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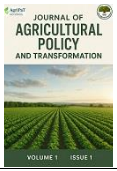

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Eco-Friendly Biochar for Stress Mitigation and Sustainable Crop Farming

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ABSTRACT

Climate change, land degradation, and the need to feed a growing population pose serious threats to global agriculture. Abiotic stresses such as drought, salinity, and nutrient loss reduce crop productivity, while intensive farming further depletes soil quality. These challenges highlight the importance of sustainable soil management practices that enhance resilience and environmental sustainability. Among emerging solutions, biochar, a carbon-rich material produced through the pyrolysis of organic matter, has shown great potential as a soil amendment.

This review synthesizes recent research on the role of biochar in alleviating abiotic stress and promoting sustainable crop production. Evidence from the past 15 years indicates that biochar improves soil's physical, chemical, and biological properties, leading to enhanced water retention, nutrient availability, and microbial activity. These benefits strengthen crop tolerance to drought and salinity, stabilize yields, and support efficient resource use. Additionally, biochar contributes to climate change mitigation by capturing carbon dioxide and reducing greenhouse gas emissions.

Despite its promise, biochar adoption faces barriers such as inconsistent feedstock quality, high production costs, and limited policy support. Future research should optimize production methods, assess long-term impacts, and develop supportive frameworks to integrate biochar into sustainable agriculture for improved food security and climate resilience.

1. Introduction

Climate change, land degradation and the pressing demand to provide food security to an expanding population is increasingly posing problems to global agriculture. Crop productivity is at a risk due to abiotic stresses which include drought, salinity and decreasing nutrient levels and the fact that intensive farming has led to the rise in soil degradation. As a result, the desire to find solutions to eco-friendly and sustainable soil management methods has increased, and special focus on organic amendments that could help to improve the quality of the soil, increase the resilience of crops, and help to achieve environmental sustainability.

In these amendments, biochar has come out as a potential remediation tool of soil. Biochar is an organic biomass that has been subjected to pyrolysis to create an organic product that contains carbon. Contrary to other traditional amendments of soil, biochar is very stable in soil, hence can be considered as a means of soil fertilization and an opportunity of long-term carbon capturing. Its use has been extensively investigated to enhance soil physical (e.g., water-holding capacity, aggregate stability, aeration and bulk density) and chemical (e.g. nutrient holding capacity, cation exchange capacity and pH regulation) and biological (e.g. rhizosphere microbial diversity, enzymatic functions, and nutrient cycling) properties.

The recent research has shown that biochar can counter the harmful impact of the environmental stress. Biochar makes plants more resilient to drought and salinity, which are two of the most important stressors in the age of climate variability by improving soil water retention, nutrient availability, as well as nutrient-microbe interactions.

Furthermore, agricultural residues turned into biochar have an added advantage being able to reduce the challenge of waste disposal as well as greenhouse gas emissions and encourage the concept of a circular economy within the agricultural domain (Gasim, 2024).

Biochar can be used to augment a variety of larger ecosystem services besides improving the health of the soil and the performance of crops. Being a stable type of carbon, it holds a long duration of CO_2 in the atmosphere and, therefore, assists in mitigating climate change. It has also been used in reclamation of degraded land and improvement of biodiversity and ecosystem processes. These qualities make biochar a key ingredient in climate-resilient agrifood and a global sustainability project (Imran et al., 2022; Rani et al., 2019). Pilot experiments indicate that use of biochar has the potential to promote crop production, soil quality, and dependence on artificial fertilizers, thereby promoting sustainable and regenerative agriculture. It is also porous and therefore it aids in retaining soil moisture, adsorbing pollutants as well as reducing nutrient leaching hence leading to enhanced soil and water quality. Moreover, biochar will help to restrain the emission of greenhouse gases and eliminate land degradation by increasing the content of the soil organic matter and decreasing soil erosion.

Although biochar appears to have very good potential in reducing stress and achieving sustainable food production, many gaps and concerns exist in terms of cost-effectiveness, long-term implications on soil and ecosystems, as well as risks of contaminants introduction in case of improper processing. Standardized production procedures, techno-economic studies, and policy measures are very much required so as to integrate successfully into agricultural systems (Xu et al. in 2025). Moreover, the understanding of the principles of long-term performance and the most effective ways of application. We also have big empty spaces in the long-term relationships involving biochar, soil and plants in dry and semi-arid areas. Past studies reveal that there exist differences in the type of materials and pyrolysis condition applied to produce biochar. Also, recommendations are difficult with the use of biochar in fields. In order to recommend on ways of reducing stress and the ecological production of agriculture, a synthesis of the state of the art on the role of the ecological biochar is needed. In order to have biochar used in a wide manner, efficiently and permanently, it will be necessary to fill these gaps. This review synthesizes the current knowledge on the role of eco-friendly biochar in stress mitigation and sustainable crop production. The specific objectives are as follows 1) Evaluate the benefits of biochar in reducing abiotic stress (drought and salinity) in crop production. 2) Assess the potential of biochar to improve soil quality, nutrient cycling, and water retention. 3) Highlight the role of biochar in enhancing climate resilience, sustainable farming, and ecosystem health and 4) Identify the challenges and policy innovations required to support its large-scale adoption.

