



Aquatic Weed-Derived Biochar: Impacts on Ecosystem Restoration and Sustainable Agriculture

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Abstract

The unregulated spread of aquatic weeds like Eichhornia crassipes, Typha angustifolia, Hydrilla verticillata, Lemna spp, and Pistia stratiotes can trigger significant ecological, agronomic, and socio-economic problems by worsening water quality, affecting water availability to farms, and disrupting the nutrient cycle. By collecting recent empirical findings and global peer-reviewed literature, this review detail the potential of biochar derived from aquatic weeds to serve as a multi-faceted tool for ecosystem restoration, and for agricultural and climate change mitigation. Due to the significant nutrient levels and the high biomass yield of aquatic weeds, they tend to be a good feedstock for biochar production. The biochar from these weeds produces a carbon-rich material with desirable physicochemical properties that improve soil structure and nutrient retention, enhance microbial activity, stimulate crop growth, and sequester carbon for the long term thus mitigating climate change. Furthermore, biochar from aquatic weeds possesses a significant sorption capacity for contaminants and excess nutrients, thus water quality is improved, and the control of eutrophication is more achievable. Alkalinity, salinity, and contaminant accumulation from the biochar may create environmental risks, thus control of feedstock pyrolysis, and other environmental variables, is very important.

1. Introduction

One of the current issues affecting the ecological situation of freshwater ecosystems worldwide is the spread of invasive aquatic weed (e.g., *Eichhornia crassipes*, *Typha angustifolia*, *Hydrilla verticillata*, *Lemna* spp. and *Pistia stratiotes*). These species that are not always intentionally introduced or with anthropogenic disturbances have proven to have a phenomenal degree of rapid growth and colonization that has resulted in major changes in aquatic environments (Kumari et al., 2021). Their unregulated proliferation is also associated with the disappearance of the indigenous biodiversity, deterioration of water quality, eutrophication, and disruption

of the hydrology and nutrient cycles, consequently reducing the availability of water to irrigation, domestic, and industrial use. Moreover, the thick growth of aquatic plants may obstruct the passage of ships, block irrigation systems, and promote the incidence of the colonies, which exacerbate the socio-economic and environmental strains (Marghade et al., 2022).

The conventional management methods such as mechanical weeding, mechanical weed elimination, application of chemical herbicides and biological control, have been extensively used to contain the spread of invasive aquatic weeds. Nevertheless, the methods are usually constrained

considerably. Mechanical harvesting is a labor intensive, expensive and one that only offers temporary remedy whereas chemical herbicides have secondary impacts on the environment e.g. toxicity to non-target organism and residual effects on aquatic life. The biological forms of control, despite being ecologically safer, are often limited in efficiency and have unwanted effects on new ecosystems. All these limitations, in turn, underline the pressing necessity of new sustainable, innovative, and economically viable approaches that would not only help to cope with invasive biomass but would also offer more ecological and farming-wide advantages (Sarkar et al., 2021; Moran et al., 2021).

In this regard, the bioconversion of invasive aquatic weeds into biochar is a multidimensional and prospective solution. Biochar is a pyrolyzed, stable material with high carbon content, which facilitates a sustainable solution of utilizing problematic biomass in a circular bioeconomy. With the creation of biochar out of the invasive weeds, it is a possibility to remove ecological pressure due to the invasiveness of weeds, heal aquatic and terrestrial ecosystems, and increase soil fertility, and benefit climate mitigation by long-term carbon sequestration (Lehmann and Joseph 2015). New studies indicate that biochar made by using aquatic weeds can enhance the chemical and physical characteristics of soil, raise the capacity to retain water, grow nutrient accessibility, cause the proliferation of crops, and adsorb environmental pollutants, such as heavy metals and an excessive amount of nutrients (Mukherjee, Zimmerman, & Harris, 2011; Beesley et al., 2011; Wang et al., 2016). Such results indicate that aquatic weed biochar is not just a waste management resource but is a revolutionary way of sustainable farming and environmental purification (Gurav et al., 2021).

