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Review article

Water hyacinth: Prospects for biochar-based, nano-enabled biofertilizer development

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ABSTRACT

The widespread proliferation of water hyacinth (*Eichhornia crassipes*) in aquatic ecosystems has raised significant ecological, environmental, and socioeconomic concerns globally. These concerns include reduced biodiversity, impeded water transportation and recreational activities, damage to marine infrastructure, and obstructions in power generation dams and irrigation systems. This review critically evaluates the challenges posed by water hyacinth (WH) and investigates potential strategies for converting its biomass into value-added agricultural products, specifically nanonutrients-fortified, biochar-based, green fertilizer. The review examines various methods for producing functional nanobiochar and green fertilizer to enhance plant nutrient uptake and improve soil nutrient retention. These methods include slow or fast pyrolysis, gasification, laser ablation, arc discharge, or chemical precipitation used for producing biochar which can then be further reduced to nano-sized biochar through ball milling, a top-down approach. Through these means, utilization of WH-derived biomass in economically viable, eco-friendly, sustainable, precision-driven, and smart agricultural practices can be achieved. The positive socioeconomic impacts of repurposing this invasive aquatic plant are also discussed, including the prospects of a circular economy, job creation, reduced agricultural input costs, increased agricultural productivity, and sustainable environmental management. Utilizing WH for nanobiochar (or nano-enabled biochar) for green fertilizer production offers a promising strategy for waste management, environmental remediation, improvement of waterway transportation infrastructure, and agricultural sustainability. To underscore the importance of this work, a metadata analysis of literature carried out reveals that an insignificant section of the body of research on WH and biochar have focused on the nano-fortification of WH biochar for fertilizer development. Therefore, this review aims to expand knowledge on the upcycling of non-food crop biomass, particularly using WH as feedstock, and provides crucial insights into a viable solution for mitigating the ecological impacts of this invasive species while enhancing agricultural productivity.

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1. Introduction

1.1. Background and rationale

Longstanding environmental sustainability concerns have more recently been heightened by a rapidly expanding global human population, climate change and related environmental challenges, and the dwindling state of natural resources. In the agriculture and environmental realms, this trend is most notably represented by ongoing soil degradation; loss of productivity; and rampant air, soil, and water pollution from agricultural activities, all of which together contribute to worsening global food and nutrition insecurity [1]. Contemporary efforts to address the pollution and declining productivity of agricultural lands gave rise to a host of crop production techniques such as conventional fertilizer application, organic matter incorporation, crop rotation, irrigation, and agroforestry [2]. While these measures were aimed at increasing crop productivity in many regions, the rising demand for food to sustain the swarming human population and the associated environmental pollution have rendered these practices largely unsustainable. Against this backdrop, recent technological advances have highlighted the potential for nanotechnology-based materials to improve soil health and productivity to desired levels [3–5]. Among such advances, the development of biochar as a soil amendment product is notable. Besides exploiting the carbon storage, soil liming, and inherent high water holding capacity effects of biochar, the preparation of this additive in the nanoscale range (1–100 nm; nm) improves its physicochemical properties in the form of intraparticle forces, cation-exchange potential, and enhanced surface area to volume ratio [6]. In addition, the environmental sustainability profile of such nanoscale interventions can be enhanced by using bio-based materials for their development [7].

Water hyacinth (*Eichhornia crassipes*) is an invasive aquatic weed commonly found in water bodies in different parts of the world. It is reputed for its rapid growth and high reproductive rate of up to 201 % within 7 days with its seeds able to maintain dormancy for up to 15 years [8].The negative impacts of WH proliferation include reduction in biodiversity; impediments to water transportation, aquatic recreation, and fishing; destruction of bridges and other marine infrastructure; and clogging of waterways, power generation dams and irrigation water systems. WH proliferation also affects the social well-being of the communities around water bodies. These problems have been widely documented in various regions of the globe. For instance, in India, several lakes have been invaded, including, among others, the Katraj, Pichola, and Ulsooru lakes in Pune, Udaipur, and Bangalore, respectively [9]. In South America, after chemical treatments, control programs have been contending with re-infestation in the Guadalupe Dam in Mexico. Furthermore, major infestations of WH invaded Lake Victoria in East Africa, causing negative impacts on fishing communities. Such a bad reputation led the plant to be bestowed with several names in various parts of the world; as indicated in Fig. 1, for example, the fishing communities in southwestern Nigeria call it "water terror" [10].

To reduce the menace of WH, researchers have identified its agricultural promise and suggested using it as a sustainable raw material for nanobiochar production [11]. Therefore, the current review aims to assess the upcycling of this notorious weed for bio-based nanobiochar and nanofertilizers. The review discusses key research findings on upcycling WH for nanobiochar production. It examines the extant research on the properties of WH, its environmental impact, and challenges in controlling its invasion of inland waters. In addition, the review covers the production methods of nanobiochar and the possible environmental benefits of WH exploitation for nano-enabled biofertilizer development. Finally, an overview of the research on supporting government policies and regulatory framework for this application of WH is presented. We note that upcycling of WH would serve the dual role of environmental management by way of WH clean-up to improve both the aesthetics and the operations of aquatic systems and to sustainably improve soil quality and nutrient utilization efficiency by way of biochar and bio-based, nanonutrient-enhanced efficiency fertilizers. Combined, these approaches will resolve the environmental menace of WHs and mitigate the environmental footprint of conventional mineral-based fertilizers.

Generally, as shown in the search, a gamut of studies done on biochar production, including those involving WH feedstock [12,13], have focused on various applications such as heavy metal remediation and sequestering of emerging organic contaminants [14–22], organic amendments for improving soil quality [23–26], carbon electrodes and electricity generation [27–30], wastewater treatment

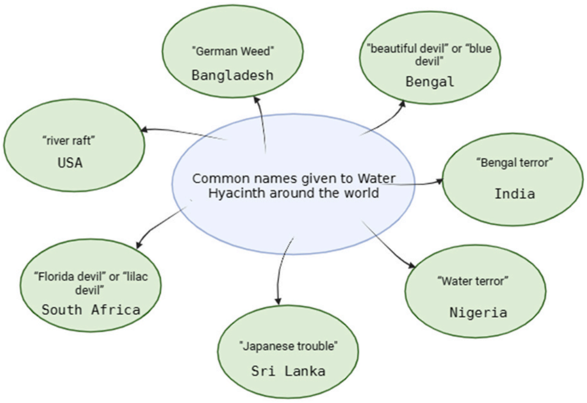

Fig. 1. Names given to water hyacinth (*Eichhornia crassipes*) in different countries.

[31–36], animal feeds [37], and biofuel [13,38–40].

Fig. 2a, illustrates the advanced search of databases used to quantify existing publications on WH biochar-based nanoformulations. Fig. 2b presents the average number of publications per search item across the databases. For instance, "WH" yielded an average of 30,286 publications, while "WH + NF" (water hyacinth and nanofertilizer search couplet) resulted in 29 publications. Fig. 2c, revealed a significant increase in publications on WH, rising from 1415 between 2000 and 2004 to 9087 from 2019 to 2024. Publications on biochar (BC) saw an even steeper upsurge, from 339 (2000–2004) to 71,996 (2019–2024). However, for the combined advanced search item "WH + NF + BC" (water hyacinth, nanofertilizer and biochar), publications grew from zero to only 25 over the same periods.

