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Review

A Review on Harnessing the Invasive Water Hyacinth (*Eichhornia crassipes*) for Use as an Agricultural Soil Amendment

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Abstract: Water hyacinth (*Eichhornia crassipes*) is a globally invasive aquatic weed with high biomass productivity and nutrient content, offering potential as a low-cost organic soil amendment. This review synthesizes findings from 35 studies identified through a structured Web of Science search, examining its use as mulch, compost, biochar, and foliar extract. Reported agronomic benefits include improvements in soil organic carbon, nutrient availability (particularly nitrogen and potassium), microbial activity, and crop yields. However, most studies are short-term and conducted under greenhouse or pot conditions, limiting field-scale generalizability. Additionally, reporting of compost composition and contaminant levels is inconsistent, raising concerns about food safety. While logistical and economic feasibility remain underexplored, emerging evidence suggests that with proper processing, water hyacinth amendments could reduce fertilizer dependence and contribute to circular bioeconomy goals. Future research should prioritize field trials, standardized production protocols, and life cycle assessments to evaluate long-term performance, risks, and climate benefits.

Keywords: water hyacinth; organic soil amendment; invasive species management; circular bioeconomy; bioresource reuse; nutrient cycling; sustainable agriculture

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1. Introduction

Organic mulches and composts can improve soil health by helping to regulate soil temperature, reduce water evaporation, and minimize erosion by providing a protective cover over the soil surface [1–3]. Composts, rich in decomposed organic matter, contribute to soil structure by increasing aggregate stability and porosity, promoting better aeration and water infiltration [3]. As organic amendments are decomposed, they also supply nutrients such as nitrogen, phosphorus, and potassium in plant-available forms, boosting fertility while reducing reliance on synthetic fertilizers [4–6]. Furthermore, organic amendments enhance microbial activity and biodiversity, which can help support processes like nutrient cycling, organic matter decomposition, and disease suppression [4,7,8]. Organic inputs can also increase soil organic carbon, which not only improves soil structure but also contributes to long-term carbon sequestration [9–11].

While mulches from tree biomass or crop residues are common and generally readily available, they usually have relatively high carbon:nitrogen levels compared to non-lignin amendments or composts supplemented with nitrogen-rich feedstocks [12,13]. As an alternative, water hyacinth (*Eichhornia crassipes*), a fast-growing, nutrient-rich invasive aquatic macrophyte, offers both opportunities and challenges [14–16]. Widely known for clogging waterways, disrupting ecosystems, and impeding human activities, water hyacinth presents a major ecological and economic burden [14]. Traditional control methods such as herbicide application and physical removal are often unsustainable [14]. A more circular approach involves repurposing harvested water hyacinth for agricultural use through composting, biochar production, or direct mulching [16–18]. These uses not only address biomass disposal but also contribute to nutrient cycling. However, the effectiveness of water hyacinth-based amendments remains uncertain across different soils, crops, and environmental conditions [19]. Despite these possibilities, questions remain about the effectiveness of water hyacinth-based amendments under different soil types, cropping systems, and environmental conditions.

Soil amendments improve soil health by modifying its physical, chemical, or biological properties. Organic amendments, such as compost, green manure, and mulches, enhance soil structure by increasing aggregate stability, porosity, and water-holding capacity [4]. They also supply nutrients as they decompose and support microbial activity, which drives nutrient cycling and organic matter turnover. Inorganic amendments, such as synthetic fertilizers, lime, or gypsum, are used to supply specific nutrients, correct soil pH, or improve soil structure in sodic or degraded soils. Biochar can improve nutrient retention and reduce leaching losses due to its high surface area and cation exchange capacity [20,21]. However, the effectiveness of any soil amendment depends on the characteristics of the soil, cropping system, and environmental conditions. For example, sandy soils may benefit more from amendments that improve water retention, while heavy clay soils may need amendments that enhance drainage and aeration [5,22]. High-input cropping systems may demand amendments with readily available nutrients, whereas low-input or organic systems may prioritize long-term nutrient release and microbial benefits [23–25]. Climate factors such as rainfall and temperature also influence decomposition rates, nutrient availability, and microbial activity, further affecting amendment performance [23,26]. A good soil amendment is therefore one that is suited to the local context, improving fertility or structure without introducing contaminants or causing imbalances, and contributes to long-term soil function and sustainability [27–29].

Understanding how water hyacinth-based amendments influence soil processes is crucial if its use in agriculture is to be beneficial and sustainable. Soil microbial communities play a central role in mediating nutrient cycling, organic matter decomposition, and plant health [30–32]. The diversity and composition of microbial communities, along with their functional traits, are indicators of soil ecosystem health and resilience [33,34]. Investigating how these communities respond to water hyacinth amendments can provide insights into the mechanisms driving soil improvement and identify potential trade-offs [35]. Furthermore, if the mulch alters soil nutrient cycling and this improves nutrient retention, then this may result in enhanced nutrient use efficiency and reduced environmental losses [1]. Despite the growing interest in using invasive biomass as a resource, systematic understanding of the agronomic and ecological impacts of water hyacinth amendments remains limited.

To address these gaps, this report presents a literature review that aims to synthesize current evidence on the use of water hyacinth as a soil amendment, evaluating its effects on soil structure, nutrient availability, and microbial assemblages. In doing so, it seeks to identify key benefits, limitations, and research gaps to inform future applications and research directions. This literature review seeks to inform the following questions:

1. Where and how has water hyacinth been used as a soil amendment?
2. How have water hyacinth-based soil amendments ameliorated soils via the alteration of soil structure, nutrient availability, and soil microbe assemblages?

2. Methods

To identify potentially relevant scientific publications, the following search string (examining all fields) was used to identify all records in the Web of Science database:

("water hyacinth" OR "Eichhornia crassipes") AND "Soil" AND ("amendment" OR "conditioner" OR "improvement" OR "structure" OR "texture" OR "porosity" OR "nutrients" OR "microb*") AND "agricultur*"

This yielded 76 results, which were then further refined using their abstracts to determine their relevance to informing the above questions. Contaminant remediation uses were excluded, as were studies that did not involve an assessment of the influence on soil or plant growth of a water hyacinth product as an agricultural amendment. After screening abstracts, 35 studies were included in the review (Figure 1).