Although gaining popularity, the prospect of aquatic weed biochar has not been adequately explored in several important ways. Most of the long-term ecological effects, optimal production conditions, soil-biochar-crop relationships, nutrient dynamics, and scalability to various agro-ecological situations need to be investigated. Also, issues on socio-economic aspects, such as cost-effectiveness, marketability, and policy justification are not sufficiently addressed, especially in areas that are most hit by invasive aquatic weeds. The broad implementation of this prospective approach may be hampered unless there is extensive incorporation of ecological, agronomic, and policy approaches.

This review offers an in-depth summary of the existing information on biochar based on invasive aquatic weeds, synthesizing the results of the world research, and recent empirical data of the authors. The importance is put on ecological restoration, improvement of the soil fertility,

mitigation of the contaminants, and potential of the carbon sequestration, and the ecological and socio-economic risks. It is hoped that the review will inform future studies, sustainable management practices, and policy formulation to reduce the ecological and economic consequences of the invasion of invasive aquatic weeds to the local, regional, and global levels through critical assessment of production, agronomic application, and policy frameworks. Finally, the example of aquatic weed-based biochar is a cross-cutting of ecological innovation, sustainable agriculture, and climate action and reflects the possibilities of the circular bioeconomy to turn environmental problems into opportunities.

2. Literature Search Methodology

The present review is founded on an in-depth review of peer-reviewed sources that were retrieved in Google Scholar, Web of Science, and Scopus. Systematic research used the following key words and phrases: aquatic weed biochar, water hyacinth biochar, Typha biochar, invasive aquatic plants, soil amendment, ecosystem services, and agricultural productivity, to ensure a wide, yet narrow, coverage of useful literature. English-language articles in indexed journals were reviewed to achieve scientific rigor and accessibility. Especially more focus was on the papers that have provided a detailed physicochemical characterization of biochars, their influence on soil properties and crop performance, carbon stabilization mechanisms, and their impact at the broader ecosystem level. Besides, the contributions of the authors as research studies were considered as primary empirical sources with the aim of giving continuity and contextual relevance and allowing critical synthesis. This method allowed conducting a comprehensive evaluation of existing data on the topic of aquatic weeds biochar and their possible future use in the sustainable agricultural sphere and the environment.

3. Aquatic Weeds as Feedstock for Biochar Production

Some of the unique properties of the aquatic weeds in comparison to the terrestrial biomass are high moisture content, high ash fractions and rapid growth rate of the nutrients (Table 1). Their active proliferation in the waters rich in nutrients tends to produce biochars which are enriched in basic macro- and micronutrients including nitrogen, phosphorus, potassium, calcium and magnesium giving them inherent fertilizing capabilities (Beesley et al., 2011). Nonetheless, large ash content and potential absorption of heavy metals require the careful selection and pre-treatment of feedstock to reduce the environmental impact and guarantee a stable agronomic performance (Mukherjee et al., 2011; Wang et al., 2016).

The temperature of pyrolysis is one of the major determinants of biochar. Low temperatures (300-400 °C) are better preservers of labile nutrients and reactive surface functional

The invasive aquatic weed harvest also improves hydrological processes by enhancing water circulation, increasing the penetration of light, and elevated dissolved

Table 1. Aquatic weeds used for biochar, pyrolysis conditions, and physicochemical properties

Aquatic Weed	Common Name	Pyrolysis Temp (°C)	Key Properties	Reference
<i>Typha angustifolia</i>	Cattails	450	pH 7.8, CEC 12 cmol/kg, N 1.2%, P 0.5%	Xu et al., 2020
<i>Eichhornia crassipes</i>	Water hyacinth	400	pH 7.2, CEC 10 cmol/kg, N 1.1%, P 0.4%	Beesley et al., 2011
<i>Lemna minor</i>	Duckweed	350	pH 6.9, CEC 8 cmol/kg, N 0.9%, P 0.3%	Wang et al., 2016
<i>Pistia stratiotes</i>	Water lettuce	400	pH 7.1, CEC 11 cmol/kg, N 1.0%, P 0.4%	Mukherjee et al., 2011

groups, cation exchange capacity, and nutrient availability, but higher temperatures (500-700 °C) are better at increasing aromaticity, porosity, surface area, and long-term carbon stability, but at the cost of decreasing nutrient contents (Lehmann and Joseph, 2015; Joseph et al., 2010). In the case of aquatic biochars of weed, the intermediate pyrolysis conditions are also likely to create the best balance between agronomic performance and environmental friendliness, maximizing the nutrient retention and favoring structural integrity.