Taken together, however, as summarized in Fig. 2b and c, only a few have focused on fortifying biochar derived from WH with nanoscale nutrients to synthesize nano-enabled biochar-based fertilizers as indicated by the data extracted from these databases as of June 20th, 2024. Hence, this review is pertinent to highlight both the few advances made to date and the research gap in this area.

Therefore, this review as part of the ongoing research studies by the authors is aimed at bridging this identified research gap to maximize the benefits derivable from the use of WH-derived biochar.

2. Water hyacinth: an aquatic menace

2.1. *Brief overview of water hyacinth and its impact on inland waters*

Motivated by the plant's invasive nature and its detrimental environmental and economic implications, research on WH has become expansive, covering the entire scope from the weed's origin and spread from its native Amazon to its impact on water quality and potential valuable applications. Belonging to the family Pontoderiaceae, WH is a free-floating aquatic plant that thrives in inland freshwater collections, particularly lakes, rivers, and ponds [41]. It features broad leaves and purple spiky flowers. With buoyancy-mediated petiolar air sacs, the plant has a variable height that sometimes approaches 1 m [42]. Its reproductive cycle comprises both asexual vegetative and sexual, making the plant remarkably invasive, a characteristic that is also assured by its genetic uniformity [43]. The plant was introduced from the Amazon as ornamental plants and gifts in the early 20th century, eventually spreading to over 50 countries on five continents [42,44]. Figs. 3 and 4 show that many countries worldwide are affected by widespread WH infestations. However, it should be noted that the distribution of WH may change over time due to efforts to manage and control its spread and changes in environmental conditions. Specific to Africa, Mujingni [44] notes that the continent has borne an exceptionally high burden following the weed's initial introduction in Zimbabwe in 1937, after which it heavily colonized key water bodies in Mozambique, Ethiopia, Rwanda, Kenya, Tanzania, and Nigeria [45]. In general, nutrient-rich agricultural runoff and industrial waste products in inland water bodies stimulate the avid growth of WHs associated with dense overcoats on the water surface. The persistence of WHs in tropical waters is enhanced by conducive climatic conditions and hydrodynamic factors that sustain its spread [46]. Today, WH is best known for its aggressive invasiveness, water quality degradation, and economic cost, making it a significant environmental and socioeconomic concern in many fishing communities and communities reliant on water as the principal mode of transportation and recreation.

Several studies have demonstrated the environmental effects of WH invasion [41,44,47–52]. Patel [53] notes that the high fecundity exhibited by WH enables it to outcompete most native species for nutrients, resulting in diminished biodiversity in affected water bodies. In addition to driving biodiversity loss, WH disrupts local food chains and suppresses the growth of phytoplankton and other resident microbes. Studies have also demonstrated measurable degradation of water quality in areas with dense WH cover, mainly in the form of sediment and microparticle dissemination and oxygen depletion, which can, in turn, result in asphyxiation of marine flora and fauna [54–56]. Unlike submerged vegetation in water bodies, WH does not release oxygen into the surrounding water, lowering its concentration and reducing other plants' survival. In studying the effects of the weed on the water quality and phytoplankton health in Kenya's Lake Naivasha, Mironga et al. [52] found an inverse relationship between the dissolved oxygen and phytoplankton chlorophyll concentration and WH cover (or infestations). Furthermore, Villamagna and Murphy [47] pointed out that surface coverage by WH is associated with a higher evapotranspiration rate than that recorded in open waters. Furthermore, the dense

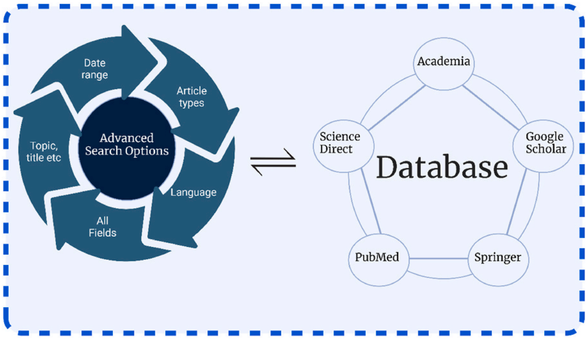

Fig. 2a. Databases sampled and the advanced search options utilized.

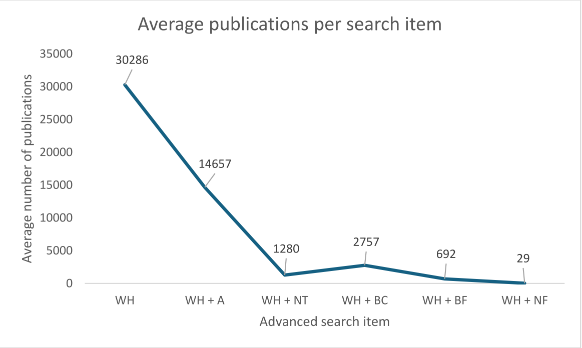

Fig. 2b. Average number of publications per advanced search item from all databases.
Legend: WH = water hyacinth. Other items were searched in couplets of WH with A = Agriculture, NT = Nanotechnology, BC = Biochar, BF= Biofertilizer and NF = Nanofertilizer.

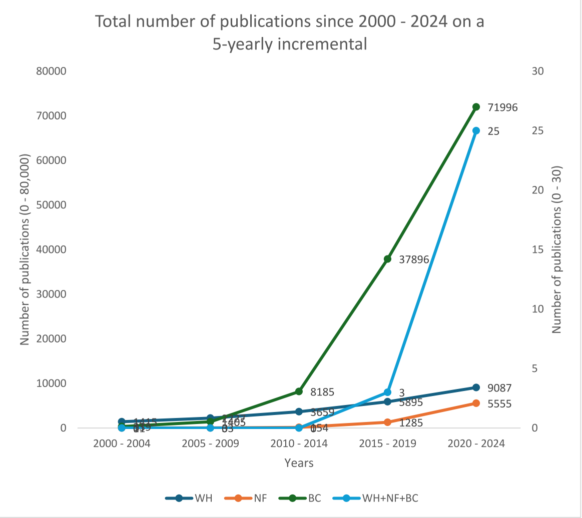

Fig. 2c. Total number of publications per search item from 2000 to 2024 on a 5-yearly basis.
Legend: WH = Water hyacinth, NF = Nanofertilizer, BC = Biochar and WH + NF + BC = all criteria searched as a single item. **(NB: only WH + NF + BC data points reference secondary axes: 0–30).**

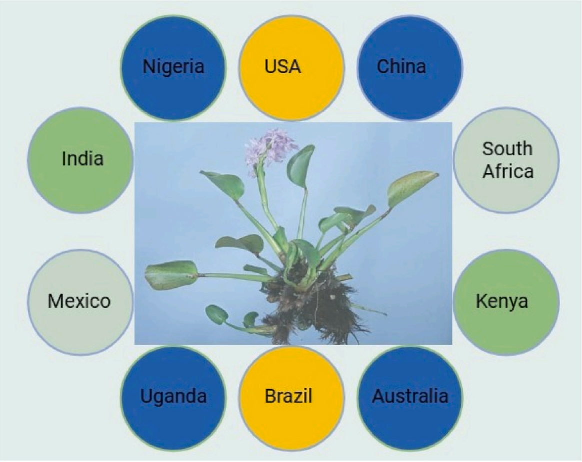

Fig. 3. Some countries with reported cases of significant water hyacinth invasion.

