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REVIEW

Soil and Ecosystem Processes

Mechanistic role of biochar as a geobiochemical amendment: Mitigating abiotic stress and enhancing soil–plant interactions

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Abstract

Abiotic stressors, including drought, salinity, and heavy metal contamination, pose escalating threats to global food security, challenges further exacerbated by climate change and progressive soil degradation. As a strategic geochemical amendment, biochar is increasingly proposed to enhance soil resilience and agricultural sustainability, directly supporting sustainable development goal (SDG) 2 (Zero Hunger) and SDG 13 (Climate Action). This review critically evaluates biochar in stress mitigation, focusing on production principles, soil physicochemical adjustments, and changes in the soil-plant microbiome and soil–plant–microbe interactions. Specifically, we synthesize data demonstrating biochar's multifaceted efficacy: regulating ion homeostasis to reduce Na^+ uptake by 20%–40% under saline conditions, enhancing water use efficiency by 15%–30% in arid environments, and immobilizing heavy metals to reduce cadmium (Cd) accumulation by 25%–50%. These synergistic soil–plant interactions further contribute to SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land). However, significant challenges remain regarding feedstock variability, dosage optimization, and long-term field stability. Furthermore, performance discrepancies under combined multi-stress scenarios underscore the urgent need for standardized biochar formulations. Integrating biochar into precision frameworks offers a promising geobiochemical frontier for modulating multi-stress crop resilience and shifting soil–plant–microbe dynamics toward climate-adaptive landscapes. Such advancements are essential for ensuring global food security for a projected population of 9.7 billion by 2050.

Abbreviations: CAT, catalase; CEC, cation exchange capacity; EPFR, environmentally persistent free radical; ETc, evapotranspiration; HKT, high-affinity potassium transporter; HTC, hydrothermal carbonization; MDA, malondialdehyde; ROS, reactive oxygen species; RWC, relative water content; SDG, sustainable development goal; SOC, soil organic carbon; SOD, superoxide dismutase; WUE, water use efficiency.

Plain Language Summary
Farmers worldwide are struggling to grow crops due to extreme drought, salty soils, and heavy metal pollution. These issues are worsening due to climate change and soil erosion, threatening global food supplies. Scientists are exploring biochar, charcoal made from recycled plant waste, as a natural solution. This review explains how biochar acts as a shield for crops. We examined how it changes soil chemistry to help plants survive harsh conditions and support global goals for ending hunger and protecting the environment. Biochar acts like a sponge to hold water during droughts and filters the soil by trapping harmful salts and toxic metals. It can reduce salt intake in plants by 40% and cut toxic metal levels by half, leading to healthier harvests and cleaner land. Biochar is a powerful tool for sustainable farming. While we need to standardize "recipes" for different soils, combining biochar with new technology will enhance its effectiveness and accelerate its adoption in global agriculture.

1 | INTRODUCTION

1.1 | Biochar fundamentals and design principles

Biochar is a stable type of carbon (C)-based substance that can be developed using the pyrolysis of organic biomass in the presence of limited oxygen, which is an inexpensive amendment that can increase the quality of the soil and the resilience of crops in contemporary agriculture. Rooted in historical terra preta models, biochar serves as an active interface mediator, modulating bidirectional rhizosphere signaling loops and root exudate feedback to protect crops against climate-driven abiotic stressors. It is relevant because it can sequester carbon in the long run and enhance the fertility of soils, contributing to sustainable development goal (SDG) 13: Climate Action by helping mitigate climate change through carbon storage. Meta-analyses across the world show that organic carbon in soils grows by an average of 20%–30% in amended soils over 3–5 years (Z. Xu, Zhou, et al., 2025). As an example, application of biochar at the rate of 10–30 t ha^{-1} in low-fertility tropical soils has been reported to increase the pH by 0.5–1.5 units, which lowered the acidity and opened the nutrient accessibility of crops such as maize and legumes (Ghorbani et al., 2024). This makes biochar not only a conditioning agent of soil but also a major constituent of sustainable production systems, which contribute to SDG 2: Zero Hunger by improving crop yields and SDG 6: Clean Water and Sanitation by enhancing water retention and quality. Biochar reduces the emission of greenhouse gases by 15%–25% due to the decrease in nitrous oxide emissions (Chaplot et al., 2025), directly supporting SDG 13: Climate Action. Biochar helps maintain the stability of the yield, and a 15% increase in wheat yields has been reported in changing rainfall conditions (X. Zhang et al., 2024), reflecting its role in promoting SDG 15: Life on Land by improving soil health and reducing degradation. Nevertheless, its effectiveness is context-specific, and it is important to highlight that it requires specific designs to achieve the maximum utility of agriculture with no environmental trade-offs.

Unlike reviews focusing solely on individual stresses, this article synthesizes mechanistic links between drought, salinity, and heavy metal stress, focusing on the soil/plant microbiome, soil–plant–microbe interactions, and cross-stress synergies. It critically reviews production optimization for targeted stress mitigation, identifies performance differences in multi-stress field conditions, and outlines potential pathways to implementation, including advanced formulations. The integrated view is relevant in the light of the growing number of multiple abiotic stresses in the context of climate change, and the requirement for context-specific and scalable solutions to meet the global challenge of food security.

1.2 | Feedstock selection and property optimization

Feedstock selection is pivotal in optimizing biochar's physicochemical properties, directly influencing its agricultural performance through variations in carbon content, porosity, and nutrient profile. Popular feedstocks include agricultural residues, such as rice husk, woody biomass, and manure, with distinct qualities such as high cation exchange capacity (CEC) in manure-based biochar, up to 20–40 cmol kg^{-1}, that help to retain nutrients (Jeong et al., 2025). Optimization means balancing ash content and surface area; making use of woody biochar, which has a known surface area of 200–800 m^2 g^{-1}, woody biochar is able to increase the water-holding ability in sandy soil by 10%–20% (Chang et al., 2021).

Recent reports have indicated that blending feedstock, including a combination of lignocellulosic material with manure, can boost the total carbon richness to 60%–80%, which facilitates the long-term fixation of carbon into the soil at 0.5–1 t C ha^{-1} $year^{-1}$ (Hu et al., 2025; Oelbermann et al., 2023). This section investigates the ways such optimizations can be in accordance with the requirements of crops so that biochar can be a precision amendment to stressful environments. Table 1 data show that the variations in primary biochar characteristics, including alkalinity, conductivity, and moisture retention, differ among biomass sources and processing temperatures. These parameters dictate soil interactions, though optimization must suppress pyrolytic formation of environmentally persistent free radicals (EPFRs) that induce cellular toxicity (Table 1).

1.3 | Production techniques for targeted applications

There are several different methods of producing biochar, such as slow pyrolysis, fast pyrolysis, gasification, and hydrothermal carbonization (HTC), which result in biochars with very different properties that directly affect their potential for stress mitigation. Slow pyrolysis (300˚C–600˚C) gives highly stable carbon-rich biochar (50%–70% C), which is suitable for long-term carbon sequestration and heavy metal immobilization but may not have as high a surface area for immediate nutrient or water retention. Fast pyrolysis (>500˚C), on the other hand, produces a biochar having a higher surface area (300–600 m^2 g^{-1}), which is favorable to the contaminant adsorption, but with lower solid yield (Chatterjee et al., 2020). HTC is advantageous for wet feedstocks and produces hydrochar with improved hydrophobicity, enhancing water retention by 15%–25% in drought-prone soils (Acharya et al., 2024; P. Wang et al., 2024). However, each method involves trade-offs: high-temperature processes can reduce nutrient retention capacity and increase energy input, while low-temperature biochars may be less stable over time. Gasification yields minimal biochar but maximizes syngas, making it less favorable for soil amendment purposes. Pyrolysis parameters must optimize surface characteristics that target specific abiotic deficits while simultaneously fostering colonizable structures that maximize beneficial plant–microbe symbioses (Table 2).

1.4 | Quality metrics and standardization needs

Quality indicators of biochar include stability, level of contaminants, and activity, and standardization is necessary to achieve standard agricultural performance. The ratios, such as the H/C molar ratio less than 0.7, are used to show high stability, which guarantees the persistence of carbon through 100–1000 years. The iodine number is used to determine the adsorption capacity, usually more than 500 mg g^{-1} in optimized biochar (C. Zhao et al., 2023). Standardization must tackle variability, such as the guidelines of the International Biochar Initiative (IBI) to recommend a pH of 6.5–9.0 and ash below 60% to avoid salinity problems, but the world practices it differently, resulting in inconsistencies in yield of 5%–15% (Szostek et al., 2024; Yunusa et al., 2006). Evolving standardization criteria look beyond basic chemistry, establishing functional benchmarks for soil microbiology preservation, consistent disease suppression performance, and predictable multi-stress field outcomes. Biochar production processes are sequenced based on choices of feedstock and processing conditions, which eventually determine the final effects of biochar on farmers. This cascade brings out the effects of initial inputs on ultimate properties such as porosity and nutrient content in order to optimize the advantages of soils and crops (Figure 1).

Core Ideas

- Nanosensors enable real-time detection of plant stress signals (H_2O_2, SA) before visible symptom development.
- Multiplexed sensing with machine learning discriminates biotic from abiotic stress with >96% accuracy.
- Stimuli-responsive nanocarriers deliver agrochemicals, nutrients, and genetic cargo in response to physiological triggers.
- Redox- and enzyme-responsive carriers provide direct molecular coupling for stress-triggered therapeutic release.
- Fully autonomous sensor-carrier integration for closed-loop plant management remains a future research objective.
- Field-scale efficacy averages only 60–70% of greenhouse performance; biosafety and regulatory frameworks remain incomplete.
- Nano-enabled resilience involves coordinated antioxidant, transcriptional, metabolic, and microbiome responses.
- Research priorities include multi-stress field validation, predictive nanocarrier design, and interoperable data systems.

TABLE 1 Biochar physicochemical profiles categorized by feedstock class and thermal regime.

Feedstock category	Thermal range applied (°C)	Dominant chemical reaction	Carbon richness (%)	Exchange behavior	Water-related functionality	Reference
Woody biomass (e.g., *Acacia*, *Prosopis*, pine sawdust)	300–700	Weakly acidic → strongly alkaline with temperature escalation	67–90	Very high at low–mid temperatures; declines at ≥500°C	High moisture retention (up to ∼380%)	(Angalaeeswari & Kamaludeen, 2017; Pituya et al., 2017)
Agricultural residues (rice husk, corn cob, cotton stalk)	250–600+	Neutral to alkaline	Moderate to high (≈42–82)	Moderate; increases with ash content	Moderate; texture-dependent	(Abrishamkesh et al., 2015; Speratti et al., 2017)
Aquatic biomass (water hyacinth)	250–550	Rapid alkalization with temperature	Not consistently reported	Variable; peaks near 450°C	Limited data	(Q. Zhang et al., 2015)
Animal-derived residues (cow dung, poultry waste)	<400 (reported)	Mildly alkaline	Low–moderate (∼23–30)	Relatively high due to mineral ash	Limited data	(Sukartono et al., 2011)
Industrial crop residues (oil palm EFB, fronds, trunk)	∼500	Neutral to alkaline	42–67	Moderate	Not reported	(Bindu et al., 2019)

Note: Feedstock identity and pyrolysis temperature jointly determine surface charge behavior, alkalinity, and moisture interaction rather than any single intrinsic property.

