

Role of Biochar in Modulating Soil Properties and Stress Tolerance of Barley under Salinity and Drought Conditions

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Abstract

Barley (*Hordeum vulgare* L.), a key cereal crop with moderate tolerance to abiotic stresses, faces escalating threats from soil salinity (affecting ~10% of irrigated lands) and drought, which collectively impair >50% of global crop yields. This comprehensive review synthesizes the multifaceted role of biochar a carbon-rich pyrolytic amendment in enhancing soil properties and barley resilience under these conditions. Biochar's efficacy depends on feedstock (e.g., crop residues, woody biomass, manures) and pyrolysis temperature (300–650°C), influencing its porosity, surface area, pH, and functional groups. It ameliorates soil physicochemical traits by reducing bulk density, boosting aggregate stability, elevating water holding capacity (up to 33% increase in plant-available water), and lowering electrical conductivity through Na⁺ and Cl⁻ adsorption. Nutrient dynamics are optimized via enhanced cation exchange capacity, improved K⁺/Na⁺ ratios, and higher utilization efficiencies (e.g., 20–53% for N, 38–230% for P). Physiologically, biochar preserves relative water content, chlorophyll integrity (up to 72% increase), stomatal conductance, and photosynthetic efficiency, leading to morphological gains (e.g., 13–57% taller plants) and yield enhancements (up to 53% higher grain weight). Antioxidant defenses are bolstered by reduced reactive oxygen species and elevated enzyme activities (SOD, POD, CAT), while microbial synergies (e.g., with PGPR) further promote rhizosphere health and greenhouse gas mitigation. Socio-economic barriers to adoption include high production costs and scalability issues, yet integrated strategies combining biochar with gypsum, compost, or nano-

forms offer sustainable pathways for arid agriculture. Overall, biochar emerges as a versatile tool for climate-resilient barley production, though context-specific optimization is essential.

Keywords: Biochar, Barley (*Hordeum Vulgare*), Salinity Stress, Drought Tolerance, Soil Amendment, Water Holding Capacity, Ion Homeostasis, Photosynthetic Efficiency, Antioxidant Enzymes, Nutrient Use Efficiency, Sustainable Agriculture

