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IMPLEMENTATION OF BIOCHAR IN PLANTS TO IMPROVE THEIR ABIOTIC STRESS RESILIENCE

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Abstract

Biochar is a sustainable material that can boost agricultural yields and has enormous potential for application worldwide to improve stress tolerance. Crop yield, ecosystem sustainability, and soil health are all significantly impacted by biochar. It affects the diversity, composition, and functional soil microbial communities. The physicochemical characteristics of soil, including pH, organic matter, and nutrient availability, are also affected. It may increase a crop's resistance to abiotic stresses such salt, drought, and extremely high or low temperatures. It enables crops to tolerate stress by triggering hormonal regulation, osmotic adjustment, and antioxidant defence. Crop stress tolerance and its function in regulating the soil microbiota have significant ramifications for sustainable agriculture. It is a useful instrument for enhancing agricultural sustainability because of its advantages for crop productivity and stress tolerance. Biochar can increase crop yields, lessen soil degradation, and support ecosystem services when used in agriculture. As a result, this analysis advances our knowledge of the connections among biochar, soil microbiota, and crop resilience while highlighting biochar's potential as a useful supplement for enhancing crop stress tolerance.

Key words: Biochar; Plant physiology; Stress resistance; Environmental sustainability

Introduction

The agricultural potential of biochar (BC) has been widely recognized due to its numerous advantages in crop production under biotic and abiotic stressors. Its ability to increase crop output and lessen the harmful impacts of abiotic stressors has recently drawn attention from all around the world (Gao *et al*., 2024). Biochar has environmental advantages that impact soil quality and ecological balance worldwide, and its advantages are significant and far more varied than just supporting plant life (Arshad, 2024). Produced through pyrolysis, which involves two main stages of combustion and gasification biochar is considered a self-regulating technology with significant implications for soil and environmental management (Levin *et al*., 2016). Biochar contains 70-90% stable C as compared to compost containing only 2-14% stable C, thus playing an important role in carbon sequestration (Oldfield *et al*., 2018). In agricultural soils, BC plays a major role in improving biological carbon sequestration (Ali *et al*., 2023). Various authors apprehended the notion of BC use for climate change mitigation in 1993 (Paustian *et al*., 2016). It has been demonstrated that BC improves soil porosity and water retention, thereby can lessen the negative impacts of drought stress on plants (Thao *et al*., 2024). BC also provides nutrients to undernourished soils and counteracts the undesirable effects of salinity (Huang *et al*., 2023). One important amendment that improves soil fertility is biochar (BC), which is rich in carbon and contains a substantial number of specific nutrients (Javeed *et al*., 2022: Waqar *et al*., 2022). There is a lot of interest in using biochar (BC) as a soil amendment to increase carbon sinks and it increases the movement of nutrients (Haider *et al*., 2022; Ali *et al*., 2022).

Crop productivity and worldwide food security are truly threatened by the adverse impacts of abiotic stressors. Crop productivity is being adversely influenced by the steadily rising severity of abiotic stressors, such as heat, salt, heavy metals (HMs), and drought (Hassan *et al*., 2021). Nowadays, biochar is being used as an alternate approach to stressful situations since it is getting more and more well-liked worldwide for enhancing the physiochemical properties of soil. (Rogers *et al*., 2022; Wu *et al*., 2023). This paper synthesizes findings from several studies and highlights the pivotal role of BC in promoting sustainable agricultural practices. By reducing biotic and abiotic stresses, BC contributes not only to enhancing plant health but also to improving environmental management.

The potential contribution of biochar to climate change mitigation: The global discourse on mitigating the effects of climate change acknowledges the importance of multiple approaches (Xu *et al*., 2024). Given that biochar can be generated at various scales, from individual farms to massive industrial complexes (Rajput *et al*., 2022) and even at the household level (Whitman & Lehmann, 2009), it is pertinent to a diversity of socioeconomic situations. BC could include chemicals that could harm the environment if they are discharged. These include HMs, which are present in BC because they are present in the feedstock, and polycyclic aromatic hydrocarbons (PAHs), which are produced during the pyrolysis process (Sokołowski *et al*., 2015; Reizer *et al*., 2022). The pyrolysis of organic biomass yields biochar, which is a promising way to increase soil fertility, store carbon, and boost agricultural output (Chaudhry *et al*., 2025). Bio-oil and biogas are byproducts of the pyrolysis process that

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creates biochar (Kung *et al*., 2022). Solo utilization of BC improves soil bulk density and water-holding capacity thus directly affecting methane production and nitrogen dioxide emissions from soil. Biochar soil amendments increase methanophillic bacteria and decreases methanogenic bacteria (Huang *et al*., 2023), thus reduced GHG emissions. By absorbing carbon from the atmosphere and lowering greenhouse gas emissions from the rhizosphere, the use of biochar in agriculture can help mitigate global warming (Xu *et al*., 2024).

