et al. 2021b). Biochar–microbial inoculants systems also alter root exudates—reducing sugars and increasing phenolics—to inhibit pathogens like *Fusarium oxysporum*, with feedstock-specific efficacy (e.g., wood biochar + AMF outperformed green waste biochar) (Akhter et al. 2015; Huang et al. 2014). Combined with microbial inoculants-produced hydrolytic enzymes, these mechanisms synergistically enhance plant resilience and pathogen suppression (Jin et al. 2023). Biochar produced at higher pyrolysis temperatures exhibits stronger inhibitory effects on microbial signaling pathways: biochar generated at 700 °C suppressed acyl-homoserine lactone-mediated quorum sensing tenfold more effectively than biochar pyrolyzed at 300 °C, directly impacting biofilm formation and microbial population dynamics (Masiello et al. 2013). Furthermore, biochar's physicochemical traits, such as pore structure, surface area, and nutrient content, affect microbial inoculants growth and metabolism. Biochar pyrolyzed at 500 °C, for example, enhances the proliferation of beneficial bacteria like *Pseudomonas stutzeri* and *Shewanella putrefaciens* (Yan et al. 2023). These effects are tied to biochar's feedstock and production conditions—factors like carbon content, pore size, and functional groups (e.g., carboxyl and ketonic carbons) critically determine microbial inoculants shelf life and soil survival (Shabir et al. 2023; Wang et al. 2022). Strategies for optimizing biochar–microbial inoculants formulations involve selecting feedstock and pyrolysis parameters, though post-production modifications, while effective, remain cost-prohibitive for large-scale use. Current applications focus on screening natural microbial inoculants candidates (e.g., *Bacillus*, *Pseudomonas*, and *Trichoderma* species) or engineering synthetic communities (SynComs) from rhizosphere microbiomes, prioritizing strains with field resilience and scalable production (O'Brien 2017). Biochar produced at lower pyrolysis temperatures (300–500 °C) using nutrient-rich feedstocks is optimal for coupling with microbial inoculants. However, biochar may contain toxic compounds such as heavy metals (e.g., Cu, Zn, and Cd in sewage sludge biochar), harmful organic matter (e.g., polycyclic aromatic hydrocarbons, and free radicals (e.g., in sludge biochar pyrolyzed at 400 °C), which can suppress microbial biomass and activity (Xiang et al. 2021; Khan et al. 2013; Wang et al. 2007). For instance, pinewood biochars water extracts inhibit aquatic photosynthetic microorganisms (Smith et al. 2013), while sludge biochars with free radicals induce oxidative stress in *Pseudomonas putida* (Qian et al. 2020). Toxicity varies by feedstock: *Acorus calamus* biochar shows negligible effects on *Pseudomonas aeruginosa* compared to rice husk or sawdust biochars (Wang et al. 2017). Screening biochar for harmful components is critical before loading viable microbial inoculants ($>10^8$ CFU g^{-1}) via adsorption or mixing (Shabir et al. 2023). Biochar–microbial inoculants formulations effectively suppress plant diseases by enhancing plant resistance, inhibiting pathogens, and improving soil quality. Synthetic microbial communities (SynComs) improve biocontrol consistency across environments (O'Brien 2017), though optimal biochar–microbial inoculants doses require further study. Despite their potential, there is limited research on the combinations of biochar and microbial inoculants for disease control, highlighting the need for more field trials to support commercialization. While progress has been made, significant research gaps remain, particularly in integrating modified biochar with microbial inoculants for effective disease management. Tailoring the properties of biochar to meet the requirements of microbial inoculants can enhance their effectiveness in sustainable agriculture, balancing microbial viability with functional performance in soil-plant systems. Overall, biochar-microbial inoculants systems improve soil properties—such as nutrient availability, enzyme activity, and microbial diversity—creating an unfavorable environment for pathogens while promoting plant health. This dual role emphasizes their importance in sustainable disease management.

6 Field Considerations: Economics, longevity, and Adoption Barriers

Field trials demonstrate highly variable optimal application rates, typically ranging from 10 to 30 Mg ha^{-1}. In NE Washington State, biochar applied at ≥18 Mg ha^{-1} outperformed hydrated lime as a liming agent, increasing yields by 2.88× over two years (Phillips et al. 2018). Similarly, tobacco field studies showed dose-dependent carbon footprint reduction at 10–30 t ha^{-1}, though higher rates did not consistently improve economic returns (Sun et al. 2025). However, economic feasibility remains challenging: Slovakian field experiments found biochar application (even with nitrogen fertilization) unprofitable under current commodity prices and input costs (Šimansky et al. 2020). On-farm gasification systems (e.g., converting grass waste to biochar) offer potential for cost-effective production while meeting energy and soil amendment needs (Phillips et al. 2018), but scalability requires region-specific cost-benefit analysis.

