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Beneficial effects of biochar application on mitigating the drought and salinity stress implications on plants

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Abstract

Biochar, an amorphous and highly porous carbonaceous substance derived from the thermal decomposition of organic matter, has been empirically proven to enhance soil water retention capacity, mitigate soil salinity, and augment nutrient bioavailability. Consequently, these improvements exert a stimulating influence on the growth and development of medicinal plants. Numerous scientific investigations have corroborated that the incorporation of biochar into the cultivation of medicinal flora can lead to increased plant biomass, heightened photosynthetic efficiency, and augmented accumulation of bioactive compounds. Furthermore, the utilization of biochar exhibits the potential to curtail the necessity for chemical fertilizers, which can otherwise have deleterious effects on soil health and the environment. A comprehensive comprehension of biochar's prospective role as a sustainable, long-term strategy for augmenting the productivity and resilience of medicinal plant cultivation in arid and saline environments holds paramount importance for ensuring a consistent supply of medicinal plants in the forthcoming years. This review aims to delve into the mechanistic foundations underpinning the beneficial impacts of biochar on plant development and the accumulation of bioactive constituents. It also explores the feasibility of biochar as a sustainable instrument for enhancing the cultivation of medicinal plants under adverse environmental conditions.

Keywords

Biochar, medicinal plants, salinity stress, drought stress

Introduction

Biochar is a carbon-rich substance produced through the pyrolysis of organic materials, such as wood or agricultural residues, under controlled, low-oxygen conditions (1). This process results in a highly porous and chemically stable material with versatile applications. One prominent application involves utilizing biochar as a soil amendment in agriculture to augment soil quality and fertility significantly. Extensive research has demonstrated its capacity to increase crop yields, reduce the reliance on synthetic fertilizers and pesticides, and enhance soil water retention (2). Importantly, biochar's exceptional stability allows it to persist in the soil for extended periods, potentially spanning hundreds to thousands of years, enabling it to serve as a carbon sequestration tool. Consequently, the integration of biochar into agricultural practices yields a dual benefit: it enhances soil health while simultaneously contributing to climate change mitigation through long-term carbon retention (3). Figure 1 illustrates the various types of biochar with applications relevant to soil health improvement.

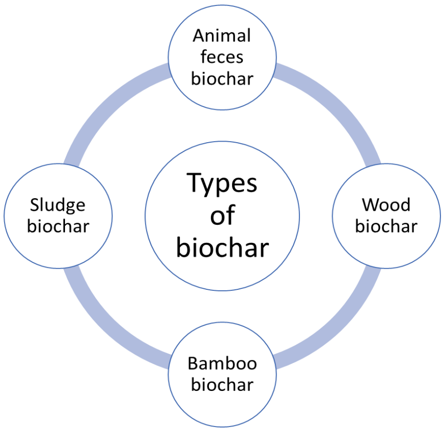

Fig. 1. Types of biochar

Drought and salinity stress are significant environmental factors that can profoundly impact the growth, development, and chemical composition of medicinal plants, potentially leading to diminished yield, compromised quality, and reduced potency of bioactive phytochemicals, frequently employed in both traditional medicinal practices and contemporary pharmaceuticals (4, 5). Drought stress manifests when plants are subjected to prolonged periods of diminished water availability, resulting in decreased vegetative growth, desiccation of leaves, and diminished photosynthetic activity (6). Various types of biochar have been documented to exhibit favorable effects (Table 1).

As a consequence, the synthesis of secondary metabolites in medicinal plants, including alkaloids and flavonoids, can be significantly reduced, leading to compromised therapeutic efficacy (12-14). Conversely, salinity stress occurs when plants are exposed to elevated salt levels in the soil or water, resulting in ion toxicity and osmotic stress. This can manifest as leaf chlorosis, inhibited plant growth, and ultimately, plant mortality. Excessive salt levels can also disrupt the uptake and transport of essential nutrients, causing imbalances in plant metabolism and a reduction in the production of bioactive compounds (15, 16). To mitigate the adverse effects of drought and salinity stress on medicinal plants, various strategies can be implemented, such as utilizing drought and salt-tolerant plant varieties, incorporating biochar, employing plant growth-promoting rhizobacteria, amending soil to enhance its structure and water-holding capacity, and adopting more efficient irrigation methods (17). Additionally, several plant growth regulators and natural products, such as extracts from seaweed, have demonstrated the ability to stimulate plant growth and promote the synthesis of secondary metabolites in medicinal plants under conditions of drought and salinity stress (18). Biochar possesses notable water retention capacity, enabling it to support medicinal plants in enduring drought conditions. Furthermore, biochar has the capacity to absorb and retain nutrients, thereby making them accessible to medicinal plants even in saline environments. Studies have revealed that biochar can enhance the production of secondary metabolites in plants, including medicinal species, consequently enhancing their therapeutic potential (19).

