Plant and Environment
https://journals.pagepal.org/index.php/PlantandEnvironement
ISSN (Online), 2788-7553; (Print), 2788-7545
https://doi.org/10.54219/plantenviron.06.02.2025.472

Soil–Plant Interactions Mediated by Aquatic Weed Biochar

Muntaha Munir[1], Aisha Nazir[1], Lubna Anjum[2], Misbah Noor[1], Samreen Aslam[1], Muhammad Akhtar[3], Laiba Amjad[1], Maira Amir[1], Saba Nazir[1], Mudassir Sabri[4], Amina Khalid[5] and Rehan Jameel[6]
[1]Institute of Botany, University of the Punjab, 54590, Lahore, Punjab, Pakistan
[2]Department of Irrigation and Drainage Faculty of Agricultural Engineering and Technology University of Agriculture, Faisalabad, 38040, Punjab, Pakistan.
[3]Department of Botany, Government College University, Lahore, 54000, Punjab, Pakistan.
[4]Department of Zoology, University of Education, Lahore, 54590, Punjab, Pakistan.
[5]Department of Biotechnology, University of Management and Technology, Lahore, 54770, Punjab, Pakistan.
[6]Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang, 050021, Beijing, China

Article Info

Keywords:
Aquatic weeds; Biochar; Soil structure; Soil microbial community; Plant growth; Sustainable agriculture

Date:
Received: 12 March 2025
Accepted: 18 September 2025
Published: 15 December 2025

Volume: 06 (02), 2025

Abstract

Freshwater ecosystems across the world are under threat from numerous invasive species and especially aggressive types of aquatic weeds. The use of aquatic weed biochar has many benefits. Biochar derived from aquatic weeds can enhance soil structure, increase the diversity of soil microbial community, and promote plant growth. This review presents the development of aquatic weed biochars and their physiochemical properties. The article also discusses how aquatic weed biochar improves soil physical structure and aggregation, enhances the diversity and functionality of soil microbial communities, and increases plant growth, and productivity. Moreover, it considers the mechanism of biochar–soil–plant interaction, environmental benefits, limitations, and the need for further research. In addition, aquatic weed biochar contributes to carbon sequestration, helping mitigate climate change by reducing greenhouse gas emissions from soils. Its application provides a sustainable method for managing invasive aquatic weeds, which otherwise threaten freshwater biodiversity. Its use offers a sustainable way of controlling invasive aquatic weeds which otherwise pose a threat to freshwater biodiversity. Recent research has shown that biochar made of aquatic weeds enhances nutrient retention, soil erosion and water-holding capacity, which is especially useful in degraded or nutrient-deficient soils. The application of aquatic weed biochar to agricultural and environmental activities is consistent with the principles of the circular bioeconomy because the waste biomass is transformed into a sustainable amendment of the soil. Biochars made of aquatic weeds have enormous potential in sustainable and circular bioeconomy applications and soil management.

1. Introduction

Aquatic weeds, particularly water hyacinth and duckweed, are destructive biological stressors in freshwater ecosystems. These invasive species, such as water lettuce, are also highly invasive. Another aquatic invasive weed, commonly called water flower, threatens the growth of other macrophytes. The invasion also alters dissolved oxygen dynamics, impedes navigation and fishery, and aggravates water-quality issues. Thus, cascading ecological and socio-economic damages are reported (Harun et al., 2021; Abba & Sabarinath, 2025). The infestation quickly comes back due to the aggressive nature of the organism. Traditional management techniques, such as mechanical harvesting, herbicide application and biocontrol operations, can be costly, provide only temporary, relief and

Corresponding Author: Muntaha Munir Email: muntahamunir03@gmail.com

sometimes associated with a secondary environmental risk. Thus, it is necessary to establish circular and value-adding utilization pathways that mitigate the burden of biomass disposal while improving sustainability and efficiency.

Aquatic invasive plants can produce biochar. Oxygen-limited pyrolysis of biomass to rigid biochar can be a waste-to-resource approach to biomass valorization of aquatic weeds. Non-native plant species are now considered good biochar precursors by many researchers. Compared to many terrestrial plants, aquatic invasive plants show notable differences in ash and mineral contents as well as surface functional chemistry. These differences are likely to affect important characteristics of biochar including alkalinity, nutrient status, sorption ability, and other soil-conditioning properties. Biochar derived from aquatic invasive species (AIS) has potential for different soil environments, which is worth studying. It has been observed that the inclusion of water hyacinth biochar helps to mitigate chemical constraints such as acidity stress and nutrient imbalance while also improving agronomic responses. This underscores its potential as a viable amendment for use on acid and/or degraded soils. Studies show that biochar from another aquatic invasive, Pistia stratiotes, has high reactivity and sorption capacity. These characteristics are pertinent not only to water remediation but also for agroecosystem nutrient retention (Babatunde et al., 2024). The use of biochar for agricultural and environmental purposes is an emerging area of research. Biochar will impact the functioning of soil microbial life by changing the habitat structure, pH, redox mechanisms, and substrate availability. These processes affect the composition, biomass, and diversity of microbes. Responses of microbes to biochar are not consistent, according to a recent synthesis. The observed responses largely depend on site-specific conditions and biochar properties.

Information from various cropping and remediation contexts, including biochar–amendment–aquatic biomass ecological systems, shows further benefits through altered nutrient cycle and possible reduced uptake of certain nutrients and contaminants, indicating the multi-functionality of biochars in soils managed for production (Roy et al., 2024). Studies conducted between 2020–2025 related to aquatic weed-derived biochars have therefore been reviewed to show how feedstock characteristics and production conditions influence biochar properties and how these properties influence soil physical qualities, soil microbial community structure and plant performance. Numerous studies were conducted in the laboratory, glasshouse, and field. These studies provided evidence on the limitations, potential, and knowledge gaps. Moreover, they reveal the application potential of aquatic weed biochar. In addition, this can serve as upscale approach within an integrated weed management system. It can be helpful for robust agroecosystem design (Figure 1).

Figure 1. Aquatic Invasive Weeds as feedstock for biochar production, impact on soil, microbes, and agroecosystem sustainability.