TABLE 2 Comparative summary of major biochar synthesis routes and their operational benefits.

Method	Operating parameters	Feedstock condition	Distinctive benefits/suitability	Reference
Traditional open combustion	Field pit or clay–brick furnace; partial oxygen restriction; incomplete burning of residues.	Air-dry agricultural residues.	Simplest low-cost method; requires no external energy or advanced equipment; widely used in rural applications.	(Gabhane et al., 2020; Mašek, 2022; Thines et al., 2017)
Slow pyrolysis	300°C–600°C; 5°C–7°C min^{-1}; 60–120 min; O_2-free.	Dried lignocellulosic material.	Produces relatively stable carbon-rich biochar; minimal energy use; high yield.	(Awogbemi & Kallon, 2023; Méndez et al., 2015)
Fast pyrolysis	>500°C; ≈300°C min^{-1}; <20 min.	Pre-dried feedstock.	Generates a large bio-oil fraction (≈60%); suited to industrial reactors.	(Laird et al., 2010; Méndez et al., 2015)
Flash/ultra-fast pyrolysis	∼1000°C s^{-1}; residence ≤1 min.	Finely milled residues.	Extremely short processing time; efficient conversion; limited solid yield (10%–15%).	(Adelawon et al., 2022; Gabhane et al., 2020)
Gasification	700°C–1500°C with air/steam/O_2/CO_2 mixtures.	Moist or partially dried biomass.	Produces high-quality syngas and small amounts of biochar; strong environmental potential.	(Dafiqurrohman et al., 2022; You et al., 2018; W. Zhang et al., 2022)
Hydrothermal carbonization (HTC)	150°C–350°C; 2–10 MPa; several hours.	Wet biomass (no drying needed).	Converts waste directly to hydrochar; enhances hydrophobicity and dewaterability.	(Chi et al., 2021; de Almeida Moreira et al., 2021; Pauline & Joseph, 2020)
Hydrothermal liquefaction (HTL)	250–374°C; 2–25 MPa; subcritical water.	High-moisture organic waste.	Yields ≤70% bio-oil plus solid biochar fraction; minimal water consumption; high energy recovery.	(Chi et al., 2021; Gollakota et al., 2018)

Note: *Summary insight*: Among all, slow pyrolysis remains the most balanced approach for agricultural applications, whereas gasification and HTL favor energy-oriented systems.
Abbreviations: HR, heating rate; RT, residence time; TR, temperature range.

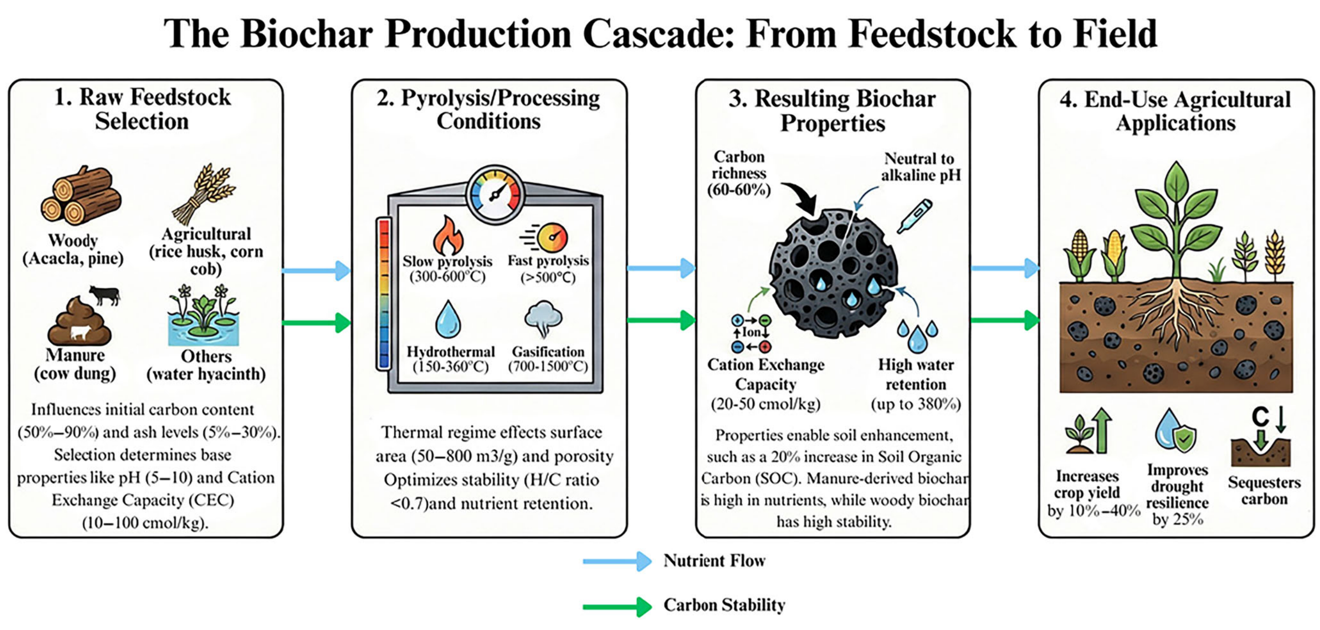

FIGURE 1 Biochar production Cascade.2 biochar interactions with soil ecosystems.

1.5 | Chemical modifications and nutrient dynamics

Biochar's integration into soil ecosystems initiates profound chemical modifications, primarily through alterations in pH, CEC, and nutrient cycling, which collectively enhances soil fertility and plant nutrient availability. After amendment, biochar is alkaline (goes to pH of 7.5–10.5) and promotes liming effects, increasing soil pH by 0.5–1.5 units in acidic soils (pH below 5.5), thereby mitigating the level of aluminum toxicity and enhancing phosphorus (P) dissolution (Sharma et al., 2025). Meta-analyses show that biochar application typically increases soil organic carbon (SOC) content by 20%–40% in the short to medium term (3–5 years), with manure-based biochars contributing additional labile carbon pools of 15%–25% (Hossain et al., 2020). These effects are driven by surface functional groups (carboxyl and hydroxyl) that increase CEC by 20–50 cmol kg^{-1}, particularly in sandy soils (Costa et al., 2020). While these dynamics optimize key macronutrient retention, transient processing hazards like EPFR generation can temporarily disrupt localized microbial ecologies (Di & Cameron, 2016). These changes help to sustain healthy nutrient pools in low-fertility environments to promote the resilience of agroecosystems facing escalating environmental stress. The evidence provided demonstrates directional changes in soil parameters, characterized by approximately 45% higher CEC by about 45% and elevated pH, which underlie the mechanisms of enhanced nutrient retention and acidity neutralization. These trends reflect the ability of biochar to maximize chemical equilibria, which are directly related to enhancing soil productivity and minimizing gaseous emissions, which is central to the role of biochar in ecosystem improvement (Table 3).

1.6 | Physical structure enhancements

Biochar also enhances physical soil structure through an increase of bulk density, porosity, and water-holding capacity to induce a more favorable physical matrix upon which roots proliferate and the soil hydrology attains equilibrium. Biochar application at rates of 10–30 t ha^{-1} typically reduces soil bulk density by 10%–20% (e.g., from 1.3 to 1.5 g cm^{-3} toward more favorable values), particularly in compacted clay soils, thereby improving aggregation, aeration, and root proliferation (Blanco-Canqui, 2017). Microporous structure in which the surface areas larger than 50 m^2 g^{-1} increase water retention by 15%–25% in sandy textures, reducing the effects of drought caused by capillary action and evaporation (Omondi et al., 2016). These physical alterations are associated with an enhancement of hydraulic conductivity, in which biochar amendments have increased infiltration rates in loamy soils, thereby improving water distribution and reducing erosion. In the mechanism, the fixed carbon structure of biochar (which becomes stable) becomes populations of soil particles, which combine into macroaggregates to increase the structural stability of the soil over time, where results indicate that the persistence effects of biochar persist 3–5 years after application (Fouché et al., 2023). These modified pore networks stimulate a dynamic interface, accelerating bidirectional root–soil structural feedback that optimizes continuous resource exchange between the plant and surrounding substrate.

TABLE 3 Effects of biochar amendment on key soil functions.

Soil function influenced	Amendment context	Net response magnitude	Response trend/notes	Reference
Soil pH (acidity)	Biochar application (various rates, long-term)	↑ 0.38–0.81 pH units (at 11.2–44.8 t ha^{-1})	Positive liming effect, persistent >10 years	(Machado et al., 2026)
Cation exchange capacity (CEC)	High-rate biochar (44.8 t ha^{-1}, long-term)	↑ to 17.7 meq 100 g^{-1}	Consistently positive, enhanced nutrient retention	(Machado et al., 2026)
Bulk density	Biochar (20–30 g kg^{-1})	↓ (significant reduction observed)	Structurally beneficial, improved porosity	(Xiu et al., 2025)
Soil porosity/structure	Biochar amendment (general)	↑ (enhanced aggregate stability & porosity)	Positive, improves aeration and water dynamics	(Zhu et al., 2025)
Soil water retention/water holding capacity (WHC)	Biochar in coarse-textured soils	↑ ~30% available water (meta)	Stronger in sandy/coarse soils	(Oyebiyi et al., 2026)
Soil water retention	Biochar (various, physical improvement)	↑ (increased field capacity and plant-available water)	Positive, especially in arid/sandy conditions	(Ali et al., 2025)
Nitrogen retention/transformation	Biochar (1%) in acidic soils (pH 4.5–6.4)	Enhanced gross NH_4^+ immobilization	Positive within specific pH range	(Qian et al., 2023)
Fertilizer/nutrient efficiency	Biochar co-application	↑ nutrient retention (N, P, K)	Economically relevant, reduced leaching	(Y. Zhao et al., 2022)
Methane emissions (rice paddies)	Continuous biochar + water-saving irrigation (2.5 t ha^{-1} yr^{-1})	↓ ~29.32% (5-year cumulative)	Seasonally stable with repeated application	(Han et al., 2026)
Methane emissions	Biochar amendment (various rates)	↓ 33.6%–43.5% annual	Reduced mcrA/pmoA ratio	(Ma et al., 2025)
Bulk density	Biochar (10%–20% range, various studies)	↓ 10%–12%	Positive structural change	(Tang, 2025)
Soil organic carbon (SOC)	Long-term biochar (high rates)	↑ 95%–207% (initial, sustained)	Long-term carbon sequestration	(Machado et al., 2026)

