



REVIEW ARTICLE

Biochar-driven climate-smart agriculture: integrating soil functions, microbiome dynamics and stress resilience for sustainable crop productivity

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Abstract

Biochar has gained global recognition as a versatile soil amendment capable of tackling the interconnected issues of soil degradation, declining crop yields, and climate stress. Made through pyrolysis of biomass in limited oxygen, biochar features a distinctive porous structure, surface functional groups, and stable carbon matrices that positively interact with soil's physical, chemical, and biological processes. This review compiles current understanding of the various ways biochar enhances soil health and crop productivity. Physically, biochar improves soil structure, boosts porosity, decreases bulk density, and increases water retention, supporting stronger root development and reducing drought damage. Chemically, it adjusts soil pH, raises cation exchange capacity, enhances nutrient retention, and minimizes nutrient loss through leaching or volatilization. Biologically, biochar influences microbial communities, fosters beneficial plant growth-promoting bacteria and fungi, and stabilizes enzymes vital for nutrient cycling. These combined effects help plants withstand drought, salinity, temperature extremes, and heavy metal stress by reinforcing antioxidant defenses, osmoprotection, and maintaining ion balance. When integrated with compost, fertilizers, and microbial inoculants, biochar produces synergistic improvements in soil fertility and crop yields across cereals, legumes, and horticultural systems. Its enduring carbon structure also positions biochar as a key element of climate-smart agriculture through long-term carbon storage and greenhouse gas reduction. Although promising, challenges remain concerning performance variability, economic viability, and the necessity for long-term, multi-site field validation. Future developments, including engineered biochars and mechanistic insights from panomics, will be essential to fully unlocking biochar's potential for sustainable crop improvement.

Keywords: Biochar, climate-smart agriculture, crop productivity, microbial interactions, soil health

Introduction

Global agriculture faces a critical crossroads, challenged by a range of interconnected issues that threaten long-term food and nutritional security. Rapid population growth, expected to reach nearly 10 billion by 2050, will likely

cause a 50–60% increase in global food demand (Falcon *et al.* 2022). Meanwhile, arable land is diminishing due to urbanization, soil degradation, and unsustainable land-use practices. Climate change worsens these problems by intensifying droughts, floods, heat stress, and salinity intrusion, all of which destabilize crop yields and farming livelihoods (Chakraborty *et al.* 2014; Roychowdhury 2014). Declining soil fertility, organic matter depletion, micronutrient deficiencies, and rising reliance on chemical fertilizers collectively weaken ecosystem resilience. These challenges highlight the urgent need for sustainable soil-management strategies that boost productivity while reducing environmental impact (Roychowdhury *et al.* 2020). In this context, the development of climate-smart, resource-efficient agricultural technologies has gained significant momentum. Biochar, a carbon-rich, highly porous organic material produced through pyrolysis of biomass under limited oxygen, has become a promising tool for restoring soil health and enhancing crop performance.

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Its properties are influenced by several factors, including feedstock type (such., crop residues, wood chips, manure), pyrolysis temperature, and residence time. Higher pyrolysis temperatures usually produce biochar with increased aromaticity, stability, and surface area, while feedstock composition influences nutrient content and ash levels. The resulting biochar is characterized by its high surface area, variable pH, abundant micropores, stable carbon structure, and substantial cation exchange capacity (Zhang *et al.* 2018). These physicochemical traits give biochar the ability to modify soil properties in ways that conventional organic amendments rarely achieve. Notably, biochar can be produced from locally available agricultural waste, offering a sustainable solution for residue management and reducing open-field burning and emissions. The rationale for using biochar in crop improvement is based on its multifunctional capabilities to address multiple soil constraints simultaneously (Guo *et al.* 2026). When added to soil, biochar enhances water retention, improves soil structure, increases porosity, and reduces bulk density especially beneficial in sandy or degraded soils. Chemically, biochar improves nutrient retention through its inherent cation exchange capacity, reduces nutrient leaching, adjusts soil pH, and sometimes supplies slow-release macro- and micronutrients. These effects improve nutrient-use efficiency and decrease reliance on synthetic fertilizers. Beyond physical and chemical improvements, biochar plays a key role in shaping soil biological communities (Palansooriya *et al.* 2019). Its porous structure provides microhabitats for beneficial microorganisms, boosting microbial biomass, diversity, and activity. This can strengthen plant-microbe interactions, promote nutrient cycling, and suppress soil-borne diseases. Additionally, biochar has been shown to increase plant resilience to abiotic stresses such as drought, salinity, and heavy metals (Wu *et al.* 2023). It immobilizes toxic ions, reduces oxidative stress, and enhances vital physiological processes—including photosynthesis, osmotic regulation, and root development. As a stable form of carbon, biochar also significantly contributes to long-term carbon sequestration, lowering greenhouse gas emissions and supporting climate mitigation efforts in agriculture.

Despite extensive evidence supporting biochar-mediated improvements in soil quality and crop performance, significant uncertainty remains regarding the mechanistic pathways linking biochar properties with plant adaptation under climate stress conditions. Current studies often focus on agronomic outcomes without integrating soil physicochemical modifications, microbial dynamics, and plant molecular responses into a unified framework. Furthermore, large variations in feedstock composition, pyrolysis conditions, soil characteristics, and environmental factors limit the development of predictive recommendations. In this review, we propose that biochar functions as a systems-level regulator operating through

interconnected tripartite soil-microbiome-plant pathways. We hypothesize that biochar-induced modifications in soil structure, nutrient dynamics, microbial community assembly, and antioxidant signaling collectively enhance crop resilience under climate-related stresses. This review critically evaluates these emerging mechanisms and presents an integrated framework for understanding biochar-driven climate-smart agriculture.

Biochar production, properties, and characterization

Biochar is a carbon-rich, porous material produced through the thermochemical conversion of biomass under oxygen-limited conditions. Its properties and agronomic performance are largely determined by feedstock type and production conditions, making standardized characterization essential for ensuring product quality and suitability for specific applications.