Fig. 4. Early-stage water hyacinth invasion of a Lake at the CORENADR Research Center Xochimilco, Mexico (photo courtesy Chris Dimkpa).

mat of WH that forms on rivers can impede navigation and irrigation and increase the risk of flooding adjacent areas [57]. However, a less injurious environmental effect of WH is its high absorption capacity, which has been validated in multiple field studies and shown to be useful in removing soil and water contaminants [58,59]. According to Churko et al. [60], WH can serve as a potent bioremediation tool for the extraction of contaminating heavy metals, agrochemical leachates, and inorganic contaminants from the water. Altogether, WH has multiple well-studied negative environmental impacts; recent research highlights potentially beneficial ecological applications of the weed [60]. Table 1 highlights some of the modes of WH menace.

2.2. Challenges of effective management of water hyacinth infestations

Owing to its rapid growth and invasive nature, WH has been described as one of the world's most difficult weeds to manage [42,57,66–70]. Motivated by aesthetic and biodiversity conservation goals, several large-scale WH management programs have been implemented across different countries, often involving extensive financial and logistical mobilization but achieving limited or short-lasting results. The plant often reinvades the reclaimed ecosystems within a few years. An extensive weed eradication program launched in East Africa's Lake Victoria (mainly in Tanzania and Uganda) and West Africa's Lake Nokoue (Benin) ended with the WH reinvading the lakes less than a decade after the respective programs were completed. In many settings, weed control often relies on mechanical harvesting, which requires investment in heavy machinery such as weed harvesters. Alternative weed management techniques, such as chemical and biological control, have been applied in response to the ineffectiveness of mechanical and physical removal strategies. However, the effectiveness of these approaches, particularly on the large scale necessitated by extensive weed cover, has been limited. While chemical herbicides can kill the weed and limit its expansion, these compounds threaten non-target species, limiting the ecological safety of chemical control methods [67,71]. Similarly, biological control of WH using predator insects such as the weevil beetle is disadvantaged by the limited commercial availability and less significant effectiveness of the method [72–74]. Overall, the control of WH is subject to multiple challenges, with each failure adding to the negative economic implications of the aquatic weed.

2.3. Nanobiochar and its applications

As the nanobiochar precursor, biochar is a carbon-rich material derived from the pyrolysis of crop residues, wood, or other

Table 1
Summary of modes of WH menace.

Negative effects of water hyacinth	References
Loss of biodiversity: WH outcompetes native species for nutrients, thereby causing loss of biodiversity	[50,61]
Disruption of local food chain: WH causes disruption of local food chain via suppression of phytoplankton and other microbes	[53]
Degradation of water quality: WH causes degradation of water quality through deposition of sediments and microparticles in the water.	[44,49,52]
Reduction in dissolved oxygen: In areas of dense coverage, WH causes reduction in dissolved oxygen by limiting photosynthetic activities within the aquatic ecosystem	[62,63]
Impeding of navigational routes and irrigation systems: WH negatively impacts the use of water for navigation and irrigation purposes	[47,51]
Clogging of dams: hydroelectric power generation systems clogging through WH biomass	[57,64]
Increased risk of flooding in adjacent areas: By impeding free-flow of water and creating excessive sediments, WH can increase the risks of flooding in adjacent areas.	[65]

agricultural wastes. Biochar has gained increasing attention for its potential applications in diverse fields, particularly agriculture, environmental remediation, and carbon management [75,76]. An ancient material dating back to civilizations like the Amazonians exemplified by the creation of the historic *terra preta* anthropogenic dark soils that retained their fertility for centuries, biochar bears unique physicochemical properties central to its versatility and utility in various applications [6]. Chiefly, biochar has a remarkable surface area to volume ratio, is highly porous, and provides an ideal habitat for microbes [77]. Importantly, its porous microstructure fosters nutrient retention and improves the material's soil water-holding capacity, which helps enhance plant growth and resilience [76,78,79]. Moreover, biochar's carbon-rich composition not only stores carbon for an extended period but also mitigates greenhouse gas emissions by preventing the rapid decomposition of organic matter in the soil [80].

The general properties and physicochemical characteristics of biochar depend on its precursor material, the pyrolytic process conditions, and the type of reactor used. The pyrolytic process usually occurs in the absence or near-absence of oxygen and typically at temperatures ranging from 300 °C to 700 °C [81]. The specific conditions and methods used can significantly affect the properties and effectiveness of the biochar, such as slow pyrolysis, flash pyrolysis, carbonization, and gasification [82]. The latter requires temperatures ranging between 1000 °C and 1600 °C. Some drawbacks of bulk biochar production include the energy cost for the thermochemical conversion, the high variability in properties due to differences in feedstocks and pyrolytic conditions, possible emissions of pollutants during the production process, and so forth. Researchers, however, are seeking various ways to mitigate these disadvantages in biochar production, including conversion to nanobiochar to enhance its value.

The innovation from bulk or conventional biochar to nanobiochar, which entails the preparation of biochar with structural size in the nanoscale (1–100 nm), has provided a means of extending its beneficial physicochemical and morphological characteristics by modulating the production methods [6,83]. Nanobiochar development involves the integration of nanomaterials into the biochar matrix, which allows purpose-driven modifications and incorporation of specific nanoparticles for tailored applications in different industries [2]. By incorporating nanoparticles such as graphene or metal oxides, the material gains enhanced reactivity, increased adsorption capacity, and improved electrical conductivity compared to bulk biochar [84]. From an agricultural perspective, nanobiochar production represents an exciting opportunity for engineering purpose-specific, tunable, and environment-friendly solutions to longstanding crop productivity and environmental challenges.