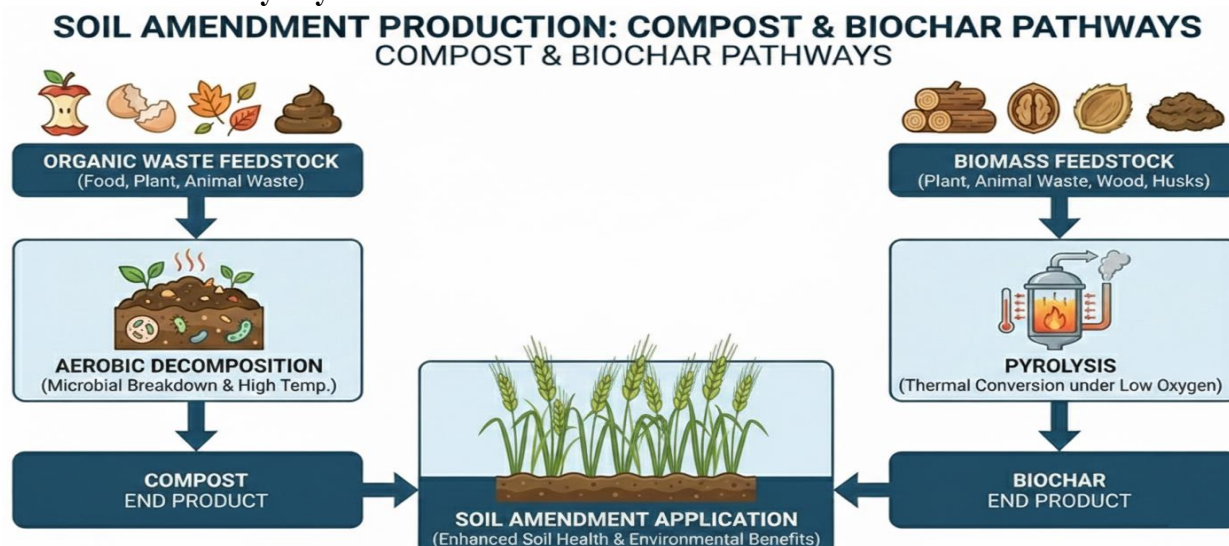
1. Introduction

The global agricultural sector faces an unprecedented convergence of environmental crises, characterized by the progressive salinization of arable lands and the increasing frequency of severe drought events. Currently, abiotic stressors contribute to over 50% of crop production losses globally, affecting nearly 91% of the world's cropland (Younis et al., 2020). Soil salinity alone impacts approximately 1.38 billion hectares, representing over 10% of global land area, with roughly 10% of all irrigated croplands currently compromised by salt accumulation (FAO, 2024). Barley (*Hordeum vulgare* L.), ranked as the fourth most significant cereal crop globally after wheat, rice, and maize, is a strategic asset in this landscape due to its inherent resilience and moderate tolerance to both salinity and drought (Abdelaal et al., 2020). However, the intensification of these stresses under rapid climate change necessitates advanced soil management strategies to sustain productivity. Biochar (BC), a stable, carbon-rich material produced through the thermochemical conversion of biomass under oxygen-limited conditions, has emerged as a transformative amendment capable of reconfiguring soil architecture and enhancing the biological resilience of barley (Rajhi et al., 2024).

2. The Thermochemical Ontogeny and Physicochemical Architecture of Biochar

The efficacy of biochar as a soil ameliorant is fundamentally governed by its production parameters, specifically the choice of feedstock and the pyrolysis temperature. Feedstocks range from agricultural residues like wheat straw, rice husks, and corn cobs to forestry waste, animal manure, and specialized materials like date palm fronds or seafood shell powder (Burezq, 2025). The conversion process involves a series of stages: drying (30–150 degrees C), initial carbonization (120–250 degrees C), and final carbonization (up to 450–650 degrees C), during which volatile matter is expelled, and stable aromatic carbon structures are formed (Alzahrani, 2025).

Figure 1. Comparative Production Pathways: Aerobic Decomposition for Compost vs. Thermochemical Pyrolysis for Biochar.



Pyrolysis temperature acts as the primary performance driver, dictating the resulting biochar's surface area, porosity, and nutrient profile. Low-temperature biochars (300–400 degrees C) typically retain a higher density of oxygenated functional groups (such as carboxyl and hydroxyl groups), which enhances their cation exchange capacity (CEC) and makes them superior for nutrient retention in sandy or low-fertility soils. These low-temperature products also contain higher levels of labile carbon, which can temporarily stimulate microbial activity a phenomenon known as positive priming (Toczydlowski et al., 2023). Conversely, high-temperature biochars (above 550 degrees C) exhibit significantly higher specific surface area and micro-porosity, facilitating the adsorption of toxic ions and supporting long-term carbon sequestration due to their biological recalcitrance (Wei et al., 2021).

Table 1. Characteristics of biochar derived from different feedstocks and their roles in mitigating abiotic stress.

Feedstock Category	Pyrolysis Temperature (C)	Key Physicochemical Attribute	Impact on Salinity/Drought Mitigation
Crop Residues (Rice/Wheat Straw)	400–500	High internal micro-porosity.	Enhances water retention and nutrient buffering (Toczydlowski et al., 2023).
Woody Biomass (Willow/Pine)	450–650	Large specific surface area; stable C.	Long-term soil structure stability and Na ⁺ adsorption (Toczydlowski et al., 2023).
Animal Manures (Poultry/Cattle)	350–450	High ash content; mineral-rich (N, P, K).	Direct nutrient supply; improves CEC in degraded soils (Toczydlowski et al., 2023).
Date Palm Debris	400–500	High organic matter (approx. 29.7%).	Improves WHC and SOM in arid sandy soils (Burezq, 2025).
Engineered/Nanocomposites	Variable	High stability; more active sites.	Enhanced pollutant removal and structural benefits (Younis et al., 2020).

