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REVIEW

Utilization of *Eichhornia crassipes* biomass for production of biochar and its feasibility in agroecosystems: a review

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Abstract
Biochar is a carbon-rich product, derived from the pyrolysis of biomass in the absence of oxygen. It is a widely accepted soil amendment for increasing the amount of soil carbon, nutrients, organic matter, enhancing population of soil microbes, soil retention and aeration capacity. Biochar can be produced using agriculture residues, plant biomass, and animal waste. *Eichhornia crassipes* is a high biomass producing aquatic plant used for a variety of purposes around the world. This review highlights the fabrication of biochar from *E. crassipes* biomass. The biochar produced from *E. crassipes* biomass bears good nutritive values and its application to the soil enhances agricultural crop productivity with improved soil health. The conversion of *E. crassipes* biomass in to biochar not only provides a significantly better alternative to chemical fertilizers but also a sustainable management strategy of this invasive plant species.

Keywords Water hyacinth (*Eichhornia crassipes*) · Waste valorization · Biomass · Biochar

Introduction

The expanding population has led to depletion of natural resources with their increasing demands. This concurrent effect can decline the sustainable agricultural production and food security. For this, a variety of chemical synthetic fertilizers, pesticides, and other products have been used for enhancement of crop yields. Nevertheless, these chemical fertilizers contain toxic metals which degrade the soil health with set of certain antagonistic reactions, as a result of which soil becomes degraded resulting in stressful conditions for plants. Therefore, with the excessive use of chemical and inorganic fertilizers, the agricultural yield and soil fertility declines. In this connection, some sustainable approaches have been investigated including organic farming, agroecology, agroforestry etc. (Nair et al. 2017). The utilization of natural substances or the products derived from them are found economically viable and environmentally sound, for not only enhancing the crop yield but also soil fertility. Biochar, a carbonaceous solid material, is one of these products which has good percentage of aromatization and strong anti-decomposition capabilities (Yuan et al. 2019). Moreover, it can be produced from various materials such as weeds, food wastes, timber debris, straw, rice shell, crop residues, etc., (Ding et al. 2016; Rehman and Razzaq 2017; Das et al. 2021; Jia et al. 2021). Biochar produced from organic biomass is quite a novel alternative to improve the soil fertility, agricultural yield, and organic matter, in order to prevent soil deterioration (Das et al. 2021; Jia et al. 2021). In many countries like India, Europe, China, Japan, and America, biochar is being used as an amendment for improving soil fertility (Gabhane et al. 2020).

Utilization of weeds especially high biomass producing species for production of biochar has become a novel tool due to its easy availability and cost-effective nature. The exponential growth of aquatic weeds has is of concern to both environment and ecologists (Zedler and Kercher 2004; Chamier et al. 2012; Brundu 2015). However, silver lining is that these species have been found to bear significant potential to be used for the preparation of biochar. *Eichhornia crassipes* (water hyacinth) is a major exotic weed, well known for its obstinate growth around the water bodies. Hence, it can severely affect the biodiversity, nutrient cycle, and water quality. Resultantly, numerous physical, chemical and mechanical techniques have been suggested

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to suppress growth of this invasive weed but the incurring expenditure becomes a snag to it. On the other hand, these techniques remain unsatisfactory in genuinely managing the problem, regardless of being a cause of multiple environmental dilemmas (like increase in pollutant load, heavy metals, etc.) (Gao and Li 2004). Besides the drawbacks, aquatic invasive species also possesses evident qualities like, high biomass, improved metabolic properties, superior tolerance level, and greater efficiency to decontaminate the water. Thereby, to control the load on environment due to the invasion, a new and sustainable approach is gaining a great deal of attention throughout the globe. Bio-waste valorization, which facilitates conversion of waste-biomass into eco-friendly bio-products is now becoming important to tackle to utilise the waste biomass (Abosede et al. 2017; Ahmed et al. 2020; Ulusal et al. 2020). *Eichhornia* biomass can be a good alternative source and can be utilized in many possible ways such as in phytoremediation, preparation of compost or vermicompost, manure, biochar, paper, board and energy production, due to its rich cellulosic properties (cellulose, hemicellulose and lignin content), and higher biodegradability when disposed directly into the soil (Wilson et al. 2005; Cai et al. 2017; Sindhu et al. 2017). Also, due to rapid and high biomass producing potential, it has considerable ability of carbon dioxide (CO_2) sequestration (Spokas et al. 2012; Gupta et al. 2020). These alternatives can be useful as low-cost operation, waste minimization, economical, ecological and societal development (Ban et al. 2019; Kwon et al. 2020; Wang et al. 2020).