This review aims to explore the advantageous ramifications of biochar application in ameliorating the adverse effects of drought and salinity stress on medicinal plants. The primary focus of this review is to delve into the underlying mechanisms that drive the beneficial influence of biochar on plant growth and the accumulation of bioactive compounds. Gaining insights into the potential of biochar as a sustainable agronomic approach for augmenting the productivity and resilience of medicinal plant cultivation in arid and saline environments is imperative for securing a consistent supply of medicinal plants in the forthcoming years.

The effects of biochar on plant growth and physiology

Biochar exerts significant effects on plant development and physiological processes. A primary advantage of biochar lies in its ability to enhance soil structure and augment water retention capacity, thereby fostering optimal conditions for plant growth and development. Moreover, biochar serves as a reservoir of essential nutrients, including nitrogen, phosphate, and potassium, which are gradually released into the soil over time, ensuring a sustained supply of plant nutrition (20, 21). Additionally, biochar exhibits the capacity to stimulate soil microbial activity, thereby conferring benefits upon plant health. It has been empirically demonstrated to promote the proliferation of beneficial microorganisms, such as mycorrhizal fungi, which enhance plant nutrient uptake and bolster resistance to diseases (22). Notably, the carbon-sequestering property of biochar in soil holds promise for environmental conservation, as it aids in carbon storage, reduces greenhouse gas emissions, and contributes to mitigating climate change effects (23).

In sum, biochar emerges as a valuable tool for advancing sustainable agriculture and environmental management, given its profound influence on plant growth and physiological processes. However, it is

Table 1. Effect of different types of biochar on soil and plant health

Type of biochar	Reported for	Reference
Manure-based biochar	Improvement of the water holding capacity of the soil and improve crop yield by conserving the rainfall water in arid regions.	(7)
Cow manure-based biochar	Soil amendment for reducing cadmium availability and accumulation by *Brassica chinensis* L. in acidic red soil	(8)
Soft wood biochar	Reduction in N_2O emission in long-term.	(9)
Sewage sludge biochar	Improvement in corn fruit yield	(10)
Bamboo biochar	Improvement of soil health	(11)

imperative to acknowledge that the appropriate rate and timing of biochar application may vary contingent upon soil type, plant species, and prevailing weather conditions. Hence, further research is imperative to comprehensively elucidate its multifaceted impacts on plant growth and physiology (24).

Biochar's ability to mitigate drought stress

Biochar has been identified as a potential mitigation strategy for alleviating drought-induced stress in plants. It achieves this by enhancing soil's water retention capacity, thereby serving as a pivotal mechanism for aiding plants in coping with water scarcity (25). Biochar's efficacy in ameliorating drought stress stems from its high porosity and water-retention capabilities. Consequently, it plays a vital role in maintaining adequate soil moisture levels, mitigating stress on plants. Furthermore, aside from its water-holding capacity, biochar has been demonstrated to improve soil structure and aeration. These improvements augment the soil's pore space, which in turn enhances water infiltration and retention (26). The enhanced aeration facilitated by biochar is also instrumental in increasing oxygen availability to plant roots, a critical factor for optimal plant growth and development, especially in arid conditions. Additionally, the presence of biochar in the environment has been associated with the proliferation of mycorrhizal fungi, which assist plants in more efficiently absorbing nutrients and water. This microbial interaction further contributes to enhanced plant growth and heightened resistance to water stress (27).

In summary, one noteworthy advantage of utilizing biochar as a soil amendment is its potential to alleviate drought-induced stress in plants. Nonetheless, it is crucial to acknowledge that the effectiveness of biochar in reducing drought stress may vary depending on factors such as application rate, timing, and prevailing soil conditions. Consequently, further research is imperative to gain a comprehensive understanding of the underlying mechanisms governing biochar's ability to mitigate drought stress and to identify optimal strategies for leveraging biochar to enhance plant resilience in water-limited environments (28).

Biochar's ability to mitigate salinity stress

Biochar has emerged as a promising solution for mitigating salinity-induced stress on plants, albeit its effectiveness is contingent upon several factors, including application rate, timing, and soil conditions. This natural carbonaceous material, when incorporated into soil, can enhance its structural integrity and water retention capacity, thereby ameliorating the adverse effects of salinity stress. Biochar's high porosity and water-absorbing capabilities become particularly valuable during periods of water scarcity induced by excessive salinity. By reducing the detrimental impacts of salt on plants, biochar aids in preserving soil moisture levels (29). In soil environments afflicted with excessive salinity and waterlogging, biochar proves instrumental in improving soil aeration, which, in turn, enhances the availability of oxygen to plant roots. This oxygen supply is pivotal for optimal plant growth and development, especially in conditions of water shortage (30).