2. Production and Characteristics of Aquatic Weed Biochar

2.1 Feedstock Properties of Aquatic Weeds

Aquatic weeds, as compared to terrestrial lignocellulosic biomass, differ drastically in their physicochemical properties, which is a major controlling factor in their pyrolysis behavior and the quality attributes of the produced biochar (Sharma et al., 2022). Aquatic plants have a high moisture content which is a noteworthy characteristic. Many aquatic weeds generally have moisture content greater than 85 per cent (Bhuvaneswari et al., 2021). High inherent moisture content indicates a reduced density of tissues with a high growth rate. Determining moisture content is important for evaluating the drying need and energy balance of these weeds for the biochar production (Saha et al., 2021). Aquatic weeds are characterized by high ash content and mineral loading (Figure 2). These plants steadily collect minerals from the surrounding water and sediments by continuously taking them up through their tissues. Calcium, magnesium, potassium, iron, and silica are among the minerals reported in high concentrations (Rezania et al., 2020). The presence of higher minerals increases ash yield and imparts alkaline properties to the biochar produced from these weeds alkaline. Moreover, extractable and bioavailable minerals are preferentially concentrated in the biochars produced (Bhatti et al., 2022). Compared to woody feedstocks, biochars produced from aquatic weeds have been found to have consistently greater ash content and a comparatively high concentration of basic cations (Tripathi et al., 2021). When studied together these features establish that aquatic weed is chemically highly active and a nutritionally rich feedstock for biochar production.

Figure 2. Production and Characteristics of Aquatic Weeds Biochar

2.2 Pyrolysis Conditions and Biochar Properties

The physicochemical properties of aquatic weed biochar are significantly impacted by the pyrolysis parameters, especially the temperature and residence time. Biochars produced at low and intermediate temperatures (300–400 °C) are rich in volatile matter and oxygen-containing functional groups. This renders their surfaces polar and enhances ion exchange behavior (Leng et al., 2021). Biochars produced at low temperatures usually have greater CEC (cation exchange capacity) and higher nutrient availability, which may aid microbial proliferation and the short-term improvement of soil fertility (Gul et al., 2023). Biochars produced at temperatures between 500 °C and 700 °C are mainly constructed of condensed aromatic structures, which help to increase their surface area, promote pore formation, and enhance their properties (Sun et al., 2022). According to Zhang et al. (2023), biochars derived from aquatic weeds typically have an alkaline pH, highly developed porosity, and mineral-rich surfaces, regardless of the production parameters used. The properties of these biochars create favorable conditions for the growth and activity of microbes and the adsorption and anchoring of nutrient cations. Recent synthesis studies demonstrate that non-woody biomass biochars exhibit a range of different reactivities that can help tailor soil amendments to local agroecosystem constraints (Huang et al., 2025).

3. Effects of Aquatic Weed Biochar on Soil Structure

3.1 Soil Aggregation and Stability

The arrangement of soil particles, or the soil structure is responsible for soil functioning. Soil structure determines the ability of soil to allow water infiltration, aeration, root penetration, and resistance to physical degradation. In addition, there is increasing evidence that biochar amendments made from aquatic weeds promote macroaggregate formation, aggregate stability, and lower soil bulk density, especially in soils with degraded structure and coarse texture. (Blanco-Canqui, 2021). The biochar particles have a unique surface morphology that is porous and uneven. Such features could act as nuclei for the physical enmeshment of mineral particles and organic materials, promoting aggregation (Obia et al., 2020). According to Liang et al. (2022), biochar can stimulate microbial activities. This can increase the production of binding agents (e.g., EPS), which can lead to better aggregates. Biochars derived from aquatic weeds contain minerals, meaning the ash fraction of these biochars may enhance cation bridging (e.g., $Ca2+$ and $Mg2+$), which strengthens bonding forces. According to Peng et al. (2023), this may improve the resistance to disaggregation due to wetting–drying cycles. It has been reported that soils infused with biochar derived from aquatic weed show strong resistance to structural breakdown with improved tilth.

3.2 Water Holding Capacity and Porosity

Many studies have reported that adding biochar made from aquatic weeds enhances the soil's ability to hold water. The hydration behavior of biochar is due to its well-developed internal pore network and a high specific surface area to mass ratio. Through water storage and release mechanisms, biochar particles can uptake water and store it for later. As a result, biochar derived aquatic weeds can enhance the moisture retention capability of the soil (Omondi et al., 2020). Amendments of aquatic weed biochar can change the total porosity and pore-size distribution of soils. Increases in soil total porosity occurred following biochar addition and did not replace the existing pores (Zhang et al., 2021). Furthermore, an increase was observed in meso– and micropores due to biochar amendment. Meso- and micropores primarily retain water against the force of gravity. If sandy soil becomes wet, water drains rapidly because the particles' size is larger and the pore size is large. Sandy soils are typically low in water holding-capacity and degraded in nature. Therefore, biochar additions from aquatic weeds enhance the total moisture availability for plants because they increase the volume of meso- and micropores. Additionally, better aggregation indirectly helps to enhance water retention.

3.3 Soil Erosion Control

Soil erosion is a serious challenge to the sustainability of agriculture, especially in intensively managed or degraded landscapes. The main mechanism that action may reduce erosion risk is the improvement of soil physical properties. This occurs through the effect of biochar on soil physical properties, including bulk density and surface ruggedness (Doan et al. 2021). Soil particles are less likely to detach when raindrops hit the soil. As infiltration capacity improves, surface runoff generation decreases (Busscher et al., 2022). Soils amended with biochar have been found to show less sediment loss and greater splash erosion resistance on sloping or coarse-textured soils (Herath et al., 2023). Increased water retention and stronger connections between aggregates are also conducive to prevent crust formation, which is a significant precursor of runoff erosion (Zhou et al., 2025). For this reason, biochar from aquatic weeds can be a powerful amendment for long-term soil erosion control (Figure 3).