Long-term field experiments (since 2014) confirm persistent economic hurdles under existing market conditions, necessitating policy incentives (Šimansky et al. 2020). A global meta-analysis of field trials revealed region-specific yield impacts: significant maize yield gains in arid Africa/Asia, but potential declines elsewhere (Kern et al. 2025). Biochar's aging and nutrient retention dynamics critically influence long-term efficacy. While initial improvements in soil organic carbon, bulk density, and nutrient cycling are documented, persistence varies substantially with soil type, climate, and biochar feedstock (Wang et al. 2024; Mukherjee and Lal 2014; Archontoulis et al. 2016). Life Cycle Assessments (LCAs) indicate biochar can enhance Net Ecosystem Economic Benefits (NEEB) but may increase N_2O emissions, offsetting carbon footprint reductions (Sun et al. 2025).

Profitable commercial-scale deployment remains rare due to logistical constraints (e.g., co-locating waste streams, production facilities, and farms) and high initial costs (Phillips et al. 2018; Šimansky et al. 2020). Gasification shows better economic viability than pyrolysis or hydrothermal carbonization (Li et al. 2024), yet universal standards and industrial-scale data are lacking. Adoption hinges on overcoming context-specific socio-agronomic barriers, including farmer participation, regional cooperation, and policy frameworks (Müller et al. 2019). Collaborative efforts among governments, industry, and academia—supported by robust incentives—are essential to scale implementation (Senadheera et al. 2025).

7 Synergistic and Antagonistic Interactions of Biochar with Other Soil Amendments

Biochar interacts with various soil amendments (Table 2), exhibiting both synergistic and antagonistic effects. When co-composted, biochar and compost enhance nutrient retention, reduce leaching, increase soil organic carbon (SOC), boost microbial activity, and improve remediation efficiency for heavy metals and other pollutants in contaminated soils (Wu et al. 2017; Plaza et al. 2016; Tran et al. 2023; Mikajlo et al. 2024; Beesley et al. 2014). Similarly, combining biochar with microbial inoculants significantly increases soil nitrogen (N), organic carbon concentrations, and crop productivity, with fungal inoculants demonstrating stronger effects than bacterial ones (Ross and Emery 2025). Biochar combined with arbuscular mycorrhizal fungi (AMF) specifically promotes fungal populations and plant growth, particularly in contaminated soils (Liu et al. 2018). Biochar paired with organic fertilizers (e.g., municipal solid waste compost and sewage sludge) enhances SOC content, improves soil structure via organo-mineral complexes, and increases microbial diversity and enzyme activities, supporting better nutrient cycling and soil health (Wu et al. 2025a, b; Plaza et al. 2016). Meta-analysis of 57 studies (627 data points) (Bai et al. 2022) also revealed that biochar application alone increased crop yield by 25.3%. Co-application with inorganic fertilizer further enhanced yields by an additional 10% compared to inorganic fertilizer alone. The highest yield increase (179.6%) occurred when biochar was combined with both organic and inorganic fertilizers, though this finding requires cautious interpretation due to limited data. Yield responses were significantly influenced by biochar application rate, crop type, and fertilizer treatment. Optimal results were achieved with biochar produced at 401–500 °C and with a C: N ratio of 31–100. The greatest yield benefits occurred in very acidic soils (pH ≤ 5), where yields increased by 41.9%. These findings demonstrate that integrating biochar with fertilizers, particularly in acidic soils, can substantially improve crop productivity and fertilizer efficiency. However, combining biochar with high-nitrogen fertilizers and mycorrhizal fungi can decrease plant biomass due to induced fungal parasitism (LeCroy et al. 2013). Additionally, while biochar generally reduces CH_4 and N_2O emissions, its combination with organic amendments can increase soil CO_2 emissions (Fu et al. 2023), indicating antagonistic effects on CO_2 mitigation. One key mechanism by which biochar can negatively interact with other

Table 2 Effects of Biochar in the combination with other soil amendments on plant root resilience parameters under stress conditions