The effectiveness of aquatic weed biochar as a soil amendment directly relies on these physicochemical properties, and the accumulating evidence reveals that it has considerable benefits on crop growth and crop productivity (Mehariya et al., 2021; Liao et al., 2013). Indicatively, okra plant growth parameters (plant height, biomass, and yield) were significantly boosted by *Typha angustifolia* biochar that was prepared at 600 °C, which suggests that this biochar could be used as a biofertilizer (Marghade et al., 2022). It was also found that after water hyacinth biochar is used together with inorganic fertilizers, the soil acidity, porosity and nutrient availability, and maize grain yield were enhanced over 30 % and the efficiency of nitrogen use improved (Kaur et al., 2018). Other researchers report high gains in wheat biomass and grain yield after biochar had been applied which was attributed to enhancement in the physicochemical properties of the soil. Taken together, these results are in line with the potential of aquatic weed biochars in the amendment of the soil with a sustainable cultivation of crops, especially in nutrient-deprived and acidic soils.

4. Effects on Ecosystem Health

4.1 Water Quality and Water Ecosystems Restoration.

oxygen, all of which promote the aquatic biodiversity. In addition to physical removal, biochar that is produced out of these weeds has other benefits to the ecosystem. Its high porosity, high surface area, and rich functional groups allow ammonium, phosphate, pesticides, and heavy metals to be adsorbed on it to reduce eutrophication and increase the general water quality (Beesley et al., 2011; Wang et al., 2016). A two-fold environmental result is attainable by combining weed management with biochar production, i.e., the rehabilitation of the aquatic ecosystems as well as the production of a value-added amendment to the soil (Roberts et al., 2015; Ouedraogo et al., 2021).

4.2 Greenhouse Gas mitigation and Carbon Sequestration.

Biochar in aquatic weeds can be considered a stable carbon pool, which decreases carbon emissions through decomposition biomass and over time led to carbon sequestration (Lehmann & Joseph, 2015; Mukherjee et al., 2011). These biochars when added to soils are able to regulate the activity of microbes and redox status thus reducing the release of methane and nitrous oxide.

4.3 Biodiversity Factors and Environmental risks.

Although they have advantages, aquatic weed biochars can potentially be dangerous to the environment when not properly handled as mentioned in Table 2. High PH, salinity or a contaminated environment with heavy metals may have adverse effects on soil microbial communities, plant growth and sensitive aquatic life (Li et al., 2020). Thus, risk evaluation, thorough feedstock screening, and ongoing monitoring of the ecosystems must be undertaken to ensure the optimization of the ecological effects and decrease the likelihood of undesirable effects. These risks can also be

reduced by strategic application rates and post-production therapy to make sure that the integration is safe and sustainable into the agricultural and environmental management approaches (Yang et al., 2022; Abideen et al., 2022).

5. Agricultural Effects of Aquatic Weed Biochar

5.1. Soil Physical Properties

Weed-based biochar generated in water has been found to

soil structure are essential especially to the areas that have nutrient-depleted soils or those that experience frequent soil erosion, and this is where aquatic weed biochar can play a restorative role as a soil amendment (Aslam et al., 2014).