Feedstocks

Biochar can be produced from diverse feedstocks, including agricultural residues, woody biomass, animal manures, municipal organic wastes, and aquatic biomass. Feedstock selection strongly influences biochar properties. Lignocellulosic materials such as rice husk, wheat straw, maize stover, and wood chips generally produce biochars with high fixed-carbon content, low ash content, and well-developed pore structures, whereas manure-derived biochars typically have higher ash content, greater nutrient concentrations (P, K, Ca, and Mg), and stronger liming potential (Guo *et al.* 2021). Other feedstocks, including food-processing wastes, paper sludge, algae, and seaweed, can yield biochars with distinct mineral compositions and surface chemistries suited for specific agricultural or environmental applications (Table 1).

Pyrolysis conditions

Production conditions influence biochar functionality as much as feedstock characteristics. Slow pyrolysis (350–600 °C) is the most common method for agricultural applications because it produces stable, carbon-rich biochar with high aromaticity (Abbas *et al.* 2026). In contrast, fast pyrolysis, gasification, and hydrothermal carbonization generate materials with distinct structural and chemical properties. Pyrolysis temperature is a key determinant of biochar characteristics: lower temperatures preserve oxygen-containing functional groups and reactive carbon fractions, whereas higher temperatures increase aromaticity, surface area, porosity, and long-term carbon stability (Liu *et al.* 2015). Additional factors such as heating rate, residence time, and pre-treatment methods also influence pore structure and surface chemistry (see Figure 1 for more details).

Physical, chemical, and biological attributes

Biochar's agronomic benefits arise from its combined physical, chemical, and biological properties. Its porous

Table 1: Key attributes of different biochar feedstocks and their agronomic implications

Feedstock type	Typical properties	Nutrient content	Advantages in agriculture	Potential limitations	References
lignocellulosic residues (rice husk, wood chips, straw)	High fixed carbon, low ash, well-developed micropores	Low N, P, K	Improves soil structure, enhances porosity, long-term carbon sequestration	Low initial nutrient value	Mukherjee <i>et al.</i> (2022)
Manures (poultry litter, cow dung)	High ash, alkaline pH, moderate–high porosity	Rich in P, K, Ca, Mg	Strong liming effect, nutrient-rich, good for acidic soils	Risk of heavy metals, variable product quality	Khan <i>et al.</i> (2026)
Municipal/industrial organics	Highly variable composition	Variable micro- and macronutrients	Waste valorization, supports circular economy	May require pre-treatment to remove contaminants	Guilayn <i>et al.</i> (2022)
Aquatic biomass (algae, seaweed)	High mineral content, moderate ash	High K, Ca, trace elements	Enhances micronutrient availability	High salinity; may require washing	Ruben <i>et al.</i> (2025)
Food processing wastes	Moderate ash, variable carbon content	Moderate N, P	Readily available, cost-effective	Consistency varies across batches	Rosli <i>et al.</i> (2026)

structure and low bulk density improve soil aeration, water retention, aggregation, and root growth (Alghamdi 2018). Chemically, biochar contains stable aromatic carbon, various functional groups, and appreciable cation exchange capacity, contributing to nutrient retention and reduced leaching. Nutrient-rich manure biochars can additionally supply macro- and micronutrients. Biologically, biochar provides protected habitats for soil microorganisms, including plant growth-promoting rhizobacteria and mycorrhizal fungi, thereby enhancing microbial activity and nutrient cycling processes (Shang *et al.* 2023). These effects

are influenced by biochar type, soil conditions, climate, and management practices.

Standard methods for characterization

Reliable characterization enables meaningful comparison among biochar studies and supports appropriate field application. Common analyses include surface area and porosity measurements (BET), scanning electron microscopy, bulk density, elemental and proximate analyses, pH, electrical conductivity, Fourier-transform infrared spectroscopy (FTIR), and X-ray diffraction (XRD)

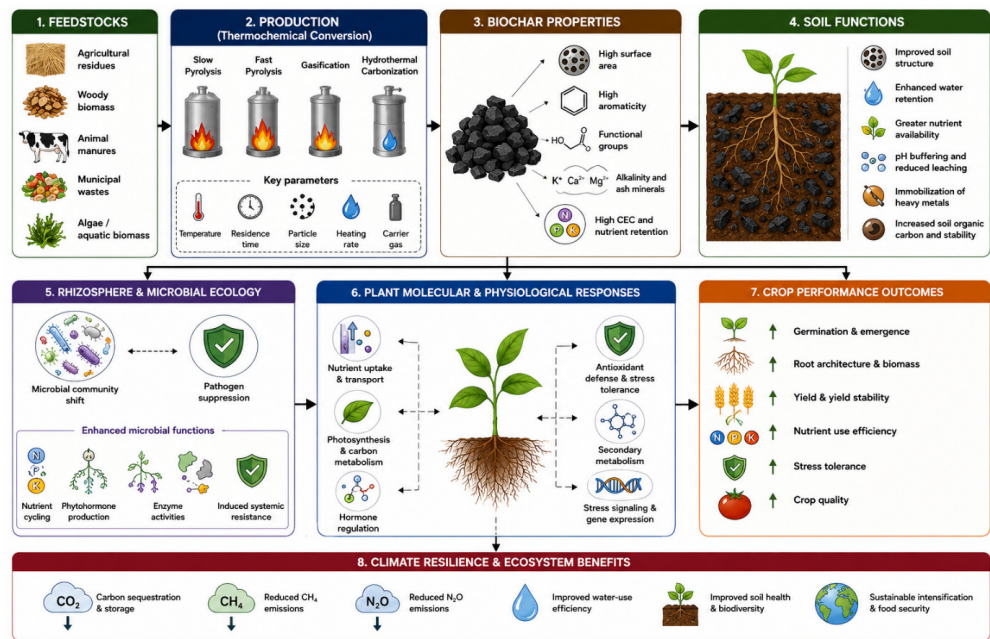


Figure 1: Integrated mechanistic framework linking biochar properties to soil functions, microbial ecology, plant molecular responses, and crop performance under climate stress