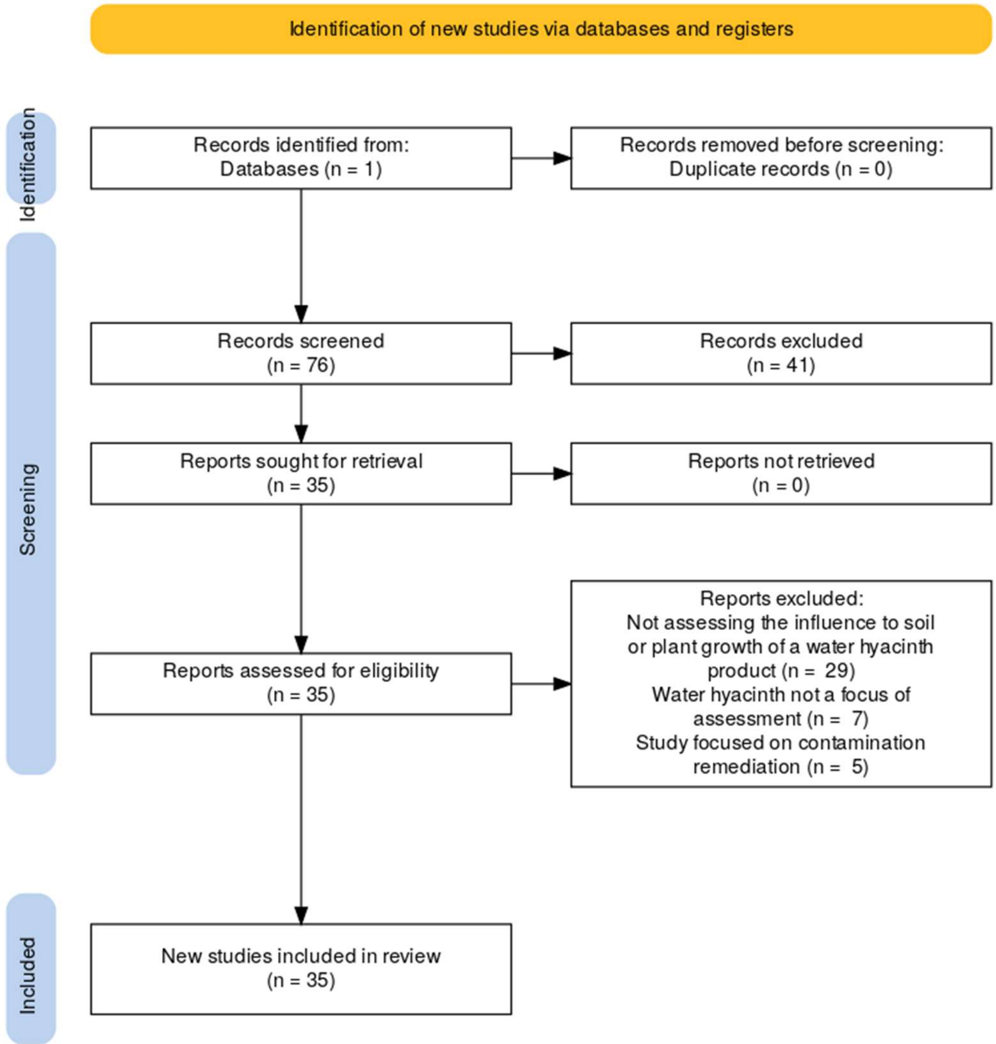

Figure 1. PRISMA flow diagram for the systematic review of the Web of Science database, including the number of abstracts screened and the full texts retrieved.

3. Characteristics and Agronomic Use of Water Hyacinth-Based Amendments

3.1. Nutrient Composition and Properties

Water hyacinth (*Eichhornia crassipes*) contains a range of nutrients relevant for soil fertility, including nitrogen (0.7–1.9%), phosphorus (0.1–0.3%), potassium (1.4–2.7%), calcium, magnesium, and trace elements such as iron and zinc (Tables 1 and 2). When processed into compost or biochar, these values vary depending on the blend, processing method, and growth environment. Composts and vermicompost typically report CEC values from 76 to 118 and C:N ratios around 14–16 when blended with bulking agents (Table 1). Biochar produced at lower pyrolysis temperatures (300–400 °C) retains more nitrogen and CEC, whereas higher temperatures (>600 °C) enhance stability, surface area, and liming potential (pH > 10) but reduce nutrient content (Table 2). Water hyacinth's moderate C:N ratio (~30:1) allows composting with minimal carbon supplementation, though many studies co-compost with sawdust or manure to optimize decomposition. As water hyacinth accumulates nutrients directly from aquatic environments, it also concentrates metals, particularly iron, zinc, and manganese. In some cases, elevated concentrations of copper, lead, or nickel were recorded, with higher bioavailability in soils and crops treated with drum composts. The presence and concentration of these elements vary by location, making site-specific testing essential before field application. While water hyacinth-based products offer agronomic potential through nutrient supply, pH buffering, and soil conditioning, their effectiveness and safety depend on processing methods and contaminant screening.

Table 1. Summary of nutrient compositions for the different feedstocks and composts reported in studies in this section. WH is the water hyacinth feedstock, while comp is compost, vcomp is vermicompost, drum is drum compost, and CEC is cation exchange capacity.