5.2. Soil Chemical Fertility

Along with the physical enhancements, aquatic weed biochars also have positive changes to the soil chemical. The

Table 2. Ecosystem services versus potential environmental risks

Ecosystem Service	Positive Effect	Potential Risk	Reference
Water purification	Adsorption of nutrients and metals	Release of adsorbed contaminants	Beesley et al., 2011
Carbon sequestration	Long-term soil C storage	Altered microbial activity	Lehmann & Joseph, 2015
Biodiversity support	Improved aquatic habitats	pH and salinity stress	Wang et al., 2016

Table 3. Effects of aquatic weed biochar on soil physical, chemical, and biological traits

Trait	Effect of Biochar	Reference
Bulk density	Decrease	Chang et al., 2021
Water holding capacity	Increase	Barna et al., 2020
Soil pH	Increase	Hammam et al., 2022
Organic C	Increase	Ghosh & Maiti, 2021
Microbial biomass	Increase	Mukherjee et al., 2011

enhance the physical properties of soil drastically particularly in degraded soil, sandy soil and compacted soil. Their porous network and the high surface area improve the soil aggregation, the total porosity, and water retention capacity, which facilitate deeper and more extensive root growth (Joseph et al., 2010; Burrell et al., 2016). This also leads to increased resilience to drought or intermittent irrigation in the face of limited water availability as increased soil water-holding capacity leads to less stress on water by the plants, and enhanced crop performance (Blanco-Canqui et al., 2017; DONG and Lin, 2021). In addition, the amendments of biochar can enhance the bulk density of soils, as well as decreasing soil compaction in the long run and providing a better soil environment in the form of aeration, nutrient transport, and microbial settlement. Such modifications in the

use of biochar can elevate the pH of the soil which removes acids thus in addition to the capacity of cation exchange (CEC) and retention of nutrients, leaking of vital elements is also reduced (Das et al., 2020; Sun et al., 2019). The use of biochars that are rich in nutrients like typha, water hyacinth has been reported to increase the availability of nitrogen, phosphorus, potassium and micronutrients in the soil.

5.3. Soil Biological Responses

The effects of aquatic weed biochar on soil biological activity are also considerable, and it increases microbial biomass, the enzymatic activity, and the health of the soil (Table 3). The porosity and surface functional groups of biochars hosts microorganisms, making biochar be colonized and

establishing favorable interaction between plants and microorganisms, such as nutrient cycling and disease control (Mukherjee et al., 2011; Beesley et al., 2011). Feedstock type, pyrolysis temperature, particle size and application rate, however, affect the magnitude of the biological responses. As an example, intermediate temperatures of pyrolysis conserve labile carbon and functional groups, which act as microbial food, whereas too high temperatures can lower biochar bioavailability and bioactivity through microbial stimulation. These mechanisms make aquatic weed biochars useful in the management of sustainable soil fertility, and add to long-term soil productivity, resilience, and ecosystem functionality (Masto et al., 2013).

6. Conceptual Framework and Circular Bioeconomy Perspective

Combination of aquatic weeds and biochar production is a promising route towards restoration of the ecosystem and sustainable agriculture. The conceptual framework, which is shown in Figure 1, is based on the idea that the invasive aquatic weeds will be transformed into biochar, which can further be used to sustain soil enhancement, carbon capture, and the increase in crop yield. This model highlights that there are two advantages to reducing the spread of aquatic weeds and producing a value-added harvest that enhances the health of soil and the sustainability of agriculture.

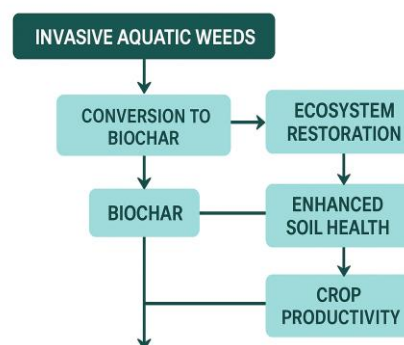
In a circular bioeconomy view, nutrient and carbon cycling of water bodies to the agricultural soils through biochar makes it a closed system which maximizes the efficiency of resources and the services of the ecosystem (Figure 2). The nutrients in the weeds that grow in water are recycled into productive agrarian soils, which lowers the use of synthetic fertilizers, lowers the amount of nutrient run off, and at the same time enhances water quality in the freshwater ecosystems (Lehmann and Joseph 2015). This methodology is the best example of sustainable practices in production because it connects waste valorization, restoration of the ecosystem, and increased agricultural yields.