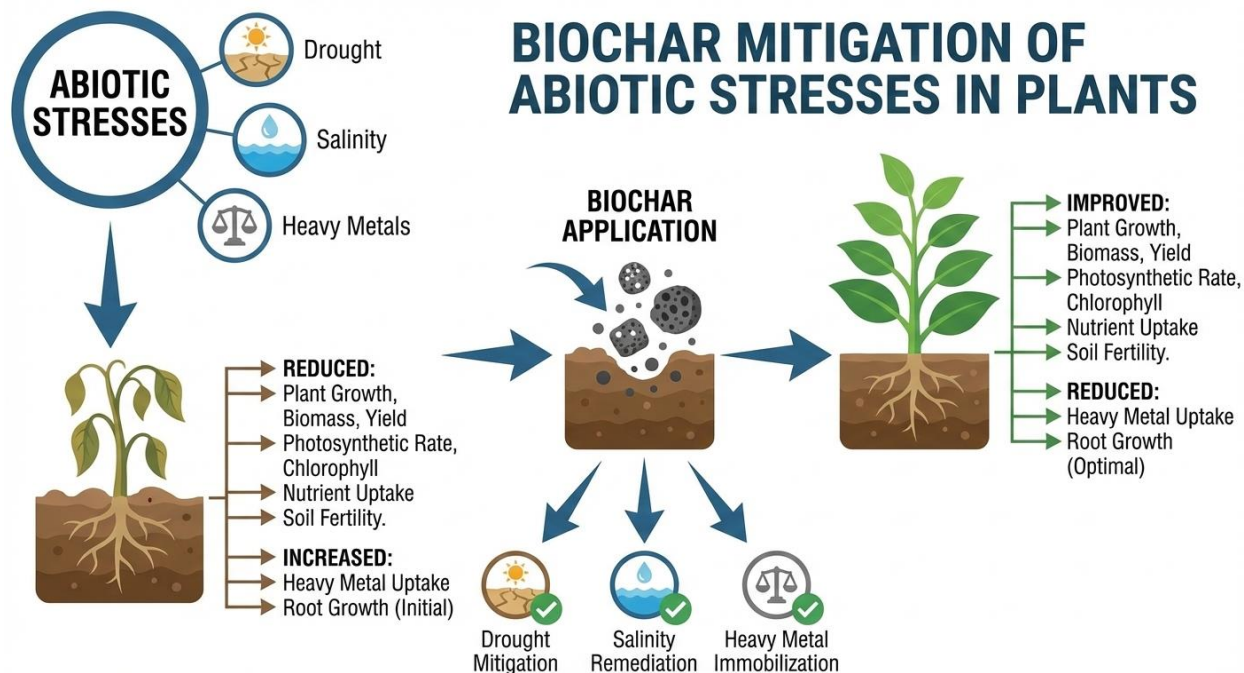
The interaction between feedstock and temperature determines the biochar's pH and EC. High-temperature pyrolysis tends to concentrate basic elements like Ca²⁺ and Mg²⁺, resulting in a more alkaline product which can serve as a liming agent in acidic soils, but must be managed carefully in calcareous arid soils where pH is already high (Rekaby et al., 2021).

3. Reconfiguration of Soil Physicochemical Properties under Stress

In saline and drought-prone environments, the physical degradation of soil is a primary constraint on plant growth. Salinity, particularly sodicity, causes the dispersion of soil clay particles, leading to the collapse of soil aggregates, reduced aeration, and a significant increase in bulk density

(Bagues et al., 2024). Biochar application mitigates these structural failures by promoting macro-aggregation (aggregates >0.25 mm) and increasing soil organic matter (SOM). By reducing soil bulk density, biochar improves the hydraulic conductivity and infiltration rates, which are crucial for the downward leaching of excess salts from the root zone (Zhang et al., 2023).

Figure 2. Mechanistic Overview of Biochar-Mediated Alleviation of Abiotic Stresses in Plants.



Under drought conditions, biochar functions as a subterranean reservoir. Its highly porous structure, particularly in biochars derived from hardwoods or crop residues, acts like a sponge, capturing and holding moisture that would otherwise be lost to evaporation or deep percolation (Ghouili et al., 2025). This enhancement of water holding capacity (WHC) is especially pronounced in sandy soils, which are inherently poor at retaining water. Furthermore, biochar modifies the soil's thermal properties and reduces water evaporation, stabilizing the rhizosphere environment against the rapid fluctuations common in arid climates (Li et al., 2021).

Table 2. Biochar-driven improvements in soil physicochemical properties under saline and drought conditions.

Soil Property	Mechanism of Biochar Influence	Observed Effect under Stress
Bulk Density	Dilution effect and improved structural porosity.	Significant reduction; improved aeration (Zhang et al., 2023).
Aggregate Stability	Binding of particles via functional groups and microbial hyphae.	Increased macro-aggregation and structural resilience (Zhang et al., 2023).
Water Retention	Physical entrapment in internal micro- and meso-pores.	Increased plant-available water (PAW) by up to 33% (Zhang et al., 2023).
Electrical Conductivity (EC)	Adsorption of Na ⁺ and Cl ⁻ on exchange sites.	Decreased EC in the root zone via sequestration and leaching (Rajhi et al., 2024).