Factor	WH [36]	Comp [36]	Vcomp [36]	WH [37]	Comp [37]	Drum [38]	Vcomp [38]
TOC (%)	-	-	-	2.6	6.88	3.8	4.6
TKN (%)	1.75	1.91	1.99	1.23	0.5	0.38	0.76
Total P (%)	0.29	0.32	0.37	0.1	0.14	0.15	0.25
Total K (%)	1.61	1.77	1.83	2.69	0.06	0.2	0.3
C:N Ratio	31	16	14	2.11	14.6	-	-
C:P Ratio	190	97	76	-	-	-	-
Fe (mg/kg)	7203	10,080	10,385	-	-	363	14
Cu (mg/kg)	14	30	35	-	-	78.1	5.6
Zn (mg/kg)	62	105	113	-	-	73.4	12.2
Mn (mg/kg)	1002	1526	1697	-	-	56.6	7.5
CEC	76	105	118	-	-	-	-

3.2. Application Methods

3.2.1. Mulch and Direct Application

Water hyacinth (*Eichhornia crassipes*) has been tested as a mulch or direct organic fertilizer in various cropping systems. These studies explore its effects on soil fertility, plant productivity, and pest suppression—particularly nematodes. For example, Hernández-Fernández et al. [39] evaluated different quantities of dried water hyacinth in combination with red ferralytic soil for cultivating common chilli (*Capsicum annuum*) in Cuba. A 400 g application significantly increased fruit yield (7.5 $\pm$ 1.8 fruits/plant) compared to the control (0.2 $\pm$ 0.2). Higher application rates did not yield any additional benefits. While promising, the study lacked information on the nutrient profile of the water hyacinth or baseline soil properties, limiting insight into mechanisms behind yield improvement.

Majee et al. [40] also reported increased plant growth when using an organic fertilizer composed of water hyacinth, rice husk ash, and steamed bone meal for growing potted marigold (*Tagetes* spp.) in India. The amended soils produced plants with greater length compared to the control. However, the absence of treatment replication and elemental analysis considerably limits the reliability of the findings and their applicability.

In addition to improving crop growth, water hyacinth has also been trialed as a mulch for pest suppression. Khan et al. [41] examined the use of mulch made from billygoat weed (*Ageratum conyzoides*) or water hyacinth, and the inoculation of the nematophagous fungus *Pochonia chlamydosporia*, to control root-knot nematode (Meloidogyne incognita) in chickpea (*Cicer arietinum*). The study, conducted under glasshouse conditions in India, found that the combined application of *P. chlamydosporia* and water hyacinth mulch resulted in a significant reduction in the number of galls (14.20 ± 1.41) compared to the control (112 ± 7), although it was less effective than billygoat weed (*Ageratum conyzoides*) mulch. Despite water hyacinth being the least effective treatment, all amended treatments outperformed the control, demonstrating that water hyacinth mulch can contribute to nematode management.

Biodegradable mulch formulations using water hyacinth and coconut coir have also been evaluated for their ability to support short-cycle crops by modifying the soil microclimate [42]. In a study on horenso (*Spinacia oleracea* L.), all tested mulch compositions (40–80% water hyacinth) reduced soil temperature by 1–2 °C and maintained soil moisture between 63–84%. While no significant differences were found among mulch types, all outperformed the control, increasing fresh shoot weight by 38–55%, fresh root weight by 55–94%, and dry shoot weight by 1.6–2.8 times [42]. These results suggest water hyacinth-based mulch can enhance early crop performance while offering a biodegradable alternative to plastic.

Ramdas et al. [43] investigated the medium-term effects of various organic and inorganic nutrient sources on soil organic carbon (SOC), carbon accumulation, and microbial and enzyme activities in flooded rice plots in India. Treatments included vermicompost, glyricidia and eupatorium (GE), dhaincha (SR), farmyard manure (FYM), a mix of dry paddy straw and water hyacinth (PsWh), and mineral fertilizers. The PsWh treatment notably increased SOC levels, comparable to those achieved with FYM and exceeding untreated controls as well as GE and SR treatments. The PsWh treatment also showed an increase in soil microbial biomass, greater than GE, SR, and mineral fertilizers, though FYM remained superior in supporting microbial biomass. In terms of microbial efficiency, PsWh exhibited a lower metabolic quotient compared to mineral fertilizers and untreated controls, suggesting a more efficient microbial community under PsWh. Enzyme activities, particularly dehydrogenase and phosphatase, were elevated in the PsWh treatment. While dehydrogenase activity was lower than FYM, it surpassed levels found in mineral fertilizers, GE, and untreated controls. Phosphatase activity was high, second only to FYM, and higher than that observed in soils treated with vermicompost, GE, SR, and the control. Urease activity was similar across most treatments, with PsWh showing comparable levels to FYM. Combining paddy straw and water hyacinth enhances SOC, microbial biomass, and enzyme activities, often outperforming other amendments. The increased phosphatase activity may improve phosphorus mineralization, addressing phosphorus's tendency to bind with soil particles and become less available to plants. Typically, only a small fraction of applied phosphorus remains plant-available, depending on soil characteristics. Phosphatase facilitates the release of bound phosphorus, improving availability for crops. If water hyacinth reliably elevates phosphatase, it may be a useful tool in nutrient management, particularly for improving phosphorus availability.

Similarly, a long-term field study by Mahajan et al. [44] assessed soil quality and productivity in lowland rice under different nutrient management strategies, including treatments combining paddy straw and water hyacinth. The study found that water hyacinth-based amendments improved soil quality indicators such as microbial biomass carbon, phosphatase activity, and nutrient availability. While farmyard manure achieved the highest score using their soil quality index, the paddy straw and water hyacinth treatment ranked closely, outperforming green manures and mineral fertilizers. This supports the potential of water hyacinth to enhance soil function and sustainability when used in organic nutrient management systems.

3.2.2. Compost and Vermicompost

Water hyacinth can be processed into compost or vermicompost to produce organic amendments that improve soil fertility and crop productivity. Composting typically involves aerobic microbial decomposition, often with bulking agents such as straw or manure. Vermicomposting involves earthworms, which enhance fragmentation and microbial turnover, often resulting in amendments with finer texture, higher microbial biomass, and more rapid nutrient release. Several studies directly compare WH compost and vermicompost, while others focus on only one approach. Outcomes depend heavily on feedstock composition, co-substrates, composting conditions, and local environmental factors.