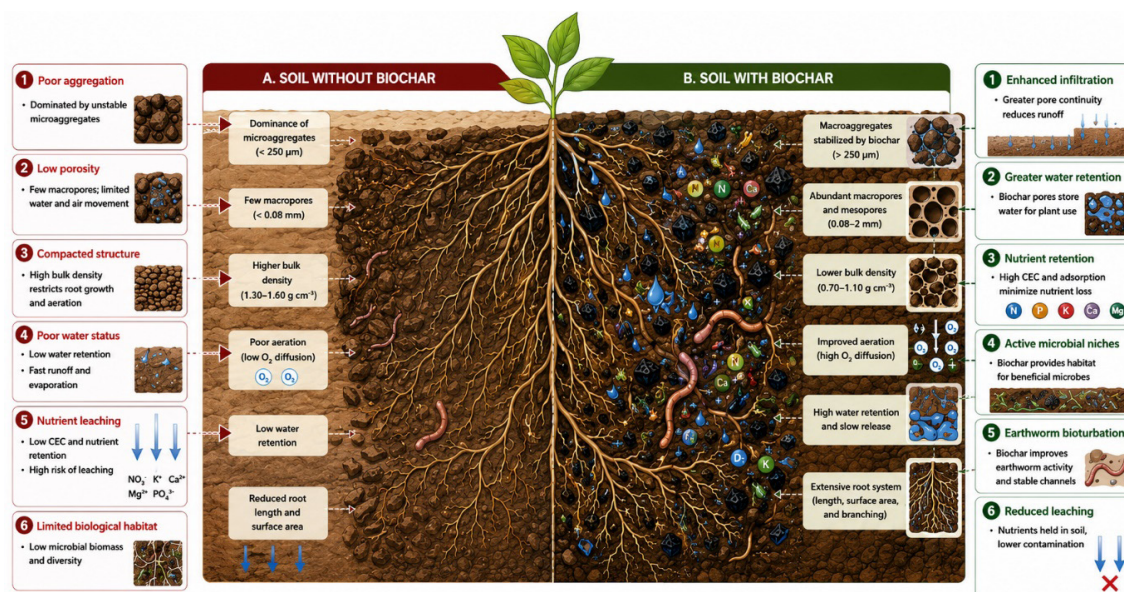


Figure 2: Mechanisms governing biochar-induced soil structural improvement and rhizosphere function

(Racero-Galaraga *et al.* 2024). Biological assessments often involve microbial biomass, community composition, and soil enzyme activities associated with nutrient cycling (Shahsavari *et al.* 2017). In addition, certification standards provide guidelines for contaminant assessment, including heavy metals and polycyclic aromatic hydrocarbons, to ensure environmental safety and agronomic quality.

Influence of biochar on soil physical properties

Water retention and hydraulic conductivity

Biochar consistently improves soil water dynamics by increasing water retention and affecting hydraulic conductivity depending on soil texture. In coarse-textured and sandy soils, biochar's high surface area and hierarchical pore network help store moisture in micro- and mesopores, boosting plant-available water. This extra storage helps plants withstand short-term droughts and stabilize yields during irregular rainfall. In finer-textured soils, biochar can also enhance water retention, but the extent depends on initial clay content, soil structure, and application rate (Liu *et al.* 2026). Hydraulic conductivity tends to decrease slightly in sands after adding biochar because of pore filling and increased tortuosity, which reduces deep percolation and nutrient leaching. Conversely, in structured loams and clays, improved aggregation and macropore continuity can sustain or even raise saturated conductivity, supporting infiltration and reducing surface runoff. These effects are influenced by biochar particle size, application rate, and mixing depth, highlighting the importance of matching biochar properties with soil texture to achieve optimal hydrologic results (Lee *et al.* 2026).

Soil structure, porosity, and bulk density

Biochar enhances soil structure by promoting aggregate formation and stabilizing existing aggregates through both physical and chemical processes (Ma *et al.* 2026). Its low bulk density and angular particles create contact points that support interparticle bridging, while biochar surfaces offer sites for organo-mineral associations and microbial binding agents such as extracellular polysaccharides. The outcome is an increase in total porosity with a beneficial redistribution across micro-, meso-, and macropore domains (Figure 2). Improved pore connectivity boosts aeration, root growth, and gas exchange, which in turn enhances rhizosphere activity and nutrient cycling. A decrease in bulk density is a consistent and meaningful benefit, especially in compacted or degraded soils where root penetration and tillage energy are limited. Over time, biochar can serve as a core for organo-mineral complexes that resist slaking and erosion, thereby strengthening structural stability during wetting–drying and freeze–thaw cycles (Rao *et al.* 2024). These improvements are further enhanced when biochar is co-applied with organic residues or compost, which supply easily available carbon and binding agents that complement biochar's physical structure. Overall, the structural benefits of biochar lead to improved tilth, reduced compaction, and more resilient soil physical functions across various cropping systems.

Chemical impacts of biochar in soil

Soil pH and CEC

Biochar often raises soil pH, especially when made from ash-rich feedstocks or at higher pyrolysis temperatures.

This liming effect can reduce aluminium and manganese toxicities in acidic soils and improve the availability of essential nutrients like phosphorus and molybdenum. At the same time, biochar can boost the soil's cation exchange capacity through surface functional groups and mineral charge sites (Bo *et al.* 2026). Although initial CEC might be modest in high-temperature, highly aromatic biochars, surface oxidation during field aging usually increases functional group density and charge, which enhances nutrient retention over time. These changes help improve nutrient-use efficiency by decreasing leaching losses of base cations and ammonium, particularly in coarse-textured soils with naturally low CEC.

Nutrient dynamics

Biochar influences nutrient dynamics through sorption, complexation, and mineral interactions that collectively regulate nutrient availability and loss pathways. Its surfaces can adsorb ammonium and potassium, reducing their mobility and leaching loss. Phosphate behavior is more complex and depends on biochar mineralogy and soil pH; biochar can either increase phosphate availability by decreasing fixation to iron and aluminium oxides in acidic soils or, in some cases, sorb phosphate, which may require adjustments in rate and timing (Dabare and Munaweera 2026). Biochar may also immobilize toxic metals such as cadmium and lead, lowering competition for nutrient uptake and reducing plant stress. Manure-derived biochars can directly supply macro- and micronutrients, acting as a slow-release source that complements fertilizer schedules. Over time, biochar promotes microbial transformations, such as mineralization, nitrification, and phosphatase activity, that further manage nutrient pools in sync with plant needs (Pan *et al.* 2021).