Amendment	Test plant	Type of stress	Observed effect	References
Biochar and compost	Tomato (*Solanum lycopersicum* L.)	Salinity	• Growth attributes ↑ up to 45% • Shoot Na^+ ↓40%, root Na^+ ↓47% • SPAD ↑, Chl. *a* ↑18.3% (vs. non-saline) • Relative water content ↑12.1%, membrane stability index ↑22.6% (vs. non-saline)	Ud Din et al. (2023)
Compost mixed biochar (CB) and *Alcaligenes faecalis*, and *Bacillus amyloliquefaciens*	Mint (*Mentha piperita* L.)	Heavy metal	• Root dry weight ↑58%, leaf dry weight ↑32% • Chlorophyll ↑37% • Leaf N ↑46%, P ↑39%, K ↑63% • Leaf Pb uptake ↓13.5% • Soil organic matter ↑, N/P/K ↑, and pH/EC ↓	Zafar-ul-Hye et al. (2021)
Biochar (cotton sticks) in the combination with bacterial strains (*Paraburkholderia phytofirmans* and *Bacillus* sp.)	Soybean (*Glycine max* L.)	Drought	• Photosynthetic activity ↑12–30% • Antioxidant enzymes ↑5–20% (Superoxide dismutase and catalase) • Grain yield ↑14% • Gas exchange characteristics ↑ (reduced drought decline)	Nawaz et al. (2023)
Biochar (groundnut shell waste) in the combination with bacterial strain (*Bacillus pseudomycoides* ARN7)	Corn (*Zea mays* L.)	Heavy metal	• Shoot length ↑48%, root length ↑98% • Chlorophyll ↑64%, proteins ↑65%, relative water content ↑26% • Cd in shoots ↓35% (Ni), ↓10% (Zn) • Soil dehydrogenase activity ↑320%	Anbuganesan et al. (2024)
Olive-pruning-derived biochar in the combination with bacterial strain (*Bacillus siamensis*)	Olive trees (*Olea europaea* cv. Picual)	Drought	• Aerial dry weight ↑19% • Absecic acid ↓40%, proline ↓45% • Malondialdehyde ↓67%, H_2O_2↓ • *OePIP1.1*/*OePIP2.1* (AQP) genes ↓60–80% • *OeDHN* (dehydrin) gene ↓50%	Crespo-Barreiro et al. (2025)
Rice straw biochar in the combination with AMF strain (*Funneliformis mosseae*)	Rice (*Oryza sativa* L.)	Heavy metal	• Root biomass ↑42% • Root Cd accumulation ↑48.7% (immobilization) • Shoot Cd ↓26%, seed Cd ↓ • Cd in seeds ↓ to < 0.2 mg kg^{-1} (at 1 mg kg^{-1} soil Cd) • Superoxide dismutase activity ↑, *IBRv2* (oxidative stress) ↓	Zhao et al. (2024)
Biochar (obtained from a natural mine) in the combination with AMF strains (*Funneliformis mosseae*, *Rhizophagus intraradices*, and *Claroideoglomus etunicatum*)	**Lavander (*Lavandula angustifolia*L.)**	**Drought**	• Highest growth, chlorophyll, carotenoids under normal irrigation • Essential oil concentration ↑ under mild stress • Essential oil yield ↑ under normal irrigation • Antioxidant enzymes ↑, proline ↓, and malondialdehyde ↓ under stress • Linalool/camphor/borneol ↑ under mild stress	Haghaninia et al. (2024)
Biochar in the combination with organic fertilizer (pig manure)	Wheat (*Triticum aestivum* L.)	-	• Yield ↑37.32% (vs. 100% chemical fertilizer) • Photosynthetic capacity ↑54.97% (seedling stage) • Root N ↑21.44–60.16% (tillering) • Leaf N ↑4.71% (heading) • Grain N ↑4.38% (maturity)	Gu et al. (2025)
Wheat straw biochar in the combination with chemical, green and biological nitrogen fertilizers	Bread wheat (*Triticum aestivum* L.)	-	• Grain yield: urea + biochar ↑337%, legume residues + biochar ↑312% vs. control • Grain N yield: legume residues + biochar ↑880% vs. control • N-recovery efficiency: 70% (legume residues + biochar) • N-harvest index: 91% (legume residues + biochar) • Reduced nitrate leaching (legume residues + biochar vs. urea alone)	Ghorbani et al. (2022)
Date palm biochar in the combination of with vermicompost	Eggplant (*Solanum melongena* L.)	Drought	• Total yield ↑ (highest: vermicompost + pistachio biochar at 100% plant water requirement) • Early yield ↑ (highest: pistachio biochar at 50% plant water requirement) • Water use efficiency ↑ (highest: vermicompost + pistachio BC at 50% plant water requirement) • Leaf nutrients (N, P, K, Fe, and Mn) ↑ (highest: vermicompost + pistachio BC at 100% plant water requirement) • Stress markers (malondialdehyde, peroxidase, superoxide dismutase, and catalase) ↓	Ebrahimi et al. (2021)