Nanobiochar has found several applications, capitalizing on the unique combination of its carbon-rich structure and the additional functionalities conferred by incorporating nanoparticles. For instance, an attempt was made to find an innovative use for WH as a green precursor for carbon composite adsorbents and supercapacitor electrodes [30]. Also, another study Mahmoud et al. [85] investigated the effect of biochar solely or combined with nanosilica and nanopotassium on the agro-physiological and biochemical constituents of potatoes. The results show that the biochar with the nano-scale elements significantly improved plants' agronomic variables. Generally, the properties of nano-enhanced biochar that confer soil improvement include its high surface area, adsorption, and nanoscale-derived reactivity. These properties also make nanobiochar well-suited for other applications, including soil amendments, stabilization of soil organic matter, improved soil fertility, reduced nitrous oxide emissions, carbon sequestration, removal of heavy metals, organic pollutants, and other contaminants from wastewater and drinking water sources [34,86–93]. Recently, nanobiochar has been studied as an emerging ecological remediation tool utilized in waste management processes to adsorb odors, toxic gases, heavy metals, and other pollutants in landfills, water bodies, and wastewater treatment facilities [94–96]. In addition, nanobiochar has been used to remediate polluted soil profiles. In this role, its ability to adsorb contaminants, such as pesticides, hydrocarbons, heavy metals, and PFAS (per- and polyfluoroalkyl substances), is critical for the restoration of soil quality and productivity [77,97]. In addition, studies have shown that nanobiochar improves soil fertility and plant growth by enhancing nutrient and water retention and promoting crop nutrient uptake [2]. Furthermore, nanoparticles impart specific beneficial characteristics, including

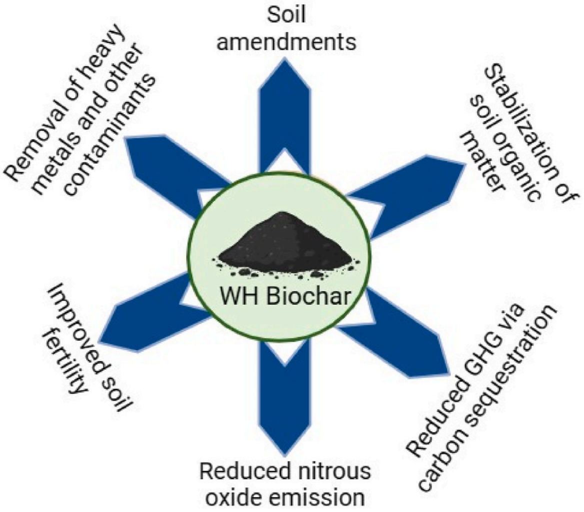

Fig. 5. Possible benefits of water hyacinth derived biochar (WH Biochar) application.

improvements in nutrient release or disease resistance. Like bulk biochar, nanobiochar is also used for carbon sequestration, which involves burying nanobiochar in soil to reduce the release of atmospheric carbon dioxide and the associated greenhouse effect [24,98]. Altogether, the controlled addition of nanomaterials has extended the utility of biochar in a wide range of applications [85,99,100]. Therefore, leveraging the aggressive proliferation of WH in aquatic ecosystems to upcycle its biomass as feedstock for biochar production could have several benefits, as shown in Fig. 5.

2.4. Technical approaches to nanobiochar production

Environmental concerns continue to drive efforts to develop sustainable processes for nanostructured materials, with approaches focusing on low energy consumption, less use of toxic solvents, and utilization of bio-based materials. Bulk biochar, which can be subsequently converted to nano-sized biochar or nano-enabled biochar (commonly called nanobiochar), can be prepared using such feedstocks as animal wastes [101], rice husk [92,102], sugar cane bagasse [103], wood residues [28], and sewage sludge [104]. Conventionally, carbonaceous nanoparticles have been produced using such processes as slow or fast pyrolysis, gasification, laser ablation, arc discharge, or chemical precipitation [2,6,22,105]. However, limiting the material's ecological footprint demands methods that utilize less energy and more readily available precursors. Naghdi et al. [106] describe the production and characterization of nanobiochar using ball milling. This low-cost top-down method involves the application of mechanical forces for particle size reduction to nanopowders of different sizes. Table 2 shows a summary of various biochar feedstocks, methods of preparation, and key applications while Table 3 focuses on some examples of biochar derived from WH and its various applications.

The process utilizes small, spherical grinding media such as steel or ceramic balls that are agitated within a milling chamber containing the feedstock. The repeated impact and shear forces generated by the moving balls effectively break down the biochar into smaller particles, including nanoscale particles, when the milling process is appropriately controlled [20,112,113]. Ball milling has drawn significant scholarly attention as a low-cost approach to producing nanoporous carbon, with the particle size being regulated by varying the speed of the rotating steel and the milling time. However, Ramanayaka et al. [114] noted that ball milling renders non-uniform-sized nanoparticles, which tend to collide and aggregate, resulting in unintended large particle sizes [114,115]. To overcome these shortfalls, the authors suggest double-disc milling as a more refined method for fabricating nanobiochar with evenly sized particles, higher quantities, and more granular procedural control. A strategic approach to the sustainable synthesis of biochar, which is of utmost importance, should entail the selection of non-competing, non-food, and locally sourced feedstock materials. This emphasis on the importance of feedstock selection and location can make the residents feel responsible for the sustainable production, fostering a sense of duty towards the environment [116].

However, regardless of the raw material source, nanobiochar has been prepared using a variety of techniques, ranging from ball-milling to microwave pyrolysis. In addition to direct synthesis of nanobiochar from various raw materials, nanosized biochar molecules are readily formed during preparation of bulk biochar, although its yield is limited to less than 2 % [117]. The common nanobiochar fabrication techniques can be classified into two: top-down and bottom-up [114]. In general, the top-down approach involves breaking down bulk feedstocks into smaller structures, and comprises of fabrication techniques such as cutting, grinding, and centrifugation. This approach has been popularized because of its relative ease of use and low energy consumption and cost. In contrast, the bottom-up approach entails up-constructing materials from precursors to the nanoscale, including wet chemistry methods such as precipitation, ionic gelation, and sol-gel methods, among several others. However, the most common and widely studied nanobiochar production approach is ball-milling, a top-down method involving grinding of the feedstock material between stainless steel balls of varying shape and speed. According to Amusat et al. [20], ball milling is effective as it can fabricate nanobiochar while preserving the material's crystal structure. Moreover, ball milling, with its eco-friendly and low-cost nature, reassures of its sustainability. Other top-down techniques for nanobiochar fabrication include disc-milling, chemical treatment, and in-situ pyrolysis. The physicochemical properties of nanobiochar can be varied by changing the feedstock, milling time, and pyrolysis temperature. Zhang et al. [36] prepared WH-derived nanobiochar through in-situ pyrolysis at different temperatures between 250 °C and 550 °C, yielding the highest adsorption capacity at 450 °C pyrolytic temperature. Other studies have incorporated a pre-treatment step, such as carbonization or pre-heating, for optimization of feedstock prior to ball-milling, improving particle size and reducing the chance for re-aggregation [28,

Table 2
Examples of biochar feedstock materials, percentage yield, pyrolytic conditions and applications.