By consolidating insights from recent studies, this review seeks to provide a comprehensive understanding of the potential and limitations of biochar, paving the way for its integration into sustainable farming practices that contribute to food security and environmental stewardship.

2. Materials and Methods

Thousands of research papers were searched, including databases like Google scholar, Clarivate, pub med, and MDPI. The research examines the secondary data in connection to the subject and peer-reviewed articles published within the past 15 years. The search methodology was aimed at the literature related to the application of organic amendment biochar in the alleviation of abiotic stresses and sustainable production of crops. It is a synthesis of the recent experimental results and analyses related to the utilisation of biochar in mitigating stress, amending soils, and climate-smart agriculture. The focus was given on certain screening criteria narrowing, specifically, the scale of search. Database search keywords such as organic soil amendment, sustainable crop production and mitigation of stress against crop farming were used. A total of 38 specific searches were run, which searched both directly and closely the topic of biochar role in mitigation of stress and sustainable agriculture under the conditions of water limitation.

3. Results

The review revealed that biochar improves plant growth under stress conditions, enhances nutrient availability, and supports microbial activity in the soil. These effects contribute to better yield stability and enhanced resource efficiency. It also underscores that context-specific applications (e.g., crop type, soil texture, and climate) are critical for maximizing benefits. The overall role of biochar is categorized as follows:

The Role of Biochar in Stress Mitigation

The application of biochar extends beyond immediate agricultural benefits and delves into the realm of climate resilience, particularly in the context of changing weather patterns and extreme events. As climate change intensifies, the resilience of agricultural systems becomes paramount, and the role of biochar as a carbon sink and soil enhancer can significantly contribute to this resilience. Studies have shown that biochar not only improves soil properties but also helps reduce the impacts of abiotic stress by modulating plant physiological responses, such as enhancing photosynthetic efficiency and antioxidant activity, which are crucial for crop survival under stress conditions. Furthermore, the integration of biochar into agroecosystems can lead to improved water management, as its porous structure allows for better moisture retention, thereby supporting crops during drought periods (Jiang et al., 2020). As the multifaceted potential of biochar is explored, it becomes clear that its adoption is not merely a trend but a strategic necessity for sustainable agriculture in a rapidly changing world.

The porous structure of biochar is crucial for retaining soil moisture, as it enhances the water-holding capacity of the soil, which is particularly beneficial in areas prone to drought (Rani et al., 2019; Li & Tan, 2021). By maintaining soil moisture levels, biochar reduces the need for irrigation, thus alleviating drought stress on crops (Li & Tan, 2021). Besides, biochar optimizes nutrient absorption, which is vital for plant growth under stress. It minimizes nutrient leaching, ensuring a steady supply of essential minerals to plants (Adnan et al., 2023). In addition, biochar enhances nutrient uptake efficiency, leading to improved crop yields even in nutrient-deficient conditions (Costa, 2023). Furthermore, biochar boosts soil organic matter, supporting microbial and enzymatic activities that are crucial for nutrient cycling (Gao et al., 2024). Practically exploiting biochar in crop farming could improve abiotic stress mitigation, which promotes crop growth and yield.

Improving drought tolerance and salinity stress

Using biochar significantly boosts plant resilience to drought and salinity stress by enhancing soil quality and plant responses. It improves soil structure, water retention, and nutrient availability, all of which are vital for plant growth under stressful conditions. Biochar also affects plant physiological processes, such as water uptake and stress hormone regulation, which in turn improve drought and salinity tolerance. By improving soil physical properties, such as aggregate stability and water-holding capacity, biochar helps maintain soil moisture during droughts (Wu et al., 2023; Zhang et al., 2023). It also enhances soil nutrient retention, providing a more stable nutrient supply to plants under stress (Abdou et al., 2024).

