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Biochar in Plant Science: Linking Soil Health, Root Dynamics, and Ecosystem Sustainability: A Review

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Abstract

Biochar is a stable, carbon-dense material produced through the thermal conversion of plant biomass under oxygen-limited conditions. In contemporary botanical and ecological research, biochar is increasingly regarded not only as a soil conditioner but also as an influential modifier of the plant growth environment. From a plant-centered perspective, biochar alters root–soil interfaces, nutrient availability, microbial associations, and physiological responses to environmental stress. This review integrates recent advances in biochar research with emphasis on plant–soil–microbe interactions and botanical relevance. Available evidence demonstrates that biochar enhances soil structural stability, improves nutrient retention, promotes functionally diverse rhizospheric microbial communities, and supports improved plant growth and stress adaptation. Its applications in sustainable agriculture, horticulture, forestry, and ecological restoration are critically examined, alongside current limitations and future research needs. Overall, this review positions biochar as a long-term, plant-focused strategy for advancing sustainable and climate-resilient ecosystems.

Keywords: Biochar; Botany; Plant–soil interactions; Rhizosphere; Sustainable agriculture; Climate resilience

1. Introduction

Modern botanical research increasingly recognizes plants as integral components of complex ecological systems rather than isolated biological entities. Soil serves as the primary interface through which plants obtain water, mineral nutrients, and microbial partners, thereby exerting a decisive influence on plant growth, development, and survival. Any persistent modification of soil physical, chemical, or biological properties inevitably shapes root behavior, nutrient acquisition strategies, and plant physiological performance.

Biochar, produced through the thermochemical transformation of plant-based materials, has gained increasing attention as a long-lasting component of sustainable soil and plant management systems. Renewed scientific interest in biochar emerged following studies of Terra Preta soils in the Amazon Basin, where charcoal-enriched soils exhibited remarkable fertility and long-term productivity [1,2]. These anthropogenic soils provided compelling evidence that carbonized plant residues can exert durable effects on soil–plant systems far beyond the lifespan of conventional organic amendments.

Unlike readily decomposable organic matter, biochar remains stable in soils for extended periods—often decades to centuries—owing to its condensed aromatic carbon structure [3]. From a botanical perspective, this persistence is particularly relevant for sustainable agriculture, ecosystem restoration, and climate change mitigation, where long-term improvements in plant growth environments are essential.

2. Biochar Production and Botanical Relevance

Biochar is generated from a wide range of plant-derived feedstocks, including agricultural residues, woody biomass, forest litter, sawdust, invasive plant species, and agro-industrial by-products, through controlled pyrolysis processes. The botanical origin of the feedstock plays a crucial role in determining biochar properties such as nutrient composition, ash content, surface functional groups, and pH [4]. These attributes ultimately govern how biochar interacts with soil constituents and plant roots.

Pyrolysis temperature strongly influences biochar characteristics. Biochar's produced at relatively lower temperatures tend to retain higher concentrations of labile organic compounds and mineral nutrients, whereas high-temperature biochar's are dominated by highly aromatic carbon structures, increased porosity, and enhanced chemical stability [5]. These physicochemical properties determine the behavior of biochar within soil matrices and its interactions with plant roots.

From a botanical standpoint, the porous architecture of biochar resembles natural soil aggregates and provides microsites that support root hair proliferation and microbial colonization. Such features effectively expand the functional root zone and facilitate early plant establishment, particularly in degraded or nutrient-poor soils.

3. Biochar and Soil–Plant Interactions

3.1 Soil Physical Properties and Root Development

Root growth and distribution are strongly influenced by soil compaction, aeration status, and water availability. Incorporation of biochar into soil systems has been shown to enhance aggregate stability, lower soil compaction, and modify pore distribution, thereby improving aeration and water retention [6]. These changes directly influence root penetration and spatial expansion.

Botanical studies consistently report increased root length density, enhanced lateral root formation, and greater root biomass in biochar-amended soils [7]. Improved root architecture enables plants to explore a larger soil volume, facilitating more efficient acquisition of water and nutrients and supporting overall plant vigor, particularly under marginal soil conditions.

3.2 Nutrient Dynamics and Plant Nutrition

Biochar influences nutrient cycling through adsorption, retention, and gradual release of essential macro- and micronutrients. Its high cation exchange capacity reduces nutrient losses through leaching, especially for nitrogen and potassium in sandy or highly weathered soils [8].