So, during the process of biochar production, cellulosic carbons in water hyacinth biomass can be converted into stable aromatic carbons, which may help in attracting the soil particles through decomposition process and increasing the soil carbon content. Meanwhile, several scientific studies have proved that biochar has a greater role in enrichment of soil properties (Ding et al. 2016; Rehman and Razzaq 2017). Thus, the present review is aimed to explore the potential, characteristics and production methods of biochar from *E. crassipes*. The application of biochar in agroecosystems and their effects on soil fertility parameters, plant growth and yield are also discussed.

Eichhornia crassipes: a recalcitrant alien weed

E. crassipes (water hyacinth), an exotic free-floating perennial vascular aquatic plant, is known for its impetuous growth all around the world coupled with serious ecological and socio-economic changes to the ecosystem (Center et al. 1999). It belongs to family "Pontederiaceae" and is native to Amazon basin of tropical and sub-tropical South America. It reproduces both sexually and asexually (Mitchell 1985) however, for the prolific growth and reproduction of water hyacinth, high nutrient concentrations and optimum temperature are deemed as the strongest factors (Wilson et al. 2005). In contrast to other emergent macrophytes, water hyacinth is not confined to shallow water because of its free-floating root system. It has nearly invaded in around 50 countries on different continents and, may expand to top-level latitudes as temperature rises due to increased green house gas emissions and climate change (Rodriguez-Gallego et al. 2004; Hellmann et al. 2008; Rahel and Olden 2008). *E. crassipes* is pervasive across Southeast Asia, the Central and Western Africa, the Southeastern United States and Central America (Fig. 1) (Brendonck et al. 2003; Lu et al. 2007; Téllez et al. 2008; UNEP 2013). The accelerated growth of water hyacinth affects the drainage systems and irrigation patterns, spread the pathogens, alters the quality of water and hydropower and water supply ways, sabotage water transport, obstructs the canals and rivers causing floods, lowers the dissolved oxygen of water, and reduces the aesthetic value of tourist places (Singh 2005; Martinez-Jimenez and Gomez-Balandra 2007). Irrespective of the adverse impacts, water hyacinth also possesses some benefits, it can be used in traditional medicines, biogas production, as mushroom bedding material, carbon black production, making of ropes, production of fiber boards, as animal fodder and fish feed, green manure, compost, biochar and as an ornamental plant (Abosede et al. 2017; Ahmed et al. 2020; Ulusal et al. 2020).

Biochar (BC): an environmental medicament

Biochar is rich in active organic clusters and aromatic configurations with reasonably high cation exchange capacity, optimum pH, extensive surface area, and negative surface charge (Chan et al. 2007; Li et al. 2016a, b; Cheng et al. 2020). As described in Fig. 2 biochar application enhances the soil organic matter and soil enzymes, stimulates soil microbial population, aids in improved water holding capacity, limits the leaching behavior of chemically derived fertilizers, promotes soil aeration, stretches the retention time of nutrients and increases soil stress tolerance capacity and other environmental problems as well (Amonette and Joseph 2009; Cao and Harris 2010; Chen and Yuan 2011; Jiang et al. 2012). Also, biochar has higher adsorption potential due to its greater surface area, when added to contaminated sites (Zhao et al. 2019). Moreover, the biochar can act as pH regulator of the soil, as a result of which, soil retains high moisture to immobilize the metals released from chemical fertilizers (Renner 2007; Kumar et al. 2018). Microstructure of the biochar is a captivating material to stimulate the bio-availability of toxic pesticides or herbicides. The effects and behavior of biochar depends on adsorption or desorption, degradation and bio-accessibility in the soil along with leaching of chemical pollutants (Manyà 2012; Zhang et al. 2012; Safaei Khorram et al. 2016; Cai et al. 2017). Higher proportion of carbon can be sequestered and confiscated for