1.7 | Biological community shifts

Biochar alters the soil and plant microbiome by creating habitats and substrates that stimulate soil–plant–microbe interactions essential for decomposition, nutrient conversion, and symbiotic resilience. Metadata indicate that biochar enhances microbial diversity (bacterial Shannon index up 5%–15%), specifically modifying fungal community structures and colonizable niches without triggering harmful pathogenic shifts (M. Wang et al., 2023). The enzymatic activity, including dehydrogenase and urease, increases 20%–30% regarding the porous shelter of biochar, promoting the growth of microorganisms and eliminating oxidative stress (Mushtaq et al., 2025). Root colonization rates by beneficial arbuscular mycorrhizal fungi increase by 10%–25%, extending hyphal networks for optimized nutrient uptake and suppressive activity against deleterious soil organisms (Ingraffia et al., 2019). These mechanism-driven shifts leverage carbon surfaces to absorb toxins and alter plant–microbe signaling pathways, enhancing macro-biota activities vital for long-term ecosystem stability. The highlighted mechanisms in the summary underline such mechanisms as surface oxidation to improve CEC and porous structures to provide buffering of moisture, which implies how biochar can stimulate functional properties in nutrient retention and greenhouse gases (GHG) mitigation. This depiction highlights the parallel routes that facilitate biological vitality that support the chemical and physical changes mentioned above (Table 4).

1.8 | Integrated soil health outcomes

Integrating biochar's chemical, physical, and biological properties results in holistic results of soil health, which reflect through an increase in soil fertility, soil resilience, and carbon fixation in agricultural systems. Integrated application of biochar's chemical, physical, and biological effects generally increases SOC by 25%–35% and total nitrogen by 10%–20%, while reducing bulk density by ∼15%. Meta-analyses further report reductions in methane and nitrous oxide emissions of 20%–40% in paddy and upland systems (Jiang et al., 2021). These improvements stabilize microbial networks and elevate beneficial consortia, balancing physical soil structures with active biological disease suppression to secure long-term ecosystem service performance (Zheng et al., 2023). More importantly, integrated assessments also involve the purpose of biochar to pollutant immobilization, with adsorption of heavy metals (reduction of 30%–50% of available), thereby protecting biological integrity (Y. Wang et al., 2022). This comprehensive perspective is an amalgamation of the dimen-

TABLE 4 Mechanism-driven summary of biochar-mediated soil improvements.

Dominant mechanism	Functional outcome	Soil process affected	Reference
Surface oxidation and charge development	Increased nutrient retention	CEC enhancement	(Singh et al., 2022)
Carbonate and oxide release	pH elevation	Acidity neutralization	(Martinsen et al., 2015)
Porous microstructure	Enhanced water storage	Moisture buffering	(Liu et al., 2016)
Microbial habitat provision	Enhanced microbial diversity & colonization	Bacterial, fungal, and nematode dynamics	(Yamato et al., 2006)
Gas diffusion limitation	Reduced GHG flux	CH_4 and N_2O mitigation	(Sriphirom et al., 2021; Yanai et al., 2007)

Abbreviation: CEC, Cation exchange capacity.

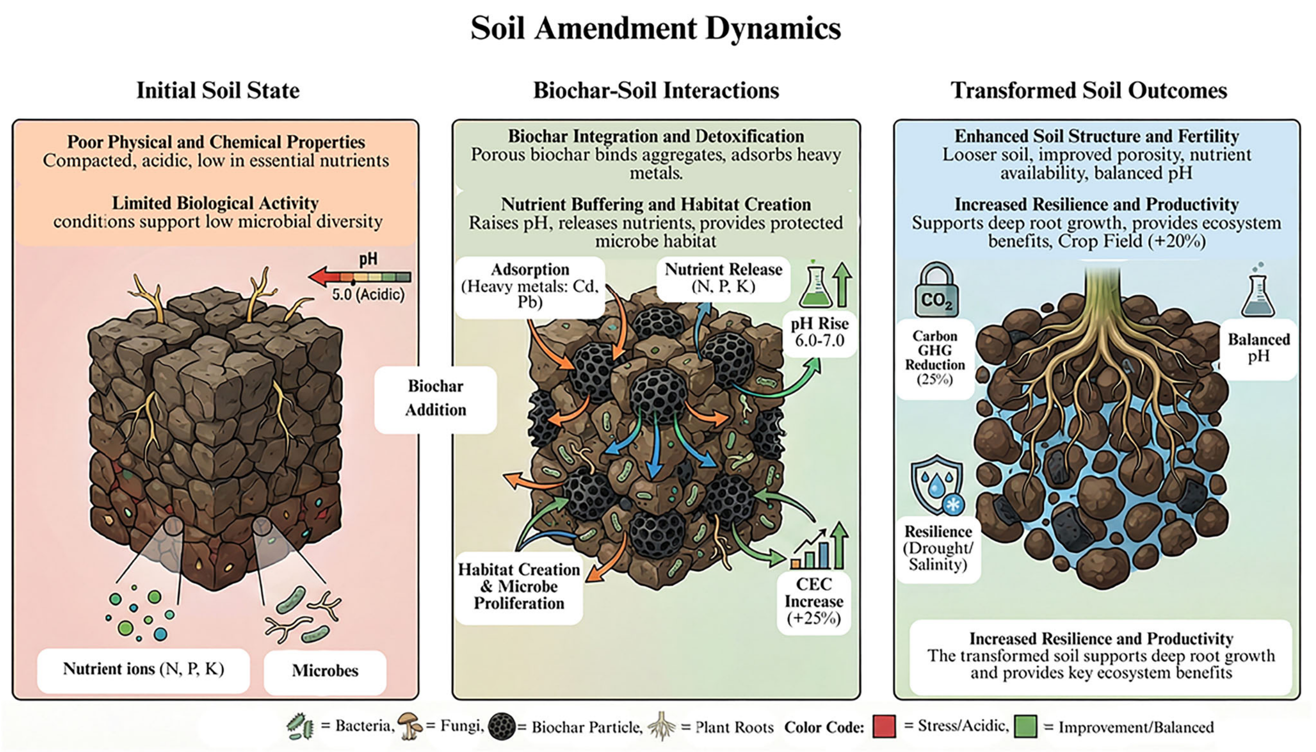

FIGURE 2 Soil amendment dynamics. CEC, cation exchange capacity.

sions above, with the focus being on how biochar can be used to achieve sustainable soil management. The amendment of soil caused by biochar results in a chain of interrelated reactions, starting with pH corrections and still culminating in microbial improvements, which cause stable, well-established ecosystems (Figure 2).

2 | BIOCHAR INFLUENCE ON CROP GROWTH PATTERNS

2.1 | Baseline physiological responses

Biochar has a systemic effect on the baseline crop physiological activity by balancing the main processes of photosynthesis, water use efficiency (WUE), and hormonal signaling, which is the precondition of improved growth in standard conditions. Biochar amendments in meta-analyses have been demonstrated to enhance the rate of photosynthesis by 15%–25% in cereals (e.g., maize and wheat) by enhancing the chlorophyll content (e.g., chlorophyll a/b ratio increased by 10%–20%) and stomatal constraints (Schmidt et al., 2021). An example is the enhancement of relative water content (RWC) rates by 12%–18% in tomato seedlings with the use of rice husk biochar at 5% w/w, which helps to elevate the ability to regulate osmotic adjustment and sustain cellular turgor (Murtaza et al., 2024). These reactions are mechanistically associated with the porous structure of biochar that promotes the rate of root exudation and microbial interactions, resulting in an increase in the level of auxin and cytokinin

TABLE 5 Overview of plant responses to different biochar types, feedstocks, and application regimes.

Plant species	Scientific name	Biochar source/feedstock	Production conditions	Applied rate	Growth and physiological outcomes	Reference
Pumpkin	*Cucurbita pepo*	Maize straw	Pyrolyzed at ∼350˚C	10–20 t ha^{-1}	Enhanced leaf relative water content (RWC) and vigor under field conditions.	(Safahani Langeroodi et al., 2019)
Tomato	*Lycopersicon esculentum*	Cottonseed shell + rice husk mixture	∼400˚C (slow pyrolysis)	5% (w/w)	Improved photosynthetic efficiency, leaf RWC, and overall shoot growth.	(Akhtar et al., 2014)
Apple seedling	*Malus domestica*	Rice husk	∼450˚C	80 g kg^{-1} of soil	Promoted seedling height, respiration rate, and finer root network.	(Y. Wang et al., 2019)
Asian lotus	*Nelumbo nucifera* Gaertn.	Pinewood residues	–	10% (w/w)	Increased root and leaf fresh mass, rhizome dry matter, and chlorophyll accumulation.	(Liu et al., 2016)
Chickpea	*Cicer arietinum*	Red sage plant waste	∼450˚C	3.5 t ha^{-1}	Notable rise in seed and haulm yield, and improved biomass partitioning.	(MEENA, 2023)
Sweet basil	*Ocimum basilicum*	Black cherry wood	∼450˚C	2%–3% (w/w)	Boosted germination, pigment levels, and root surface development.	(Jabborova et al., 2021)
Ginger	*Zingiber officinale*	Black cherry wood	∼450˚C	1%–3% (w/w)	Improved emergence rate, leaf number, and both shoot and root dry matter.	(Jabborova et al., 2021)
Peanut	*Arachis hypogaea*	Maize straw	∼600˚C	10–20 t ha^{-1}	Strengthened photosynthesis and fluorescence performance; yield improved.	(S. Wang et al., 2021)
Mixed vegetables	*Raphanus sativus*, *Lactuca sativa*, *Capsicum annuum*	Maritime pine wood chips	∼600˚C	≈2 kg m^{-2} (≈10 t ha^{-1})	Higher fresh weight and overall productivity of fruits and vegetables.	(González-Pernas et al., 2022)
Maize	*Zea mays*	Hardwood	–	18.4 Mg ha^{-1}	Achieved top grain yield without residue removal.	(Rogovska et al., 2016)
Tea	*Camellia sinensis*	Tea plant residues	∼550˚C	20 g plant^{-1}	Elevated leaf N, P, K, and biomass accumulation.	(Zou et al., 2023)

Note: *Analytical summary*: Across diverse crops, biochar consistently enhanced photosynthetic traits, water relations, and yield components, with effects dependent on both feedstock origin and application dosage.

by 8%–15% that facilitates cell division and cell expansion (Z. Xu, Lu, et al., 2025). This physiological dynamism primes systemic defense pathways, helping suppress soil-borne pathogens while positioning biochar to effectively safeguard the inherent crop yield potential under biotic pressure. The presented observations indicate the differences in growth parameters, including increased RWC (10%–20%) and chlorophyll biomass among different species and amendment schemes. These trends are the potential of biochar to strengthen basic physiological characteristics, which explicitly contribute to increased energy and performance defined in the baseline responses (Table 5).