Moreover, the application of biochar increases the root water potential and osmotic potential, enabling better water uptake and retention in plants under drought and salinity stress. This reduces the concentration of abscisic acid in the xylem sap, which is linked to improved water relations and reduced stress signaling in plants (Zhang et al., 2023; Hou et al., 2023). Biochar increases photosynthetic activity and chlorophyll synthesis, both of which are crucial for maintaining plant growth and productivity under stressful conditions. It also supports better biomass production and plant growth by improving the internal CO2 concentration and net CO2 assimilation rate (Wu et al., 2023; Rajhi et al., 2024). According to Wu et al. (2023), biochar increases antioxidant activity, improves water absorption, preserves nutritional homeostasis, and lowers the generation of reactive oxygen species (ROS). The material's porous structure serves as a reservoir for water, assisting plants in staying hydrated in situations where water is scarce (Lohar et al., 2024). Plant stress tolerance, osmotic adjustment, and ion homeostasis are all improved by biochar, which increases salt resilience (Sultan et al., 2024). This substance lowers oxidative damage in saline environments and aids in maintaining the stability of cellular membranes (Wu et al., 2023). Salt stress mainly disrupts the balance of ions in vegetables by causing excessive sodium accumulation, which makes it harder for plants to absorb water and essential nutrients. Biochar has high porosity, a large surface area, and a strong ability to exchange ions, allowing it to absorb sodium in the soil and reduce its toxicity. In addition, biochar releases beneficial ions, such as potassium, calcium, and magnesium, into the soil. These elements are crucial for plant growth and compete with sodium for adsorption sites, indirectly reducing the negative effects of sodium. Furthermore, these nutrients help maintain the osmotic balance in plant cells, thereby enhancing their tolerance to salt stress (Ren et al., 2025).

Under drought conditions, crop growth is severely restricted. The application of biochar can alleviate this limitation by improving the soil structure, particularly its water-holding capacity. Soils with coarse textures, such as sandy soils, respond well to biochar because their large pores and rapid water loss lead to poor water retention. The addition of fine-grained biochar can fill these large pores, reduce water loss, and increase water retention. In contrast, fine-textured soils, especially those that are heavily compacted, benefit from biochar, which improves their aggregate structure. This creates larger pores, thereby enhancing the water infiltration and saturated hydraulic conductivity. This dual regulatory effect helps plants absorb water under drought or saline conditions, contributing to soil and water conservation in arid and semi-arid regions (Murtaza et al. 2024). Biochar is a good option in arid and semi-arid environments because of its enormous potential to increase crop productivity under abiotic conditions.

Table 1: Comparative performance of soil amendments

Amendment Type	Drought Resilience Mechanisms	Crop/Yield Impact	Notes/Limitations	Citations
Biochar (alone)	↑ Water retention, WUE, antioxidant defense	↑ Yield, soil fertility	Benefits may decline over time	(Xiao et al., 2016; Haider et al., 2020)
Biochar + Compost	↑ Soil structure, nutrient status	↑ Recovery, yield	Sometimes less effective than biochar alone	(Hazman et al., 2023; Abideen et al., 2024)
Biochar + Mineral Fertilizer	↑ Nutrient use efficiency, yield	↑Productivity, profit	Best with balanced NPK	(Mohamed et al., 2024; Arif et al., 2020; El-Syed et al., 2023)
Biochar + Microbes/Silicon NP	↑ Soil biology, stress tolerance	↑ Yield, soil health	Synergistic effects	(Zulfiqar et al., 2024; Ahmad et al., 2020)
Compost/Organic Alone	↑ Organic matter, nutrients	↑ Yield	Less water retention than biochar	(Shaaban et al., 2024; Al-Suhaibani et al., 2020)
Zeolite/Perlite	↑ Water retention	Variable	Less effective, costlier	(Ndede et al., 2022)
Cover Crops	↑ Soil health	Site-specific	No synergy with biochar in semi-arid soils	(Blanco-Canqui et al., 2024)

* $^{\uparrow}$Representing a positive effect of soil amendment on drought resilience and crop yield

Climate resilience, sustainable crop production, and ecosystem health

Biochar plays a significant role in enhancing climate resilience, promoting sustainable crop production, and improving the health of ecosystems. Biochar, a carbon-rich soil amendment produced through pyrolysis, contributes to soil fertility, water retention, and microbial activity, which are essential for sustainable agriculture. Its ability to sequester carbon for extended periods also aids in mitigating climate change.

Biochar enhances crop resilience to climate change by improving soil structure and nutrient retention, helping crops withstand extreme weather events such as droughts and floods (Kundu & Kumar, 2024; Adak et al., 2024). This reduces the need for synthetic fertilizers, thereby lowering the greenhouse gas emissions associated with their use (Adak et al., 2024; Keerthi, 2024).