Use of biochar to enhance plants under abiotic stresses: Numerous research documented how adding biochar during abiotic or biotic stress conditions can prolong plant development and improve resilience to stress (Mansoor *et al*., 2021). Various strategies have been implemented to improve crop performance under abiotic stress (Gupta & Shrestha, 2023). Breeding methods, agronomic procedures, grafting, microbial seed treatment, microorganism inoculation, seed priming, and the application of osmoprotectants and plant growth regulators are some of these tactics (Oyebamiji *et al*., 2024).

It is widely recognised that reactive oxygen species (ROS) in plants play a concentration-dependent dual role in plant stress responses as both harmful agents and signalling molecules (Khan *et al*., 2023). Biochar can mediate ROS production when added as an amendment to improve phytoremediation of HMs pollution. However, little is known about the function of biochar-mediated ROS (BMR) in soil–plant phytoremediation (Jia *et al*., 2015). According to earlier research, the addition of BC decreased intracellular ROS concentrations in plants and increased antioxidant enzyme activity in HMs stress systems (Abbas *et al*., 2020).

Abiotic stresses significantly affect soil health and agricultural productivity. It has been observed that adding biochar to the soil increases its moisture content, porosity, and organic carbon (Zaheer *et al*., 2021). Under a variety of abiotic stresses, involving drought, salinity, and HMs contamination, BC has shown promise as an environmentally acceptable amendment for improving soil nutritional profiles. In saline soils, adding BC improves the soil's physical, chemical, biological, and mineral-nutrient properties (Rathinapriya *et al*., 2025). To overcome these disadvantages, a number of investigations concentrate on creating new BC employing nanocomposites to eliminate aqueous pollutants (Dong *et al*., 2023).

Effects of biochar on plant nutrient uptake: By changing the physical composition of soil and increasing its capacity for cation exchange, BC improves nutrient uptake and makes water available to crops. The enhanced nutritional and water status promotes the effective maintenance of physiological functions in plants under environmental stress, hence reducing ROS production (Wani *et al*., 2022). In contaminated surroundings, plants that experience less oxidative stress are healthier and more productive (Sahin *et al*., 2024).

According to Ali *et al*., (2017), BC enhances the nutrient intake, photosynthesis, and gas exchange characteristics of salt-stressed plants, while also increasing biomass and production simultaneously enhancing the soil's biological, biochemical, and physical qualities. Additionally, in abiotic stress circumstances, it increases K uptake and decreases Na uptake (Chaganti & Crohn, 2015). According to Glaser *et al*., (2002), applying BC enhanced the concentrations of Ca, Mg, and K in soil solution, which raised nutrient availability under stress. According to Zoghi *et al*., (2019), applying BC enhances nitrogen absorption, potentially by raising soil water uptake capacity (WUC) and water use efficiency (WUE) in drought stress conditions. A study showed 89% increased N uptake in soybean application of manure biochar (Lin *et al*., 2023). Biochar is known to exert a range of effects on plant ecophysiology, including improved nutrient retention, water-holding capacity, and soil structure (Kumar *et al*., 2022).

Effect of biochar on soil microbial activity: Recently, biochar has garnered a lot of interest, because of its capacity to enhance the soil environment and its beneficial effects on the soil microbial community (Zhou *et al*., 2020). The decomposition of organic matter, recycling of nutrients, preservation of soil structure, control of pests and diseases, and release of plant growth stimulants are all facilitated by soil microorganisms (Kirchman, 2018). Biochar encourages microorganisms to proliferate, which increases their quantity and number (Gou *et al*., 2020). According to Prayogo *et al*., (2014), adding BC raised the pH of the soil, which in turn led to a notable rise in the bacterial community's abundance. Numerous beneficial bacteria, such as Proteobacteria, Firmicutes, Actinobacteria, and Bacteroidota, as well as certain fungal species, such as Chaetomium and Pinnularia, were found in abundance (Ali *et al*., 2025). The stability and ecological function of terrestrial ecosystems depend heavily on soil microorganisms, which are important regulators of soil biological and chemical processes (Xu *et al*., 2021). Changes caused by biochar amendments may also influence the C metabolic activity and functional diversity of the microbial community, which are indicators of the functional response of the soil microorganisms. As per previous researches, 70% validate application of biochar for management of plant pathogens, 10% showed various factors affecting biochar efficiency in plant disease control and 20% showed ineffectiveness of biochar for *Rhizocotina solani* and *Pythium ultimum* (de Medeiros *et al*., 2021).