Table 2 (continued)

Amendment	Test plant	Type of stress	Observed effect	References
Biochar in the combination of with vermicompost	Wheat (*Triticum aestivum* L.)	Drought and salinity	• Highest grain yield & nutrient uptake (N, P, K) at 75% field capacity • Relative water content ↑, chlorophyll ↑, stomatal conductance ↑ • Oxidative stress ↓ (Catalase/ascorbate peroxidase activities & gene expression ↓) • Leaf Na^+ ↓, proline ↓, leaf K^+ ↑	Hafez et al. (2021)
Biochar (BC) in the combination of with vermicompost (VC)	*Berberis integerrima*	Heavy metal	• Cd accumulation ↓ in roots/leaves (BC + VC most effective) • Chlorophyll ↑ & RWC ↑ (BC + VC restored at 20–30 mg Cd kg^{-1}) • Total phenolic content ↑ (highest at 20 mg Cd kg^{-1} + BC + VC) • Total flavonoid content ↑ (peaked at 20 mg Cd kg^{-1} with amendments) • Superoxide dismutase/phenylalanine ammonia-lyase activity ↑ (max at 30 mg Cd/kg with BC/VC)	Khosropour et al. (2022)
Biochar (BC) in the combination of with vermicompost (VC) and compost	Sweet pepper	-	• Total yield ↑: 31.12% (VC), 26.47% (75%VC:25%BC), 22.53% (50%VC:50%BC) • Fruit nitrate ↓ (all BC combinations) • Growth attributes ↑: Height, SPAD, leaf area, leaves/branches • Fruit quality ↑: Weight, length, diameter, flesh thickness, total phenolic content, total soluble solids, ascorbic acid, Beta-carotene, and titratable acidity • Leaf nutrients ↑: N, P, K, and Ca	EL-Mogy et al. (2024)

soil amendments is nutrient immobilization, where biochar adsorbs essential nutrients such as P and N, reducing their availability to plants. This effect is particularly pronounced in alkaline soils, where biochar can form complexes with iron and aluminum, further immobilizing P and decreasing crop yields (Baigorri et al. 2020). Additionally, biochar can disrupt microbial communities by altering microbial biomass, enzyme activities, and community composition, which can impair nutrient cycling and destabilize microbial networks; biochar's adsorption of microbial signaling molecules further interferes with microbial communication and function (Zhu et al. 2017; Cao et al. 2025). Changes in soil pH and cation exchange capacity (CEC) caused by biochar application may also negatively impact nutrient solubility and availability, especially in alkaline soils (Baigorri et al. 2020; Wu et al. 2017). Moreover, biochar can interfere with mycorrhizal fungi by hindering their colonization and symbiotic functions, sometimes promoting parasitism that reduces plant growth (LeCroy et al. 2013; Paymaneh et al. 2018). Although biochar often improves soil water retention and structure, these physical benefits do not always consistently translate into enhanced plant growth, especially when combined with other amendments that modify soil physical properties in complex ways (Madari et al. 2017). Lastly, the interactions between biochar and plant growth-promoting rhizobacteria (PGPR) remain largely uncertain, highlighting the need for further research to understand and optimize potential benefits from such combinations (Bhoi et al. 2024). In general, biochar's interactions with soil amendments are complex and context-dependent. While synergistic benefits for soil fertility, microbial activity, and remediation are common with compost and microbial inoculants, combinations with chemical fertilizers can be detrimental. Understanding these mechanisms is crucial for optimizing biochar use in sustainable agriculture. Further research is needed to elucidate specific interaction pathways and develop best application practices across diverse agricultural settings.