A. Comparative Studies of Compost and Vermicompost

Patra et al. [36] composted five types of organic waste—leaf litter, water hyacinth, cauliflower waste, coir pith, and mushroom spent—both with and without earthworms (*Eisenia fetida*), using cow dung as a co-substrate at a 5:1 ratio. Nutrient compositions of water hyacinth compost and vermicompost were similar, but the vermicompost had higher bacterial abundance and lower fungal abundance. This shift in the bacteria-to-fungi ratio has implications for nutrient cycling and carbon dynamics: bacterial-dominated soils support rapid nutrient turnover, while fungal-dominated soils promote carbon stability and aggregation. In general, soil disturbances such as tilling promote bacterial-dominated soil assemblages, while stable, lignin-rich soils support greater fungal abundance. Additionally, long-term incubation studies in Bangladesh have shown that nitrogen mineralization from water hyacinth compost is temperature-dependent, with slower nitrogen release compared to manures like poultry litter or vermicompost [45]. This has implications for synchronizing nutrient availability with crop demand in tropical climates, highlighting the need to consider environmental conditions when selecting organic amendments.

Goswami et al. [38] compared drum-composted water hyacinth, livestock manure, and vermicompost as soil amendments for intensively cultivated tomato and cabbage crops over an 80-day trial in Tezpur, India, using NPK fertilizer (75–60–60 kg/ha). Soil quality was assessed through nitrogen, organic carbon, Bray's phosphorus, exchangeable potassium, microbial biomass, humification (aromatic/aliphatic C), and metal bioavailability. Crop quality was evaluated via growth, yield, nutrient density, and metal content. The WH compost was produced by composting a wet-weight mixture of six parts water hyacinth, three parts cattle manure, and one part sawdust in a rotary bin for 30 days. Although nutrient concentrations were similar across amended soils, tomatoes grown with WH compost and vermicompost had higher yield, longer shelf life, and thicker pericarp than those grown with manure. Cabbage size and shape also improved under WH treatments. Notably, the WH drum compost had the highest heavy metal concentrations, likely due to uptake during growth, resulting in greater bioaccumulation in soils and crops. This highlights the influence of both compost formulation and feedstock origin on agronomic outcomes and food safety.

B. WH Compost: Soil and Crop Responses

Shyam et al. [37] examined whether water hyacinth compost can be improved by the addition of pond sediment as a bulking agent. They compared three treatments: (1) water hyacinth without pond sediment; (2) 1:5 mixture of pond sediment to water hyacinth; and (3) a 1:2 mixture of pond sediment to water hyacinth. Prior to composting, the water hyacinth was rinsed, sun dried for 24 h and mulched into 3–5 cm fragments. They found the 1:5 mixture yielded a compost with the greatest level of available nutrients. They also cautioned that composts using aquatic macrophytes and pond sediments should be tested for the presence of heavy metals prior to field application. Nutrients within water hyacinth and pond sediment are likely to vary between locations, potentially limiting the wider applicability of this study. The nutrient contents of the raw materials and composts are in Table 3.

Bhatti et al. [46] conducted a replicated field trial in Pakistan to compare the effects of composts from different plant wastes (including water hyacinth), mineral fertiliser, and untreated controls on fodder maize. All composts were applied at 15 t/ha and co-composted with cattle manure at a 3:1 ratio. WH compost increased plant height, stem girth, and fresh biomass by 20–25% over controls. Nitrogen, phosphorus, and potassium levels in maize leaves increased by 46%, 27%, and 38%, respectively. However, the composting process was poorly described and the source of WH and final nutrient content were not reported. This omission makes it difficult to determine how WH contributed to the observed effects and whether the results are transferrable to other contexts.

In the Philippines, a locally produced water hyacinth-based compost (GIDI organic fertilizer) was tested on corn under field conditions using a randomized block design with five treatments [47]. Application of 3000 kg/ha significantly increased plant height, ear length and diameter, kernel count, thousand seed weight, and grain yield (4.07 t/ha), outperforming both untreated controls (1.8 t/ha) and lower application rates. While ear height and number of ears per plant were not significantly affected, the results suggest water hyacinth compost provides key macronutrients (N, P, K) and supports beneficial microbial activity. However, the study did not report compost nutrient content or soil changes, limiting broader inference.

C. WH Vermicompost: Formulation and Performance

Yadav and Garg [48] evaluated earthworm performance in vermicompost systems using eight different bedding mixtures of cow dung (CD), fine inert soil (FIS), water hyacinth (WH), and parthenium (PH). WH was included in Vermibins 2, 3, 4, and 8, while Vermibins 1, 5, 6, and 7 excluded WH. Among WH-containing treatments, Vermibin 8 (25% CD, 25% FIS, 25% WH, 25% PH) performed best, achieving a maximum worm biomass of 980 mg worm^{-1}, a net gain of 715 mg worm^{-1}, and a growth rate of 12.76 mg worm^{-1} day^{-1}. Vermibins 2–4 also showed strong growth performance, with net biomass gains ranging from 601–680 mg worm^{-1} and growth rates of 10.70–11.25 mg worm^{-1} day^{-1}. Among the non-WH bins, Vermibin 1 (100% CD) yielded the highest maximum biomass (990 mg worm^{-1}) and the fastest growth rate (16.97 mg worm^{-1} day^{-1}), although other combinations without WH showed more variable results. Reproductive success, measured by cocoon and hatchling production, was highest in Vermibin 8 (356 cocoons, 121 hatchlings, 25.2 g hatchling biomass), followed by Vermibins 2 and 3. The lowest reproductive performance occurred in Vermibin 7 (152 cocoons). Overall, mixtures containing water hyacinth supported robust worm growth and reproduction, though cow dung alone (Vermibin 1) achieved the highest individual growth metrics. These results suggest WH is a suitable vermicomposting substrate when combined with complementary materials.