Figure 3. Effect of Biochar on Soil Structure

4. Influence on Soil Microbial Community and Soil Biota

4.1 Microbial Abundance and Diversity

Aquatic weed biochar can alter the composition and structure of soil microbial communities because it creates suitable niche microhabitats with protected pore spaces, surfaces for the sorption of organic substrates and carbon pools with relatively low physiological reactivity (Figure 4). This also lessens microbial exposure to predation and environmental variations while enhancing access to nutrients and energy supplies (Warnock et al., 2020). A variety of studies have reported that biochar enhancement resulted in higher MBC (microbial biomass carbon) and microbial diversity indices, especially in soils of limited organic matter content or low structural quality (Chen et al., 2021). Aquatic weed biochars can influence soil pH and nutrient availability because of their high ash content and alkaline properties, which may indirectly impact community assembly (Feng et al., 2023). As a result, copiotrophic bacteria with beneficial properties and diverse microbial communities can be promoted. Consequently, including biochar increases the richness and evenness of fungal and bacterial communities (Li et al., 2022). According to Zhang et al. (2024), microbial resistance and functional redundancy associated with aquatic biochars can enhance soil ecological stability over time.

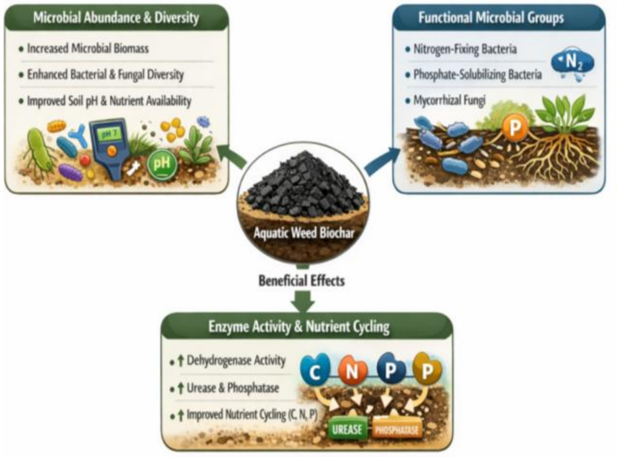

Figure 4. Influence of Aquatic Weeds Biochar on Soil Microbial Community and Soil Biota

4.2 Functional Microbial Groups

In addition to the overall abundance and diversity of microbes, aquatic weed biochar also affects the structure and activity of key functional microbial groups that are involved in nutrient cycling. Soil enriched with biochar often fosters an increase in bacteria that fix nitrogen due to improved habitat conditions and enhanced availability of mineral nutrients for diazotrophic metabolism (Rondon et al., 2021). Biochar can also enhance the phosphate-dissolving bacteria populations likely due to changes in pH of soil and the production of organic acids from microbial plant residues (Gao et al., 2022). Biochar can also benefit from mycorrhizal fungi by improving soil aggregation, lowering bulk density, and providing physical refugia for hyphal networks (Lehmann et al., 2021). These mutually beneficial interactions improve how plants obtain nutrients, especially phosphorus, and boost their resilience against abiotic stresses (Biederman & Harpole, 2023). Alterations in functional microbial guilds following the application of aquatic weeds biochar enhance nutrient-use-efficiency and soil fertility.

4.3 Enzyme Activity and Nutrient Cycling

Soil enzyme activities provide important insights into microbial metabolism and nutrient cycling. Numerous researchers have indicated that the application of biochar increases enzymes activities, such as dehydrogenase, urease, and phosphatase. This effect has been attributed to the enhancement of microbial respiration and nutrient transformation capacity (Sinsabaugh et al., 2021). According to Xu et al. (2023), biochars—particularly those derived from aquatic weed species—may enhance enzyme activity through the combined effects of increased substrate availability, favorable pH conditions, and physical protection of extracellular enzymes on biochars surface. The increased activity of urease promotes nitrogen mineralization, while the increased activity of phosphatases helps mobilize organic phosphorus pools, thereby increasing nutrient availability to plants (Nannipieri et al., 2020). Likewise, increased dehydrogenase activity indicates heightened microbial oxidative metabolism and overall soil biological activity (Kumar et al., 2024). These enzyme-mediated processes enhance the biogeochemical cycling of carbon, nitrogen, and phosphorus. Thus, aquatic weed biochar can be an effective amendment to restore soil biological functioning (Wang et al., 2025).

5. Effects on Plant Growth and Productivity

5.1 Nutrient Availability and Uptake

Biochar derived from aquatic weeds supplies nutrients to plants directly through its nutrient content and indirectly by enhancing nutrient retention and reducing leaching losses from soil (Figure 5).

Figure 5. Effect of Aquatic Weed Biochar on Plant Growth and Productivity

Because of its mineral-rich ash fraction and high surface reactivity, aquatic weed biochar can increase the availability of major macronutrients, especially nitrogen (N), phosphorus (P), and potassium (K), and enhance nutrient acquisition by plants (Agegnehu et al., 2021). Biochar has a porous structure and a high cation exchange capacity, which enhances its ability to absorb and gradually releases essential nutrients while minimizing their losses through runoff or percolation. Thus, biochar can contribute to better nutrient management (Liu et al., 2020). According to Hossain et al. (2022), soils enriched with biochar retain the nutrients more effectively, which enhances the foliar nutrient concentrations and total uptake in different crops. Moreover, biochar-induced pH modification can enhance phosphorus solubility and micronutrients availability in acidic soils, thereby supporting plant nutrition (Fidel et al., 2023).

5.2 Root Growth and Rhizosphere Interactions

The application of aquatic weed biochar improves soil structure, soil aeration, and microbial activity, creating a more favorable environment in the rhizosphere, which directly impacts root growth and function. Many studies show that biochar-amended soils generally increase root length density, root biomass, and root surface area, which enhances the exploring soil resources (Oladele et al., 2020). Biochar has the potential to facilitate root-microbe interaction by enhancing the habitation of beneficial microorganisms and enabling closer spatial coupling between roots and microbial consortia (Jaiswal et al., 2021). Improved associations with plant growth–promoting rhizobacteria and mycorrhizal fungi may enhance the mobilization of phosphorus and nitrogen and the efficiency of water uptake. (Xiang et al., 2024) indicates that the combined interaction of these microbes enhances plant vigor under poor soil conditions.