8 Factors Influencing Biochar Efficacy in Alleviating Stresses

The factors affecting the effectiveness of biochar include feedstock type, pyrolysis temperature, application rate, soil type, climate, plant species-specific responses, and interactions with stressors (Biederman and Harpole 2013; Lehmann and Joseph 2024; Zhang et al. 2013a; Jeffery et al. 2011; Tenic et al. 2020) (Table 3). These factors collectively determine how biochar influences root growth under various stress conditions. The type of feedstock from which biochar is produced significantly influences its physicochemical properties, nutrient content (Biederman and Harpole 2013; Razzaghi et al. 2020), and overall efficacy in promoting root growth. Different feedstocks yield biochars with varying nutrient compositions, surface areas, and CECs (Lehmann and Joseph 2024). For instance, manure-derived biochars typically exhibit higher nutrient levels compared to wood-derived biochars, making them more effective in nutrient-intensive applications. Moreover, the carbon content and the presence of specific functional groups can affect the adsorption of contaminants and the bioavailability of nutrients for root uptake (Zhang et al. 2013a; Hossain et al. 2020; Alkharabsheh et al. 2021). Pyrolysis temperature significantly influences critical biochar properties such as surface area,

Table 3 Some factors affecting the efficacy of Biochar (BC) in alleviating environmental stresses

Factor category	Key variables	Impact on biochar efficacy	References
Biochar (BC) properties	Feedstock type (wood, manure, and crop residue)	Determines porosity, nutrient content, and contamination risks (e.g., manure-derived BC higher in nutrients; sludge BC may contain heavy metals)	Lehmann and Joseph (2024), Ahmad et al. (2014), and Wang et al. (2021a)
	Pyrolysis temperature and duration	Influences stability, surface area, and functional groups (e.g., > 500 °C → higher porosity but lower nutrients; 300–500 °C optimal for microbial inoculants)	Chen et al. (2018a), Sohi et al. (2010), and Jia et al. (2022)
	pH, CEC, surface area, and nutrient content	Alkaline BC may neutralize acidic soils but worsen salinity; high CEC improves nutrient retention but may immobilize P in alkaline soils	Biederman and Harpole (2013) and Baigorri et al. (2020)
Application methods	Dosage (rate per hectare)	Over-application can saturate soil; under-application may lack measurable benefits.	Phillips et al. (2018); Šimansky et al. (2020), and Liu et al. (2013)
	Particle size (fine vs. coarse)	Fine particles integrate better in soil; coarse particles improve drainage.	Ndede et al. (2022) and Chen et al. (2018a)
	Pre-treatment (nutrient charging, composting)	Reduces short-term nutrient lockup and phytotoxicity.	Tsolis and Barouchas (2023) and Wu et al. (2023)
Environmental context	Soil type (sandy, clay, degraded)	Sandy soils benefit most from water retention; clay soils gain improved aeration.	Razzaghi et al. (2020) and Kern et al. (2025)
	Stress type (drought, salinity, and heavy metals)	Biochar must be tailored (e.g., high porosity for drought, functionalized for metal binding).	Chaganti and Crohn (2015), Chen et al. (2018b), and Park et al. (2011)
	Climate (arid vs. humid)	Arid regions need water retention without increasing alkalinity; humid regions reduce leaching.	Crane-Droesch et al. (2013) and Durukan et al. (2020)
Biological interactions	Soil microbiome (microbial diversity, activity)	Biochar can stimulate beneficial microbes (e.g., mycorrhizae) or suppress pathogens.	Meier et al. (2017), Gorovtsov et al. (2020), and Liu et al. (2023b)
	Plant species (crop-specific responses)	Legumes benefit from N retention (+ 25% nodulation); salt-sensitive crops require low-salt BC; variable root plasticity responses	Rondon et al. (2007) and Olmo and Villar (2019)
Synergistic practices	Co-application with fertilizers/compost/microbes	Enhances nutrient availability and organic matter.	LeCroy et al. (2013) and Bai et al. (2022)
	Aging/weathering effects	Aged biochar has higher CEC; fresh biochar may release phytotoxins.	Wang et al. (2022) and Zhu et al. (2018)
Socio-economic & logistical	Cost, accessibility, and farmer knowledge	High costs and lack of training limit adoption; localized production reduces expenses	Phillips et al. (2018) Müller et al. (2019)
	Policy support (subsidies and carbon credits)	Incentives drive adoption and scalability	Lehmann and Joseph (2024) and Senadheera et al. (2025)