In northeast India, vermicompost made from rice straw, *Eichhornia crassipes*, *Ipomoea carnea*, and mixed biomass were enriched with microbial inoculants (*Azotobacter chroococcum*, *Azospirillum brasilense*, *Pseudomonas fluorescens*) and evaluated for their effect on rice growth and soil fertility [49]. Enrichment with *A. chroococcum* consistently yielded the highest nitrogen content and microbial populations in the composts, with Ipomoea-based vermicompost outperforming *Eichhornia*. Pot experiments revealed that Azotobacter-enriched vermicompost improved rice grain yield by 27.3% over non-enriched vermicompost, and enhanced leaf chlorophyll content, nitrate reductase activity, and nutrient uptake. Post-harvest soil had increased organic carbon, available N, P, and K, and microbial biomass, particularly in the Azotobacter treatment. While *Ipomoea*-based vermicompost performed slightly better than WH in this trial, the findings demonstrate that enriched WH vermicompost can improve soil fertility and crop performance, particularly in nutrient-poor, acidic soils.

3.2.3. Biochar

Recent studies on water hyacinth (WH) biochar have demonstrated its potential for enhancing soil fertility, moisture retention, and microbial health, with findings indicating that specific properties of biochar—such as cation exchange capacity (CEC), carbon stability, water-holding capacity, and nutrient content—are significantly influenced by pyrolysis temperature and biochar composition (Tables 1 and 2).

Studies by Gezahegn et al. [50] and Bao et al. [51] found that low-temperature pyrolysis (300–400 °C) produced WH biochar with higher CEC and nitrogen content than biochar made from other materials, such as wood or agricultural residues. This high CEC makes WH biochar effective in nutrient-poor soils by enhancing nutrient retention. For example, WH biochar's C/N ratio at 350 °C was markedly lower than those of biochars from woody feedstocks, supporting faster nutrient cycling and more immediate fertility benefits. However, as pyrolysis temperature increased to 550–750 °C, WH biochar demonstrated greater stability, with low H/C ratios indicative of high carbon stability due to fused aromatic ring structures. At 750 °C, WH biochar had the highest water-holding capacity and increased pore volume, outperforming most woody or fibrous biochars, which tend to have smaller pore volumes and lower water retention. Gezahegn et al. [50], however, noted that these high-temperature biochars, while more stable, might have a slower nutrient release, suggesting a trade-off between stability and immediate fertility enhancement.

Khatun et al. [52] compared WH biochar with biochars derived from rice straw, sawdust, and a mixed feedstock blend (1:1:1) produced at 400 °C. WH biochar had superior water-holding capacity, surface area, and nutrient content, including phosphorus, potassium, sulfur, calcium, and zinc, compared to biochar from the other feedstocks. WH biochar's water-holding capacity outperformed rice straw and sawdust biochars, which are typically low in available nutrients and water retention. These findings suggest that WH biochar offers a dual benefit of nutrient and moisture enhancement, potentially reducing the need for separate soil amendments.

The liming potential of water hyacinth (WH) biochar was highlighted in Jutakanoke et al. [53], who investigated its application in acidic sulfate soils in Rangsit, Thailand. WH biochar, with a pH of 7.62, improved water spinach (*Ipomoea aquatica*) growth in these conditions, yielding greater plant height and biomass compared to unamended soils. The study also examined changes in soil microbial communities using 16S amplicon sequencing. WH biochar-amended soils had higher populations of *Bacillus*, *Paenibacillus*, and *Sphingomonas*, beneficial bacteria known for promoting plant growth through mechanisms like phytohormone production, phosphorus solubilization, and nitrogen fixation. In unamended soils, *Ktedonobacterales* were three times more prevalent, while *Bacillus* was twice as abundant in biochar-treated soils. Without comparisons to other biochars or soil amendments, the study offers limited insight into WH biochar's performance against other liming amendments.

In humid, high-rainfall conditions, He et al. [54], tested compost-biochar mixtures with varying WH biochar content (15%, 30%, and 45%) and compared these to compost alone. WH biochar treatments helped stabilize soil pH and increased soil electrical conductivity, indicating improved nutrient exchange. The 45% WH biochar treatment maintained pH levels with minimal fluctuation, in contrast to compost-only treatments, where pH dropped substantially. The increased conductivity in WH biochar-treated soils suggested greater nutrient availability, although there was no assessment of potential salt accumulation from the elevated conductivity, a potential risk for plant growth in the long term.

Table 2. A comparison of properties between water hyacinth (WH) biochar produced at low (300–400 °C) or high temperatures (550–750 °C) along with a narrative comparison to biochars made from common feedstock including wood, straw and manure [50,51].

Property	Low Temperature (300–400 °C)	High Temperature (550–750 °C)	Other Biochars (Wood, Rice Straw, Chicken Manure)
C/N Ratio	Low	Very Low	Typically higher, slower nutrient cycling
Nitrogen Content (%)	High	Low	Lower than WH biochar, except chicken manure biochar
Cation Exchange Capacity	High	Moderate	Moderate, less effective for nutrient retention
pH	Neutral to Alkaline	Neutral	Varies, often lower than WH biochar for liming
Water-Holding Capacity	Very High	High	Moderate, typically higher in WH biochar
Surface Area (m^2/g)	Moderate	High	Varies, usually lower than high-temperature WH biochar
Phosphorus (P)	Moderate to High	Low to Moderate	Generally lower than WH biochar
Potassium (K)	Low to Moderate	Moderate	Moderate, similar to WH biochar
Calcium (Ca)	Moderate	High	Often lower than WH biochar, especially at higher temperatures
Electrical Conductivity	Moderate	Moderate to High	Varies, generally lower than WH biochar