Feedstock	Biochar yield (wt%)	Pyrolytic conditions	Biochar application	reference
Animal waste (Bovine bone)	63 %	650 °C–1000 °C 2 – 4hrs resident time	Adsorbent for textile dye contaminated waste water	Côrtes et al., 2019
Animal waste (Fish scale)	43 %	650 °C–1000 °C 2 – 4hrs resident time	Adsorbent for textile dye contaminated waste water	Côrtes et al., 2019
Rice husk	40–45 %	500 °C	Agricultural (nutrient release) and environmental (pollutant adsorption) applications for biochar	Bushra & Remya, 2024; Nagaraju et al., 2023
sugar cane bagasse	23 % and 58 %	450 °C for 4hrs and 600 °C	Application in soil enhancement, carbon sequestration and plants (pak choi, maize and groundnut) growth	Nie et al., 2018; [107]
wood residues	21 %–27 %	200 °C for 1hr followed by 750 °C for 1hr	Use as supercapacitor electrodes and Cu2+ and Zn2+ adsorbents	J. Jiang et al., 2013a; [108]
sewage sludge	N/A	400 °C–800 °C	Application as catalyst for pollutant degradation	J. Jiang et al., 2013a

Table 3
Examples of WH biochar, percentage yield, pyrolytic conditions and various applications.

Biochar yield (wt %)	Pyrolytic conditions	Main elemental composition (%)	Biochar application	reference
16.2–46.8	300–450 °C for 30–60mins	C: 32.8 % H: 2.7 % P: 0.7 % N: 3.0 % S: 0.2 % K: 4.1 %	Testing effect on plant and fish growth	[109]
42.3–48.8	350 °C and 500 °C for 60mins	Not determined	Adsorption of ciprofloxacin by biochar	[110]
39	350–400 °C	C: 53.4 % O: 42.8 % H: 2.0 % N: 1.8 %	Hydromechanical properties of soil amended with biochar	[111]

118–121]. Sonification is an alternative, high-energy nanobiochar production technique that utilizes ultrasonic radiation for bulk biochar disintegration, which is then suspended in an alkaline solvent (sodium hexametaphosphate) and separated through sieving and centrifugation. Altogether, multiple methods of nanobiochar fabrication have been developed and are applicable to the synthesis of the material from WH feedstock [23,36,122,123].

3. Repurposing water hyacinth as nano-enabled biochar

3.1. *Environmental benefits of water hyacinth as a biochar feedstock*

Besides posing severe threats to agroecosystems across the globe, WH has proved particularly difficult to control, defying virtually all mitigation methods employed to limit its expansion on nutrient-rich water bodies. Consequently, significant research has been directed at finding alternative uses for the invasive weed, including biogas formation, conversion into animal feeds, green fertilizer, ecological remediation, and synthesis of biochar and nanobiochar [38,41,116,122–125]. As a feedstock for nanobiochar production, WH is a rapidly regenerating, low-cost, biodegradable, and sustainable raw material [23,126]. Moreover, the high lignocellulose content of WH ranging from 60.8 % to 73 % of its dry biomass [127,128], renders it suitable for pyrolysis, which is the crucial biochar production process. Therefore, the utilization of WH as a raw material for nanobiochar production constitutes a convenient means of effectively controlling the plant's aggressive spread while sustainably producing nanobiochar, with no feedstock acquisition cost other than the cost incurred in the transportation of the biomass to a processing center [23,115,123,126].

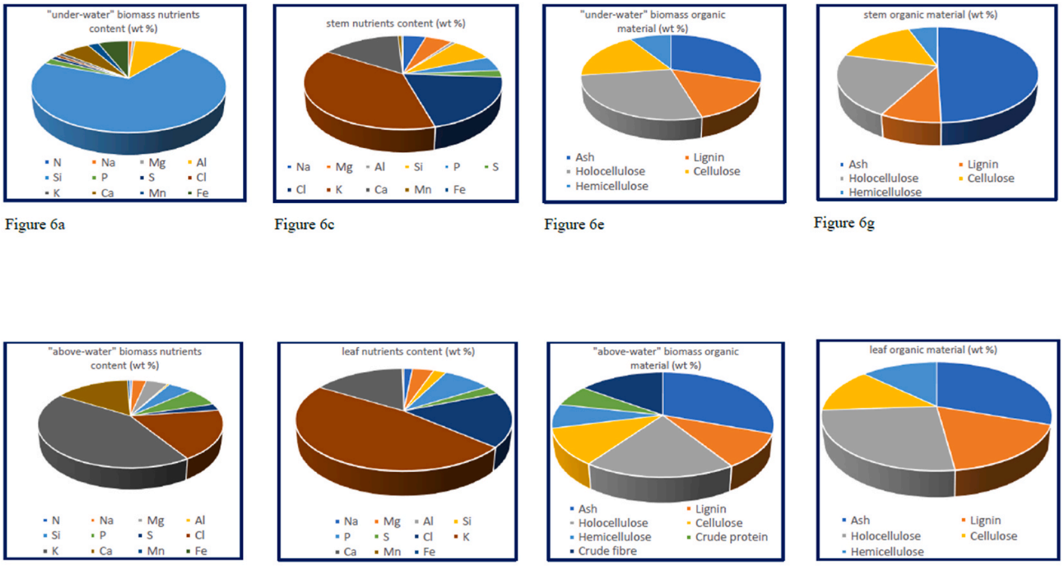

Figure 6a Figure 6c Figure 6e Figure 6g

Figure 6b Figure 6d Figure 6f Figure 6h

Figure Legend:
"above-water" = stem + leaves
"below-water" = roots

Fig. 6. Elemental and organic compound composition of water hyacinth (*Eichhornia crassipes*). Data adapted from [127,128].

Bio-based nanobiochar fabricated from WH feedstock holds notable environmental and sustainability advantages. The conversion of WH into nanobiochar represents a sustainable approach to removing invasive aquatic weeds from water bodies, mitigating oxygen depletion and loss of biodiversity effects associated with such proliferation. Moreover, the role of nanobiochar as a carbon sink that sequesters greenhouse gas and mitigates emissions, especially of CO2, is well reported in the literature [79,87,92,129–131]. Furthermore, WH-based nanobiochar has been used to remediate nutrient-depleted soils, improving soil structure and enhancing nutrient retention and water-holding capacity. Studies have also ascertained the effectiveness of both WH and nanobiochar as an adsorbent material valuable in the removal of heavy metals and other pollutants from water bodies [11,23,47,57–60,132,133]. Studies have shown that WH-derived biochar has a high water-retention capacity and potential to act as a carbon sink in environmental protection programs (reviewed, for example, in Ref. [134]). Elbehiry et al. [135] noted that WH-based nanobiochar was a highly efficient absorbent for removing heavy metals from contaminated water. These uses highlight the environmental benefits of upcycling WH as a raw material for nanobiochar production. As a strategy to develop more novel applications for the prolific aquatic weed, WH is also being explored for possible use in a microbial fuel cell for wastewater treatment and electricity generation [113], and for activated electrodes formulation in an eco-friendly and sustainable system [27–30,136].