Interaction with fertilizers

Biochar works synergistically with both organic and inorganic fertilizers by improving retention, reducing volatilization and leaching, and helping nutrients stay close to roots (Imran 2024). When used with nitrogen fertilizers, biochar can lower nitrous oxide emissions and ammonia loss by adsorbing ammonium and changing microsite redox conditions. With phosphorus fertilizers, biochar may decrease fixation in acidic soils, increasing fertilizer efficiency and allowing for lower application rates without sacrificing yield. Combining biochar and compost often provides additive or synergistic benefits: compost supplies easily available carbon and nutrients that boost microbial activity, while biochar offers stable surfaces and chemical buffering to maintain these benefits over multiple seasons (Luo *et al.* 2026). Achieving the best results requires matching the type and amount of biochar with the fertilizer type, soil chemistry, and crop growth stage. Carefully integrating biochar into

nutrient management plans can turn its chemical functions into real improvements in crop yield and environmental health.

Biological and microbial responses

Microbial community shifts

Biochar amendments consistently modify soil microbial communities by changing the physical habitat, chemical environment, and energy landscape of the rhizosphere. The porous structure and high internal surface area of biochar create refuge areas that protect microorganisms from predators and drying out, while also increasing the diversity of microhabitats. These features often lead to higher microbial biomass and a balanced community composition, although the specific changes depend on soil type, biochar properties, and environmental conditions. In many soils, biochar boosts the relative abundance of Actinobacteria and certain Proteobacteria linked to nutrient cycling, while shifts in fungal communities can indicate improved habitat connectivity and pH changes (Dai *et al.* 2021). Soil pH adjustment is a key factor in community restructuring. In acidic soils, the liming effect of ash-rich or high-temperature biochar reduces aluminium toxicity, creating a wider niche for pH-sensitive microbes, increasing bacterial diversity, and supporting fungal groups that prefer more neutral conditions. Biochar's absorptive capacity also influences communities by trapping ammonium, phosphate, and dissolved organic molecules, thereby buffering nutrient pulses and reducing osmotic stress, thereby stabilizing microbial processes. On the other hand, strong sorption of easily degradable substrates may temporarily lower microbial activity where carbon is scarce, especially with high-temperature, nutrient-poor biochar (Ali *et al.* 2025). Aging processes also impact community dynamics. Over weeks to months, biochar surfaces oxidize and form organomineral coatings that increase cation exchange capacity and provide new binding sites for enzymes and extracellular polymeric substances. This gradual "conditioning" can initially promote colonization by copiotrophic bacteria and later by more specialized oligotrophs, leading to successional patterns over time. The presence of root exudates further interacts with biochar, creating hotspots of microbial activity that often improve rhizosphere functions such as nitrification, phosphate solubilization, and siderophore production.

Role in promoting beneficial microbes

Biochar encourages beneficial microbes by providing physical spaces, adjusting chemical conditions, and buffering environmental stressors. Its internal pore network provides protected microsites where helpful bacteria and fungi can form biofilms, exchange signals, and withstand moisture fluctuations. This protection is

especially key in coarse or degraded soils where drying and predation are high. Chemically, biochar can boost nutrient availability or retention, which are critical for microbes, while also moderating pH and reducing metal and toxin toxicity (Kumar and Radziemska 2022). These shifts help beneficial microbes outcompete opportunists, especially when nutrients are aligned with crop needs. For example, increased retention of ammonium and potassium near roots concentrates resources where plant–microbe interactions are strongest. Simultaneously, the sorption of harmful compounds, including phenolics and herbicide residues, can enhance microbial enzyme activity and improve nutrient cycling. Biochar often works synergistically with organic amendments and microbial inoculants (Bamdad *et al.* 2022). When combined with compost, biochar's durable surfaces stabilize organic matter, reduce nitrogen loss, and extend microbial activity. As a carrier for inoculants, biochar protects cells during application, promotes their colonization of the rhizosphere, and enables sustained release into the soil. These effects are especially noticeable for microbes that depend on close root proximity or are sensitive to drying. In drought-prone systems, improved water retention and moderated redox conditions further support beneficial communities by lessening physiological stress. By increasing the abundance and longevity of these organisms, biochar indirectly boosts nutrient uptake, disease resistance, and stress tolerance, collectively contributing to resilient crop performance in variable field conditions.

Biochar–microbe interactions

Biochar engages in complex interactions with plant growth–promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), often strengthening the plant–microbe symbiosis (Malik *et al.* 2022). For PGPR, biochar's micro- and mesoporous surfaces support cell adhesion and biofilm development, helping stabilize populations of nitrogen fixers, phosphate solubilizers, and hormone producers. The retention of root exudates and signaling molecules on biochar surfaces can boost quorum sensing and chemotaxis, effectively increasing PGPR presence near roots. PGPR functions such as indole-3-acetic acid production, ACC deaminase activity, and siderophore-mediated iron acquisition are usually more effective when moisture and nutrient levels are stabilized by biochar (Pradhan *et al.* 2025). This results in better root structure, higher nutrient uptake, and increased tolerance to drought and salinity. For AMF, biochar can enhance hyphal growth by improving macropore connectivity and reducing soil compaction, which lowers the energy needed for hyphal exploration. In acidic soils, the liming effect reduces aluminium and manganese toxicity, promoting root health and aiding mycorrhizal colonization. Biochar can also decrease phosphorus fixation in some soils, increasing the amount of plant-available phosphate that AMF can transfer

to roots. However, the relationship is complex, very high phosphorus availability may reduce AMF colonization, and excessive biochar with strong sorptive capacity can sequester signaling molecules or micronutrients essential for symbiosis. Therefore, optimal results are achieved when biochar type and application rate are matched to soil P levels and crop species. In co-inoculation strategies, biochar used as a carrier can improve the establishment of PGPR and AMF by protecting propagules and minimizing desiccation (Fang *et al.* 2024). This tripartite interaction i.e. biochar, microbes, and plants, often results in increased nutrient-use efficiency, reduced pathogen pressure through competitive exclusion and induced systemic resistance, and enhanced resilience under stress. Careful design of biochar–microbe systems, considering pore structure, surface chemistry, and soil conditions, allows for targeted enhancement of these mutualisms, leading to measurable improvements in crop growth and yield stability.