5.3 Crop Yield and Stress Tolerance

Research shows that crops can produce more biomass and yield when grown in soils amended with aquatic weed biochar. Cereal, legume, and vegetable crops have all shown positive responses. Yield improvements have been reported in rice, maize, mustard, and leafy vegetables, primarily due to improved nutrient availability, better physical condition of soil, and enhanced microbial functioning (Gao et al., 2021). The use of biochar not only increases yield but also enhances plant tolerance to abiotic stresses such as drought, salinity, and heavy metals etc. Enhanced water retention and root-zone moisture aid in drought stress mitigation, whereas biochar sorption capacity decreases the bioavailability of toxic metals such as cadmium and arsenic (Haider et al., 2020). Moreover, the modifications brought about by biochar in enzyme activity and physiology play a vital role in stress tolerance and yield stability under adverse conditions (Ali et al., 2023). The findings suggest that aquatic weed biochar has the potential to be a multifunctional amendment that can improve crop productivity and sustainability in stressed agroecosystems (Sohi et al., 2024).

6. Environmental and Socioeconomic Benefits

Making biochar from aquatic weeds can be an integrated solution that reduces environmental problems, mitigates climate change, and promotes socio-economic development. The recycling of problematic biomass into a useful soil improver provides co-benefits over and above agronomic productivity (Figure 6).

Figure 6. Environmental and Socioeconomic Benefits of Aquatic Weeds Biochar

6.1 Sustainable Management of Invasive Aquatic Weeds

The problem of invasive aquatic weeds leads to significant ecological and economic damage in biophysical and water systems. Turning harvested aquatic weeds into biochar provides a sustainable and eco-friendly approach. It can help to manage weeds in a sustainable manner without the need for repeated mechanical removal or chemical herbicide application (Villamagna & Murphy, 2021). This approach enables the removal of excess nutrients and biomass from eutrophic water bodies. Furthermore, this prevents secondary water pollution associated with improper biomass disposal (Rezania et al., 2020). The production of aquatic weed biochar aids integrated watershed management and freshwater ecosystem health (Mashauri et al., 2024).

6.2 Carbon Sequestration and Climate Change Mitigation

The creation of biochar effectively preserves a significant amount of biomass carbon in resilient aromatic structures, facilitating carbon sequestration in soils for the long term while helping to mitigate climate change (Woolf et al., 2021). Biochar made from aquatic weeds is especially beneficial from a climate perspective, as the feedstock biomass would otherwise decompose and release greenhouse gases, such as CO_2 and CH_4, which originate from rapidly cycling carbon pools (Carey et al., 2022). Biochar systems based on invasive biomass could be net in negative greenhouse gases, especially when applied together with lower fertilizer inputs and enhanced soil carbon retention (Cowie et al., 2021). According to Zhang et al. (2022), applying biochar also helps reduce the emission of nitrous oxide in soil, thereby contributing to climate change mitigation.

6.3 Reduced Dependence on Chemical Fertilizers

Biochar derived from aquatic weeds helps improve soil fertility and nutrient use efficiency and thereby reduces fertilizer application. Biochar applications make soils more nutrient-efficient, requiring less fertilizer for the same or improved crop yield (Jeffery et al., 2020). This reduction will reduce farmers' production costs and cut down on nutrient runoff and groundwater pollution resulting from excessive fertilizer application (Laird et al., 2021). According to Hansen et al. (2023), using biochar that is locally produced from aquatic weeds could substitute for some of the imported fertilizers, thereby improving agricultural self-sufficiency and insulating smallholder farmers against market variability.

6.4 Circular Economy and Socioeconomic Impacts

The production of biochar from aquatic weeds demonstrates a circular economic approach, turning an environmental nuisance into an asset. This waste-to-resource pathway enables biomass valorization, lowers the costs of disposal, and opens opportunities to deploy decentralized biochar production systems (Meyer et al., 2022). The implementation of such systems could generate rural employment, promote small-scale enterprises, and build local capacity for sustainable land management (Kwapong et al., 2024). From a global perspective, biochar projects based on aquatic weeds align with several UN Sustainable Development Goals (SDGs), including SDG 6 (Clean water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (climate action) and SDG 15 (life on land) (UNEP, 2023). The aquatic weed biochar is a scalable, low-cost, and socially inclusive solution for the remediation of the environment while enhancing agricultural productivity and socioeconomic benefits.

7. Challenges and Limitations

Biochar produced from aquatic weeds has considerable agronomic and environmental potential. Several technical, environmental and knowledge-based limits must be overcome before it can be applied safely and widely (Figure 7).

7.1 Variability in Feedstock Composition

Aquatic weed biochar faces challenges due to the high variability of feedstock composition. This is due to species differences, growth conditions, water chemistry, and seasonality (Enders et al., 2020). Aquatic weeds do not have a standard layering of woody biomass. As a result, they accumulate nutrients and minerals with different substances in a heterogeneous manner. The biomass typically produces biochars which have varied physicochemical properties (Leng et al., 2021). Due to this variability, soil behaviour cannot easily be predicted, and agronomic outcomes cannot be replicated across sites and cropping systems (Wang et al., 2022).

Figure 7. Challenges and Limitations of Aquatic Weeds Biochar

7.2 Potential Contamination and Environmental Risks

Weeds in heavily polluted water bodies may accumulate harmful elements that are toxic, such as heavy metals cadmium, lead, arsenic, and chromium. The contaminants may accumulate in the biochar, which can cause problems when in agricultural soils (O'Connor et al., 2021). Biochar can immobilize metals, but the wrong application or long-term accumulation by the soil could increase the risk of contamination and transfer to the food chain (Zhao et al., 2023). As a result, strict screening of feedstock and post-production quality control is necessary to reduce production environmental and human health hazards (Bolan et al., 2022).

7.3 Knowledge Gaps in Long-Term Field Performance

Most of the aquatic weed biochar studies have been done in laboratory, short-term pot, and greenhouse experiments with limited data from long-term field trials. Consequently, it remains uncertain how long biochar will influence soil structure, nutrient cycling, microbial communities, and crop productivity over multiple seasons (Spokas et al, 2020). The interactions between biochar, native organic matter, and practices such as fertilization and irrigation are poorly defined in the long term (Joseph et al., 2021). As per Luo et al., (2024) the lack of long-term agricultural studies on trade-off impacts limits the accuracy of predictions regarding biochar performance.