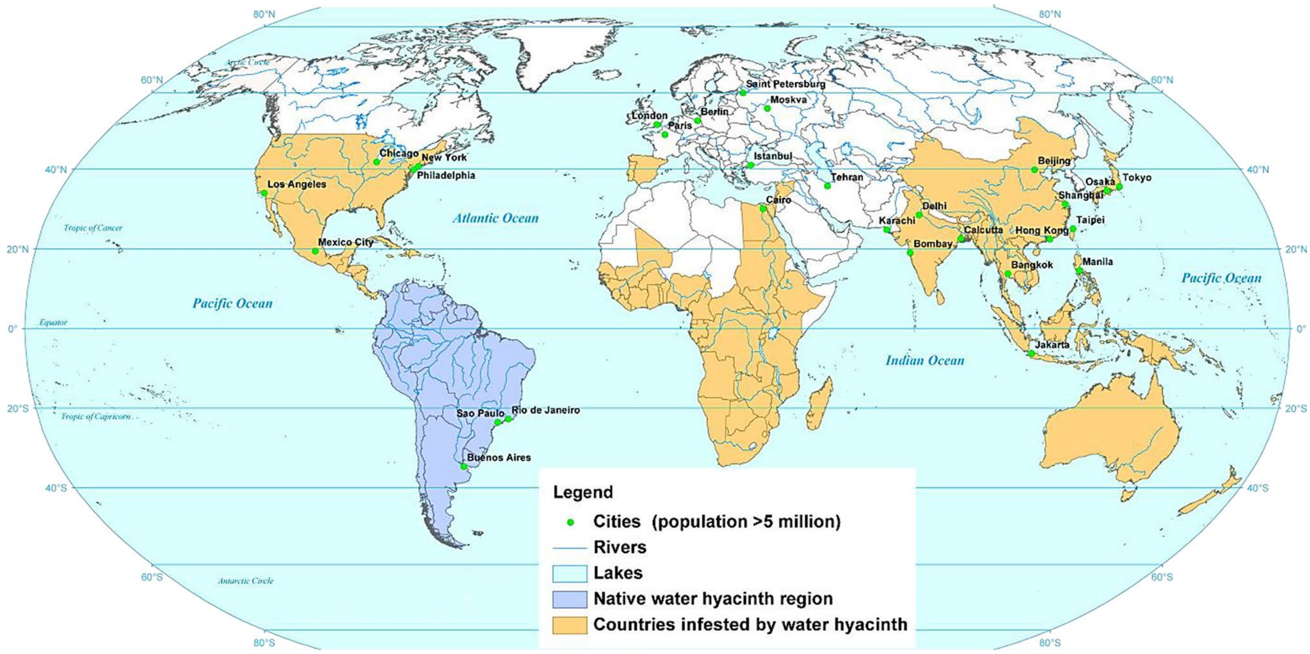

Fig. 1 Global distribution of water hyacinth (Map source: Téllez et al. 2008; UNEP 2013)