Biochar-mediated stress tolerance

Drought, salinity, and temperature stress

Biochar enhances drought tolerance mainly by improving soil water movement and stabilizing plant water status (Table 2) (Wu *et al.* 2023). Its layered pore structure increases plant-accessible water while reducing evaporation, delaying the start of water deficiency in the root zone. Improved aggregate stability and pore connectivity enhance infiltration and reduce runoff, helping maintain soil moisture during sporadic rainfall. Under salinity stress, biochar can lower sodium ion activity in soil solutions through cation exchange and surface complexation, reducing sodium uptake and decreasing the Na^+/K^+ ratio in plant tissues (Batool *et al.* 2026). This ionic regulation, along with improved calcium and potassium retention, supports membrane integrity and enzyme activity. Regarding temperature extremes, biochar's influence on soil thermal properties and moisture helps buffer high-temperature spikes and diminishes heat stress around roots (Saklani *et al.* 2026). Additionally, improved aeration and redox conditions reduce hypoxia during temporary waterlogging and cold spells that hinder gas exchange.

Heavy metal immobilization

Biochar immobilizes heavy metals through surface adsorption, ion exchange, mineral precipitation, and complexation with oxygen-containing groups (Wang *et al.* 2022). High-ash or manure-based biochars often contain carbonates and phosphates that promote the formation of less soluble metal precipitates, reducing the bioavailability of cadmium, lead, nickel, and copper. The alkaline nature of many biochars raises soil pH, shifting metal forms toward less mobile types, while their porous structure offers many sorption sites that compete with plant roots for metal ions (Fathy *et al.* 2026). Over time, aging and oxidation of biochar

Table 2: Biochar-mediated mitigation of abiotic and biotic stresses through soil, physiological, and molecular mechanisms

<i>Stress type</i>	<i>Major soil-level effects of biochar</i>	<i>Physiological and molecular responses</i>	<i>Agronomic outcome</i>	<i>References</i>
Drought stress	Increased water-holding capacity, aggregation, soil organic carbon	Increased SOD, CAT, POD, APX activities; osmolyte accumulation; ABA signaling; improved membrane stability	Improved water-use efficiency and yield stability	Wu <i>et al.</i> (2023)
Salinity stress	Reduced Na ⁺ toxicity, improved nutrient balance and soil structure	Enhanced ROS scavenging, Na ⁺ /K ⁺ homeostasis, chlorophyll retention	Improved salt tolerance and productivity	Ali <i>et al.</i> (2017)
Heat stress	Improved soil moisture buffering and microbial resilience	Enhanced antioxidant defense and heat-shock responses	Reduced oxidative damage and yield loss	Ali <i>et al.</i> (2026)
Heavy-metal stress (Cd, Pb, As)	Metal immobilization through sorption and precipitation	Reduced ROS generation and membrane damage	Lower metal uptake and improved growth	Imran <i>et al.</i> (2025)
Nutrient deficiency	Increased nutrient retention and cation exchange capacity	Enhanced nutrient uptake and transporter activity	Improved nutrient-use efficiency	Sharma <i>et al.</i> (2025)
Oxidative stress	Improved soil environment and root function	Increased SOD, CAT, POD, glutathione metabolism; reduced H ₂ O ₂ and MDA accumulation	Improved stress resilience	Lee <i>et al.</i> (2025)
Fusarium wilt (<i>Fusarium oxysporum</i>)	Enhanced antagonistic microbial populations; suppression of pathogen inoculum	Induced systemic resistance (ISR), activation of SA/JA pathways	Reduced disease incidence and improved plant vigor	Asif <i>et al.</i> (2023)
Rhizoctonia root rot (<i>Rhizoctonia solani</i>)	Enhanced disease-suppressive microbiome and soil health	Increased defense-related enzymes and antioxidant activities	Reduced root rot severity	Abid <i>et al.</i> (2023)
Pythium damping-off (<i>Pythium spp.</i>)	Improved microbial competition and pathogen suppression	Enhanced root health and induced defense responses	Better seedling establishment	Bhatt <i>et al.</i> (2024)
Phytophthora blight (<i>Phytophthora spp.</i>)	Altered rhizosphere microbial structure and reduced pathogen colonization	Activation of systemic resistance pathways	Reduced disease severity	Iacomino <i>et al.</i> (2022)
Verticillium wilt (<i>Verticillium spp.</i>)	Enhancement of beneficial microbial communities	Upregulation of plant defense signaling and antioxidant enzymes	Reduced vascular wilt symptoms	Crespo-Barreiro <i>et al.</i> (2025)
Bacterial wilt (<i>Ralstonia spp.</i>)	Reduced pathogen survival via microbiome-mediated suppression	Enhanced host resistance and rhizosphere competition	Lower wilt incidence	Wang <i>et al.</i> (2025)
Root-knot nematode (<i>Meloidogyne graminicola</i>)	Increased nematode-antagonistic microorganisms and release of suppressive compounds	Induction of plant defense mechanisms	Reduced gall formation and root damage	Mondal <i>et al.</i> (2021)
General soil-borne disease complex	Improved soil physicochemical properties; enhanced beneficial microbiota; adsorption of phytotoxins	Activation of SA-, JA- and ET-dependent defense pathways; enhanced antioxidant enzymes	Broad-spectrum disease suppression and yield improvement	Chen <i>et al.</i> (2024)

ROS, reactive oxygen species; SOD, superoxide dismutase; CAT, catalase; POD, peroxidase; APX, ascorbate peroxidase; ABA, abscisic acid; ISR, induced systemic resistance; SA, salicylic acid; JA, jasmonic acid; ET, ethylene.

surfaces can increase functional groups and strengthen metal binding. These processes collectively reduce plant uptake, lessen oxidative stress caused by metal toxicity, and promote safer crop production on contaminated or marginal soils.

Mechanistic insights (antioxidant systems, osmoprotection)