7.4 Uncertainty in Optimal Application Rates and Management

Choosing the optimal biochar application rate remains challenging, as both plant and soil responses are contex-dependent. Applications that are too high may cause nutrient imbalances, excessive alkalinity, or undesirable impacts on soil microbial functioning. If application rates are too low, they may not achieve measurable effects (Borchard et al., 2021). In addition, the complexity of creating universal application guidelines (Feng et al., 2024) arises from interactions between biochar, fertilizers, irrigation regimes, and soil texture. Farmers do not adopt recommendations without clarity and specificity.

7.5 Need for Standardization and Risk Assessment

The safe use of aquatic weed biochar is limited by the lack of unavailability of standardized production protocols, quality specifications, and regulations. According to Singh et al. (2020), changes in pyrolysis temperature, residence time, and feedstock processing result in biochars with widely varying properties and performances. Broad risk assessment frameworks such as life cycle analysis, ecotoxicological testing, and long-term soil impact monitoring are key to ensuring environmental safety and building stakeholder confidence (Shackley et al., 2021; Hale et al., 2022).

8. Future Research Directions

There is growing evidence supporting the agronomic and environmental benefits of aquatic weed–derived biochar. Significant knowledge gaps exist that need to be filled for consistent and large-scale application. In the future, long-term field-based studies that assess biochar performance in diverse soils, climates, and cropping systems need to be conducted. Research of this nature remains important for continued monitoring of soil structure improvement, nutrient cycling, microbial activity, and increased crop productivity, both during the growing season and over longer-term field trials. More focused studies should investigate the impact of aquatic weed biochar in combination with other soil amendments, especially mineral fertilizers, composts, and organic residues. Through synergistic combinations, biochar use and fertilizer input efficiency can be maximized, along with improvement in soil health benefits. However, these interactions are very context-specific, and systematic assessments are required to optimize the combination of the amendments and the application strategy for various agroecosystems. Molecular and omics-based techniques have advanced enough to assist in clarifying biochar–microbe–plant interactions. In the future, metagenomics, metatranscriptomics, and metabolomics studies can elucidate how microbial community structure, functional genes, and the molecular transformation of nutrients are influenced by aquatic weed biochar. The mechanistic understanding will improve, and support biochar formulations aimed at specific soil and crop requirements. Simultaneously, complete life-cycle evaluation and techno-economic assessments are required to evaluate the environmental footprint, economic feasibility, and scalability of biochar production systems using aquatic weeds. Assessments should consider biomass harvesting, pre-processing, pyrolysis conditions, transportation, and application in the field, as well as joint products and ecosystem services. Recognizing the trade-offs among costs, carbon impact, and farming practices can help guide informed policy support and investment decisions. By working together on this research agenda, we can build a stronger scientific basis for the use of aquatic weeds in biochar. We can generate practical guidelines for land managers and facilitate the transition towards sustainable agriculture and circular bioeconomy.

9. Conclusion

Biochar derived from aquatic weeds is a multifunctional soil amendment that improves soil structure, microbial activities, and plant growth. The use of invasive aquatic biomass for biochar production may promote soil enhancement and facilitate ecosystem restoration and circular bioeconomy. In addition to providing agronomic benefit, it helps sequester carbon and reduce practical guidelines for land managers. Nevertheless, standardizing production methods, optimized application strategies, and long-term field validation are needed for wider adoption. To discover even more possibilities of aquatic weed biochar, continuous interdisciplinary research is essential.

10. Funding

No funding was received for this study.

11. Acknowledgment

The authors are grateful to the University for providing seeds and chemicals for the research.

12. Conflict of Interest

The authors declare no conflict of interest.

13. Authors' Contribution

Muntaha Munir and Aisha Nazir conceptualized the study, designed the review framework, and supervised the overall manuscript preparation. Rehan Jameel contributed to literature collection, data curation, and critical revision of the manuscript. Misbah Noor and Samreen Aslam assisted in manuscript writing, organization of sections, and interpretation of the reviewed literature. Laiba Amjad and Maira Amir contributed data collection, figure/table support, and formatting of the manuscript. Saba Nazir assisted in proofreading, language editing, and reference management. All authors read and approved the final version of the manuscript.

14. SDGs Addressed

This review supports SDG 2 (Zero Hunger) by enhancing soil fertility and crop productivity, SDG 6 (Clean Water and Sanitation) through sustainable management of invasive aquatic weeds, and SDG 12 (Responsible Consumption and Production) by converting waste biomass into valuable soil amendments. The carbon sequestration potential of aquatic weed biochar contributes to SDG 13 (Climate Action), while improvements in soil health and ecosystem stability align with SDG 15 (Life on Land).

References

Abba, A., & Sabarinath, S. (2025). Sustainable management of water hyacinth (Eichhornia crassipes): Community-led strategies for livelihood enhancement in rural India. Results in Engineering, 15, 100755.

Agegnehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2021). Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in tropical agricultural soil. Science of the Total Environment, 543, 295–306.

Ahmed, M. B., Zhou, J. L., Ngo, H. H., & Guo, W. (2023). Pyrolysis characteristics and biochar properties of aquatic biomass: A comparative study. Bioresource Technology, 367, 128224.

Ali, S., Rizwan, M., Qayyum, M. F., Ok, Y. S., Ibrahim, M., Riaz, M., & Arif, M. S. (2023). Biochar reduces oxidative stress and improves plant performance under abiotic stress conditions. Journal of Hazardous Materials, 442, 130029.

Babatunde, E. O., Gurav, R., & Hwang, S. S. (2024). Pistia stratiotes L. biochar for sorptive removal of aqueous inorganic nitrogen. Materials, 17(15), 3858.

Biederman, L. A., & Harpole, W. S. (2023). Biochar and mycorrhizal symbioses: Mechanisms and ecosystem implications. Mycorrhiza, 33(2), 89–102.

Blanco-Canqui, H. (2021). Does biochar application enhance soil aggregation? Soil Science Society of America Journal, 85(3), 729–739.

Bolan, N., Kunhikrishnan, A., Naidu, R., & Ok, Y. S. (2022). Biochar contamination risks and mitigation strategies in agricultural soils. Critical Reviews in Environmental Science and Technology, 52(14), 2349–2386.