The impact of WH biochar on water retention and soil structure has also been examined. Bao et al. [51] showed that WH biochar produced at 300 °C retained 79.07% water, outperforming biochar produced at 600 °C (41.29%) and biochar from wood and chicken manure, which typically held 10–20% water. Huang et al. [55] tested WH biochar in sandy soils at two temperatures (300 °C and 600 °C) and found that 10% WH biochar at 300 °C increased water retention by 371% compared to non-amended soil, which exceeded the 5–20% retention gains from wood and chicken manure biochar. Mei et al. [56] investigated WH biochar's influence on soil cracking and moisture retention through drying-wetting cycles, finding WH biochar reduced soil cracking and improved water retention at all temperatures, with the highest retention at 700 °C. In addition, Garg et al. [57] assessed WH biochar in sandy soils at varying compaction levels and observed that 10% WH biochar provided optimal water retention under low compaction, with benefits decreasing at higher compaction levels. Bordoloi et al. [58] also found that a 15% WH biochar application improved water retention to around 48%, compared to 29.5% in unamended soils, while reducing soil cracking across drying-wetting cycles. Collectively, WH biochar demonstrates superior water retention and structural stability across a range of conditions and is especially effective at low pyrolysis temperatures, high application rates, and in sandy, low-compaction soils. However, all studies lacked field-based validation, leaving questions about long-term effectiveness.

Infiltration dynamics have also been explored in WH biochar-amended soils. A study evaluating bare soil and soils amended with 5% and 10% WH biochar over 63 days and nine drying–wetting cycles found that increasing WH biochar content reduced infiltration rates, with 10% amendment resulting in the lowest rates [59]. Using artificial neural network (ANN) modeling, the study found that crack intensity factor (CIF) strongly influenced infiltration in bare soils, while volumetric water content (VWC) gained greater predictive importance in biochar-amended soils. Suction remained a consistently relevant factor across all treatments. These findings suggest that WH biochar may help reduce infiltration rates where moisture regulation and reduced percolation are desirable, such as on slopes or landfill covers, particularly under stable moisture regimes.

Recent research in Ethiopia provides both laboratory and field evidence of WH biochar's potential in acidic soils [60,61]. An incubation study on acidic Nitisols in the northwest highlands demonstrated that WH biochar—particularly when produced via furnace pyrolysis—was more effective than lime at resisting acidification stress, reducing exchangeable acidity and Al^{3+}, and increasing pH, ammonium retention, and phosphorus availability [60]. WH biochar slowed nitrification and buffered soil pH under simulated acid rain and fertilizer stress, highlighting its dual role in reducing acidification and improving nutrient dynamics. A complementary field trial in the Amhara Region applied WH biochar to teff (*Eragrostis tef*) at varying rates, showing that a moderate application (2500 kg/ha) improved pH, nutrient availability (N, P, K, and organic carbon), and grain yield [61]. Higher rates reduced yield, likely due to waterlogging or reduced porosity. When combined with mineral fertilizer, WH biochar further enhanced yield, supporting its practical utility in sustainable fertility management under real cropping conditions.

The polymer hydrogel created by Rop et al. [62] using water hyacinth fibers presented a different approach, where the material, rather than acting as a soil amendment, was designed to enhance soil moisture-holding capacity. The hydrogel enhanced the soil's moisture-holding capacity significantly, with moisture retention increasing from 35% in unamended soil to 68% when amended with 1.5% copolymer by weight. This suggests potential benefits in water-limited regions where soil moisture retention is critical. However, as a synthetic material, this cellulose-graft-poly (ammonium acrylate-co-acrylic acid) hydrogel might introduce microplastic contaminants if it degrades over time, a concern not associated with natural biochar amendments. While the authors did not examine the potential environmental impact of microplastic residues, such considerations are increasingly relevant given the known persistence and ecological risks of synthetic polymers. Further studies are warranted to assess the long-term decomposition of this hydrogel in soil environments and its suitability for sustainable agricultural applications.

3.2.4. Extracts and Isolates

Elgala et al. [63] experimentally assessed the efficiency of aqueous water hyacinth shoot extract as a source of nutrients foliar sprayed to tomato plants. The efficacy was compared alongside plants grown without any foliar spray and plants sprayed with a commercial synthetic solution. All treatments also had a baseline soil application of superphosphate (144 kg ha^{-1}) and a fertigation three-part delivery of ammonium nitrate (total 360 kg ha^{-1}). The experiment was conducted during the summer of 2019 in a greenhouse in Qalubia Governorate, Egypt. In preparing the aqueous water hyacinth extract, the roots were removed due to heavy metal toxicity, and only shoots were used. The extract properties and nutrient concentrations are in Table 4. They found that water hyacinth extract treated planted had fresh and dry weights and fruit yields that were greater than the no-spray control, 37.5, 56.8 and 72.2%, respectively. The water hyacinth extract application increased the net return of tomato cultivation by approximately 1.84 times compared with the conventional practice (control).

Kato-Noguchi et al. [64] examined the possible allelopathic effects of extracts and isolated allelopathic substances in water hyacinth on the growth of cress (*Lepidium sativum*), lettuce (*Lactuca sativa*), alfalfa (*Medicago sativa*), timothy (*Phleum pratense*) and ryegrass (*Lolium multiflorum*). In all instances, the growth of roots and shoots were reduced, with increasing extract concentrations having more severe stunting. Using chromatography, the main allelopathically active substance was loliolide. As such, water hyacinth extract may be useful as a soil additive to control weeds.

Table 3. Summary of nutrient compositions for the different water hyacinth (WH) feedstocks and biochars reported in studies in this section. ND is not detected.