porosity, and stability. Higher pyrolysis temperatures generally produce biochar with greater surface area and enhanced adsorption capacities. Furthermore, high-temperature biochars tend to be more stable and resistant to decomposition, which is beneficial for long-term soil amendment. However, there may be trade-offs, as biochars produced at very high temperatures might have lower nutrient content compared to those produced at lower temperatures (Lehmann and Joseph 2024; Novak et al. 2009; Atkinson et al. 2010; Biederman and Harpole 2013). The effectiveness of biochar also depends on the application rate. Optimal application rates can enhance soil structure, improve moisture retention, and increase nutrient availability, while excessive application can lead to negative effects such as soil pore blockage and nutrient imbalances. The ideal application rate may vary based on soil type, environmental conditions, and specific crop requirements. Studies suggest a range of 1–15% (w/w) is generally effective for most agricultural applications (Jeffery et al. 2011; Agegnehu et al. 2016; Atkinson et al. 2010; Liu et al. 2013; Crane-Droesch et al. 2013). The physical and chemical properties of the soil, including texture, pH, organic matter content, and nutrient status, significantly affect biochar performance. Sandy soils may benefit more from biochar application due to increased water retention, while clay soils may require different management practices. Additionally, biochar can help improve soil structure, which is particularly beneficial in compacted or degraded soils (Razzaghi et al. 2020; Atkinson et al. 2010; Lehmann and Joseph 2024; Jeffery et al. 2011; Liu et al. 2013). Climate factors such as temperature, precipitation, and humidity can influence the efficacy of biochar in improving root growth. In arid environments, for example, biochar can enhance water retention, thus benefiting root systems. Conversely, in wetter conditions, biochar may influence nutrient leaching and aeration (Crane-Droesch et al. 2013; Lehmann and Joseph 2024; Lehmann et al. 2021). Understanding local climate conditions is essential for determining the appropriate application of biochar to enhance root growth under varying stress conditions. The impact of biochar on root growth can vary significantly among different plant species due to genetic, physiological, and morphological differences. Some plant species may be more responsive to biochar amendments in terms of root growth and resilience under stress, leading to differences in optimal application rates and practices (Biederman and Harpole 2013; Thomas et al. 2013; Noguera et al. 2010; Sorrenti 2015). Identifying plant-specific responses to biochar can help in tailoring application strategies for maximizing its benefits across various crops.

9 Challenges and Limitations of Biochar Application

Despite the numerous benefits of biochar, its application also presents certain challenges and limitations that need to be addressed (Table 4). For example, it is known that excessive application of biochar may lead to undesirable effects. Over-application can cause nutrient imbalances, leading to potential toxicity and reduced crop yields. High amounts of biochar may also exacerbate the immobilization of P and other essential nutrients, creating nutrient lockup conditions that negatively affect plant uptake (Liu et al. 2013; Lehmann and Joseph 2024; Yu et al. 2019; Glaser and Lehr 2019). Biochar, while widely recognized for its potential to improve soil health and plant growth, can under certain conditions exhibit toxic effects and inhibit microbial activity. These adverse effects are influenced by factors such as feedstock type, pyrolysis temperature, biochar application rate, and the presence of potentially harmful compounds in the biochar (Kloss et al. 2012; Lehmann and Joseph 2024; Lehmann et al. 2011; Gorovtsov et al. 2020). Therefore, it is crucial to determine and adhere to optimal application rates based on specific soil and crop conditions to avoid over-reliance on biochar. Biochar can significantly alter the pH of soils, especially if derived from alkaline feedstocks. In soils that are already alkaline, the introduction of biochar may lead to further increases in pH, which can hinder the availability of micronutrients such as phosphorus, iron, zinc, and manganese (Biederman and Harpole 2013; Lehmann and Joseph 2024). This nutrient deficiency can adversely affect plant health, particularly for crops sensitive to pH fluctuations. Careful consideration of the initial soil pH and the soil's buffering capacity is essential when applying biochar.

The impact of biochar application on crop root growth can vary significantly (Jeffery et al. 2011; Olmo and Villar 2019; Prendergast-Miller et al. 2014). The presence of biochar can sometimes lead to nutrient immobilization, particularly in nutrient-poor soils, where biochar adsorbs nutrients and thus reduces their availability to plants (Biederman and Harpole 2013). This phenomenon can be especially problematic in scenarios where immediate nutrient availability is critical for crop establishment and root growth. For instance, the effect of biochar on plant establishment and root growth is often influenced by soil nutrient content (Clough et al. 2013; Van Zwieten et al. 2010; Liu et al. 2021a). In fertile soils, biochar has been shown to have a clear positive effect on plant growth, whereas this benefit is less pronounced or absent in low-fertility soils (Noguera et al. 2010). Some studies have demonstrated that biochar, when combined with mineral fertilization, can significantly enhance plant growth and even double grain production (Steiner et al. 2007), while also increasing root length when paired with nitrogen fertilization (Prendergast-Miller et al. 2011). However, other research has indicated that biochar can boost crop yield and root growth regardless of the soil nutrient application rate (Backer et al. 2017). To mitigate these effects, it may be necessary to apply complementary nutrient sources alongside biochar amendments to ensure optimal nutrient availability and plant health.