Biochar preserves hormonal balance and osmolyte: Under stress, abscisic acid (ABA) contents rose whereas Indole-3-acetic acid (IAA) and gibberellic acid (GA) contents reduced. However, BC also caused soybean-treated plants to have higher levels of IAA and GA and lower levels of ABA (Gullap *et al*., 2022). As a result, BC preserves hormones and osmolyte accumulation. This shield plants from oxidative damage brought on by dehydration and significantly increase drought tolerance (Wu *et al*., 2023). The plants' weight and yield increase under the combined influence of BC because it enhances the antioxidant system, which lowers oxidative stress, water uptake, nutritional homeostasis, photosynthetic activity, chlorophyll synthesis, osmolytes, hormonal balance, and membrane stability (Dawood *et al*., 2013). Despite extensive research on the influence of BC on soil microorganisms, the processes by which BC affects soil microbial communities are still unknown (Zhang *et al*., 2018), and the reactions of various functional groups vary (Luo *et al*., 2017).

The potential of biochar to heavy metal mitigation: A few aspects of biochar's impact on HM sorption and remediation of contaminated soils have been assessed in previous research studies; however, more research is needed to fully understand how biochar modulates HM geochemical transformation by inducing soil physiochemical and biological properties, HM sorption through direct and indirect mechanisms, and morpho-physiological attributes of plant growth (Khan *et al*., 2022). By improving soil characteristics like pH, cation exchange capacity, and microbial activity, BC additives promote a healthier soil environment that helps with HMs contamination cleanup (Pramanick *et al*., 2025). Because of its properties, biochar is one of the best materials for handling and cleaning up various heavy metals (Awad *et al*., 2021). Through several methods, BC increases plant development and yield in PTE-stressed situations, while reducing potentially harmful elements (PTEs), such as the uptake of HMs by plants (Medyńska-Juraszek & Jadhav, 2023). It has been discovered that BC strengthens plants' antioxidant defense mechanisms, allowing them to withstand oxidative stress brought on by metals (liod) (Mehmood *et al*., 2020). To aid sequester metal (loid) toxicity, the presence of BC in the soil matrix can promote the synthesis of phytochelatins and metal-binding peptides (Shi *et al*., 2022).

Enhanced stress-responsive proteins and gene expression by biochar: Biochar application has been reported to improve gene expression associated with salt tolerance, particularly by inducing salt tolerance mechanisms (Wu *et al*., 2023). It also increases CO_2 diffusion, which guarantees a plentiful supply of substrates for photosynthesis and the absorption of carbohydrates (Groszmann *et al*., 2017). Stressors like heat, ethanol, or osmotic stress can activate a variety of stress-responsive genes, including those that encode the heat shock protein (HSPs), enzymes that break down proteins (like ubiquitin ligase), and proteins connected to the metabolism of trehalose and glycogen in yeast (Adhikari *et al*., 2022). The effectiveness of biostimulants, including biochar, in mitigating stress depends on the regulation of key genes within stress-signaling networks. Alterations in genes that are directly involved in pathways regulated by biostimulants may reduce their protective impact against oxidative and abiotic stressors. Conversely, gene modifications outside these regulatory pathways are unlikely to compromise biostimulant-mediated stress protection (Gechev, 2025). At the molecular level, temperature stress alters the expression of genes encoding heat shock proteins (HSPs), detoxifying enzymes, osmoprotectants, ion transporters, and transcription factors. Among these, HSPs are the most commonly and strongly expressed genes in plants exposed to heat stress, highlighting their central role in temperature stress tolerance (Kutlu, 2025).

Conclusion

Biochar is a promising soil amendment with the potential to substantially enhance crop resilience against a wide range of abiotic stresses. It has been shown to be helpful in lowering soil salinity, improving microbial activity that is essential for nutrient cycling and plant health, and reducing drought stress by increasing soil water retention. There is no denying biochar's potential to contribute significantly to sustainable agriculture and future food security. However, biochar effectiveness depends upon feedstock type, pyrolysis temperature and soil conditions. As global challenges such as resource scarcity and climate change intensify, the integration of biochar into agricultural practices offers a practical pathway to improve productivity, strengthen resilience, and promote long-term environmental sustainability. Future researches are needed to optimize feedstock and pyrolysis process to reduce GHG emissions and enhance biochar yield. Nanotechnology has also been emerging as powerful tool for crop improvement and mitigation of crop stress. Novel nanobiochar composites can potentially be more efficient for controlled application of crop amendments.

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