Enhanced nutrient retention translates into improved plant physiological performance. Increased nitrogen and magnesium availability supports chlorophyll synthesis and photosynthetic efficiency, while improved phosphorus dynamics contribute to energy transfer and root development. As a result, plants cultivated in biochar-amended soils frequently exhibit greater biomass accumulation, improved photosynthetic activity, and enhanced reproductive output [9].

3.3 Rhizosphere Processes and Microbial Interactions

The rhizosphere is a biologically active zone where plant roots interact with microorganisms and soil constituents. Biochar provides a stable carbon matrix and protective microhabitats that favor the establishment of beneficial microbial communities, including nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, and arbuscular mycorrhizal fungi [10].

These microbial groups enhance nutrient mobilization, produce plant growth–promoting compounds, and suppress soil-borne pathogens. From a botanical perspective, biochar-mediated enhancement of plant–microbe interactions contribute to improved nutrient uptake efficiency, stress tolerance, and overall plant resilience [11].

4. Biochar and Plant Stress Physiology

4.1 Abiotic Stress Tolerance

Plants are increasingly exposed to abiotic stresses such as drought, salinity, and heavy metal contamination. Biochar-amended soils exhibit improved moisture retention, allowing plants to maintain higher relative water content during drought conditions [12]. In addition, biochar can immobilize potentially toxic metals, thereby reducing their bioavailability and uptake by plant roots.

Physiological investigations report improved stomatal regulation, enhanced antioxidant enzyme activity, and reduced oxidative damage in plants grown in biochar-treated soils [13]. These physiological adjustments collectively strengthen plant tolerance to adverse environmental conditions.

4.2 Growth, Yield, and Developmental Responses

Both greenhouse and field experiments consistently demonstrate increases in vegetative growth, leaf area development, flowering intensity, and yield following biochar application [14]. These benefits are often amplified when biochar is applied in combination with composts or organic fertilizers.

From a developmental perspective, biochar supports balanced vegetative and reproductive growth by stabilizing nutrient and moisture availability within the root zone, thereby contributing to sustained plant productivity.

5. Applications from a Botanical Perspective

5.1 Sustainable Agriculture and Horticulture

Biochar is increasingly incorporated into organic and sustainable farming systems due to its compatibility with composts, biofertilizers, and reduced chemical inputs. Its long-term stability minimizes the need for repeated soil amendments, making it particularly suitable for horticultural crops, medicinal plants, and nursery production systems [15].

5.2 Forestry and Agroforestry Systems

In forestry applications, biochar improves seedling establishment, root development, and survival under stressful site conditions. Agroforestry systems benefit from improved soil moisture retention and nutrient availability without adversely affecting native plant diversity or ecosystem function [16].

5.3 Ecological Restoration and Conservation Botany

Biochar has shown considerable potential in the rehabilitation of degraded lands, mine spoils, and saline or acidic soils. By improving soil structure and nutrient availability, biochar facilitates the re-establishment of native plant species and supports long-term ecosystem recovery [17]. From a conservation botany perspective, biochar contributes to ecosystem stability and biodiversity conservation.

6. Challenges and Future Research Directions

Despite its demonstrated benefits, biochar application faces challenges related to variability in properties arising from differences in feedstock composition and pyrolysis conditions. Long-term, field-based studies are required to evaluate species-specific plant responses and ecosystem-level outcomes. Future botanical research should focus on molecular-scale interactions among plant roots, biochar surfaces, and rhizospheric microorganisms to elucidate underlying mechanisms governing plant responses [18].

7. Conclusion

From a botanical standpoint, biochar represents a multifunctional material capable of reshaping the plant growth environment through its integrated effects on soil physical structure, nutrient retention, microbial activity, and plant physiological performance. Unlike short-lived organic amendments, biochar offers sustained benefits by stabilizing plant-derived carbon within soils while supporting root development and rhizosphere functioning. Accumulating evidence confirms its role in improving nutrient use efficiency, enhancing tolerance to abiotic stress, and maintaining productivity across agricultural, forestry, and restoration systems [7,9,14].

Biochar should therefore be regarded not merely as a soil amendment but as a plant-centered ecological tool that links carbon sequestration with sustainable plant production. Its thoughtful integration into modern botanical practices offers a scientifically robust pathway toward climate-resilient ecosystems, improved soil health, and long-term plant sustainability.

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