2.2 | Nutrient uptake and biomass allocation

Biochar enhances nutrient uptake and biomass distribution in crops better through improved ion exchange and root architecture, resulting in efficient resource partitioning to grow. It is noted that worldwide data reveal biochar enhances the uptake of phosphorus by 20%–35% in vegetables and oil crops, which is caused by high total phosphorus levels (≥1.0%), which prompts the phosphorus to be mineralized by the microbes (Gao et al., 2019). Woody biochar increases potassium in maize by increasing the uptake of the root by 15%–25% and resulting in an allocation of the dry matter of shoots by 10%–20% (Dai et al., 2020). In the case of legumes, biochar obtained through manure increases nitrogen fixation by 10%–20%, leading to a biomass increase of 15%–30% invested in reproductive organs (Chagas et al., 2022). These interactions optimize nutrient allocation, strengthening structural cell walls to physically restrict pest invasion and support sustainable plant health in disease-conducive agroecosystems.

2.3 | Water relations and photosynthetic gains

Biochar modulates crop water relations and photosynthetic gains by improving hydraulic conductivity and gas exchange, critical for maintaining productivity in varying moisture regimes. Research indicates that the presence of a certain surface area ≥50 $m^2\ g^{-1}$ in biochar increases water-holding capacity of the soil by 15%–25%, thereby decreasing soil water stress associated with transpiration and enhancing a leaf water potential of a drought-prone crop, such as soybean (Farhangi-Abriz et al., 2021). The net CO_2 assimilation as photosynthetic efficiency increases by 18%–28% in wheat due to a 12%–22% enhancement of stomatal conductance through improved osmotic regulation (Z. Xu, Lu, et al., 2025). Amended matrices alter root turgor signaling pathways, triggering favorable stomatal feedbacks and enhancing fluorescence traits (F_v/F_m) by 8%–15% under fluctuating moisture conditions (X. Zhang et al., 2024). In general, these interactions enhance carbon fixation, which favors strong growth in conditions that are less than optimal in terms of hydration. The recorded responses with crop groups show yield improvement of 10%–40% with an increase in biomass associated with an increase in nutrient and water dynamics under different conditions. This demonstrates the agronomic effect of biochar, which supports physiological and allocation advantages mentioned through the effect on pH and structural support (Table 6).

3 | BIOCHAR STRATEGIES AGAINST SALINITY CHALLENGES

3.1 | Ion regulation mechanisms

Biochar uses advanced ion regulation processes to overcome salinity stress in crops; this is mostly by altering sodium (Na^+) exclusion and potassium (Na^+/K^+) homeostasis, which are essential in maintaining cell integrity and osmotic balance. Biochar reduces Na^+ uptake by 20%–40% in saline soils (EC > 4 dS m^{-1}) via high CEC (20–50 cmol kg^{-1}), preferentially adsorbing Na^+ and optimizing the soil K^+/Na^+ ratios. For example, wheat-straw biochar (10–30 t ha^{-1}) increased K^+ retention by 15%–25%, improving the Na^+/K^+ ratio and reducing membrane depolarization and Na^+ translocation to shoots via ion transporters such as high-affinity potassium transporter (HKT) (Yang et al., 2020). This results in reduced load on ion channels such as HKT transporters, which retain turgor pressure and contribute to the growth in salinity-favored conditions. The evidence is a synthesis of cross-species responses that demonstrate 20%–35% decreases in Na^+ accumulation and increases in K^+/Na^+ ratios, the mechanism of which supports ion homeostasis. These trends reflect biochar's adsorptive and buffering ability, which directly confirms the regulatory processes that inhibit cellular toxicity and osmotic imbalance in a saline environment (Table 7).

3.2 | Osmotic balance support

Osmotic balance support from biochar involves enhancing water retention and compatible solute accumulation, thereby enabling crops to survive in a hyperosmotic environment caused by salinity. At salinity levels of 5–10 dS m^{-1}, biochar enhances the water-holding characteristics of soil by 15%–25%, promoting the RWC to remain at 80%–90% of leaves by contrasting with 60%–70% in control groups (Farhangi-Abriz & Torabian, 2017). Biochar supports osmotic adjustment by improving soil water-holding capacity (15%–25%) and promoting accumulation of compatible solutes. Under salinity levels of 5–10 dS m^{-1}, biochar helped maintain leaf RWC at 80%–90% compared to 60%–70% in controls (Farhangi-Abriz & Torabian, 2017). It also moderately increased proline concentration, contributing to protein and membrane stabilization (She et al., 2018). These effects are linked to reduced soil osmotic potential and enhanced aquaporin expression, facilitating better root water uptake. This support mechanism relies on biochar micropores that alleviate osmotic stress by 0.2–0.5 MPa and ease water deficits, upregulating aquaporin expression to maintain efficient root hydraulic conductivity (Huang et al., 2019). This maintains cell turgor, provided the char matrix is sufficiently aged to eliminate persistent radical structures that otherwise impair early root water uptake.

3.3 | Antioxidant system activation

Biochar activates crop antioxidant systems through enzymatic defense upregulation and by scavenging reactive oxygen species (ROS) to overcome oxidative stress associated with imbalances that are caused by salinity. Sycamore-maple biochar at 50–100 g kg^{-1} in salinity-stressed soybean (5–10 dS m^{-1}) increases superoxide dismutase (SOD) by 20%–35% and catalase (CAT) by 15%–25% to decompose H_2O_2 and O_2^- radicals (Farhangi-Abriz & Torabian, 2017).

TABLE 6 Documented field-scale responses of major crop groups to biochar amendment under diverse agroecological conditions.

Crop category	Crop species	Biochar feedstock	Amendment intensity	Dominant agronomic response	Reference
Cereal systems	Rice (*Oryza sativa*)	Forest-derived wood, wood residues, rice husk	4.13 g m^{-2}; 5.5–11 t ha^{-1}; up to 20% (w/w)	Consistent enhancement of grain yield, improved K and P availability, and superior yield components relative to untreated controls	(Agegnehu et al., 2017; Medyńska-Juraszek et al., 2021; Omondi et al., 2016; A. Zhang et al., 2012)
	Wheat (*Triticum aestivum*)	Coppiced woodland biomass, hardwood/softwood mixtures, rice straw	2–60 t ha^{-1}; up to 5% (w/w)	Significant increases in biomass accumulation, grain yield, and nutrient uptake under Mediterranean and temperate field conditions	(Curaqueo et al., 2014; Sänger et al., 2017; Y. Zhang et al., 2021)
	Maize (*Zea mays*)	Acacia bark, peanut hull	10 L m^{-2}; 0–22.4 t ha^{-1}	Marked improvement in plant vigour, root development, and final grain yield, particularly in acidic and degraded soils	(Cornelissen et al., 2018; Igalavithana et al., 2017)
Leguminous crops	Mung bean (*Vigna radiata*)	Maize straw	0–100 t ha^{-1} (optimum ≈25 t ha^{-1})	Maximum seed yield observed at intermediate application rate, attributed to improved nutrient retention	(Yi et al., 2023)
	Common bean (*Phaseolus vulgaris*)	Eucalyptus wood	10–50 t ha^{-1}	Yield stimulation linked to enhanced soil moisture status and improved macro-nutrient availability	(Latawiec et al., 2019)
Oilseed crops	Soybean (*Glycine max*)	Oak wood	10 t ha^{-1}	Increased dry matter production with improved nitrogen use efficiency	(Y. Zhang et al., 2020)
	Oilseed rape (*Brassica napus*)	Litchi branch biomass	10–30 t ha^{-1}	Positive yield response under field conditions, especially at moderate biochar loading	(Hussain et al., 2017)
Root, tuber, and vegetable crops	Sweet potato (*Ipomoea batatas*)	Tobacco-derived biochar, wheat straw	5–40 t ha^{-1}	Enhanced vine elongation, tuber mass, and total yield across multiple growing seasons	(Z. Chen et al., 2023; El-Naggar et al., 2019)
	Potato (*Solanum tuberosum*)	Biochar combined with NPK fertilizer	7.5 t ha^{-1}	Increased tuber yield due to synergistic effects with mineral nutrients	(Kamali et al., 2022)
	Onion (*Allium cepa*)	Grass-derived biochar	0.5 kg m^{-2}	Significant bulb yield improvement associated with improved soil aeration	(Yu et al., 2019)
	Carrot (*Daucus carota*)	Wood biochar	0–20 t $acre^{-1}$	Increased root fresh weight and marketable yield	(Khalifa & Yousef, 2015)

The levels of malondialdehyde (MDA) as the indicator of lipid peroxidation are reduced by 25%–40% in mung beans in the same conditions, which means that the membrane injury is less intense (Ibrahim et al., 2021). Mechanistically, biochar's redox-active surfaces donate electrons, quenching ROS directly while stimulating glutathione peroxidase and ascorbate peroxidase by 10%–20%, maintaining redox homeostasis (Jin et al., 2018). This activation is not only able to maintain chloroplast integrity but also maintain photosynthetic electron transport to counter yield losses in saline fields caused by oxidative stress up to 30%–50%.

3.4 | Yield recovery in saline environments

Biochar application in saline environments improves yield through combined physiological benefits. Studies report grain yield increases of 15%–25% in wheat and improved fruit

TABLE 7 Summary of biochar-mediated physiological and yield responses in plants exposed to salinity stress.