Pyrolysis temperature has a high impact on the functionality of aquatic weed biochar because it can affect its ability to retain nutrients, surface chemistry, and structural stability (Figure 3). Biochars with low temperature (300-400°C) are more labile nutrients and active functional groups, which are better absorbed in the soil and promote microbial activity, whereas high temperature biochars (500-700°C) are more aromatic, porous, and carbon stable (Mukherjee et al., 2011; Beesley et al., 2011). There is flexibility in matching the restoration objectives of ecosystems to crop productivity and soil management as the optimization of pyrolysis conditions results in biochars that can be used in particular agricultural and environmental purposes.

Combined with the figures and the corresponding framework, they indicate the promise of the aquatic weed biochar to unite ecological, agronomic, and economic goals to act as one of the pillars of the circular bioeconomy strategies that enhance sustainability within the aquatic and terrestrial systems.

Flow chart (Figure 1) on the conversion of invasive aquatic weeds to biochar and its further use in restoration of ecosystems, as well as in agriculture that is sustainable. The

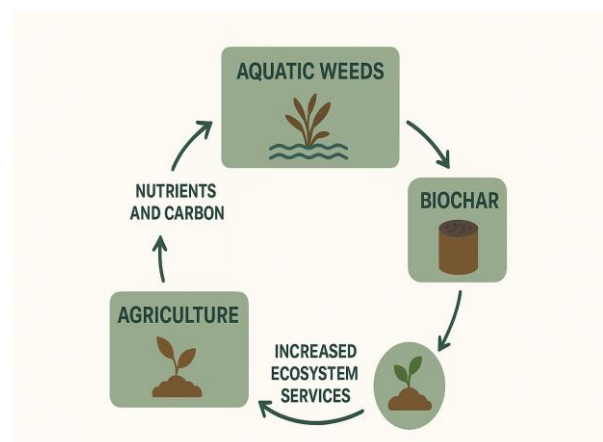
Figure 1. Aquatic Valorization of Weed Conceptual Framework.



framework demonstrates the way in which biochar can enhance soil health, crop productivity and assist in carbon storage, which gives a comprehensive understanding on how to combine aquatic weed management with agriculture sustainability (Carvalho et al., 2022).

Demonstration of the flux of nutrients and carbon in the aquatic ecosystems into agricultural soils through the production of biochar (Figure 2). This model emphasizes recycling of the nutrients in a closed loop, reduces reliance on synthetic fertilizers, reduced eutrophication, and increased

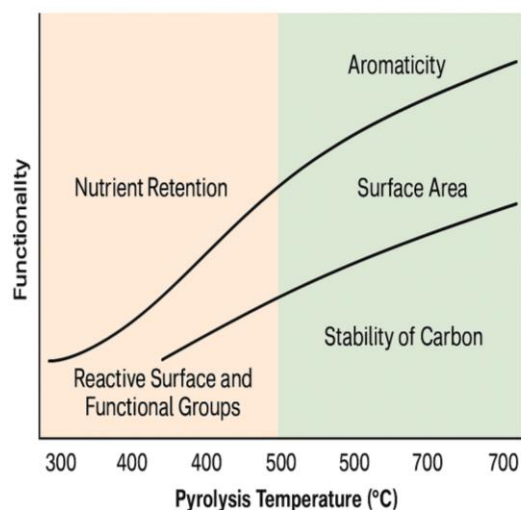
Figure 2. Aquatic Biochar Circular Bioeconomy Model.



ecosystem services, which indicates the connection of aquatic weed biochar to the development of a circular and sustainable bioeconomy (Lehmann and Joseph, 2015).

Plot (Figure 3) of possible correlation between pyrolysis temperature and the important biochar characteristics. Low temperature biochars (300–400 °C) are more conducive to the retention of nutrients and reactive surface and functional groups and high temperature biochar (500–700 °C) is more conducive to aromaticity, surface area and long-term stability of carbon (Carvalho et al., 2022). The best pyrolysis parameters enable the optimization of the biochar properties to meet the agricultural and environmental uses (Mukherjee et al., 2011; Beesley et al., 2011).