Cation Exchange Capacity	Increased surface charge from oxygenated functional groups.	Enhanced retention of K ⁺ , Ca ²⁺ , and Mg ²⁺ (FAO, 2024; Younis et al., 2020).
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The impact of biochar on soil salinity is multifaceted and sometimes debated. While some studies report a decrease in soil EC due to salt dilution in retained water and physical entrapment in pores, other research indicates a potential increase in EC if the biochar itself has a high ash content or is applied at excessive rates (e.g., >20 t ha⁻¹) without adequate irrigation for leaching (Mohamed et al., 2016). Therefore, the selection of low-EC biochar and the implementation of precise application rates are essential for sustainable management in drylands (Adhikari et al., 2023).

4. Modulation of Ion Homeostasis and Nutrient Dynamics

A hallmark of salinity stress in barley is the disruption of ionic balance, specifically the excessive uptake of sodium (Na⁺) and the concomitant inhibition of potassium (K⁺) absorption. Na⁺ toxicity interferes with metabolic enzymes, protein synthesis, and photosynthesis, while K⁺ deficiency impairs stomatal regulation and cellular turgor maintenance (Chakraborty et al., 2018). Biochar serves as a powerful tool for restoring ion homeostasis. It possesses a high salt adsorption capacity, effectively binding Na⁺ and Cl⁻ ions on its surface functional groups and within its fine pores, thereby reducing their concentration in the soil solution (Alsamadany et al., 2024).

Simultaneously, biochar acts as a source and reservoir for K⁺, Ca²⁺, and Mg²⁺. The presence of these divalent cations, particularly Ca²⁺, is critical as they activate the Ca²⁺-dependent SOS (Salt Overly Sensitive) pathway, which mediates the efflux of Na⁺ from the cytoplasm (Abdelrady et al., 2024). By increasing the availability of K⁺ and reducing the bioavailability of Na⁺, biochar significantly enhances the K⁺/Na⁺ ratio in barley tissues a key indicator of salt tolerance (Khan et al., 2024).

Table 3. Role of biochar in maintaining ionic balance and nutrient availability.

Parameter	Salinity/Drought Impact	Biochar Mitigation Mechanism
Na ⁺ Uptake	High; leads to ionic toxicity and metabolic decay.	Sequestration in pores; reduction in ESP (Rajhi et al., 2024).
K ⁺ Availability	Reduced due to Na ⁺ antagonism.	Direct supply from ash; increased soil retention (Rajhi et al., 2024).
Nitrogen (N)	High leaching and volatilization.	Adsorption of NH ₄ ⁺ ; reduced N ₂ O and NO ₃ ⁻ loss (Younis et al., 2020; Clay et al., 2025).
Phosphorus (P)	Fixation in calcareous soils.	pH moderation and SOM increase; improved P use efficiency (Younis et al., 2020; Rajhi et al., 2024).
Nutrient Retention	Poor in sandy, degraded soils.	Enhanced CEC and large surface area for ion binding (Younis et al., 2020; FAO, 2024).

Beyond ionic regulation, biochar improves the overall nutrient use efficiency (NUE) of barley. It has been shown to increase grain P utilization efficiency by 38–230% and nitrogen utilization by 20–53% compared to fertilizer alone (Tang et al., 2023). Biochar's large surface area and porous structure also provide a refuge for beneficial soil microorganisms, including nitrifying bacteria and mycorrhizal fungi, which further facilitate nutrient uptake and biological nitrogen fixation (Karunarathne et al., 2020).

5. Physiological and Morphological Adaptations of Barley

The physical and chemical improvements in the rhizosphere translate into significant enhancements in the growth and physiological performance of barley. Under salinity and drought

stress, barley typically exhibits a marked reduction in plant height, leaf number, and leaf area due to the inhibition of cell division and expansion (Abdelaal et al., 2022). Biochar amendment reverses these trends, leading to significant increases in stem height (up to 57%) and leaf number. These morphological gains are underpinned by a dramatic improvement in leaf relative water content (RWC), allowing the plant to maintain turgidity and metabolic activity even under water-deficit conditions (Kunwar et al., 2025).