Plant/cultivar	Scientific name	Salinity level (NaCl or EC)	Biochar source and dosage	Principal physiological/biochemical responses	Reference
Potato (Folva)	*Solanum tuberosum*	25–50 mM NaCl	Commercial charcoal (5%)	Elevated tuber yield, K^+ retention, and photosynthetic rate; reduced abscic ascid (ABA) and Na^+ accumulation.	(Akhtar et al., 2015)
Soybean (M7)	*Glycine max*	5–10 dS m^{-1}	Sycamore-maple residues (50–100 g kg^{-1})	Enhanced nodulation and N assimilation enzymes (GDH, GS, GOGAT); greater shoot biomass.	(Farhangi-Abriz & Torabian, 2017)
Common bean (Derakhshan)	*Phaseolus vulgaris*	6–12 dS m^{-1}	Sycamore-maple residues (5%–20%)	Increased shoot/root dry mass, total chlorophyll, Ca^{2+}, and Mg^{2+} uptake; Na^+ was suppressed.	(Farhangi-Abriz & Torabian, 2018a, 2018b)
Tomato (Yazhoufenwang)	*Lycopersicon esculentum*	1–3 dS m^{-1}	Wheat-straw biochar (BC) (2%–8%)	Raised leaf RWC and gas-exchange capacity; better osmotic adjustment.	(She et al., 2018)
Bread wheat (NARC 2009/2011)	*Triticum aestivum*	150 mM NaCl	Wheat-leaf BC (1%–2%)	Improved spike formation and kernel weight; diminished Na^+ and proline content.	(Kanwal et al., 2018)
Wheat (Sumai-10)	*Triticum aestivum*	0.3–10 dS m^{-1}	Wheat-straw BC (10–30 t ha^{-1})	Increased grain yield and nutrient use efficiency; lowered Na^+ toxicity.	(Huang et al., 2019; Yang et al., 2020)
Mung bean (MN92)	*Vigna radiata*	5–10 dS m^{-1}	Sycamore-maple residues (50–100 g kg^{-1})	Enhanced plant height and leaf water potential; mitigated oxidative injury.	(Hussien Ibrahim et al., 2020; Ibrahim et al., 2021)
Sorghum (Kambal)	*Sorghum bicolor*	0.3–12.6 dS m^{-1}	Wheat-straw BC (2.5%–10%)	Boosted chlorophyll a/b ratio, photosynthesis, and grain yield; Na^+ accumulation curtailed.	(Anwari et al., 2019; Jin et al., 2018)
Eggplant (Jaylo, Bonica F1)	*Solanum melongena*	2–300 mM NaCl	Oak/pine/maize-wood BC (≈5%)	Larger fruit biomass, improved ion balance (higher K^+/Na^+), and prolonged flowering.	(Hannachi et al., 2023)

Note: Biochar consistently mitigated salt-induced ionic and osmotic stress by improving K^+ retention, chlorophyll stability, and enzymatic antioxidant activities, leading to measurable yield recovery across both legumes and cereals.
Abbreviation: RWC, relative water content.

biomass in eggplant under moderate-to-high salinity (Hannachi et al., 2023; Kanwal et al., 2018). While salinity affects large areas globally, biochar's contribution to yield recovery is context-specific and most consistent at application rates of 5–30 t ha^{-1}. Long-term field validation across diverse soil types is still needed. Amended substrates trigger protective plant-microbe signaling that improves salt tolerance indexes while maintaining stable yield dynamics under concurrent biotic pressures (Anwari et al., 2019; He et al., 2024; Kabir et al., 2024; Shi et al., 2024). These seasonal recoveries can be maintained, and cumulative effects decrease soil electrical conductivity and provide resilient agricultural activity in 800 million ha of salt-impacted areas. A pathway of protective effects by biochar on the salinity stress, ion exclusion to antioxidant upregulation, can all help to protect cell functions and yield (Figure 3).

4 | BIOCHAR APPROACHES FOR DROUGHT ADAPTATION

4.1 | Moisture retention pathways

Biochar promotes the retention of moisture routes that occur in drought-stressed soils by increasing physical and hydrostatic characteristics of soil so that crops readily have access to water during deficit periods. The biochar micropores structure mechanically retains the water through surface areas of 50–200 m^2 g^{-1}, and the adsorption of water molecules reduces the evaporation loss of the sandy-loam soils by 10%–20% (Ye et al., 2020). International surveys show that the use of biochar can reduce crop evapotranspiration (ETc) by 1.8%–5% and increase the apparent water productivity by 14.8%–33%, especially in dry areas where the amount of organic matter in

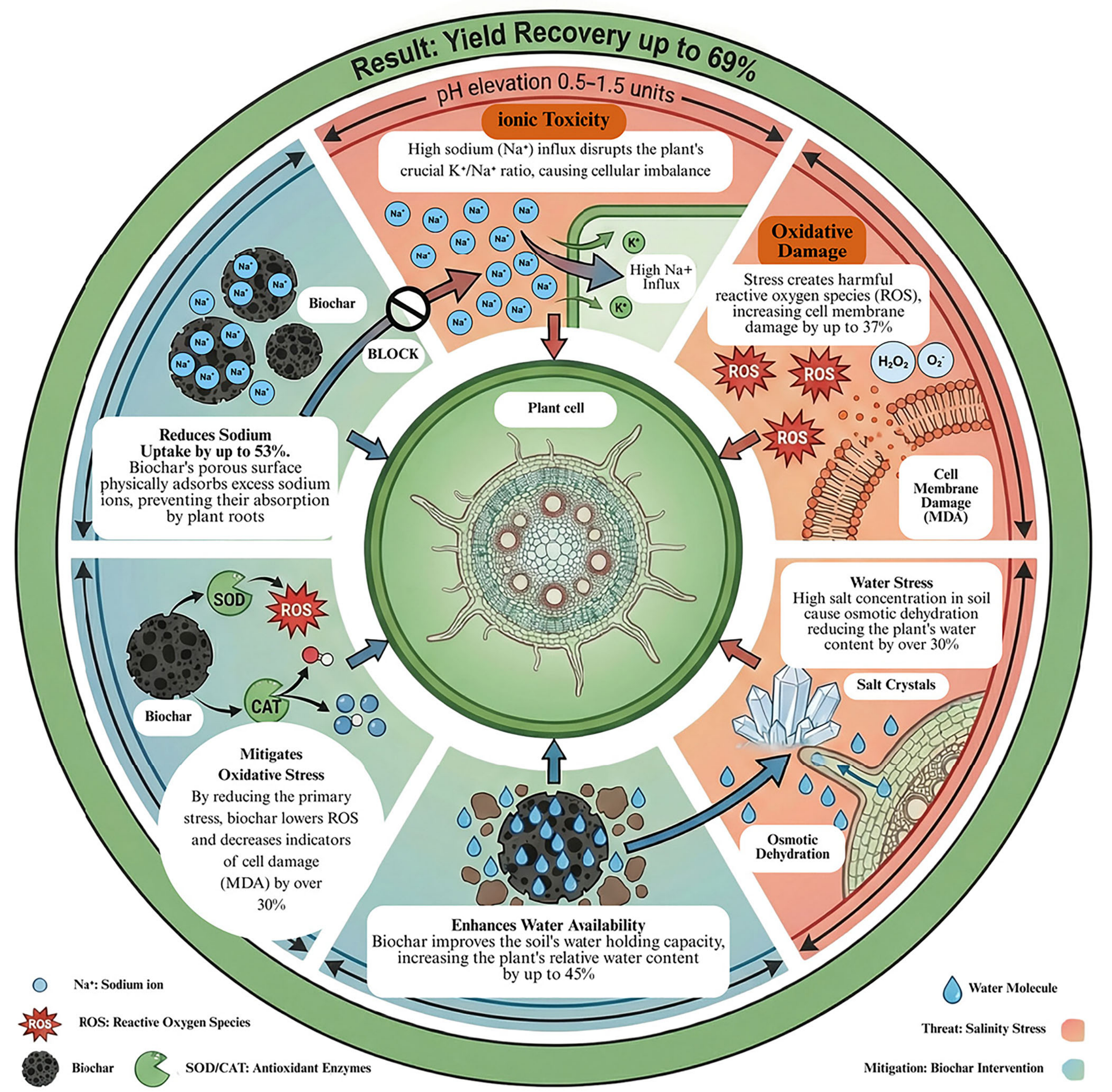

FIGURE 3 Salinity alleviation network. CAT, catalase; MDA, malondialdehyde; SOD, superoxide dismutase.

the soil increases to sustain capillary activity (Liu et al., 2016). When tomato was grown under reduced water conditions (50%–75% of field capacity) with rice husk biochar (5%–10% w/w), RWC increased to 80%–90% under osmotic adjustment and maintained turgor, alleviating the wilting process (X. Zhang et al., 2024). These pathways establish an active feedback loop with root hydraulic conductivity, driving adaptive, bidirectional water flux adjustments across drought-prone global agroecosystems. Such demonstrations support the position of biochar in enhancing the moisture processes, and this is consistent with the moisture retention routes, which have been proven in supporting crop health during drought (Table 8).

4.2 | Plant water efficiency boosts

Biochar has been shown to enhance the efficiency of plants in water uptake by regulating stomata and enhancing hydraulic conductance, enabling crops to make the maximum carbon uptake with minimal water loss during drought. Maize-straw biochar at 10 t ha^{-1} increased WUE in soybean at 60%

TABLE 8 Documented effects of biochar application on crop physiology and productivity under drought stress.

Crop/cultivar	Scientific name	Biochar origin and preparation	Application rate	Observed impacts under drought	Reference
Tomato	*Solanum lycopersicum*	Cottonseed shell + rice husk, pyrolyzed at ∼400˚C	5%–10% (w/w)	Maintained leaf RWC, enhanced photosynthesis, and improved fruit yield and quality.	(Akhtar et al., 2014; W. Zhang et al., 2023)
Soybean	*Glycine max*	Maize-straw-derived biochar	10 t ha^{-1}	Stimulated germination, leaf area, and antioxidative enzyme activity, resulting in higher seed yield.	(Hafeez et al., 2017; Y. Zhang et al., 2020)
Maize	*Zea mays*	Hardwood/mixed residues	18 Mg ha^{-1}	Enhanced water-use efficiency, biomass accumulation, and grain yield under limited irrigation.	(Hafez et al., 2021; Sattar et al., 2020)
Milk thistle	*Silybum marianum*	Wood-based feedstock	≈5% (w/w)	Improved chlorophyll stability, photosynthetic rate, and leaf water potential.	(Keshavarz Afshar et al., 2016)
Cabbage	*Brassica oleracea*	Crop residue–derived biochar	5% (w/w)	Increased stomatal conductance, chlorophyll fluorescence, and head biomass yield.	(Y. Chen et al., 2024)

Note: Across multiple plant systems, biochar acted as a soil–water buffer, enhancing drought resilience. The improvement stemmed primarily from increased soil moisture retention, osmotic balance, and biochemical protection against oxidative stress.
Abbreviation: RWC, relative water content.

field capacity by 20%–30% and raised stomatal conductance by 15%–22% and decreased transpiration. This is because biochar reduces soil osmotic potential, allowing the root water to be absorbed and, as a result, the leaf turgor to be maintained at 85%–95% RWC (Farhangi-Abriz et al., 2021). Meta-analyses indicate that biochar induces an increase in intrinsic WUE in cereals, which is associated with net photosynthetic rates that increase by 15%–25% due to improved CO_2 diffusion and better Rubisco activity (Z. Xu, Lu, et al., 2025). In cabbage with less than 5% w/w crop-residue biochar, the chlorophyll fluorescence (*Fv/Fm*) increased, which signified the reduction of photoinhibition and the increase in quantum yield under water stress (Y. Chen et al., 2024). Such increases make sure that plants are well distributed, keeping yield potential intact in situations where drought kills global crop production by 20%–40% each year.