Figure 3. Effects of Temperatures on Pyrolysis on the Functionality of Biochar.



7. Gap in Research and Future Projections

Although there is an increase in interest in biochar obtained using aquatic weed, a few gaps in the knowledge base are still critical. First, there is a lack of long-term field research evaluating crop-specific responses and ecosystem-level impacts and thus we have limited information of its longer-term agronomic and ecological consequences. Second, the life-cycle assessments should be conducted in detail to allow quantifying possible carbon sequestration benefits, as well as environmental trade-offs, such as nutrient leaching or greenhouse gas emissions. Third, the contemporary information on the dynamics of contaminants such as heavy metals, organic pollutants, and residual agrochemicals in aquatic weed biochar is not adequate (Wang et al., 2016), which is a cause of concerns about its safe usage. Lastly, biochar production, physicochemical characterization and

application rates are not standardized, and this prevents reproducibility and large-scale adoption. The gaps need to be addressed in future studies, but at the same time, a study of the regional policies and incentive initiatives that can be used to enable a sustainable application of aquatic weed biochar in agricultural and environmental practices should be undertaken.

8. Policy and Sustainability Implications

Policies promoting the adoption of aquatic weed-derived biochar offer a multifaceted strategy to address environmental, agronomic, and climate-related challenges. By incentivizing the removal and utilization of invasive aquatic plants, such policies can directly support ecosystem restoration while simultaneously generating value-added products for agriculture (Abdullah et al., 2021; He et al., 2022). Key supportive measures may include the establishment of decentralized pyrolysis facilities to process biomass locally, the formulation of robust quality and safety standards for biochar, and the integration of aquatic weed valorization within broader circular bioeconomy frameworks. These interventions are particularly critical in regions reliant on surface water agriculture, where uncontrolled proliferation of invasive weeds threatens both water quality and crop productivity (Chukwuka et al., 2020; Serelis et al., 2021). Furthermore, policy mechanisms that align financial incentives, technical support, and environmental regulations can facilitate large-scale adoption, ensuring that biochar applications contribute to sustainable soil management, carbon sequestration, and climate mitigation. Collectively, such policy-driven approaches can transform ecological liabilities into socio-economic and environmental assets, promoting resilient agricultural landscapes and long-term sustainability.

9. Conclusion

Aquatic weed-derived biochar presents a versatile and sustainable solution for environmental restoration and climate-smart agriculture. Extensive empirical evidence, including findings from recent studies, highlights its capacity to enhance soil fertility, stimulate crop productivity, sequester atmospheric carbon, and reduce nutrient runoff, thereby mitigating eutrophication in aquatic systems. Optimizing production methods, dosage, and field application is critical to maximize agronomic and environmental benefits while minimizing potential ecological risks. Within the framework of a circular bioeconomy, the valorization of invasive aquatic weeds into biochar offers a dual advantage: it addresses the persistent problem of invasive species management and contributes to resilient, multifunctional agro-ecosystems. Collectively, these attributes underscore the potential of aquatic weed

biochar as a strategic tool for integrated soil and water resource management, supporting both sustainability and ecosystem restoration goals.

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12. Conflict of Interest

The authors declare no conflict of interest.

13. Authors' Contribution

Muntaha Munir conceived and designed the study, performed the experiments, analyzed the data, and wrote the original manuscript draft. Aisha Nazir supervised the research work, contributed to study design, and critically revised the manuscript for intellectual content. Rukhsana Sadiq assisted in experimental work, data collection, and preliminary analysis. Misbah Noor contributed to data interpretation, literature review, and manuscript editing. All authors read and approved the final manuscript.

14. SDGs Addressed

This study directly addresses SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production) by utilizing aquatic weed-derived biochar to enhance soil fertility, improve crop productivity, and reduce reliance on chemical fertilizers. Additionally, it contributes to SDG 13 (Climate Action) by promoting carbon sequestration and mitigating environmental stress. Indirectly, the work supports SDG 6 (Clean Water and Sanitation) by improving water quality through nutrient and contaminant adsorption.

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