The long-term impacts of biochar application on soil health, nutrient cycling, and plant growth are not yet fully understood. Much of the research has focused on short-term benefits, with fewer studies examining the sustainability of these benefits over multiple growing seasons. Understanding the longevity of biochar's positive effects, alongside any potential negative consequences, is crucial for developing effective agricultural practices. The effects of biochar can vary significantly across different field scenarios due to factors such as soil type, climate, and management practices. Variability in biochar properties, including particle size and composition, can also lead to inconsistent results (Lehmann and Joseph 2024; Jeffery et al. 2011; Crane-Droesch et al. 2013). This heterogeneity complicates predictions regarding biochar's performance and effectiveness in real-world

Table 4 Some challenges, limitations, and solutions for Biochar use in stressed agriculture

Challenges/limitations	Description	Solutions	References
Variability in feedstock and properties	Biochar properties vary widely depending on feedstock type and pyrolysis conditions, leading to inconsistent results in agricultural applications.	Standardize production processes and conduct site-specific testing to match biochar properties with soil and crop needs.	Lehmann and Joseph (2024), Kern et al. (2025), and Chen et al. (2018b)
High production costs	The cost of producing biochar can be prohibitive, especially for small-scale farmers.	Promote low-cost, decentralized production methods using locally available biomass and waste materials. Subsidies or incentives could also reduce costs.	Phillips et al. (2018) and Šimansky et al. (2020)
Potential toxicity	Biochar may contain contaminants like polycyclic aromatic hydrocarbons, heavy metals, or volatile organic compounds, which can harm soil microbes and plants.	Use clean feedstocks and optimize pyrolysis conditions to minimize contaminants. Pre-age or wash biochar before application.	Xiang et al. (2021), Wang et al. (2017), and Qian et al. (2020)
Nutrient imbalances	Excessive biochar application can immobilize nutrients like nitrogen and phosphorus, reducing their availability to plants.	Determine optimal application rates based on soil nutrient status and crop requirements. Combine biochar with bio/fertilizers or compost to balance nutrient supply.	Baigorri et al. (2020), Biederman and Harpole (2013), and Liu et al. (2013)
Inconsistent field performance	Biochar's effects vary across soil types, climates, and management practices, making it difficult to predict outcomes.	Conduct field trials under diverse conditions to identify best practices for specific regions and crops. Develop region-specific guidelines.	Crane-Droesch et al. (2013), Kern et al. (2025), and Olmo and Villar (2019)
Soil pH alterations	Biochar's alkalinity can raise soil pH excessively, negatively affecting acid-loving crops and microbes.	Use biochar with lower pH or mix it with acidic amendments (e.g., compost) to moderate pH changes. Optimize application to soil pH needs.	Chaganti and Crohn (2015) and Bolan et al. (2023a)
Microbial inhibition	Fresh biochar can release toxic compounds or alter microbial habitats, inhibiting beneficial soil microbes.	Pre-condition biochar by aging it or mixing it with organic amendments like compost to reduce toxicity and enhance microbial colonization.	Kloss et al. (2012), Gorovtsov et al. (2020), and Wang et al. (2017)
Limited long-term data	Long-term impacts of biochar on soil health, crop productivity, and environmental sustainability are not fully understood.	Invest in long-term field studies and monitoring programs to assess biochar's durability and cumulative effects over time.	Mukherjee and Lal (2014) and Wang et al. (2020)
Over-reliance on biochar	Farmers may over-rely on biochar as a "silver bullet," neglecting other sustainable practices.	Integrate biochar into holistic soil management strategies that include crop rotation, cover cropping, and organic amendments.	Bai et al. (2022) and Steiner et al. (2008)
Scalability and accessibility	Large-scale adoption of biochar is hindered by logistical challenges and limited access to technology in some regions.	Develop scalable, low-tech pyrolysis systems and establish regional biochar production hubs to improve accessibility. Provide training and support for farmers.	Müller et al. (2019), Senadheera et al. (2025), and Phillips et al. (2018)

agricultural settings. As a result, localized testing and adaptation of biochar strategies are essential to optimize its use for specific crops and environmental conditions. In summary, while biochar presents a promising solution for enhancing soil health and plant resilience, its application is not without challenges. Careful consideration of application rates, soil conditions, and long-term impacts is crucial for ensuring biochar's effectiveness and preventing potential drawbacks in agricultural systems. Further research is needed to fully elucidate these factors and guide more effective, sustainable biochar application practices.