Photosynthetic integrity is another critical domain of biochar influence. Stress-induced stomatal closure and the degradation of chlorophyll pigments often lead to a precipitous decline in carbon assimilation (Bagues et al., 2024). Biochar application preserves photosynthetic health by maintaining higher concentrations of chlorophyll a and b (increases up to 72% reported) and protecting the photochemical efficiency of photosystem II (Fv/Fm) (Farouk et al., 2023). By ensuring better stomatal conductance and internal CO₂ concentrations, biochar allows barley to sustain its net CO₂ assimilation rate, ensuring sufficient carbohydrate supply for grain development (Mahmoud et al., 2022).

Table 4. Morphophysiological and photosynthetic gains in barley following biochar application.

Growth/Physiological Trait	Effect of Salinity/Drought	Biochar-Mediated Improvement
Plant Height	Significant reduction.	Increase (13.71–57%) (Abdelaal et al., 2022; Rajhi et al., 2024).
Relative Water Content (RWC)	Decline; leaf wilting.	Significant increase (approx. 33%) (Abdelaal et al., 2022).
Chlorophyll (a, b, and Total)	Degradation and reduced synthesis.	Preservation and enhancement (up to 72%) (Abdelaal et al., 2022).
Stomatal Conductance (gs)	Rapid closure to prevent water loss.	Maintains higher conductance under stress (Rajhi et al., 2024).
Net CO ₂ Assimilation Rate (Pn)	Inhibition due to stomatal/ionic factors.	Enhanced carbon fixation and growth (Rajhi et al., 2024).
Water Use Efficiency (WUE)	Variable; often poor under stress.	Improved through balanced water relations (Rajhi et al., 2024).

Barley yield parameters including spike length, number of grains per spike, and thousand-grain weight are all significantly bolstered by biochar application. In severe saline irrigation regimes (200 mM NaCl), grain yield in biochar-amended pots was recorded at 394.1 g m⁻² (at 2% dose) compared to significantly lower values in untreated controls (Shahzadi et al., 2025). These yield increases are often non-linear, with moderate application rates (2–5% by weight) frequently outperforming higher doses, which may lead to nutrient immobilization (Liu et al., 2022).

6. Biochemical Mechanisms and Antioxidant Defense Systems

One of the most insidious effects of drought and salinity is the induction of oxidative stress. The accumulation of reactive oxygen species (ROS), such as hydrogen peroxide (H₂O₂) and superoxide radicals (O₂⁻), leads to lipid peroxidation, protein denaturation, and DNA damage (Sachdev et al., 2021). Biochar acts as a biochemical stabilizer by drastically reducing the production of ROS and lipid peroxidation products like malondialdehyde (MDA) (Hasanuzzaman et al., 2021).

Biochar's protective role is mediated through the significant upregulation of the plant's enzymatic antioxidant system. Barley plants treated with biochar exhibit higher activities of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) (Ghouli et

al., 2025). These enzymes work in a coordinated network to scavenge free radicals and maintain cellular redox homeostasis. Furthermore, biochar promotes the accumulation of non-enzymatic antioxidants and compatible osmolytes, such as proline and soluble sugars, which facilitate osmotic adjustment and protect macromolecular structures during stress (Kamal et al., 2024).

Table 5. Enhancement of antioxidant systems and reduction of oxidative stress markers by biochar.

Biochemical Parameter	Salinity/Drought Response	Biochar-Treated Response	Physiological Implication
Malondialdehyde (MDA)	Marked increase (oxidative damage).	Reduction (47–56%) (Abdelaal et al., 2022; Rajhi et al., 2024).	Enhanced membrane stability and integrity.
Electrolyte Leakage (EL%)	High (loss of membrane control).	Reduction (approx. 54%) (Abdelaal et al., 2022).	Preservation of cellular solutes.
Superoxide Dismutase (SOD)	Variable; often overwhelmed.	1.8–2.21 fold increase (Rajhi et al., 2024).	Rapid detoxification of O ₂ ·-
Catalase (CAT)	Inhibited under severe stress.	1.76–2.29 fold increase (Abdelaal et al., 2022; Rajhi et al., 2024).	Efficient scavenging of H ₂ O ₂ .
Proline Concentration	High accumulation.	Further increased or restored balance (Ghouili et al., 2025; Rajhi et al., 2024).	Superior osmotic adjustment.
Soluble Sugars	Variable accumulation.	Increased or stabilized (Abdelaal et al., 2020; Ghouili et al., 2025).	Energy source and osmoprotectant.