4. Repurposing water hyacinth as innovative biobased fertilizers

4.1. *Composition of water hyacinth*

A significant section of the extant literature and preliminary observations from the authors indicate that WH can be a good candidate for green fertilizer, usually in the form of compost manure or nanoformulations [137]. The weed is well-suited for this purpose due to its rich nutrient and organic content, the latter described as primarily consisting of cellulose, hemicellulose, lignin, and other carbon-containing compounds that render it useful for agricultural soil remediation [137,138]. Moreover, WH has a high moisture content, which accounts for over 80 % of its fresh weight, enabling it to increase the concentration of nutrients to crops when applied as top dressing. Importantly, WH is rich in nitrogen, which accounts for up to 3.2 % of its dry weight [11], and generally occurs in proteins and amino acids, as with plants. Since nitrogen is an essential nutrient for plant growth as a critical component of fertilizers, its occurrence in WH makes the weed appropriate for use as a biobased fertilizer feedstock [139]. Similarly, WH contains appreciable amounts of phosphorus, potassium, and micronutrients like iron, manganese, zinc, and copper (Fig. 6). Overall, the chemical composition of WH makes it suitable as a sustainable component of biobased fertilizers and possible use for animal feed production. However, its ability to bioaccumulate pollutants like mercury, lead, and strontium-90 up to 10,000 times its surroundings can be a drawback [37,140–144].

4.2. *Biogenic materials for nano-enabled fertilizer development*

The use of nano-based polymers for fertilizer development represents an innovative and sustainable approach to increasing crop performance and fertilizer use efficiency. Use of various plant-based feedstocks such as wheat straw [145], rice husk [92,102], bagasse

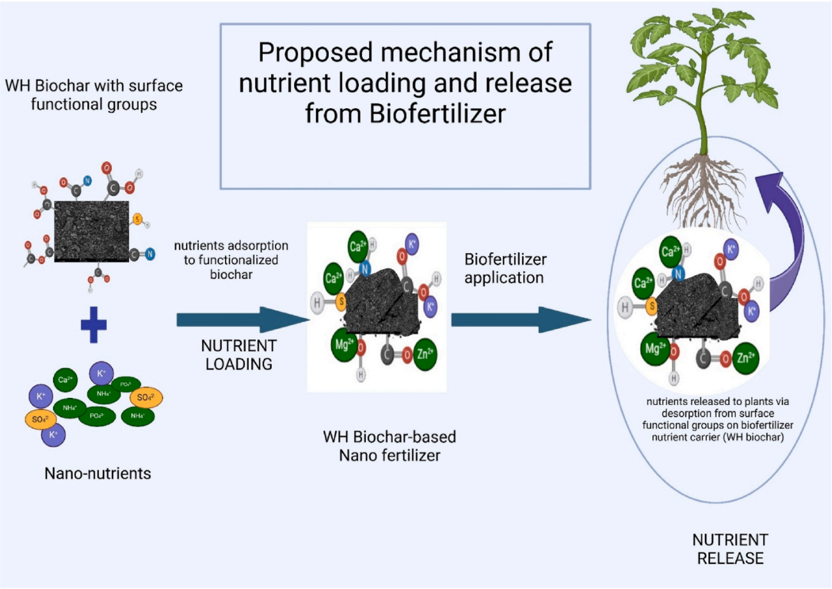

Fig. 7. Schematics of proposed mechanism for water hyacinth (WH) biochar nanonutrient loading for biofertilizer formulation and nutrient release to plants via desorption.

[146,147], bamboo [82,148], pinewood [149], corn stalk, and sawdust for production of nanofertilizers have been extensively demonstrated [2,5,76,78,96,130,150–154]. Aside from allowing for a high surface area-to-volume ratio, nanotechnology-based fertilizer development also offers the benefits of controlled nutrient release and lower environmental impact than conventional fertilizers. According to Rop et al. [155], WH has gained significant attention as an emerging bio-based nanopolymer for controlled-release fertilizer development, where their work, incorporation of water-soluble phosphate fertilizer into a WH acrylamide polymer increased the nutrient use efficiency and reduced leaching and phosphate toxicity in the local soil. In another study, Kalaivani and Ravi [156] synthesized and characterized nanocomposites of ZnO nanopolymers from a WH extract. The authors found that the nanofertilizer significantly improved root development, enhanced photosynthetic rate, and improved nitrogen use efficiency. Taken together, the sorption and desorption of nutrients in the plant biomasses by taking advantage of charged functional groups on the biomass surface are significant features of the mechanism involved (e.g. Refs. [157–159]. In this process, nutrient release could be significantly controlled, compared to regular fertilizers of equivalent chemistry. Thus, another potential area of application of WH as a nanobiofertilizer could be based on the biosorption of nanoscale nutrients such as N (as ammonium), nanohydroxyapatite (P), K, Ca, Mg, S, Zn, Fe, and other nutrients by a slurry of fine powder of the plant biomass derived from milling or grinding. In this regard, the nanoscale dimensions can be claimed from either the added nanonutrient or nano-biomaterials originating from the grinding process. In fact, this strategy can be incorporated into the nanobiochar one described above, where the biochar from WH can be used for the biosorption process. While these studies highlight the potential utility of WH as a scaffolding or adsorbent (nano)polymer in nanoscale fertilizers, the concept is still nascent and has received relatively little attention in research and development at scale. Fig. 7 shows a proposed WH biochar-based nanofertilizer mechanism in plant nutrient fortification.

In the proposed mechanism, nanonutrients are adsorbed on the surface and into the pores of the WH biochar through both chemisorption and physisorption [160]. The nutrient sorption is facilitated through electrostatic attraction by the surface charges, pore filling, hydrophobic interactions, H-bonding, complexation, ion-exchange, covalent bonding, precipitation and van der Waals forces [161,162].These nutrients can then be released to the plants at a controlled rate via desorption.

5. Benefits of sustainable upcycling of water hyacinth

As noted, several methods can be used to remove WH from water bodies, including mechanical dredging using machinery, in-situ cutting, chemical control, manual harvesting, and biological control [44,50,52,66–68,71,163]. Moreover, the challenges current WH control efforts face, particularly the high economic cost of mechanical removal and the rapid reinvasion of reclaimed water bodies by the weed, have been emphasized [47,164]. Recently, the effectiveness of WH control efforts has been hampered by resistance from stakeholders holding the view that complete eradication of the weed is inappropriate owing to its beneficial applications in agriculture, energy, and ecological remediation. Acknowledging these potential benefits, a more innovative approach is to design a sustainable method of harvesting and repurposing the weed for various industrial uses, including as a component of bio-based fertilizers [41]. Centered on a circular economy, the model proposes weed harvesting at a rate that allows sufficient regeneration to maintain a continuous supply in the future [61]. Considering the potential of WH to foster the local economy, researchers have noted that harvesting methods should be tailored to the available resources to ensure economic sustainability, with unduly labor-intensive approaches such as transport of the bulky biomass being limited to control overall cost [11,61,165]. Altogether, innovative approaches are needed to ensure that WH collection for biofertilizer development and other uses remains sustainable.

5.1. *Carbon sequestration and soil improvement*

Several studies have demonstrated the utility of nanobiochar as a carbon sink for the long-term mitigation of carbon emissions.