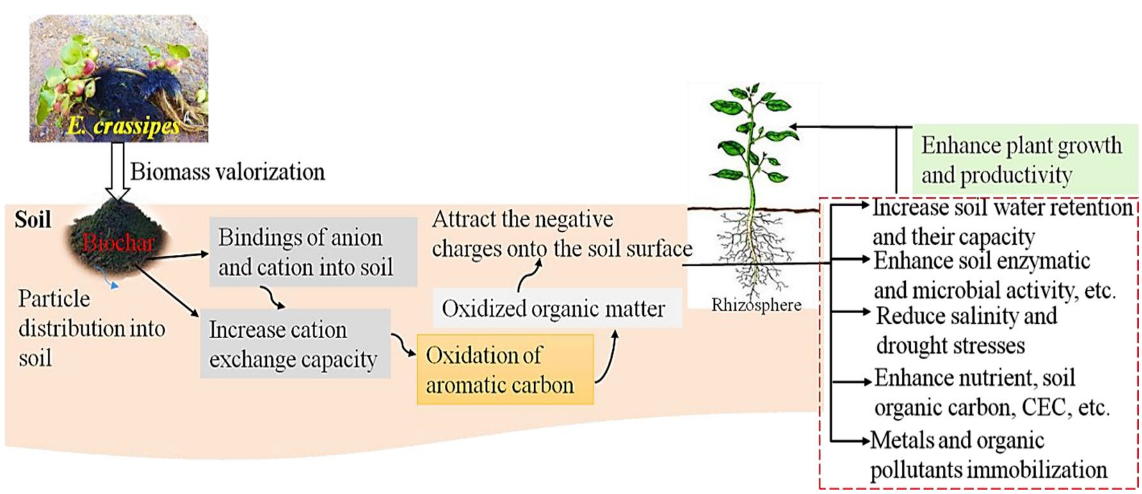

Fig. 2 Multi-benefits of application of biochar into the soil (Masto et al. 2013; Mosa et al. 2018; Najmudeen et al. 2019; Zhou et al. 2020)

a longer period in the soil by application of biochar (Kuhlbusch 1998; Kuhlbusch et al. 1996; Lehmann et al. 2005; Nguyen et al. 2009). Biochar has the ability to mineralize the complex components including pollutants through both biotic (Hamer et al. 2004; Kuzyakov et al. 2009) and abiotic mechanisms (Liang et al. 2008; Nguyen and Lehmann 2009). All these factors and conditions (mentioned above) are favorable for better plant growth and productivity (Jha et al. 2010; Kalus et al. 2019; Sánchez-Reinoso et al. 2020). Regardless of the adequate environmental benefits, the biochar commercialization stumbled due to the higher expenses involved in its manufacturing. This major hindrance can be alleviated by using cheap and locally available raw materials for its production (like, weeds and other biowaste materials) (Uchimiya et al. 2010; Masto et al. 2013; Li et al. 2016a, b; Gaurav et al. 2020). The employment of biomass waste valorization to obtain biochar and other valuable products from invasive weed species (like *E. crassipes*) can be a great initiative and may be an important plan for the suitable management and utilization of the invasive weeds (Masto et al. 2013; Li et al. 2016a, b; Gaurav et al. 2020).

Recently, the production of biochar using plant biomass has gained a lot of interest in the scientific community; however, it can be produced in a variety of ways, including thermochemical and biochemical methods. Therefore, converting biomass to biochar can improve the carbon storage and soil fertility, forging the previously known recalcitrant weed to a valuable resource. Biochar assimilation into agricultural soil has recently encouraged much scientific research for agronomic, financial and ecological benefits. Pyrolysis of feedstock at various temperatures under oxygen-limiting conditions has shown the effects and efficiency of biochar (Khan et al. 2013; Uchimiya et al. 2011). In addition, several types of feedstock have been used for biochar production such as rice straw, wood, corn stover, rice husks, bamboo, wheat straw, peanut shells, poultry litter, and animal manures (Adekiya et al. 2020; Azeem et al. 2019; El-Naggar et al. 2018; O'toole et al. 2018; Paetsch et al. 2017; Muhammad et al. 2017; Naeem et al. 2017) (Table 1). There are some common methods for biochar production which have been discussed below.

Incineration or combustion

Incineration or combustion is the oldest methodology being used to extract energy from plant biomass without any chemical processing. Biomass can be used to produce heat in the presence of air at temperature set between 800 and 1000°C leaving ash (McKendry 2002; Tripathi et al. 2016). However, the remaining ash can be utilized in degraded land for soil reclamation. Huang et al. (2016) studied that combustion of water hyacinth released various gaseous emissions like CO_2, NO_2, SO_2 and methane without pretreatment. However, the pretreatment of biomass feedstock prior to combustion improves process efficiency and suppresses overall process expenses (Goyal et al. 2008).