Biochar-mediated stress tolerance is supported by well-defined physiological and biochemical mechanisms in plants (Sattar *et al.* 2022). A consistent response involves the enhancement of antioxidant defense systems, including increased activity of superoxide dismutase, catalase, and peroxidases, which decreases reactive oxygen species

buildup under drought, salinity, or metal stress. Biochar can help maintain photosynthetic efficiency by conserving chlorophyll content, stabilizing thylakoid membranes, and improving stomatal regulation through better water management (Hussain *et al.* 2026). Osmoprotection results from the increased buildup of compatible solutes such as proline, glycine betaine, and soluble sugars, which help preserve turgor and protect macromolecules during osmotic stress. Improved nutrient balance, especially of potassium, calcium, and magnesium, supports enzyme activity, signal transduction, and membrane stability. At the rhizosphere level, biochar encourages microbial communities that produce phytohormones and osmolytes or enhance nutrient cycling, thereby strengthening plant resilience (Xu *et al.* 2026). Together, these mechanisms convert soil-based improvements in moisture and chemistry into cellular protection, balanced ion transport, and sustained metabolic processes during stress events. Emerging evidence demonstrates that biochar-induced stress mitigation extends beyond soil improvement and directly affects cellular and molecular stress-response pathways. Biochar application frequently enhances antioxidant defenses by increasing the activities of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX), and glutathione reductase (GR) (Abbasi *et al.* 2026). These enzymes collectively regulate reactive oxygen species (ROS) homeostasis, thereby limiting lipid peroxidation, membrane damage, protein oxidation, and chloroplast dysfunction under drought and salinity stress. Recent transcriptomic studies suggest that biochar may influence expression of genes associated with ABA-dependent drought signaling, aquaporin-mediated water transport, potassium transporters, SOS-mediated salt tolerance pathways, and heat shock proteins involved in thermal adaptation (Lee *et al.* 2025). These coordinated molecular responses contribute to improved photosynthetic efficiency, maintenance of cellular homeostasis, and stress resilience.

Biochar effects on crop growth, yield, and quality

Major cereal crops

In cereals like rice, wheat, and maize, biochar often improves establishment, tillering, and grain filling by boosting soil moisture, nutrient retention, and root development. The liming effect in acidic soils helps reduce aluminium toxicity, expands root exploration, and supports balanced uptake of nitrogen, phosphorus, and potassium. In rice systems, biochar can lower methane emissions when combined with optimized water management, while also enhancing ammonium retention and nitrogen-use efficiency (Ning *et al.* 2022). In maize and wheat, better soil structure and microbial activity promote stronger early growth and higher harvest indices, especially in sandy or degraded soils where water

and nutrients are limited (Kong 2014). Yield improvements are most significant when biochar is tailored to soil texture, pH, and fertilizer strategies, with moderate application rates often offering the best cost–benefit ratio.

Legumes and pulses

Legumes and pulses benefit from biochar through improved nodulation, biological nitrogen fixation, and phosphorus availability. By moderating soil acidity and immobilizing toxic metals, biochar creates a more favorable environment for rhizobial colonization and nodule function. Increased phosphorus availability via pH adjustment, reduced fixation, or co-application with P fertilizers supports energy-intensive N₂ fixation and protein synthesis (Mitran *et al.* 2018). The porous matrix also functions as a habitat for rhizobia and other beneficial microbes, boosting their persistence in the rhizosphere. These effects often lead to higher pod numbers, seed set, and protein content, especially under moisture stress or in low-fertility soils where legume performance is otherwise limited.

Horticultural crops

Horticultural crops, including vegetables and fruit trees, often respond strongly to biochar because of their sensitivity to soil physical quality and nutrient availability. Improved soil structure, water retention, and aeration promote root growth and help reduce physiological issues caused by moisture changes. Biochar can also boost fertigation efficiency by holding nutrients in the root zone, which cuts down on leaching in high-value systems with frequent watering (Alkharabsheh *et al.* 2021). Reports show that biochar can suppress diseases by supporting microbial antagonists and triggering systemic resistance, leading to fewer soil-borne pathogens. In perennial systems, biochar's long-lasting presence works well with mulches and composts to maintain soil health and root activity through the seasons, improving flowering, fruit set, and uniform size (Filipović *et al.* 2025).

Secondary metabolites and nutritional quality

Biochar can influence crop quality by affecting the production of secondary metabolites and nutrient levels (Deng *et al.* 2022). Increased availability of essential minerals and better water status can boost the accumulation of phenolics, flavonoids, and carotenoids in vegetables and fruits, enhancing antioxidant capacity and sensory qualities. In cereals and pulses, improved nitrogen and sulfur nutrition can raise grain protein content and essential amino acid balance, while better micronutrient availability may increase iron and zinc levels, although responses vary depending on soil conditions (Dawar *et al.* 2023). Biochar's role in reducing abiotic stress also helps stabilize metabolic pathways that influence flavor, texture, and shelf life, as evidenced by improved firmness and decreased postharvest losses in

some horticultural products. However, excessively high pH or application rates can hinder micronutrient availability or disrupt hormonal balance, highlighting the importance of site-specific calibration of biochar properties and application rates.

Molecular basis of biochar-induced crop improvement

Beyond its well-documented effects on soil fertility and nutrient availability, biochar can influence several molecular and physiological processes that collectively contribute to improved crop growth, productivity, and quality. Increasing evidence suggests that biochar acts not only as a soil amendment but also as an indirect regulator of plant metabolic pathways, gene expression, stress signaling, and plant–microbe interactions (Bhat *et al.* 2024).

One important mechanism involves the regulation of nutrient acquisition and transport systems. Biochar application improves the availability of essential nutrients in the rhizosphere and can enhance the expression of nutrient transporter genes associated with nitrogen, phosphorus, potassium, and micronutrient uptake. Improved nutrient acquisition promotes root development, stimulates metabolic activity, and supports the synthesis of proteins, nucleic acids, and other biomolecules required for plant growth (Dawar *et al.* 2025). Enhanced nutrient-use efficiency also contributes to greater biomass accumulation and yield stability, particularly under nutrient-limited conditions. Biochar has also been associated with the modulation of photosynthesis-related processes. Improved soil moisture retention, nutrient availability, and root function enhance chlorophyll synthesis, stomatal conductance, and photosynthetic efficiency. Several studies have reported increased chlorophyll content and improved photochemical performance in biochar-amended plants, leading to higher carbon assimilation rates and biomass production (Naz *et al.* 2025). These responses help maintain photosynthetic activity under adverse environmental conditions such as drought, salinity, and heat stress. Closely linked to enhanced photosynthesis is the stimulation of carbon fixation and assimilate partitioning pathways. By improving plant nutritional status and physiological performance, biochar promotes the allocation of photosynthetically fixed carbon toward growth, reproductive development, and grain or fruit formation. Enhanced carbon metabolism can increase carbohydrate accumulation, improve sink strength, and contribute to greater yield and quality attributes in economically important crops.