The reduction in MDA and EL% levels under biochar application is a definitive indicator of protected cell membranes. By minimizing oxidative injury, biochar ensures that the vital cellular machinery remains functional, allowing barley plants to survive and produce yield under concentrations of salt that would otherwise be lethal (Ahmed et al., 2025).

7. Molecular Landscapes: Transcriptomic Regulation and Gene Expression

The macroscopic and physiological benefits of biochar are rooted in profound alterations at the genetic level. Recent studies using RT-qPCR and RNA-Seq have begun to map the molecular response of barley to biochar amendment under stress. Biochar application significantly upregulates key stress-responsive genes that govern water transport, osmotic adjustment, and ionic regulation (Farouk et al., 2022).

Specific transcription factors, notably HvDREB (Dehydration-responsive element-binding) and HvAP2/ERF, are upregulated by biochar, initiating a cascade of stress-tolerance pathways. Functional genes involved in the biosynthesis of osmolytes, such as HvP5CS (Delta-1-pyrroline-5-carboxylate synthase), show elevated expression, correlating with the higher proline levels observed in biochemical assays (Ghouili et al., 2025). Furthermore, genes encoding water-channel proteins (aquaporins), such as HvPIP, are highly expressed in biochar-treated plants, facilitating efficient water movement and hydraulic conductivity within the plant (Ghouili et al., 2025).

In saline conditions, the regulation of ion transport genes is paramount. Biochar promotes the expression of NHX1 and NHX2 (sodium/proton exchangers), which sequester Na⁺ into the vacuole, and HKT1 (high-affinity K⁺ transporter), which helps exclude Na⁺ from the xylem or

facilitates K⁺ uptake (Rajhi et al., 2024). The upregulation of the SOS1 (Salt Overly Sensitive 1) gene further enhances the extrusion of Na⁺ from the root to the soil solution (Nabi et al., 2025).

Table 6. Modulation of stress-responsive gene expression in barley by biochar.

Target Gene/Pathway	Molecular Function in Barley	Influence of Biochar Amendment
HvDREB / HvAP2	Central stress-response transcription factors.	Significant Upregulation (Ghouili et al., 2025).
HvP5CS	Rate-limiting enzyme for proline synthesis.	Significant Upregulation (Ghouili et al., 2025).
HvPIP	Plasma membrane aquaporins (water transport).	Significant Upregulation (Ghouili et al., 2025).
HvHSP	Heat shock proteins (chaperone/protein folding).	Significant Upregulation (Ghouili et al., 2025).
NHX1, NHX2, SOS1	Na ⁺ compartmentalization and extrusion.	Significant Upregulation (Rajhi et al., 2024).
HvCAT1, HvSOD1	Transcripts for antioxidant enzyme synthesis.	Significant Upregulation (Rajhi et al., 2024).
HAK1	High-affinity potassium transporter.	Significant Upregulation (Rajhi et al., 2024).

An intriguing observation in integrated studies (biochar + compost) is the "moderation" of gene expression. When environmental stress is effectively mitigated by the combined amendments, the plant may actually downregulate certain high-level stress markers compared to plants under extreme, unmitigated stress (Bilge et al., 2025). This suggests a "reduced metabolic burden" hypothesis: by optimizing the rhizosphere, biochar reduces the need for the plant to mount an energy-intensive, systemic molecular defense, allowing those resources to be reallocated toward grain production and biomass development (Bharadwaj et al., 2025).

8. Phytohormonal Crosstalk and Signaling Modulation

Biochar application also influences the complex network of plant hormones that govern growth and stress responses. Abscisic acid (ABA) is the primary hormone associated with drought and salinity, acting as a signal for stomatal closure and the induction of stress genes (Waqas et al., 2018). Recent research in related crops and seedlings suggests that biochar can modulate ABA levels. For instance, biochar application has been found to reduce ABA content by as much as 28% in some stressed plants, while simultaneously promoting the accumulation of growth-promoting hormones like salicylic acid (SA) and gibberellic acids (GAs) (Alzahrani, 2025).