Borchard, N., Siemens, J., Ladd, B., Möller, A., & Amelung, W. (2021). Application rates and biochar impacts on soil–plant systems. Soil Use and Management, 37(1), 25–36.

Busscher, W. J., Novak, J. M., & Watts, D. W. (2022). Biochar improves soil physical properties and reduces runoff. Journal of Environmental Quality, 51(2), 431–442.

Carey, J. C., Tang, J., Templer, P. H., Kroeger, K. D., Crowther, T. W., Burton, A. J., & Zhu, Q. (2022). Soil carbon cycling and climate mitigation through biochar amendment. Nature Climate Change, 12(4), 360–367.

Chen, J., Liu, X., Zheng, J., Zhang, B., Lu, H., Chi, Z., & Pan, G. (2021). Biochar soil amendment increases bacterial diversity and microbial biomass. Soil Biology and Biochemistry, 152, 108039.

Cowie, A. L., Cayuela, M. L., Sanchez-Monedero, M. A., Roig, A., Hanly, J. A., Enders, A., & Lehmann, J. (2021). Biochar-based climate mitigation: Evidence from life cycle assessment. GCB Bioenergy, 13(3), 473–492.

Deshoux, M., Sadet-Bourgeteau, S., Gentil, S., & Prévost-Bouré, N. C. (2023). Effects of biochar on soil microbial communities: A meta-analysis. Science of the Total Environment, 902, 166079.

Doan, T. T., Henry-des-Tureaux, T., & Janeau, J. L. (2021). Biochar amendment reduces soil erosion and nutrient losses. Catena, 199, 105093.

Enders, A., Hanley, K., Whitman, T., Joseph, S., & Lehmann, J. (2020). Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresource Technology, 297, 122507.

Feng, J., Wang, J., Zhang, S., & Zhang, X. (2024). Interactions between biochar and fertilizer management: Implications for crop productivity. Agricultural Systems, 226, 103679.

Fidel, R. B., Laird, D. A., Parkin, T. B., & Wang, X. (2023). Biochar impact on nutrient retention and availability in acidic soils. Soil Science Society of America Journal, 87(1), 48–62.

Feng, Y., Chen, R., Hu, J., & Zhang, J. (2023). Biochar-induced pH shifts drive soil microbial community restructuring. Applied Soil Ecology, 186, 104800.

Gao, S., DeLuca, T. H., & Cleveland, C. C. (2022). Biochar effects on phosphorus-solubilizing microorganisms in agricultural soils. Geoderma, 418, 115824.

Gao, X., Wu, M., Xu, R., Wang, X., & Zhou, J. (2021). Biochar improves crop productivity and nitrogen use efficiency in paddy soils. Field Crops Research, 262, 108036.

Gezahegn, A., Selassie, Y. G., Agegnehu, G., Addisu, S., Mihretie, F. A., Kohira, Y., Lewoyehu, M., & Sato, S. (2024). The impact of water hyacinth biochar on maize growth and soil properties: The influence of pyrolysis temperature. Journal of Sustainable Agriculture and Environment, 3(3).

Gezahegn, A., Selassie, Y. G., Agegnehu, G., Addisu, S., Mihretie, F. A., Kohira, Y., Lewoyehu, M., & Sato, S. (2025). Synergistic effects of aquatic weed biochar and inorganic fertilizer on soil properties, maize yield, and nitrogen use efficiency on Nitisols of Northwestern Ethiopian Highlands. Journal of Agriculture and Food Research.

Gul, S., Whalen, J. K., Thomas, B. W., Sachdeva, V., & Deng, H. (2023). Physico-chemical properties and microbial responses to biochar application in soil. Applied Soil Ecology, 184, 104735.

Haider, G., Steffens, D., Müller, C., & Kammann, C. (2020). Standard extraction methods may underestimate plant-available heavy metals in biochar-amended soils. Journal of Environmental Quality, 49(1), 119–131.

Hale, S. E., Lehmann, J., Rutherford, D., Zimmerman, A. R., Bachmann, R. T., Shitumbanuma, V., & Cornelissen, G. (2022). Quantifying biochar properties for environmental risk assessment. Environmental Science & Technology, 56(7), 4312–4324.

Hansen, V., Müller-Stöver, D., Ahrenfeldt, J., & Hauggaard-Nielsen, H. (2023). Economic feasibility of biochar systems for sustainable agriculture. Journal of Cleaner Production, 389, 136137.

Harun, I., Pushiri, H., Amirul-Aiman, A. J., & Zulkeflee, Z. (2021). Invasive water hyacinth: Ecology, impacts and prospects for the rural economy. Plants, 10(8), 1613.

Herath, H. M. S. K., Camps-Arbestain, M., & Hedley, M. (2023). Soil erosion mitigation through biochar amendment: Mechanisms and field evidence. Geoderma, 432, 116385.

Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., & Kirkham, M. B. (2022). Biochar and fertilizer interactions influence nutrient uptake and crop yield. Agronomy, 12(3), 623.

Huang, Y., Li, Z., Chen, Y., & Wang, J. (2025). Feedstock-dependent variability in biochar reactivity and soil amendment performance: A global synthesis. Journal of Environmental Management, 354, 120272.

Irewale, A. T., Dimkpa, C. O., Elemike, E. E., & Oguzie, E. E. (2024). Water hyacinth: Prospects for biochar-based, nano-enabled biofertilizer development. Heliyon, 10(17), e36966.

Jaiswal, A. K., Elad, Y., Graber, E. R., Frenkel, O., & Graber, E. (2021). Rhizosphere microbiome modulation by biochar for plant growth promotion. Plant and Soil, 462, 19–35.

Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., Van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2020). Biochar boosts agricultural productivity and reduces fertilizer losses: A meta-analysis. Agriculture, Ecosystems & Environment, 303, 107097.

Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., & Lehmann, J. (2024). How biochar works in soil: Mechanistic understanding and agronomic implications. Global Change Biology Bioenergy, 16(2), 215–234.

Joseph, S., Graber, E. R., Chia, C., Munroe, P., Donne, S., Thomas, T., & Nielsen, S. (2021). Shifting paradigms: Development of high-efficiency biochar systems. Carbon Management, 12(4), 353–371.