The application of biochar has been shown to increase crop yields and stability by enhancing nutrient availability and root development (Rajalakshmi, 2020; Shanmugaraj et al., 2024). Moreover, biochar can combine soil minerals to form an organic-mineral complex, which regulates the mineralization of soil organic carbon, reduces the risk of microbial decomposition, and lowers carbon emissions (Shi et al., 2024). Additionally, the abundant pores and surface functional groups of biochar can absorb ammonium nitrogen, reducing nitrogen leaching and volatilization, and regulating soil microorganisms to promote the growth and reproduction of nitrogen-fixing bacteria, thereby enhancing nitrogen fixation and reducing the emission of the N2O greenhouse gas (Xu et al., 2025). Biochar promotes the development of beneficial microbial communities that enhance plant health and disease resistance (Shanmugaraj et al., 2024; Rajalakshmi, 2020).

Furthermore, biochar, an environmentally friendly material applied to soil, can provide significant environmental benefits. Biochar enhances the soil's carbon sequestration capacity by fixing atmospheric carbon dioxide in a stabilized form, thereby reducing greenhouse gas emissions and contributing to the mitigation of global warming. Biochar contributes to ecosystem health by reducing nutrient runoff and water pollution, thereby protecting aquatic environments (Rajalakshmi, 2020; Adak et al., 2024). Its porous structure serves as a habitat for beneficial microorganisms, thereby promoting biodiversity in soil ecosystems (Adak et al., 2024; Keerthi, 2024). Incorporating biochar into soil can reduce greenhouse gas emissions, making it an environmentally friendly alternative to traditional agricultural practices. Biochar can alleviate soil pollution, thereby enhancing the overall soil health and crop productivity (Rajalakshmi, 2020).

Regarding its numerous benefits, challenges remain in its production and integration into agricultural practices to maximize its benefits, necessitating an understanding to optimize its use across diverse environments.

Challenges and policy innovation to support scaling adaptation

Policy innovation and the decision to support biochar adaptation are paramount. Scaling adaptation in biochar application faces several challenges, including economic, technological, and policy-related barriers. Addressing these issues requires innovative policy frameworks and collaborative efforts from stakeholders. The following sections outline the key challenges and potential policy innovations to support the scaling of biochar.

Economic Challenges

High costs of production are one of the primary problems of biochar adoption, with the initial investment in technologies of biochar production being something prohibitive (Voruganti, 2023). Moreover, changes in biochar prices make the market volatile, which deter long-term investment and production planning (Pierson et al., 2024). Another issue that is restrictive of biochar potential is technological barriers. Differences in the process of production result in inconsistency in the quality of biochar, which complicates the utilization of biochar in different soils (Voruganti, 2023). Besides, additional studies are necessary to learn about the long-term effects of biochar and maximize the production processes to make them sustainable (Voruganti, 2023).

In order to overcome these challenges a number of policy innovations have been suggested. Government subsidies or even tax breaks are financial incentives that would be used to promote biochar production and use (Pourhashem et al., 2019). Standardized product guidelines would be beneficial to develop more confidence in the market and encourage consumers to accept it (Pourhashem et al., 2019). Also, demand can be triggered by educational interventions targeted at increasing awareness about the advantages of biochar to farmers, producers, and policymakers (Pourhashem et al., 2019). Although these approaches provide the possible avenues that can help to increase the use of biochar on a large scale, doubts remain about the sustainability of the biochar market in the long term as well as the creation of a robust regulatory framework to ensure the protection of the environmental health and safety (Montanarella and Lugato, 2013).

4. Conclusion and Recommendations:

Biochar is widely recognized as an environmentally friendly amendment that can reduce abiotic stress and promote sustainability in agriculture. Its benefits are well-supported, but achieving optimal results depends on matching the type and application of biochar to specific soils, crops, and stress conditions. Its effectiveness relies on application strategies, soil types, and integration with other management practices. These effects lead to increased crop resilience, stable yields, and more efficient resource use, especially in reducing drought and salinity stress. However, challenges such as variability in feedstock quality, high production costs, and the need for standardization and policy support hinder its widespread adoption. Biochar's benefits can vary by site and may decline over time due to field aging or overapplication, which can harm soil properties. Long-term impacts, ideal application rates, and interactions with other amendments (e.g., microbes, cover crops) require further research, particularly under field conditions. Future studies should focus on improving biochar production methods, evaluating long-term effects on soil health and ecosystems, and developing innovative policies to support its role in sustainable farming. Ongoing research is essential to develop guidelines for large-scale, effective, and safe use in sustainable agriculture.

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