Element/Property	Dried Biomass [52]	Dried Biomass [61]	Biochar 300 °C [51]	Biochar 300 °C [61]	Biochar 400 °C [52]	Biochar 450 °C [60]	Biochar 600 °C [51]	Biochar 650 °C [54]
Volatile Matter (VM %)	74.70	-	-	-	20.05	59.70	-	-
Fixed Carbon (%)	8.03	11.6	-	18.70	-	17.10	-	42.48
Carbon (C, %)	-	-	42.78	-	-	34.80	66.35	43.37
Nitrogen (N, %)	0.78	1.0	-	0.69	1.38	0.72	-	2.72
Phosphorus (P, g kg^{-1})	5.48	11.0	2.65	8.80	10.67	-	1.07	-
Potassium (K, g kg^{-1})	1.46	0.11	3.82	0.12	5.2	-	6.22	-
Sulfur (S, %)	4.63	0.3	0.09	0.34	6.62	-	0.14	0.16
Sodium (Na, g kg^{-1})	1.1	-	3.43	-	1.97	-	0.39	-
Calcium (Ca, g kg^{-1})	10.33	-	6.28	-	31.67	-	8.29	-
Magnesium (Mg, g kg^{-1})	6.4	0.07	3.97	0.07	25.50	-	0.67	-
Zinc (Zn, g kg^{-1})	42.01	0.0004	-	0.0003	184.45	-	-	9.11
Oxygen (O, %)	-	-	22.08	-	-	40.60	10.16	37.82
Chlorine (Cl, %)	-	-	7.87	-	-	-	6.09	-
Aluminium (Al, %)	-	-	0.04	-	-	-	0	-
Silicon (Si, %)	-	-	0.15	-	-	-	0.14	-
Rhodium (Rh, %)	-	-	0.33	-	-	-	0.13	-
Boron (B, %)	-	-	3.44	-	-	-	0	-
Tellurium (Te, %)	-	-	0.31	-	-	-	0	-
Manganese (Mn, %)	-	0.016	0	-	-	-	0.37	-
pH	-	6.10	-	8.11	8.06	10.40	-	-
Electrical Conductivity (EC, dS m^{-1})	-	13.20	-	18.70	13.03	27.70	-	-
Cation Exchange Capacity (CEC)	-	-	-	-	35.56	34.20	-	-
Arsenic (As, mg kg^{-1})	-	-	-	-	-	-	-	2.29
Cadmium (Cd, mg kg^{-1})	-	0.10	-	0.08	-	-	-	ND
Chromium (Cr, mg kg^{-1})	-	ND	-	ND	-	-	-	10.77
Copper (Cu, mg kg^{-1})	-	0.30	-	0.20	-	-	-	2.41
Lead (Pb, mg kg^{-1})	-	0.30	-	0.30	-	-	-	1.48
Mercury (Hg, mg kg^{-1})	-	-	-	-	-	-	-	ND
Nickel (Ni, mg kg^{-1})	-	0.30	-	0.50	-	-	-	22.45
Selenium (Se, mg kg^{-1})	-	-	-	-	-	-	-	ND

4. Limitations and Feasibility

Despite promising results, the current literature has several limitations that constrain broader applicability. Many studies are short-term, conducted under greenhouse or pot conditions, with limited replication and few field-scale or multi-season trials, reducing confidence in their long-term relevance. This limits the extent to which findings can be confidently applied to real-world farming, and suggests that current conclusions, particularly regarding yield gains and soil health benefits, should be treated as preliminary. Methodological details are often poorly documented, particularly regarding composting parameters (e.g., C:N ratio, turning frequency) and initial soil characteristics, making reproducibility and cross-study comparison difficult.

Reporting of nutrient composition and potential contaminants such as heavy metals is inconsistent or absent in several compost and mulch studies, making concerns about the toxicity of these amendments difficult to appraise. This lack of consistent reporting also hinders assessment of food safety risks and makes it difficult to establish whether the amendments meet regulatory thresholds for contaminants such as lead, cadmium, or arsenic.

These risks are compounded by variability in nutrient content and nutrient release patterns, particularly in compost, where mineralization may lag behind crop demand under cooler conditions. Additionally, site-specific contamination risks arise due to the potential for water hyacinth to accumulate heavy metals from polluted water bodies. These agronomic uncertainties must be considered alongside practical constraints. To mitigate such risks, rigorous quality control to test for heavy metals and pathogens, confirmation of compost maturity to prevent phytotoxicity [65–67]. As with any agricultural amendment, site-specific application strategies tailored to crop type, soil conditions, and water availability are essential [68–70]. These measures help ensure agronomic benefits are realized without compromising soil health, food safety, or environmental integrity.

The logistical and economic costs of harvesting, drying, and applying large volumes of biomass also remain key barriers to widespread adoption. Currently, few studies report comprehensive cost-benefit assessments, and there is limited evidence on labor requirements, transport feasibility, and farmer adoption potential at scale. These gaps restrict our ability to evaluate the real-world viability of water hyacinth as a fertilizer substitute.

5. Synthesis and Future Directions

Water hyacinth (*Eichhornia crassipes*) can be processed into mulch, compost, biochar, or foliar extracts, each offering distinct agronomic benefits. As a mulch, its biomass helps regulate soil temperature and moisture, improving early crop growth in leafy vegetables like horenso (*Spinacia oleracea*) [42]. Composting water hyacinth increases soil organic matter, microbial activity, and nutrient availability, with field trials reporting yield gains in crops such as maize, tomato, and rice [38,43,47]. When pyrolyzed into biochar, water hyacinth enhances cation exchange capacity, water retention, and phosphorus availability, particularly in acidic or sandy soils [50,51,71]. Foliar extracts have shown promise for boosting tomato yields, though allelopathic effects on non-target plants have been observed [63,64]. These organic amendments support microbial diversity, suppress pests like root-knot nematodes when used as mulch [41], and contribute to carbon sequestration. However, risks remain: water hyacinth may accumulate heavy metals [37,38], and N release from compost may lag behind crop demand under cooler conditions [45]. A summary comparison of water hyacinth amendment types is provided in Table 4.

Table 4. Summary of reported agronomic benefits, risks, study limitations, and suitability of different water hyacinth-derived amendments.