4.3 | Root system fortification

Root system fortification using biochar entails the encouragement of deeper and denser root structures, and exploration and acquisition of resources in drought-impacted soils. Root biomass was also increased by 42% in milk thistle with wood-based biochar at 5% w/w and length density by 12%–18% to reach subsurface moisture reserves (Keshavarz Afshar et al., 2016). Biochar's high porosity enhances defensive mycorrhizal colonization, forming protective biological barriers that competitively exclude root-rot pathogens and scavenge scarce resources (Singh et al., 2022). Experimental data on the field peanut research indicate that maize-straw biochar at 10–20 t ha^{-1} fortifies root (20%–30% volume increase and MDA decrease) and alleviates oxidative stress (P. Wang et al., 2024). All these adaptations enhance drought tolerance to alleviate root dieback, which may reduce yields by 30%–50% under water-stressed conditions.

4.4 | Combined drought management tactics

Integrated drought management practices that take advantage of biochar are in combination with irrigation, mulching, and inoculants of microbes to enhance adaptive performance and continue productivity. Biochar at 18 Mg ha^{-1} less deficit irrigation increases the grain yield 1.13–1.90 times compared to full irrigation controls, complementing reduced ETc by 1.8%–5% in saving water 20%–30% (Hafez et al., 2021). Co-applying biochar and organic mulches systematically modifies rhizosphere organic acid profiling, shifting biomass distribution through enhanced root-mediated hormonal signaling pathways (Safahani Langeroodi et al., 2019). These combined techniques, which work in 50% ETc situations, help minimize yield gaps caused by droughts as much as 26%–35%, upholding resilient agricultural production in dry areas that affect 45% of the entire world's agriculture (Sattar et al., 2020).

5 | BIOCHAR SOLUTIONS FOR HEAVY METAL RISKS

5.1 | Contaminant binding processes

Biochar can be used to reduce the risk of heavy metals in agricultural soil by initiating the binding of contaminants to the soil, which is bound through adsorption, precipitation, and complexation processes, thereby reducing their bioavailability and eliminating their entry into the food chain. Biochar reduces heavy metal bioavailability through adsorption, precipitation, and complexation. For instance, cotton-stalk biochar applied at 3%–5% (w/w) reduced extractable cadmium (Cd) (25–100 mg kg^{-1}) by 30%–50% (Abbas et al., 2017). This interaction is pH-sensitive, and biochar has been shown to increase soil pH by 0.5–1.0 units to enable the hydroxide to precipitate, and this reaction occurs in wheat fields where rice-straw biochar at 1.5%–5% w/w reduced available zinc (Zn) and manganese (Mn) by 20%–35% and 15%–25%, respectively, as a result of ion exchange between the high-CEC biochar surfaces (Shahbaz et al., 2018). Biochar has a mechanistic structure that allows π phenomena of aromatic structures and porous matrix to attract lead (Pb) by 40%–60% in multi-metal soils and in maize trials (Medyńska-Juraszek et al., 2021). Such frameworks sequester metals and restrict leaching: field measurements show groundwater contamination risks decreased by 25%–45% in amended vegetable systems, safely buffering polluted environments (Y. Chen et al., 2024). The results of the synthesized outcomes show that the accumulation of metals decreases by 20%–50% in all tissues, and there are physiological ameliorations such as the increase in chlorophyll content (10%–30%) and the decrease in the level of MDA (25%–40%). These results indicate the adsorptive properties of biochar in the inhibition of phytoavailability, which, in direct proportion, supports the plant binding of the toxicity and recovery of plant functioning in polluted soils (Table 9).

5.2 | Uptake reduction in plants

Biological mechanisms of reducing uptake of plants under exposure to heavy metals are the barrier effects of biochar at the root–soil interface, where rhizosphere chemistry is altered to reduce translocation and accumulation in edible regions. Poultry–litter biochar at 7% was found to reduce shoot Cd in lettuce with 50 mg kg^{-1} Cd by 35–45% by creating stable organo–metal complexes that inhibit apoplastic movement (Woldetsadik et al., 2016). In tomato with less than 0.13–2 mg L^{-1} Cd, cotton-stalk biochar at 1% reduced the total Cd uptake by 25%–40%, which increased the lignin deposition (10%–20%) and selective ionic channels (Younis et al., 2016). This decrease is supported by the redox capacity of biochar, which oxidizes metals such as chromium (Cr) to less soluble forms, as in the case of rapeseed, where Acacia wood-chip biochar at 2% reduced the Cr uptake by 30%–50% (Kamran et al., 2020). In general, it reduces uptake by 20%–60% in different species and maintains biomass and yield of polluted soils where heavy metal exposure can suppress productivity by half.

5.3 | Metabolic defense enhancements

Biochar improves plant defense against oxidative stress caused by heavy metals by reducing oxidative stress through the activation of antioxidant enzymes and stress-responsive pathways. Miscanthus biochar at 2% in sunflower under 77 mg kg^{-1} nickel (Ni) stress increased SOD and CAT activities by 20%–35% while decreasing lipid peroxidation (MDA) by 25%–40%, preserving membrane integrity (Zulqurnain Haider et al., 2019). Mechanically, the nutrient release of biochar (P and iron [Fe] up by 20%–30%) induces genes (such as *Nramp* and *ZIP*) to regulate the metal transport by metal transporters and reduce influx rates, as well as promote fluxes (J. Sun et al., 2020). The improvements maintain photosynthetic efficiency, and ratios of *Fv/Fm* have been increased by 8%–15% to overcome yield losses of 30%–50% in contaminated fields.

5.4 | Site-specific remediation limits

Biochar site-specific remediation limits emphasize context-dependent effectiveness, affected by the type of soil, speciation of metals, and characteristics of biochar, which requires a specific approach to prevent inefficiency. Miscanthus biochar at 2% decreased grain metals by 20%–40% in barley with multi-metals (Cd 1.25–1.91 mg kg^{-1}, copper [Cu] 200–451 mg kg^{-1}), but in high-clay soils, the bioavailability of the metal remains, as competition is observed (Medyńska-Juraszek et al., 2020). In the case of green pepper (below 20 mg kg^{-1} Cd), wheat-straw biochar at 5% reduced Cd in fruits up to 30%–50%, but its effectiveness decreases in organic-rich sites due to desorption (J. Sun et al., 2020). Limitations include high-dose nutrient imbalances and the transient presence of EPFRs, which typically degrade within weeks via natural rhizosphere weathering (Kamran et al., 2020). Although it lowers the total risks (25%–45%) by site variability, site variability needs combined approaches since there are 12% of global contaminated arable land that need adaptive limits to be used sustainably. Biochar forms multistage protection against the toxicity of metals, with soil adsorption decreasing availability by 30%–50% to root exclusion decreasing translocation by 20%–40%, ultimately protecting the metabolism of vegetation (Figure 4).

TABLE 9 Effects of biochar application on heavy-metal stress mitigation and plant performance.

Plant species	Scientific name	Metal contaminant/exposure level	Biochar feedstock and preparation	Dosage or incorporation rate	Key physiological/biochemical outcomes	Reference
Spinach	*Spinacia oleracea*	Cd (25–100 mg kg^{-1})	Cotton-stalk biochar	3%–5%	Improved chlorophyll and carotenoid contents; decreased Cd accumulation in roots and shoots.	(Abbas et al., 2017; Abid et al., 2017)
Wheat	*Triticum aestivum*	Cd (2.86 mg kg^{-1}), Zn (47.3 mg kg^{-1}), Mn (68.3 mg kg^{-1}), Ni (5.3 mg kg^{-1})	Rice-straw biochar	1.5%–5% (w/w)	Enhanced grain yield, photosynthesis, and stomatal conductance; lower MDA and heavy-metal content in tissues.	(Shahbaz et al., 2018; Zulqurnain Haider et al., 2019)
Lettuce	*Lactuca sativa*	Cd (50 mg kg^{-1})	Poultry-litter + cow-manure + coffee-husk BC	≈7%	Higher plant biomass, reduced Cd concentration in edible parts.	(Woldetsadik et al., 2016)
Tomato	*Solanum lycopersicum*	Cd (0.13–2 mg mL^{-1})	Cotton-stalk biochar	1%	Increased shoot and root dry mass, pigments, and anthocyanins; decreased total Cd uptake.	(Younis et al., 2016)
Maize	*Zea mays*	Cu (3474), Fe (25 962), Mn (1413), Pb (1360), Zn (11 239), Cd (27.8) mg kg^{-1}	Date-palm-waste BC	1%–3%	Improved P and Fe content, root development, and reduced Cd, Cu, Pb, Zn in tissues.	(Medyńska-Juraszek et al., 2020; J. Sun et al., 2020)
Sunflower	*Helianthus annuus*	Ni (77 mg kg^{-1})	*Miscanthus* residue BC	2%	Enhanced root biomass and antioxidant enzyme activity; reduced lipid peroxidation.	(Zulqurnain Haider et al., 2019)
Chinese cabbage	*Brassica chinensis*	Cd (41 mg kg^{-1})	Rice-straw/rice-hull/maize-stover BC	1.5%–3%	Increased fresh weight and leaf chlorophyll; Cd in shoots was reduced substantially.	(Li et al., 2021)
Chinese flowering cabbage	*Brassica parachinensis*	Cd (1.19 mg kg^{-1})	*Pennisetum hydridum* straw BC	2%	Higher root and shoot mass; Cd content lowered in above-ground tissues.	(X. Chen et al., 2020)
Peanut	*Arachis hypogaea*	Cd (1 mg kg^{-1})	Peanut-vine + rice-straw BC	5%	Increased pod biomass and reduced Cd in kernels.	(J. Sun et al., 2020)
Green pepper	*Capsicum annuum*	Cd (20 mg kg^{-1})	Wheat-straw BC	5%	Greater plant height and yield; lowered Cd in fruits and foliage.	(J. Sun et al., 2020)
Rapeseed	*Brassica napus*	Cd (0.28), Cr (11.3), Cu (3.6), Zn (17.9), Ni (1.4), Pb (5.8), Co (0.1), Fe (136.4) mg kg^{-1}	*Acacia nilotica* wood-chip BC	2%	Increased leaf pigments and nutrient uptake; reduced overall heavy-metal bioavailability.	(Kamran et al., 2020)
Barley	*Hordeum vulgare*	Cd (1.25–1.91 mg kg^{-1}), Cu (200–451 mg kg^{-1}), Pb (118–211 mg kg^{-1}), Zn (67–134 mg kg^{-1})	*Miscanthus* residue BC	2%	Improved grain filling and enzyme activity; reduced metal content in grains.	(Medyńska-Juraszek et al., 2020)

Note: Across diverse crop systems, biochar reduced the phytoavailability of toxic elements, especially Cd, Pb, and Ni, while improving chlorophyll stability, antioxidative defense, and nutrient assimilation. Feedstocks from lignocellulosic residues or animal waste proved particularly effective.
Abbreviation: MDA, malondialdehyde.