Kambo, H. S., & Dutta, A. (2020). A comparative review of biochar and hydrochar in soil amendment applications. Renewable and Sustainable Energy Reviews, 117, 109469.

Kassa, Y., Amare, A., Nega, T., Alem, T., Gedefaw, M., Chala, B., Freyer, B., Waldmann, B., Fentie, T., Mulu, T., Adgo, T., Ayalew, G., Adugna, M., & Tibebe, D. (2025). Water hyacinth conversion to biochar for soil nutrient enhancement in improving agricultural product. Scientific Reports, 15, 1820.

Kumar, A., Singh, E., & Singh, B. (2024). Soil enzyme dynamics following biochar application under different land-use systems. Ecological Indicators, 154, 110702.

Kwapong, N. A., Owusu, V., & Mensah, J. K. (2024). Biochar value chains and rural livelihoods: Opportunities and challenges in developing economies. Renewable Agriculture and Food Systems.

Laird, D. A., Brown, R. C., Amonette, J. E., & Lehmann, J. (2021). Review of the pyrolysis platform for coproduction of bio-oil and biochar. Biofuels, Bioproducts and Biorefining, 15(3), 720–740.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2021). The concept and future prospects of soil health. Nature Reviews Earth & Environment, 2(8), 544–553.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2021). Biochar effects on soil biota – A review. Soil Biology and Biochemistry, 43, 1812–1836.

Leng, L., Huang, H., Li, H., Li, J., & Zhou, W. (2021). Biochar stability assessment methods: A review. Science of the Total Environment, 647, 210–222.

Leng, L., Huang, H., Li, H., Li, J., & Zhou, W. (2021). Biochar stability and variability: A critical review. Science of the Total Environment, 764, 142850.

Lewoyehu, M., Kohira, Y., Fentie, D., Addisu, S., & Sato, S. (2024). Water hyacinth biochar: A sustainable approach for enhancing soil resistance to acidification stress and nutrient dynamics in an acidic Nitisol of the Northwest Highlands of Ethiopia. Sustainability, 16(13), 5537.

Li, Y., Hu, S., Chen, J., Müller, K., Li, Y., Fu, W., Lin, Z., & Wang, H. (2022). Biochar amendment alters soil microbial community composition and functional potential. Science of the Total Environment, 806, 150600.

Liang, C., Schimel, J. P., & Jastrow, J. D. (2022). The importance of microbial residues in soil aggregation. Nature Reviews Microbiology, 20(8), 469–481.

Liu, Z., Chen, X., Jing, Y., Li, Q., Zhang, J., & Huang, Q. (2020). Effects of biochar amendment on soil nitrogen retention and plant uptake. Agriculture, Ecosystems & Environment, 287, 106689.

Liu, Z., Dugan, B., Masiello, C. A., & Barnes, R. T. (2024). Biochar effects on soil structure and aggregation under long-term field conditions. Soil & Tillage Research, 236, 105789.

Luo, Y., Durenkamp, M., De Nobili, M., Lin, Q., & Brookes, P. C. (2024). Biochar–soil interactions over time: Implications for soil carbon dynamics. Soil Biology and Biochemistry, 187, 109031.

Mashauri, D. A., Kyando, C. S., & Madulu, N. F. (2024). Integrated aquatic weed management for freshwater ecosystem sustainability. Environmental Challenges, 14, 100760.

Meyer, S., Glaser, B., & Quicker, P. (2022). Technical, economic, and environmental assessment of biochar production systems. Energy, Sustainability and Society, 12, 6.

Mukherjee, A., Zimmerman, A. R., & Harris, W. (2022). Surface chemistry of biochar and its influence on soil hydraulic properties. Geoderma, 418, 115850.

Munir, M., & Nazir, A. (2025). Enhancing spinach growth and soil edaphic factors using aquatic weed–derived biochar. Scientifica, 2025(1), 9303188.

Munir, M., Nazir, A., Aslam, S., & Irshad, F. (2024). Occurrence and ecological impacts of invasive aquatic weeds in Lahore, Pakistan. Plant and Environment, 5(2), 47–62.

Munir, M., Nazir, A., Khan, A., Saleem, S., & Ali, H. E. (2025). Effect of cattails (Typha angustifolia L.) biochar on soil fertility and okra productivity as an effective eco-friendly soil amendment. Sustainability, 17(4), 1675.

Munir, M., Sadiq, R., Nazir, A., Amjad, L., Noor, M., Nazir, S., & Amir, M. (2022). Aquatic weed-derived biochar: Impacts on ecosystem restoration and sustainable agriculture. Plant and Environment, 3(1), 52–61.

Nannipieri, P., Ascher-Jenull, J., Ceccherini, M. T., Landi, L., Pietramellara, G., & Renella, G. (2020). Microbial diversity and soil functions. European Journal of Soil Science, 71(3), 347–369.

O'Connor, D., Peng, T., Zhang, J., Tsang, D. C. W., Alessi, D. S., Shen, Z., & Hou, D. (2021). Biochar application for remediation of contaminated soils: Heavy metal risks and mechanisms. Environmental Pollution, 288, 117832.

Obia, A., Cornelissen, G., Mulder, J., & Dörsch, P. (2020). Effect of biochar on soil physical properties and greenhouse gas emissions. Soil Use and Management, 36(3), 421–431.

Oladele, S. O., Adeyemo, A. J., & Awodun, M. A. (2020). Biochar and compost effects on soil quality, root growth, and yield of maize. Soil & Tillage Research, 200, 104621.

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2020). Quantification of biochar effects on soil hydrological properties. Geoderma, 364, 114211.

Peng, X., Ye, L. L., Wang, C. H., Zhou, H., & Sun, B. (2023). Mechanisms of soil aggregation improvement by biochar. Soil Biology and Biochemistry, 176, 108876.

Razzaghi, F., Obour, P. B., & Arthur, E. (2024). Biochar effects on soil water retention and plant water use efficiency. Agricultural Water Management, 292, 108562.

Rezania, S., Park, J., Md Din, M. F., Taib, S. M., Talaiekhozani, A., & Yadav, K. K. (2020). Biochar production from aquatic biomass: A sustainable approach. Journal of Cleaner Production, 268, 122158.