Amendment Type	Agronomic Benefits	Known Risks or Limitations	Field Validation	Food Safety Concerns	Optimal Use Contexts
Mulch	Improves moisture retention, reduces soil temperature, suppresses some pests (e.g., nematodes), increases biomass in leafy vegetables	Bulky to transport and apply; variable effects depending on mulch composition; limited nutrient supply	Rare, mostly pot or greenhouse trials	Low risk, but composition often untested	High-rainfall or irrigated systems; short-cycle vegetables

Table 4. *Cont.*

Amendment Type	Agronomic Benefits	Known Risks or Limitations	Field Validation	Food Safety Concerns	Optimal Use Contexts
Compost	Increases soil organic carbon, microbial activity, and NPK availability; improves crop yield in field trials (maize, rice, tomato)	Nutrient release may lag in cool climates; composting process and quality often underreported	Moderate, some field-scale studies	Often missing heavy metal data; potential contamination from polluted waterways	Suitable where organic inputs are prioritised; integrated nutrient management
Biochar	Enhances CEC, pH buffering, water retention, and nutrient retention; stabilises carbon	High-temperature biochar may release nutrients slowly; production is energy-intensive	Limited, few long-term trials	Some biochars exceed thresholds for Zn, Cr, or Ni	Acidic or sandy soils; degraded land; water-limited zones
Foliar Extract	Increases tomato yield and biomass; low-cost input	Allelopathic effects on other crops/weeds; nutrient concentrations vary	Greenhouse only	Root removal reduces metal risk; full profiles rarely provided	Supplement in horticulture; organic foliar input
Vermi-compost	Enhances microbial biomass, supports worm reproduction, improves soil fertility	Inconsistent performance depending on WH blend; traceability of compost feedstocks lacking	Limited, pot trials dominate	Potential for metal transfer if WH sourced from contaminated sites	High-value cropping where soil biology is key

Future research should address both agronomic performance and practical feasibility to clarify the scalability of water hyacinth-based amendments. Long-term, multi-season field trials are needed to verify sustained improvements in soil organic carbon, nutrient availability, and crop yields. Standardized protocols for composting and biochar production would improve reproducibility and allow meaningful cross-site comparisons. Given water hyacinth's capacity to accumulate heavy metals from aquatic environments, consistent monitoring of contaminant levels is essential to ensure safe use. In addition, economic assessments—including costs of harvesting, transport, processing, and field application—are critical to evaluate the viability of large-scale adoption in diverse agricultural contexts.

Transforming water hyacinth from an invasive aquatic weed into a nutrient-rich soil amendment aligns with circular economy principles, enabling the repurposing of biological waste into productive agricultural inputs. Its biomass contains key macronutrients (e.g., nitrogen, phosphorus) and beneficial micronutrients (e.g., calcium, zinc, magnesium), and processing methods such as pyrolysis or composting can concentrate or stabilize these elements. Utilizing water hyacinth as compost, mulch, or biochar may reduce dependence on synthetic fertilizers, potentially lowering input costs and environmental impacts. For example, supplying 30 kg P ha^{-1} to a sugarcane crop in Queensland, Australia, would require approximately 5.5 t of dried water hyacinth, offsetting 150 kg of triple superphosphate, valued at around AUD 150 ha^{-1} at current fertilizer prices.

Beyond direct fertilizer substitution, water hyacinth-based amendments may contribute to reducing greenhouse gas (GHG) emissions. The production of 1 kg of phosphorus fertilizer emits approximately 4–6 kg CO_2-eq, so replacing 30 kg P ha^{-1} with water hyacinth-derived nutrients could avoid 120–180 kg CO_2-eq. per hectare. Additional savings are possible if synthetic nitrogen inputs are also offset. Processing water hyacinth into compost or biochar can stabilize carbon and avoid methane emissions that would otherwise occur during anaerobic decomposition in waterways [51,60]. Repurposing this biomass also diverts material from landfill or incineration, reinforcing circular economy goals [54]. Full life cycle assessments (LCA) would help quantify net climate benefits and evaluate trade-offs compared to conventional fertilizers [72,73]. When well-managed, water hyacinth amendments present a viable strategy to close nutrient loops, enhance carbon sequestration, and support more resilient agroecosystems.

Taken together, the current evidence suggests that water hyacinth can be effectively transformed into a range of soil amendments that support crop productivity, soil health, and environmental sustainability. While the agronomic benefits are increasingly documented across multiple amendment types—compost, mulch, biochar, and extract—realizing their full potential will depend on addressing practical constraints, such as variability in nutrient content, processing methods, and potential contaminants. Standardizing production protocols, improving nutrient profiling, and conducting field-scale, multi-season trials will be critical next steps. Integrating water hyacinth into broader nutrient management strategies not only offers a low-cost, renewable input but also advances ecological restoration by removing an invasive species from aquatic systems. With targeted investment in research, quality control, and farmer support, water hyacinth-based amendments could play a valuable role in building more circular, resilient agricultural systems. For researchers, standardized field protocols and nutrient profiling are priorities. For policymakers, support for decentralized composting infrastructure and monitoring systems could accelerate safe adoption. For farmers, practical extension materials are needed to guide sourcing, processing, and application.

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Abbreviations

The following abbreviations are used in this manuscript:

WH	Water Hyacinth
CEC	Cation Exchange Capacity
NPK	Nitrogen, Phosphorus, Potassium
LCA	Life Cycle Assessment
TOC	Total Organic Carbon
TKN	Total Kjeldahl Nitrogen
P	Phosphorus
K	Potassium
Fe	Iron
Cu	Copper
Zn	Zinc
Mn	Manganese
CD	Cow Dung
FIS	Fine Inert Soil
PH	Parthenium
CIF	Crack Intensity Factor
VWC	Volumetric Water Content
ANN	Artificial Neural Network

GHG	Greenhouse Gas
EC	Electrical Conductivity
FYM	Farmyard Manure
GE	Glyricidia and Eupatorium
SR	Sesbania rostrata (Dhaincha)
WH	Water Hyacinth
CEC	Cation Exchange Capacity
NPK	Nitrogen, Phosphorus, Potassium
LCA	Life Cycle Assessment
TOC	Total Organic Carbon

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