Furthermore, biochar has been demonstrated to augment the cation exchange capacity (CEC) of soil, complementing its influence on soil structure and water availability. In this regard, biochar exhibits the capacity to attract and retain positively charged ions such as calcium and magnesium, thereby mitigating the detrimental consequences of excessive soil salinity (31, 32). Additionally, biochar elevates soil pH, which, in turn, reduces the availability of harmful ions in the soil solution, such as salt and chloride. This alteration in soil pH contributes to its overall efficacy in alleviating salinity-induced stress (33, 34). However, it is important to note that the effectiveness of biochar in reducing salinity stress may vary depending on the specific application rate, timing, and prevailing soil conditions (33, 34). Further research is essential to ascertain the optimal methods for applying biochar in salt-affected soils and to gain a deeper understanding of the underlying mechanisms responsible for its salinity stress-reducing capabilities. For instance, Zulfiqar et al. (35) reported notable improvements in Alpinia zerumbet plants, including a more than 28% increase in net photosynthetic rates, a 92% and 78% rise in chlorophyll a and b contents, respectively, and a 50% enhancement in carboxylation efficiency when biochar (BC) and biochar enriched with cobalt (BC+Co) were introduced, compared to those grown in unamended sandy loam soil.

Efficacy of biochar for the improvement of various plants

Biochar has emerged as a promising tool for enhancing the growth and development of medicinal plants while also promoting the synthesis of secondary metabolites with therapeutic properties (35). This is primarily attributed to its multifaceted impact on soil quality, encompassing improved fertility, enhanced soil structure, and increased water retention capacity, all of which collectively accelerate the growth of medicinal plants. Notably, biochar acts as a slow-release reservoir of essential nutrients, including nitrogen, phosphorus, and potassium, crucial for both plant growth and the biosynthesis of secondary metabolites (36). Biochar additionally fosters the establishment of beneficial soil microorganisms, particularly mycorrhizal fungi, which play a pivotal role in enhancing nutrient uptake and overall plant health. The presence of these microorganisms has been found to facilitate the synthesis of secondary metabolites, which medicinal plants typically produce in response to biotic and abiotic stressors (37).

Furthermore, biochar has been observed to exert a positive influence on the production of secondary metabolites in medicinal plants, such as phenolic compounds, flavonoids, and essential oils. These phytochemicals possess pharmacological properties, making them valuable in both traditional and contemporary medicinal applications (38). In sum, the incorporation of biochar into soil holds the potential to significantly benefit medicinal plants by promoting their growth and the production of medicinally relevant secondary metabolites. However, it is important to note that the optimal application rate and timing of biochar may vary depending on the specific medicinal plant species, soil type, and environmental conditions, necessitating further research (39).

Numerous studies have reported that biochar enhances root morphological traits (40) and physiological characteristics (41,42) in medicinal plants. Furthermore, biochar amendments have been shown to reduce plant oxidative stress, as evidenced by reduced levels of leaf free proline and glycine betaine (43). Additionally, the biomass of *Salvia miltiorrhiza* increased with the proportion of biochar in the soil mix (ranging from 0% to 32%). Importantly, biochar supplementation resulted in a significant reduction in cadmium (Cd) content in both leaves and roots of *S. miltiorrhiza*, with decreases of 52.8% and 43.6%, respectively. Moreover, extensive research has demonstrated the efficacy of biochar in mitigating the adverse effects of drought and salt stress on various plant species (Table 2).

Conclusion

In summary, biochar has demonstrated its efficacy in mitigating the adverse effects of drought and salinity stress on medicinal plants. It enhances soil's water retention capacity, diminishes soil salinity levels, and augments nutrient accessibility, thereby fostering plant growth and development. Numerous studies have reported that the application of biochar to medicinal plants results in increased plant biomass, enhanced photosynthetic activity, and heightened accumulation of bioactive compounds. Moreover, the utilization of biochar can curtail the reliance on chemical fertilizers, which can be detrimental to both soil health and the environment. In conclusion, biochar presents itself as a promising strategy for enhancing the productivity and resilience of medicinal plant cultivation in arid and saline environments. Nonetheless, further research is imperative to fine-tune biochar application methods tailored to specific plant species and environmental conditions, as well as to assess its long-term effects on soil health and plant growth.

Authors contributions

AP: Writing–Original Draft, Review and Editing. CJ: Writing, Review, Editing. DP: Writing–Original Draft, Review and Editing. SS: Conceptualization, Review, Editing. YE: Conceptualization, Review, Editing. SB: Conceptualization, Review, Editing. DJ: Conceptualization, Review, Editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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Table 2. Efficacy of biochar in agriculture to improve plants under drought and salt stress

Biochar and its benefit	Plant(s) used for the study	Reference
Improvement of plant growth under drought condition	Spinach	(44)
Improvement of root morphological traits and growth of under salinity stress	Soybean	(45)
Enhancement of plant growth and root morphological traits under drought conditions	Okra	(46)
Improvement in plant yield in salt stress	Tomato	(47)
Mitigate drought and salt stress	Quinoa	(48)
Mitigating Drought and Salt Stress	Soybean	(49)
Improvement in plant yield and physiological properties in salt stress	Forage sorghum	(50)
Induction of drought-tolerance	Basil	(51)

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