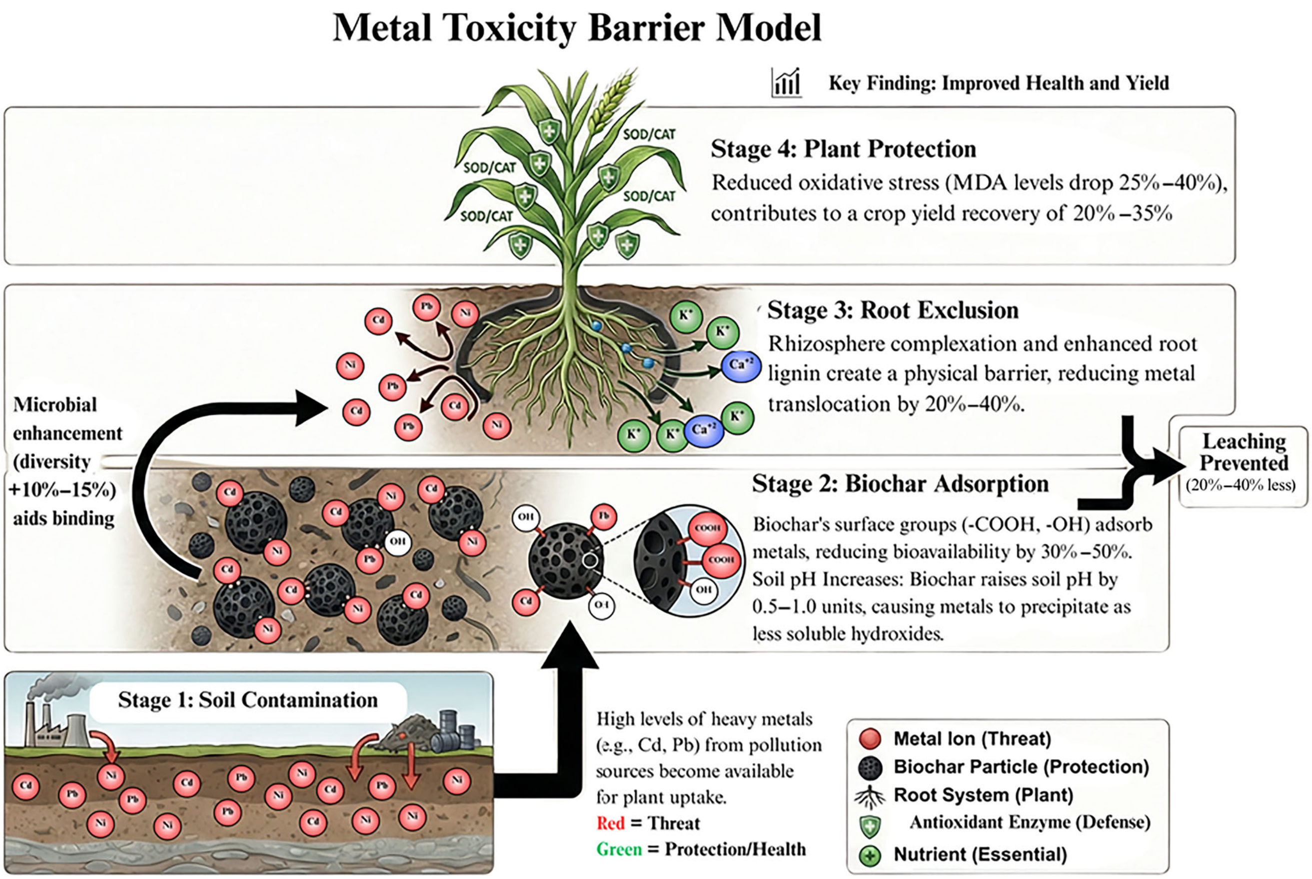

FIGURE 4 Metal toxicity barrier model. CAT, catalase; MDA, malondialdehyde; SOD, superoxide dismutase.

6 | CROSS-STRESS SYNERGIES AND BIOCHAR OPTIMIZATION

6.1 | Multi-stress interaction analysis

Biochar targets cross-stress synergies when a compound combination of abiotic factors occurs, serving as a versatile buffer that safeguards crop physiology and stabilizes soil boundary dynamics. Sycamore-maple biochar (5%) under combined drought-salinity (60% field capacity + 100 mM NaCl) conditions improves nodulation by 20%–30% and enhances nitrogen assimilation enzymes (GDH and GS) to overcome severe osmotic imbalances (Farhangi-Abriz & Torabian, 2017). Under concurrent low pH (< 5.5), high cadmium load (5 mg kg^{-1}), and drought, applying 2% rice-straw biochar enhances grain yields by 25%–35% via structural immobilization and acidity neutralization (Abbas et al., 2017). This mechanistic synergy relies on high surface areas (50–200 $m^2\ g^{-1}$), facilitating multi-contaminant adsorption and raising SOC relative concentrations by 20%–40% (Dai et al., 2020). In multi-stress scenarios, biochar modulates rhizosphere exudates to recruit beneficial consortia, cross-protecting crops against simultaneous drought and fungal root pathogens across global farmlands (Singh et al., 2022). The mentioned features reflect yield improvement of 10%–45% during different stresses, with such mechanisms as high carbon content (>70%) stabilizing soil-plant interfaces. The patterns are the adaptive synergies of biochar, which strengthen multi-stress mitigation by maintaining nutrient retention and structural support as it is analyzed (Table 10).

6.2 | Dose and type customization

Customization of dose and type of biochar is critical to achieve the highest number of synergies in cross-stress environments, where optimal rates (10–30 t ha^{-1}) and feedstocks (e.g., lignocellulosic vs. manure) are adapted to soil conditions and crop requirements to avoid the risk of over-application. Moving slightly in acidic soils, drought-prone soils moderate doses of woody biochar (10 t ha^{-1}) increase pH levels and water retention and synergistically decrease Al toxicity and water losses through transpiration by 20%–30% in maize (Z. Xu, Lu, et al., 2025). Tailored applications of silica- or nutrient-rich biochars enhance direct pathogen suppression, reducing crop losses from soil-borne diseases by 20%–40% in vulnerable vegetable cultivars (Gao et al., 2019). Excesses (>30 t ha^{-1}) may reverse the gains, increasing pH

TABLE 10 Effects of biochar characteristics on plant performance and related soil-plant properties.

Biochar characteristic	Plant/crop type	Observed effect on plant characteristics	Biochar-mediated mechanism influencing plant response	Reference
Manure-derived biochar	Vegetables, oil crops	Yield increased by ~30%–45%	High ash content and nutrient density enhance soil P and K availability, promoting vegetative and reproductive growth	(Jeffery et al., 2017; Z. Xu, Zhou, et al., 2025)
Woody biochar (high lignin feedstock)	Maize, wheat, legumes	Yield increased by ~10%–25%	High porosity and surface area improve soil aeration and microbial habitat, indirectly enhancing nutrient uptake	(Biederman & Harpole, 2013; Dai et al., 2020)
Biochar with high total carbon (>70%)	Cereal and legume crops	Increased biomass and grain yield (~15%–25%)	Stable carbon fractions increase soil organic carbon and long-term nutrient retention	(Arif et al., 2021; Chagas et al., 2022)
Biochar with high phosphorus content (>1.0%)	Vegetables, oil crops	Yield increases up to ~25%	Direct phosphorus input and enhanced microbial P mineralization improve plant P nutrition	(Gao et al., 2019; Z. Xu, Zhou, et al., 2025)
Biochar with high specific surface area (>50 $m^2\ g^{-1}$)	Broadleaf crops	Increased plant biomass and yield (~15%–30%)	Improved water-holding capacity and nutrient adsorption enhance root–soil interactions	(Dai et al., 2020; Y. Sun et al., 2014)
Biochar applied at moderate rates (10–30 t ha^{-1})	Upland crops	Yield increase ~10%–20%	Optimal balance between soil structure improvement and nutrient supply	(Biederman & Harpole, 2013; Farhangi-Abriz et al., 2021; Jeffery et al., 2011)
Biochar applied to acidic soils (pH < 5.5)	Maize, legumes	Yield increase ~25%–35%	Soil pH elevation reduces Al toxicity and increases nutrient bioavailability	(Biederman & Harpole, 2013; Dai et al., 2020)
Biochar in sandy soils	Vegetables, maize	Yield increase ~20%–40%	Increased water retention and reduced nutrient leaching improve plant nutrient use efficiency	(Awad et al., 2018; Ye et al., 2020)
Biochar in clay soils	Cereals	Yield increase ~30%–40%	Reduced bulk density and improved gas diffusion enhance root development	(Blanco-Canqui, 2017; H. Xu et al., 2021)
Biochar under low initial soil fertility	Most upland crops	Strong positive yield response	Nutrient supplementation and improved soil structure compensate for poor soil conditions	(Crane-Droesch et al., 2013; El-Naggar et al., 2019)
Biochar in flooded rice systems	Rice	No significant or inconsistent yield response	Limited soil–biochar contact and anaerobic conditions restrict nutrient interactions	(Awad et al., 2018; Ye et al., 2020)

too much as well as decreasing the availability of micronutrients by 10%–15%, and focusing accuracy is essential in a wide range of climates (Chagas et al., 2022).

6.3 | Climate context integration

Combining biochar with climate conditions enhances cross-stress interactions, adjusting to the local differences, such as arid and humid areas, where climatic conditions influence the application. Biochar at 20 t ha^{-1} raises the moisture content of the soil (20%–30%) and CEC (25%–45%) in semi-arid regions (300–500 mm $year^{-1}$), synergizing drought and salinity resistance in wheat, with a 15%–25% higher yield when subjected to combined stressors (Yang et al., 2020). High-carbon biochar (>70%) strongly suppresses nutrient leaching under high-rainfall humid tropical regimes while reducing heavy metal mobility by 30%–50% in wastewater-irrigated rapeseed (Kamran et al., 2020). In general, climate-specific biochar maximizes application in the world, covering 45% of farmlands affected by climate with adaptive synergies toward resilient production.