This antagonism to ABA signaling is significant because while ABA is necessary for survival, its chronic elevation can lead to growth inhibition and premature senescence. By reducing the ABA burden, biochar helps maintain primary root growth and photosynthetic activity (Rajhi et al., 2024). Additionally, biochar leachates contain organic molecules that can directly interact with ABA-related proteins or mimic hormonal effects, stimulating the GA and auxin-responsive growth pathways to enhance seed germination and seedling vigor under stress (Singh et al., 2026).

9. Synergistic Management Strategies: Biochar and Co-Amendments

The potential of biochar is often maximized when integrated with other soil amendments or biological agents, creating a multi-faceted defense against salinity and drought. These synergies target different physiological and soil constraints simultaneously (Islam et al., 2025).

Biochar and Gypsum (CaSO₄ · 2H₂O): In saline-sodic soils, the combination of biochar and gypsum is particularly effective. Gypsum provides Ca²⁺ to displace exchangeable Na⁺ from the soil colloids, while biochar's porosity and surface area facilitate the physical adsorption of the displaced Na⁺ and improve the soil structure for leaching (Bello et al., 2021). This combination has been shown to increase barley grain yield by over 20% and significantly improve the K⁺/Na⁺ ratio in the soil and grain (Hamoud et al., 2024).

Biochar and Compost: Applying biochar alongside compost combines the long-term structural and carbon-sequestration benefits of biochar with the immediate nutrient availability and microbial stimulus of compost. This combination has been found to optimize the molecular response of barley, leading to a "balanced and effective regulation of stress response pathways" (Ghouili et al., 2025).

Biochar and Plant Growth-Promoting Rhizobacteria (PGPR): Biochar acts as an ideal microbial niche, with its 10–100 micrometer pore architecture providing refuge for beneficial bacteria like *Serratia odorifera* (Gunarathne et al., 2020). This partnership enhances seed germination by 40% and biomass by over 50% under drought by stimulating root exudates and increasing the availability of phosphorus and nitrogen in the rhizosphere (Malik et al., 2022).

Table 7. Synergistic effects of biochar integrated with other soil amendments and biological agents.

Synergistic Combination	Targeted Physiological/Soil Constraint	Observed Agronomic Outcome
BC + NPK Fertilizer	Nutrient leaching and osmotic shock.	Highest grain yield (394.1 g m ⁻²) under 200 mM salt (Bagues et al., 2024).
BC + Gypsum + Foliar Si/Fe	Ionic toxicity and micro-nutrient deficiency.	Reduced ESP and EC; 23% increase in grain K% (Rajhi et al., 2024).
BC + Compost	Soil health and metabolic burden.	Optimal protection; moderated stress gene expression (Ghouili et al., 2025).
BC + PGPR	Nutrient solubility and microbial survival.	62.5% increase in dry biomass under drought (Ghouili et al., 2025).
BC + Chitosan	Anatomical degradation and water loss.	Improved vascular and anatomical traits; reduced EL% (Abdelaal et al., 2020).

The interaction with mineral fertilizers (NPK) is also crucial. Biochar acts as a "nutrient buffer," capturing excess nutrients and releasing them slowly, which prevents the sudden spikes in soil solution concentration that can exacerbate osmotic stress in saline environments (Ren et al., 2022).

10. Environmental Stewardship and Greenhouse Gas Mitigation

Barley production in salt-affected soils is often associated with high environmental costs, particularly the emission of greenhouse gases (GHG) such as nitrous oxide (N₂O) and carbon dioxide (CO₂). Biochar application offers a dual benefit by sequestering carbon and mitigating these emissions. In a 28-day study, biochar alone reduced N₂O and CO₂ emissions by 68% and 44% respectively during the critical emergence phase (Clay et al., 2025).

The reduction in N₂O is particularly significant, as it is a potent greenhouse gas. The synergistic effect of biochar and barley growth results in an 85% reduction in N₂O emissions compared to untreated soil (Hassan et al., 2022). This mitigation is driven by biochar's reduction of soil respiration (lowering oxygen consumption and denitrification risk) and the plant's biological impact on the microbial nitrogen cycle. Specifically, the presence of barley and biochar reduces the number of *nirK* gene copies (nitrite reductase) while increasing *nosZ* gene copies (nitrous oxide

reductase), ensuring the more complete conversion of N₂O to harmless N₂ gas (Bhattarai et al., 2025).