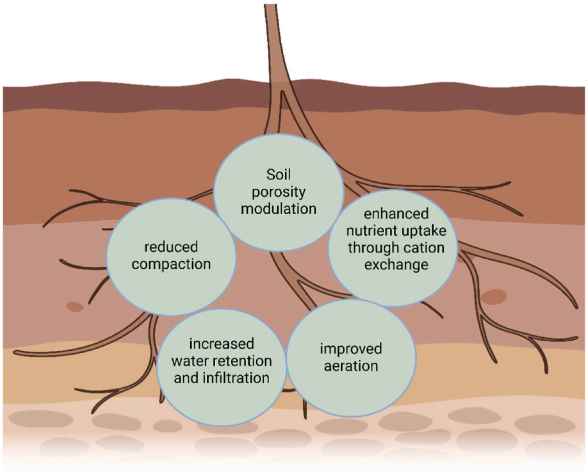

Fig. 8. Schematic diagram showing roles of nanobiochar on soil improvement.

Nanobiochar has a high carbon content, typically exceeding 70 %, which makes it an effective carbon sink. It captures and stores carbon in its organic material, reducing the release of CO2 into the atmosphere and hence contributing to climate change mitigation by offsetting carbon emissions from various sources [2,75,154,166]. Moreover, biochar is highly stable and resistant to decomposition, maintaining the sequestered residual carbon in the soil for an extended period, potentially hundreds to thousands of years, depending on the feedstock and the pyrolytic conditions [167,168]. Quantitatively, a biochar yield of 25 % with 80 % carbon will retain 40 % (20 g) of the biomass carbon assuming a 50 % carbon in the feedstock biomass [169]. Notably, this carbon would have otherwise been returned to the atmosphere via decomposition or burning of the organic biomass. To validate the carbon sequestration potential of biochar application, Wang et al. in a recent study found that 1 ha of agro-ecological space can sequester up to 30 tonnes of carbon with biochar amendments [170].

In addition, nano-sized biochar can improve soil structure by modulating soil porosity, reducing compaction, and increasing water retention capacity. Soil pore sizes usually determine its water retention capacity with the sizes usually classified into 5 according to Soil Science Society of America: macropores (>80 μm), mesopores (30–80 μm), micropores (5–30 μm), ultra-micropores (0.1–5 μm), and nanopores (<0.1 μm) [171]. Water drains quickly by gravity through macroporous soils, thereby making the water unavailable to plants. For other soil types, the mechanism of water draining differs base on the pore sizes, and the rate is directly proportional to the pore sizes. However, when amended with biochar, especially nanobiochar, the water retention capacity of the soil is enhanced because the nanobiochar intrapores are in a much smaller range (between above 50 nm to less than 2 nm). This in turn improves the soil-biochar interactions [172], ultimately enhancing the soil structure for better aeration and water infiltration, promoting root growth and enhancing plant nutrient uptake. Moreover, as shown in Fig. 8, nanobiochar has a high cation exchange capacity, enabling it to retain and slowly release essential nutrients such as nitrogen, phosphorus, and potassium [2,75,76,154]. Collectively, these properties translate to significant positive environmental and agricultural impacts of nanobiochar.

5.2. Water pollution mitigation

Nanobiochar can effectively remove pollutants from water, making it a valuable tool for water treatment and environmental remediation. Nanobiochar has a high surface area and a porous structure, which enhances its adsorption capacity. It can adsorb a wide range of water pollutants, including heavy metals and toxic elements such as lead, mercury, arsenic, and cadmium, and organic contaminants such as pesticides and other agrochemicals [2,32,75,140,173,174]. The adsorption process involves binding contaminants to the surface of nanobiochar particles through physical and chemical interactions [2]. Nanobiochar can effectively adsorb organic pollutants and pesticides from water, improving water quality in agricultural runoff, industrial effluents, and urban stormwater [29,32,34,84,93].

5.3. Biodiversity conservation

The removal and conversion of WH into nanobiochar contributes to biodiversity conservation and habitat restoration by removing the detrimental ecosystem effects of this invasive aquatic species. WH is notorious for its rapid growth and ability to outcompete native aquatic plants, resulting in the degradation of natural habitats and the displacement of native species [175]. Consequently, its removal is an effective strategy for habitat restoration of local biodiversity. Simultaneously, nanobiochar has been shown to be useful in the phytoremediation of native plants through growth enhancement and removal of ecosystem contaminants. Repurposing WH as a raw material for nanobiochar production can actively contribute to conserving aquatic biodiversity in affected water bodies.

5.4. Socioeconomic benefits

The harvesting and repurposing WH as a raw material for nanobiochar and nanofertilizer production have significant socioeconomic implications for local communities [5,47,116,176]. As a sustainable weed control strategy, this approach frees water bodies for economic uses such as fishing, irrigation, and navigation. Moreover, utilizing biochar-based nanofertilizers promises significant positive economic effects through job creation, higher agricultural productivity, and opening domestic markets for locally sourced raw materials. Due to their higher nutrient use efficiency, nanofertilizers represent a cost-effective method of increasing agricultural crop yield, thereby reducing the input of mineral fertilizers [177–180]. Notably, the use of WH as a raw material reduces the environmental impacts of mineral fertilizer use, including pollution from ammonia volatilization, emission of nitrous oxide, and leaching or run-off of nitrates and phosphates into waterbodies, while simultaneously driving ecologic remediation of cultivated soils. A notable social implication of WH repurposing is its association with the concept of ecological nudging, through which local communities are incentivized to control the invasion of WH by demonstrating its utility as a feedstock for biochar and bio-based nanofertilizers. Taken together, WH utilization for nanobiochar and bio-based fertilizer production can turn this invasive weed into a socially and economically beneficial resource.

Although, it is generally difficult to quantitatively gauge the economics of utilization of WH-derived biochar, since it is still an emerging concept, however, a simple financial analysis represented by equation (1) can give an overall insight into the possible profit by subtracting the various costs from the benefits [181–183].

$$NP = BC + E - C - F - T - O - A \qquad [1]$$

Where:

NP = net profit.
BC = biochar value (including agronomic and carbon sequestration)
E = biochar energy sales (e.g. biochar or charcoal, syngas, biofuel etc)
C = capital costs (equipment procurement, real estate costs etc)
F = feedstock costs (e.g. production, harvesting, transportation, storage)
T = biochar costs (biochar transportation and storage)
O = operational costs.
A = application costs.