10 Future Perspectives and Research Directions

To advance biochar from promising potential to reliable practice, future research must explicitly address critical unresolved questions and limitations in the current literature. Key priorities include resolving inconsistencies stemming from variability in feedstock types (e.g., wood vs. manure), pyrolysis conditions (temperature and duration), and application methods (rates, particle size, and incorporation techniques), which lead to contradictory findings across studies. A fundamental gap exists in long-term field-scale validation of biochar effects, particularly regarding its persistence in enhancing root resilience under repeated stress events and potential aging-related changes in functionality. Economic viability remains a significant barrier, requiring comprehensive assessments of cost-benefit tradeoffs across production systems, transportation logistics, and yield responses under real-world farming conditions. Research should also prioritize mechanistic understanding of context-dependent outcomes, especially where biochar benefits certain crops (e.g., tomato and maize) but shows neutral or negative effects on others in similar soils. To address these gaps, we recommend: (1) Establishing standardized, multi-year field trials across diverse agroecosystems to evaluate interactions between biochar properties and local soil-climate conditions; (2) Developing predictive models that integrate life-cycle cost analysis with agronomic performance data to guide economically feasible implementation; (3) Systematic investigation of legacy effects on soil microbiome composition, particularly regarding potential unintended shifts favoring pathogenic communities under specific biochar amendments; and (4) Coordinated interdisciplinary efforts to create decision-support frameworks that optimize biochar selection based on target stressor(s), crop species, and socioeconomic context. Only through such focused, condition-specific research can we overcome current limitations and harness biochar's full potential for enhancing root resilience in sustainable agriculture.

11 Conclusion

Biochar demonstrates potential as a soil amendment for enhancing root resilience to environmental stresses like drought, salinity, heavy metals, organic pollutants, and pathogens. Mechanistically, this resilience arises from biochar's ability to physically modify the rhizosphere (improving structure, porosity, and water retention), chemically optimize conditions (increasing cation exchange capacity, modulating pH, and immobilizing contaminants via adsorption/precipitation), and biologically enhance symbioses (promoting colonization by beneficial microbes such as arbuscular mycorrhizal fungi [e.g., *Rhizophagus irregularis*] and plant growth-promoting rhizobacteria [e.g., *Pseudomonas* spp. and *Bacillus subtilis*] under specific conditions). Critically, microbial responses are context-dependent and not uniformly positive; biochar can selectively stimulate beneficial taxa (e.g., increasing *Proteobacteria* abundance in contaminated soils or *Trichoderma* spp. for disease suppression) while potentially inhibiting others, depending on feedstock, pyrolysis temperature, soil type, and application rate. Similarly, pathogen suppression efficacy varies (e.g., against *Fusarium oxysporum* versus *Ralstonia solanacearum*) and involves specific mechanisms like adsorption of phytotoxins, induction of systemic resistance (via jasmonic acid/ethylene pathways), or alteration of root exudate profiles. To translate this potential into reliable practice, future research must prioritize mechanistic clarity on key interactions: nutrient cycling dynamics, particularly phosphorus solubility under biochar-induced pH shifts and nitrogen mineralization-immobilization trade-offs; microbial community dynamics, identifying keystone taxa (e.g., *Chloroflexi* in metal stress and *Pseudomonas* in drought) and functional shifts under combined stresses while linking specific biochar properties (e.g., pore size and labile C content) to microbiome assembly; and root exudate signaling, deciphering how biochar alters exudate composition (e.g., strigolactones and flavonoids) and subsequent microbe-plant communication. This necessitates a well-coordinated research framework entailing standardized methodologies for biochar characterization (aging and particle effects) and stress simulation (multifactorial studies), interdisciplinary integration combining soil physics, microbiology, plant genomics, and agronomy to map biochar-plant-soil feedback loops, and condition-specific optimization to develop predictive models for tailoring biochar properties to soil type, crop species, and target stressors. Addressing these priorities will advance biochar from a broad-spectrum amendment to a precision tool for enhancing root resilience and sustainable crop production under environmental stress.

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