6.4 | Performance metrics across scenarios

Biochemical measurements of biochar under cross-stress conditions include yield stability, stress tolerance indices, and environmental measurements, which give measurable targets of optimization. In the meta-studies, biochar yields 0.8–0.95 under drought-salinity-metal combos, and biomass recovery is 25%–40% greater than stressed controls (Dai et al., 2020).

Crop tolerance indices improve by 20%–35% alongside significant antioxidant upregulation (SOD levels rise 15%–30%), indicating enhanced cellular stability under multi-stress conditions. Environmental indices confirm carbon sequestration at 1−2 t ha^{-1} $year^{-1}$ and reduce leaching losses by 20%–40%, expanding total soil microbial biomass by 15%–25% (El-Naggar et al., 2019). These quantities change depending on the scenario (e.g., 30%–50% improved in low-fertility arid regions) and become scalable and optimized to organize the contribution of biochar to the reduction of 50% of the multi-stress yield gap in the world.

7 | PATHWAYS FORWARD FOR BIOCHAR DEPLOYMENT

7.1 | Scaling challenges and solutions

The utilization of biochar is challenged by complex factors such as cost of production, availability of feedstock, and limitations in infrastructure, even though both technological and supply chain innovation present some feasible solutions that can lead to large-scale adoption. Biochar is projected to generate revenues of $3.3 billion by 2025, due to increasing demand, but high production costs ($200–$600 per tonne) make biochar difficult to scale in developing countries, where the logistics of obtaining feedstock increase costs by 20%–30% (Chojnacka et al., 2025). These include decentralized pyrolysis units, and the cost of transportation can be lowered by 15%–25%, and on-farm production of 20%–35% biochar from biomass can be achieved. (Heinrich et al., 2023). Nominal economic models indicate that subsidies of $25 million on multi-site research in 2025 can speed up the scaling of research, increasing its rates of adoption by 30%–40% in agriculture (Guerrero, 2025). Overcoming these logistical barriers allows broad scaling, shifting degraded lands toward stable carbon sinks by restoring active, bidirectional chemical fluxes at the root-soil boundary.

7.2 | Innovation in advanced formulations

Recent advances include nano-biochar (<100 nm) with surface areas of 500–1000 m^2 g^{-1}, which can enhance pollutant adsorption capacity by 40%–60% compared to conventional biochar (Abed Hussein et al., 2022). Engineered composites and hydrochar-biochar hybrids also show promise for combined energy and soil applications. However, scalability, long-term environmental fate, and cost-effectiveness of these advanced materials require further field evaluation before widespread adoption. HTC processes produce advanced solid hybrids that yield up to 70% bio-oil while simultaneously lowering net operational energy consumption parameters by 20%–30% (Escudero-Curiel et al., 2023). The development of urban resilience advanced designs includes biochar in nature-based solutions, reducing the costs by 15%–25% with valorization of wastes and enhancing the soil carbon stocks by 25%–35% (El Afandi et al., 2025).

7.3 | Policy and economic frameworks

Biochar deployment depends on the policy and economic systems, which combine incentives, regulations, and market mechanisms to reduce the financial obstacles and encourage sustainable integration. The Biochar Research Network Act of 2025 provides up to $25 million in agronomic research, which would provide region-specific data that would increase the uptake by 25%–35% of farmers (Pretty, 2008). In Brazil, economic impacts indicate that biochar has cost-benefits, with amendments adding 15%–20% to yields at $100–$200 ha^{-1}, and giving 1.5–2.5 times returns on investment over 5 years (Devlin et al., 2023). Carbon credit frameworks backed by institutional mandates position biochar to capture 90% of long-term removal credits, driving projected market expansions up to $2 billion by 2032 (Buck, 2019). The EU Green Deal subsidies in Europe lower the cost of deployment by 20%–30%, which facilitates the economic feasibility with a net saving of $50–$150 per ton in emissions trading (Marelli et al., 2025).

7.4 | Research priorities for impact

The biochar field trial, life-cycle assessment, and interdisciplinary research priorities have focused on long-term field trials to inform knowledge gaps and offer guidance on high-impact applications. The economic feasibility analysis focuses on cutting the cost of $50–$100 per ton by optimization of pyrolysis, aiming at 20%–30% benefits to efficiency (Saleh et al., 2025). Elucidating biochar's dual control over chemical contaminant binding and soil microbiology optimization remains an essential research priority for high-impact agricultural deployment (Vishnu et al., 2024). Such priorities may result in faster deployment to cover 30%–40% of soil degradation globally and also boost economic returns by 1.5–2 times. The future integration of biochar is an implementation of global adoption, where application scenarios connect production hubs to research, policy, and practice synergies (Figure 5).

8 | CONCLUSION

This review integrates biochar as a flexible amendment, which integrates the physicochemical characteristics, soil ecosystem

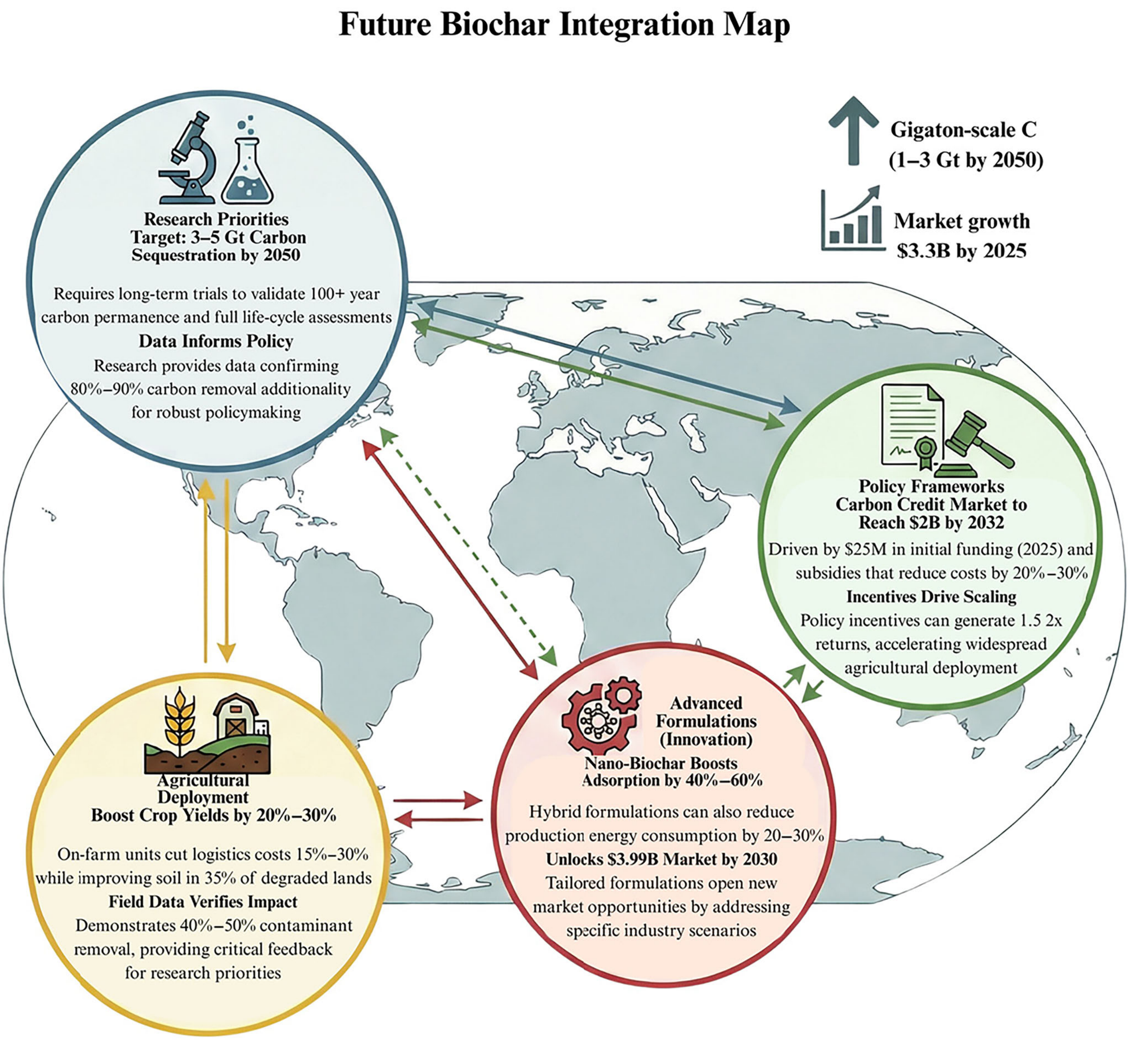

FIGURE 5 Future biochar integration map.

improvements, and crop-specific physiological advantages to illustrate a systemic approach that is effective in overcoming the abiotic stresses and enhancing yield maximization. The discipline has now grown with strong meta-analyses demonstrating a stable increase in SOC by 20%–40% and stress tolerance indexes by 20%–35%, but with doubts about scalability and context-sensitive results, especially between humid and arid climates, with efficacy ranging between 10% and 30%. Future research must prioritize multi-omics tracking to resolve biochar-induced differential gene expression patterns, train predictive artificial intelligence models, and deploy microbial consortia to close laboratory-to-field implementation gaps. In addition, economic barriers can be overcome by policy incentives, which may hasten the uptake in the developing regions. Ultimately, precision biochar application drives a transformative circular bioeconomy, minimizing cumulative yield gaps from combined abiotic stress and soil-borne pathogens to ensure long-term global food security. Widespread adoption directly advances SDG 2 (Zero Hunger) by maximizing crop productivity, SDG 3 (Good Health and Well-Being) via food safety, and SDG 15 (Life on Land) through sustainable land degradation neutrality. Biochar could also play a key role in addressing SDG 6: Clean Water and Sanitation through enhanced soil water retention and reduced pollution.

AUTHOR CONTRIBUTIONS

Waqas Haider: Conceptualization; investigation; writing—original draft. **Qudrat Ullah**: Conceptualization; data curation; visualization; writing—review and editing. **Muham-**

mad Qasim: Resources; validation; writing—review and editing. **Md. Nahid Mahmud**: Software; visualization. **Irfan Haidri**: Resources; validation; writing—review and editing. **Muhammad Ali Amir**: Formal analysis; investigation; validation; writing—review and editing. **Rashid Abbas Khan**: Data curation; formal analysis; project administration; validation; writing—review and editing. **Tauqeer Ahmed Qadri**: Data curation; validation; writing—review and editing. **Amjid Khan**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data generated and/or analyzed during the current study are included in this manuscript.

ETHICS STATEMENT

This is a review article and does not involve human or animal subjects. Therefore, ethical approval is not required.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the author(s) used ChatGPT in order to assist with language refinement, improve clarity, and enhance the overall presentation of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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