6. Regulatory framework and cost-benefit implications of repurposing water hyacinth as agrochemicals

Multiple international and national policies support the development of sustainable solutions to the challenges posed to agricultural productivity, such as the development of green nanobiochar. Along this line, several of these efforts have been enshrined in the United Nations Sustainable Development Goals, which address a range of socioeconomic and environmental issues, including zero poverty, hunger, clean water, and climate action [184,185]. Following the Paris Agreement of December 12, 2015, over 100 countries have adopted multiple components of the Nationally Determined Contributions, outlining their commitment and individual goals aimed at addressing climate change. The development of green nanobiochar and fertilizers is a key strategy for contributing to climate change action, particularly in line with the material's role in carbon sequestration and reduction of greenhouse gas emissions. Besides the international framework for environmental sustainability solutions, key regional and national government policies and initiatives continue to support the development of green nanocomposites for various applications. In the European Union, the development of green biochar is supported by the Common Agricultural Policy and the Circular Economy Action Plan, both of which reflect the union's ambition towards climate change mitigation. While other countries' policies do not feature such direct emphasis on green nanobiochar development, similar supportive regulatory frameworks are in place in many nations. Collectively, these initiatives and regulations represent a solid foundation for a future prospect for biobased nano-agro inputs development. However, any regulatory framework must be matched with a comprehensive cost-benefit analysis, a crucial step in the journey towards sustainable agriculture, to make such regulations investment-friendly.

While a formal cost-benefit analysis of the production of WH-based agrochemical has not been reported in the literature, a few studies have conducted econometric analyses of WH utilization for similar green applications. For example, Wainger et al. [186] conducted an evidence-based cost-benefit analysis of the WH management, comparing the resource costs of its harvesting to the economic returns of repurposing the weed. They found that the cost of herbicides and biological control programs were justified by the gains from navigation, fishing, water treatment, and boating businesses on reclaimed water, with a cost-benefit ratio of 34:1. A similar analysis of WH utilization for nanobiochar formation would need to be conducted and to include costs related to the weed's harvesting, labor, equipment, and the fabrication process of the agrochemical. Moreover, the ecosystem and agricultural productivity benefits of the green agrochemical increase the advantages of WH repurposing for this application, which is in addition to the economic gains from increased access to the reclaimed water bodies. This potential for WH-based agrochemicals to revolutionize sustainable agriculture is a beacon of hope in our quest for environmental sustainability.

Commercial inorganic fertilizer, which is mostly employed to boost agricultural food production, pose significant ecological sustainability and economic problems, while being characterized by high imbalance in nutrient composition [160]. This is due mainly to the low NUE which makes its application environmentally harmful and economically ineffective. For example, an average NPK fertilizer can supply 20–30 % of its nutrient to the plant with the rest volatilized, emitted, leached or washed away in runoff water to aquatic environments [178,187,188]. The cost associated with such resource wastage is enormous [184]. For example, using Nigeria as a case study, according to the Fertilizer Technical Working Group [189], fertilizer use in Nigeria has been increasing since 2011 and as of 2023, it stands at 1.64 million metric tonnes Fig. 9. If 70–80 % of this quantity is lost due to low NUE, at the current rate of N55, 000 per 50 kg of fertilizer, it amounts to a whooping loss of N1.8 trillion annually (about $1.8 billion/year). This is apart from the colossal environmental and ecological damage such nutrient loss will also cause.

7. Conclusion: challenges and future prospects

Taken together, this review aimed to promote scientific research and innovation in the field of green chemistry and environmental engineering, by controlling WH proliferation which otherwise poses great ecological and social threat [67]. By so doing, it is contributing to academic knowledge and practical solutions for sustainable agriculture [94,158,190]. Clearly, it is important to sustainably harness the benefits derivable from biochar from WH. In this regard, advances in nanotechnology, particularly the fortification of biochar with nanoscale nutrients, hold strong promise for improving soil health and productivity to provide adequate and nutritious food for the increasing human population at lower environmental cost. Notably, producing biochar at the nanoscale enhances its properties, like water retention and surface area. Therefore, WH, an otherwise invasive weed, can be used as a sustainable feedstock for producing nanobiochar, facilitating its clean-up from infested areas while improving soil quality and nutrient efficiency upon application. The peculiarity of WH, namely, rapid growth, low cost, biodegradability, and high lignocellulose content, make it ideal for pyrolysis for biochar production and other downstream products such as fertilizers. These benefits combine with related advantages in carbon sequestration that contribute to the net zero carbon by acting as a carbon sink, as well as wastewater treatment and active electrode development for sustainable energy generation.

Despite the potential socioeconomic benefits of WH exploitation for nanoscale biochar and subsequent fertilizer production, the

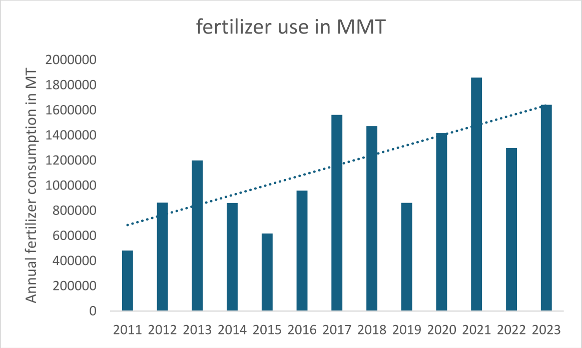

Fig. 9. Nigerian annual fertilizer consumption from 2011. (Data from Africa Fertilizer, 2024).

process is not without its challenges. The most immediate challenge is the labor-intensive nature of WH harvesting due to the weed's dense growth and the need for expensive collection operations. Hence, mechanized harvesting methods should be adopted where they are already unavailable. Another challenge is the fabrication of nanobiochar using WH at an industrial scale, which is hindered by the weed's high water content and bulkiness, necessitating large-scale drying and transport operations. Moreover, WH's avid nutrient uptake capacity predisposes it to contamination from heavy metals and other pollutants from water, introducing the risk of further contamination when the weed is utilized for nanobiochar development. The control of particle size during the production of nanobiochar on an industrial scale is also a challenge, especially under low-resource settings where WH invasion on inland water bodies is rampant. Despite these barriers, the prospects of this application are favored by an expanding agricultural sector driven by a growing population, the increasing prioritization of sustainable and eco-friendly agricultural inputs among consumers and policymakers, and growing research and development on sustainable exploitation of WH. Consequently, repurposing WH for nanobiochar and nanoscale fertilizer development must overcome several potential barriers, as enunciated above.

Current studies have firmly established the need for a sustainable approach to WH control and utilization in producing green nanobiochar and nanofertilizers. However, additional research is needed for refining and optimizing the processes involved in converting WH into these agromaterials, including, but not limited to.

- The determination of the most efficient pyrolysis conditions, including temperature and time.
- Understanding the implications of pre-processing techniques, such as the separation of plant biomass into different tissue types.
- Evaluating different post-treatment methods to enhance the quality and properties of nanobiochar, including material characterization and functionalization.
- Assessing the possible toxicity of WH-derived nanobiochar, especially concerning heavy metals bioaccumulation.
- Conducting an economic viability study of large-scale nanobiochar production from WH, including a direct cost-benefit assessment of nanobiochar development from this aquatic plant, both from the consumer standpoint and the business investor angle.

Data availability

All data used in this review will be made available upon request.

CRediT authorship contribution statement

Adewale T. Irewale: Writing – review & editing, Writing – original draft, Conceptualization. **Christian O. Dimkpa:** Writing – review & editing, Validation, Supervision, Conceptualization. **Elias E. Elemike:** Writing – review & editing, Validation, Supervision. **Emeka E. Oguzie:** Validation, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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manuscript.

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