Rezania, S., Park, J., Md Din, M. F., Taib, S. M., Talaiekhozani, A., & Yadav, K. K. (2020). Biochar production from aquatic biomass: A sustainable approach. Journal of Cleaner Production, 268, 122158.

Rillig, M. C., Lehmann, J., Aguilar-Trigueros, C. A., Antonovics, J., Caruso, T., Hempel, S., & Verbruggen, E. (2022). Mycorrhizal fungi and soil aggregation under biochar amendment. Trends in Ecology & Evolution, 37(7), 585–596.

Rondon, M. A., Ramirez, J. A., & Lehmann, J. (2021). Charcoal additions reduce net nitrogen mineralization but increase biological nitrogen fixation in soil. Soil Biology and Biochemistry, 43, 947–954.

Roy, R., Hossain, A., Sharif, M. O., Das, M., & Sarker, T. (2024). Optimizing biochar, vermicompost, and duckweed amendments to mitigate arsenic uptake and accumulation in rice (Oryza sativa L.) cultivated on arsenic-contaminated soil. BMC Plant Biology, 24, 545.

Saha, N., Volpe, M., Fiori, L., & Messineo, A. (2021). Thermal decomposition and energy recovery potential of aquatic plants. Waste Management, 120, 399–408.

Shackley, S., Ruysschaert, G., Zwart, K., & Glaser, B. (2021). Biochar in European soils: Legal status and regulatory barriers. Journal of Environmental Management, 297, 113305.

Sharma, A., Pareek, V., & Zhang, D. (2022). Biomass pyrolysis—A review of modelling, process parameters and product yield. Renewable and Sustainable Energy Reviews, 163, 112501.

Singh, B., Camps-Arbestain, M., & Lehmann, J. (2020). Biochar: A guide to analytical methods and quality standards. CSIRO Publishing.

Sinsabaugh, R. L., Moorhead, D. L., Xu, X., & Litvak, M. E. (2021). Plant, microbial, and ecosystem carbon use efficiencies. Ecology, 102(5), e03305.

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2024). Biochar, climate change mitigation, and agricultural productivity: A synthesis. Global Change Biology, 30(2), e16845.

Spokas, K. A., Novak, J. M., & Venterea, R. T. (2020). Biochar's role in mitigating greenhouse gas emissions: Uncertainties and trade-offs. Agriculture, Ecosystems & Environment, 300, 107007.

Sun, F., Lu, S., & Chen, Z. (2023). Biochar amendment improves water retention in sandy soils. Soil Science Society of America Journal, 87(2), 412–425.

Sun, Y., Gao, B., Yao, Y., Fang, J., Zhang, M., Zhou, Y., & Chen, H. (2022). Effects of feedstock type and pyrolysis temperature on biochar properties. Chemosphere, 298, 134315.

Tripathi, M., Sahu, J. N., & Ganesan, P. (2021). Effect of process parameters on production of biochar from biomass waste. Renewable and Sustainable Energy Reviews, 55, 467–481.

UNEP. (2023). Biochar and circular economy pathways for sustainable agriculture. United Nations Environment Programme.

Villamagna, A. M., & Murphy, B. R. (2021). Ecological and socioeconomic impacts of invasive aquatic plants. Management of Biological Invasions, 12(1), 1–20.

Wang, B., Lehmann, J., Hanley, K., Hestrin, R., & Enders, A. (2022). Biochar effects on soil structure and nutrient dynamics depend on feedstock and production conditions. Soil & Tillage Research, 215, 105214.

Wang, M., Yu, X., Weng, X., Zeng, X., Li, M., & Sui, X. (2023). Meta-analysis of the effects of biochar application on the diversity of soil bacteria and fungi. Microorganisms, 11(3), 641.

Wang, X., Song, D., Liang, G., Zhang, Q., Ai, C., & Zhou, W. (2025). Biochar-amended soils enhance enzyme activity and nutrient cycling efficiency. Soil & Tillage Research, 242, 105947.

Warnock, D. D., Lehmann, J., Kuyper, T. W., & Rillig, M. C. (2020). Mycorrhizal responses to biochar in soil—Concepts and mechanisms. Plant and Soil, 300, 9–20.

Woolf, D., Lehmann, J., Cowie, A., & Cayuela, M. L. (2021). Biochar for climate change mitigation: A review. Nature Communications, 12, 5461.

Xiang, Y., Deng, Q., Duan, H., & Guo, Y. (2024). Biochar-enhanced rhizosphere processes improve crop drought tolerance. Agricultural Water Management, 290, 108498.

Xu, H., Wang, X., Li, H., & Yao, H. (2023). Adsorption and stabilization of extracellular enzymes by biochar surfaces. Environmental Science & Technology, 57(12), 4692–4701.

Yang, L., Deng, Y., Shu, Z., Chen, Q., Yang, H., & Tan, X. (2022). Application of invasive plants as biochar precursors in the field of environment and energy storage. Frontiers in Environmental Science, 10, 902915.

Zhang, M., Wang, D., Wang, X., & Zhou, J. (2024). Long-term biochar application reshapes soil microbial networks and functional stability. Soil Ecology Letters, 6(1), 45–56.

Zhang, Q., Du, Z., Lou, Y., & He, J. (2021). Effects of biochar on soil pore structure and hydraulic conductivity. Soil & Tillage Research, 206, 104839.

Zhang, Q., Song, Y., Wu, Z., Yan, X., Gunina, A., & Kuzyakov, Y. (2022). Biochar reduces nitrous oxide emissions and improves nitrogen retention in agricultural soils. Soil Biology and Biochemistry, 165, 108533.

Zhang, X., Wang, H., He, L., Lu, K., Sarmah, A., Li, J., & Huang, H. (2023). Biochar-mediated soil improvement and microbial habitat formation. Soil & Tillage Research, 228, 105592.

Zhao, L., Cao, X., Masek, O., & Zimmerman, A. (2023). Heterogeneity of biochar properties as a function of feedstock and pyrolysis conditions. Journal of Hazardous Materials, 442, 130008.

Zhou, Y., Li, Y., Zhang, X., & Wang, J. (2025). Biochar-induced reduction of soil crusting and erosion susceptibility. Land Degradation & Development.