Another important mechanism underlying biochar-induced crop improvement is the activation of antioxidant signaling networks. Environmental stresses often lead to excessive production of reactive oxygen species (ROS), resulting in oxidative damage to cellular components. Biochar can enhance the activities of antioxidant enzymes,

including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX), and glutathione reductase (GR), thereby maintaining cellular redox homeostasis. Enhanced antioxidant capacity reduces membrane lipid peroxidation, protects chloroplast integrity, and preserves metabolic functions, ultimately improving plant growth and stress resilience (Cannea and Padiglia 2025). Biochar-mediated improvements in crop performance are also linked to hormone-regulated growth pathways. Biochar can influence the synthesis, transport, and signaling of plant hormones such as auxins (IAA), abscisic acid (ABA), cytokinins, gibberellins, jasmonic acid (JA), salicylic acid (SA), and ethylene (Parastesh *et al.* 2025). These hormonal changes regulate root architecture, shoot development, nutrient acquisition, flowering, stress adaptation, and defense responses. In particular, enhanced root growth and branching frequently observed in biochar-amended systems are believed to result from interactions between biochar, soil microorganisms, and hormone-signaling pathways.

In addition to growth promotion, biochar can affect secondary metabolism and quality-related traits. Improved nutrient availability and physiological status may stimulate the production of secondary metabolites such as phenolics, flavonoids, terpenoids, and antioxidant compounds (Murtaza *et al.* 2025). These metabolites play important roles in plant defense, stress tolerance, nutritional quality, and post-harvest attributes. Consequently, biochar application has been associated with increased concentrations of health-promoting phytochemicals and improved quality characteristics in fruits, vegetables, medicinal plants, and other high-value crops (Singh *et al.* 2024). Furthermore, biochar influences crop performance through its effects on plant–microbe signaling mechanisms. The porous structure of biochar provides ecological niches for beneficial microorganisms, including plant growth-promoting rhizobacteria (PGPR), nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and arbuscular mycorrhizal fungi (AMF). These microbial communities participate in nutrient cycling, phytohormone production, pathogen suppression, and induction of systemic resistance. Emerging evidence suggests that biochar may strengthen communication between plant roots and beneficial microbiota through modifications of root exudation patterns and rhizosphere signaling processes (Yang *et al.* 2025). Such interactions enhance nutrient uptake, improve stress tolerance, and contribute to sustainable crop productivity.

Integration of biochar with other soil amendments

The combination of biochar with compost has become a highly effective way to improve soil fertility and crop yields. Compost provides easily accessible nutrients and labile carbon that boost microbial activity, while biochar offers stable structural surfaces and helps retain nutrients. When compost and biochar are co-composted, the biochar

absorbs ammonium, organic acids, and volatile compounds, which reduces nitrogen losses and helps improve compost maturity (Pandiyani *et al.* 2021). This mix also promotes better microbial succession, leading to a more stable microbial community with greater functional diversity. Co-application generally enhances soil structure, lowers bulk density, and increases water retention more than either amendment alone. The synergy comes from compost enriching nutrient pools and biochar's ability to stabilize organic matter, buffer pH, and extend nutrient availability. As a result, biochar-compost blends strengthen soil health and provide longer-lasting agricultural benefits than unamended compost, especially in degraded or nutrient-poor soils. Biochar interacts strongly with microbial inoculants, including plant growth-promoting rhizobacteria (PGPR), nitrogen-fixing bacteria, and mycorrhizal fungi (Malik *et al.* 2022). The porous biochar matrix offers protected microsites that help inoculants survive desiccation, predation, and environmental fluctuations during field establishment. Many inoculants perform better when co-applied with biochar because it adsorbs root exudates and signaling molecules, thereby improving microbial colonization of the rhizosphere. Biochar also increases the retention of ammonium, phosphate, and trace minerals that support microbial metabolism and enhance symbiotic functioning (Egamberdieva *et al.* 2021). When used as a carrier material for inoculants, biochar can promote higher microbial abundance and greater persistence throughout the crop cycle. These interactions often lead to improved nutrient acquisition, enhanced root growth, and increased crop resilience to stress. Successful integration depends on matching biochar surface properties such as pore size and functional groups with the ecological traits of the inoculant

species. Biochar improves the efficiency of both organic and inorganic fertilizers by enhancing nutrient retention, reducing losses, and increasing nutrient-use efficiency (El-Syed *et al.* 2023). When combined with organic amendments like manure or green waste, biochar increases the stability of organic nitrogen, promotes humification, and reduces greenhouse gas emissions from decomposition. Inorganic fertilizers also benefit from co-application with biochar; the porous surfaces adsorb ammonium and potassium, reducing leaching losses, while pH adjustment can raise phosphorus availability in acidic soils. Additionally, biochar alleviates fertilizer-induced salt stress by buffering ionic strength and improving cation exchange sites (Eissa *et al.* 2025). The spatial co-localization of nutrients with biochar particles in the root zone improves fertilizer uptake and reduces environmental impacts. Optimal results are achieved by adjusting application rates based on soil texture, pH, and fertilizer type, ensuring that biochar complements nutrient delivery without causing micronutrient imbalances.

Biochar in climate-smart agriculture

Biochar is recognized as a long-term carbon sequestration strategy because of its highly aromatic and recalcitrant structure, which resists microbial decomposition for decades to centuries. When produced under high-temperature pyrolysis, the stability of the carbon matrix increases, allowing a significant fraction of biomass carbon to stay stored in soils rather than returning to the atmosphere. Incorporating biochar into agricultural soils integrates this stable carbon into the soil organic matter pool while improving soil fertility, providing a dual benefit (Pandian *et al.* 2024). The carbon sequestration potential is further enhanced when biochar is produced from sustainably