Furthermore, biochar serves as a permanent carbon sink, sequestering approximately 0.7–1.8 Gt CO₂ equivalent per year globally. One tonne of biochar production can remove roughly 2.68 Mg CO₂eq from the atmosphere, providing a significant offset for the carbon footprint of intensive barley cultivation (Younis et al., 2020).

11. Economic Feasibility and Regional Case Studies

Despite its scientific promise, the adoption of biochar in commercial barley production is heavily influenced by economic factors. The cost of biochar material and its application remains high, often making it difficult to achieve a positive Net Present Value (NPV) in the short term, especially in temperate regions with high labor and material costs (Haider et al., 2025). In Finland, for example, Monte Carlo simulations show that for biochar to be economically viable at current carbon prices (approx. 88 EUR/t CO₂eq), the material cost would need to be reduced by two-thirds, or carbon subsidies would need to increase significantly (Jokubè et al., 2025).

However, the economic outlook is different in arid and developing regions where soil degradation is severe. In Sub-Saharan Africa and arid parts of India and the Middle East, a one-time biochar application can provide yield benefits that persist for 30 years or more, leading to a positive NPV (Dickinson et al., 2015).

Egypt and Arab Nations: In Egypt, the cultivation of barley in "newly reclaimed" lands (85.7% of total barley area) faces extreme salinity and drought challenges. The utilization of date palm fronds of which there are over 82 million trees across Arab nations could yield over 576,000 tons of biochar annually, providing a cost-effective, local resource for soil restoration (Egyptian Ministry of Agriculture and Land Reclamation, 2020).

India (Ambajogai Region): Multi-season trials in India demonstrate that biochar's yield benefits are sustained even under recurring drought. Chickpea and soybean yields increased by 18–110% over multiple seasons from a single biochar application, illustrating its long-term resilience-building capacity (MASH Makes, 2024).

Coastal Reclamation (China): Studies in the Tiaozini Reclamation Area indicate that biochar improves barley grain yield consistently, though straw yield response is more sensitive to application rates, with excessive biochar potentially causing nutrient immobilization in the straw tissues (Zhang et al., 2023).

Table 8. Economic feasibility and regional performance of biochar across diverse agricultural contexts.

Geo-Economic Context	Feasibility Factor	Economic/Agronomic Observation
Finland (Temperate)	Carbon Subsidy / NPV	Challenging; NPV often negative (-31,414 EUR/ha) (Jokubè et al., 2025).
SSA / Arid India	Multi-year Yield Benefit	Positive NPV over 30 years; yield gains 18–110% (Dickinson et al., 2015; MASH Makes, 2024).
Egypt / Middle East	Waste Valorization	High potential from date palm; supports small-scale farmers (Burezq, 2025).
USA (Cereal Crops)	Production Scale	Profitable primarily for high-value cash crops or carbon payments (Dickinson et al., 2015).

The "nascent" state of the biochar market means that adoption is currently limited to proactive governmental projects or high-value niche applications. However, the integration of biochar into

a circular bioeconomy where waste management, energy production, and soil health are coupled offers a viable path forward (Liu et al., 2022).

12. Conclusion

In the face of intensifying salinity and drought stresses that jeopardize barley productivity and global food security, biochar stands out as a robust, multifunctional soil amendment capable of transforming degraded agroecosystems. Through its profound impacts on soil structure (reduced bulk density, enhanced aggregation and WHC), ionic balance (Na⁺ sequestration, elevated K⁺/Na⁺ ratios), nutrient cycling (improved NUE and microbial habitats), and plant physiology (preserved photosynthesis, RWC, and antioxidant defenses), biochar not only mitigates immediate abiotic constraints but also fosters long-term soil health and carbon sequestration. Yield gains of 20–53% underscore its agronomic value, particularly in arid and salt-affected regions, while synergies with complementary amendments (e.g., gypsum, PGPR, nano-biochar) amplify benefits and reduce greenhouse gas emissions. However, realizing this potential requires overcoming production costs, optimizing application rates (typically 5–20 t/ha), and addressing variability in feedstock and pyrolysis conditions through targeted research and policy support. Ultimately, integrating biochar into holistic management frameworks encompassing waste-to-resource cycles, precision agriculture, and climate-adaptive breeding offers a scalable, eco-friendly strategy to sustain barley cultivation, enhance farmer livelihoods, and contribute to resilient food systems amid accelerating environmental change.

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