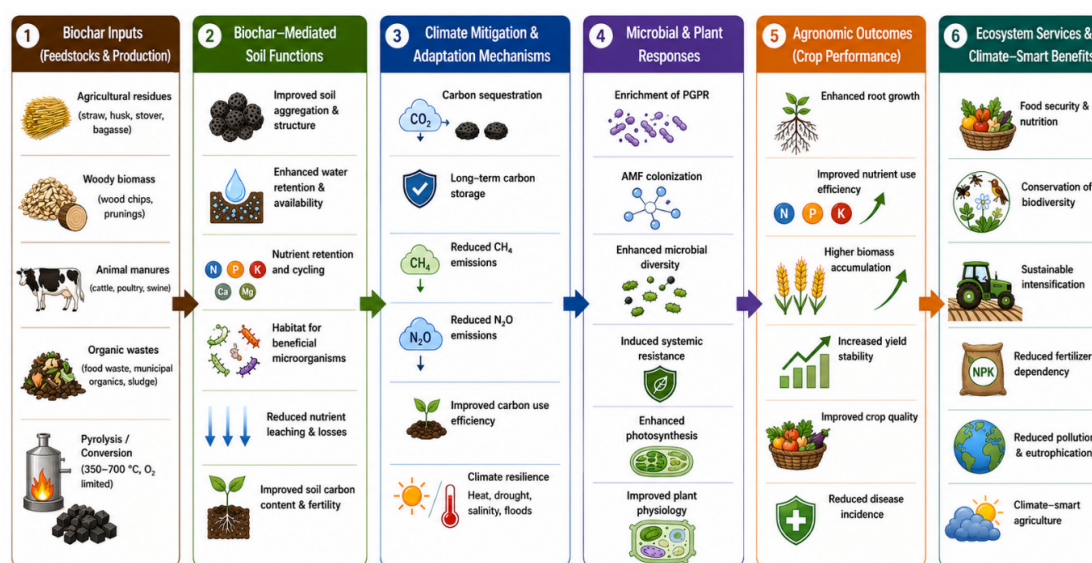


Figure 3: Biochar in climate-smart agriculture: integrated pathways linking carbon sequestration, soil health, stress resilience, and sustainable crop productivity

sourced agricultural residues or waste biomass, supporting circular bioeconomy models that reduce environmental footprints. Biochar decreases greenhouse gas emissions by altering soil physical and chemical properties that control microbial processes (Ngaba *et al.* 2026). Its ability to retain ammonium and improve aeration can suppress nitrous oxide (N_2O) emissions from fertilized soils. In anaerobic systems like rice paddies, biochar can reduce methane (CH_4) emissions by changing redox balance and encouraging methanotrophic microbial communities. Additionally, biochar stabilizes organic matter and reduces carbon dioxide (CO_2) emissions by slowing decomposition (Adekiya *et al.* 2026). These combined effects position biochar as a powerful tool for mitigating greenhouse gas emissions from agriculture while boosting productivity. Life cycle assessments (LCAs) show that biochar systems generally provide net climate benefits when emissions from feedstock collection, pyrolysis, and transportation are offset by carbon sequestration and decreased fertilizer use. However, these benefits depend on feedstock type, energy inputs, pyrolysis technology, and application rates. Properly designed biochar systems can also offer extra ecosystem benefits, including better soil biodiversity, lowered nutrient runoff, and increased resilience of cropping systems to extreme weather (Raza *et al.* 2026). Supporting healthier soils with more water retention and stable organic matter, biochar promotes long-term agricultural sustainability. Its integration into climate-smart agriculture strategies offers a practical path to simultaneously improve productivity, strengthen ecological resilience, and combat climate change (Figure 3).

Limitations, knowledge gaps, and future perspectives

Biochar performance varies widely across contexts, creating significant challenges for consistency. Results depend on feedstock type, pyrolysis temperature, particle size, application rate, soil texture, pH, climate, and management, making generalizations difficult and slowing the development of universal guidelines. Batch-to-batch differences and inconsistent quality control further limit reproducibility across studies and farm environments. While standardization frameworks exist, their adoption is inconsistent and often not tailored for specific crops or soils. Economic feasibility remains a barrier to scaling up. Costs for feedstock collection, preprocessing, pyrolysis infrastructure, transportation, and field application can outweigh short-term agricultural benefits, especially where input subsidies lower fertilizer prices. Monetizing co-benefits such as carbon credits, reduced irrigation needs, and avoided residue burning remains inconsistent, and smallholders may lack access to financing or affordable pyrolysis services. There is an urgent need for long-term, multi-location field trials that account for interannual climate variation and management

effects. Few studies examine impacts over multiple seasons on yield stability, nutrient efficiency, greenhouse gas emissions, and soil biological health simultaneously, and even fewer assess whole-farm profitability and risk under changing weather conditions. Such trials should include solid baselines, factorial designs with fertilizers and organic inputs, and standardized reporting to allow meta-analyses. Opportunities for engineered and functionalized biochars are expanding. By adjusting pore structure, surface charge, and mineral content, biochars can be designed for nutrient delivery, contaminant binding, or microbe support. Combining minerals (like Ca–Mg phosphates), polymers, or microbial communities may improve performance and enable lower application rates. However, the durability, safety, and cost-effectiveness of engineered biochar variants must be validated under actual field conditions. Panomics approaches integrating soil metagenomics, meta-transcriptomics, metabolomics, and ionomics with plant transcriptomics and phenomics can reveal mechanisms connecting biochar characteristics to rhizosphere processes and plant outcomes. These data-driven models will support precise matching of biochar types to specific soil constraints, crop stages, and climate risks.

Conclusions

Biochar has become a versatile amendment capable of enhancing soil physical properties, buffering chemical limitations, and fostering beneficial microbial communities. This promotes crop growth, stabilizes yields, and boosts resilience to drought, salinity, extreme temperatures, and heavy metal stress. Its porous structure and durable surface chemistry improve water retention, nutrient use efficiency, and cation exchange, while modifying rhizosphere conditions to support plant-growth-promoting microbes and mycorrhizae. These qualities explain the observed benefits across cereals, legumes, and horticultural crops, aligning biochar with climate-smart goals through long-term carbon storage and reductions in nitrous oxide and methane emissions. However, performance varies considerably depending on feedstock, pyrolysis conditions, soil type, climate, and management practices. Economic barriers and logistical challenges further impede adoption, especially among smallholders. Unlocking biochar's full potential requires standardized quality metrics, practical decision-support tools, and business models that recognize its carbon and ecosystem benefits. Long-term, multi-site trials that integrate agronomy, ecology, and economics are essential to develop reliable application guidelines. Future progress is likely to come from precision approaches that customize biochar properties to specific site conditions, combine biochar with compost, fertilizers, and microbial inoculants, and utilize engineered or functionalized materials for targeted functions. Omics-based research will help clarify

mechanisms and accelerate the development of biochar–soil–microbe–plant systems with predictable outcomes. With scientifically grounded standards and scalable delivery methods, biochar can become a key element of sustainable intensification enhancing productivity, improving soil health, and contributing meaningfully to climate mitigation and agricultural resilience.

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