Pyrolysis

Pyrolysis is the most promising technique being employed to convert waste into useful biochar, liquid and gas. In this process, with the increase in temperature, the quality of biochar and surface structure of particles may get affected (Gogoi et al. 2017; Gopal et al. 2019). Generally, pyrolysis is of two major types i.e., slow pyrolysis and fast pyrolysis. The fast pyrolysis easily decomposes the waste materials and produces gases, aerosol particles and biochar. This process includes high heating, less reaction time, temperature of 500ºC or more, quick char product removal and fast cooling of vapors. Apart from these, the constituent product is bio-oil obtained from dry biomass along with biochar and gas. It is a rapid process that ends within seconds. In this process the yield is indicated as 60% of bio-oil, 20% of biogas and 20% of syngas (Huang et al. 2016; Dai et al. 2017). Whereas, the slow pyrolysis is categorized by slow heating rates, more solid materials and less temperature i.e., 400°C or less as compared to fast pyrolysis. In case of slow pyrolysis, biochar is the prime product (35–45%) together with other products as bio-oil (25–35%) and syngas (20–30%) (Verma et al. 2012; Lai et al. 2013; Méndez et al. 2015). The solid fraction (biochar) product is quite evident during the process with certain volume of liquid and gas products from wet biomass upto 75 wt% (Bridgwater et al. 1999; Amutio et al. 2012). Some researchers observed that pyrolysis is the best method for the conversion of any biomass waste materials such as rice straw, wheat straw, sawdust, flax straw, bamboo biomass, etc., into biochar (Azargohar et al. 2013; Xiao and Yang 2013) (Table 2). Several authors demonstrated that the differences in pyrolysis temperature induces substantial variations in the chemical structure and biochar composition (Li et al. 2006; Scott and Glasspool 2007; Asadullah et al. 2010), that may essentially elucidate the importance and variances in biochar stability and the carbon mineralization process in the soil (Baldock and Smernik 2002; Nguyen and Lehmann 2009).

Gasification

Gasification, a thermo-chemical process, is carried out to produce the gaseous fuels and stable carbonaceous biomass at temperature of around 700–900°C in presence of nitrogen, air and CO_2 (Reddy et al. 2014; Tripathi et al. 2016). With reference to other methods, gasification discards larger volume of syngas along with diminutive emissions. Hydrogen is the primary yield of this process, though a sizeable amount of biochar is also produced (Guan et al. 2016). During this process, an internal heat transfer within particles increases the native temperature of biomass that carries off the removal of water and aids the steady release of pyrolytic volatiles. Although the biomass elements decompose at different temperatures but the entire decomposition ceases within the temperature range of 400–500°C, where biochar is the minute product. To obtain the higher energy efficiency with minimum feedstock, particle size is increased that simultaneously increases the operational cost. On the other hand, an increase in feed particle size decreases the milling costs but increases the residence time and fixed cost (Luo et al. 2009; Al-Rahbi and Williams 2017).

Hydrothermal carbonization

Basically, the hydrothermal carbonization (HTC) process is an effective and eco-friendly technique with the temperature range of 180–350°C (Sevilla and Fuertes 2009) where water is used as reaction medium above the saturation pressure. The HTC process is comparatively cleaner and hazard free method due to water as the individual reaction medium under pressure and heat. The HTC is operated in very complex pressurized rotary drums, kilns and stoves which make it a cost bearing process (Hoekman et al. 2011). During the

Table 1 Effects of biochar supplication of different feedstock materials on soil and plants

Feedstock	Preparation method	Temperature (°C)	Biochar yield (%)	Applied dose	Soil type/texture	Results	References
Hard wood	Pyrolysis	500	–	0, 10, 20 and 30 t ha^{-1}	Sandy loam	Increased in cocoyam yield by 8.1, 7.8, and 5.5% at 10, 20, and 30 t ha^{-1} biochar application, respectively	Adekiya et al. (2020)
Cow manure	Slow pyrolysis	600	–	0, 10, 15 and 20 t ha^{-1} ha	Sandy soil	Biochar treatment increased the biomass and grain yield by 24, and 7% in mash bean and 6 and 9% in wheat crops, respectively	Azeem et al. (2019)
Amur silvergrass residue, paddy straw andumbrella tree wood	Slow pyrolysis	500–600	–	30 t ha^{-1}	Sandy loam soil	Significantly enhanced crop productivity as well as nutrients status of soil	El-Naggar et al. (2018)
Miscanths Giganteous Straw	Slow pyrolysis	500–750	–	8 and 25 t ha^{-1}	Silty clay loam, Albeluvisol	No effect on crop yield	O'toole et al. (2018)
Maize	Gasification	1200	–	30 t ha^{-1}	Loamy texture	No any significant differences in *Festuca arundinacea* and *Dactylis glomerata* grass yields	Paetsch et al. (2017)
Wheat straw biochar	Pyrolysis	300–500	–	3% w/w	Psammaquent and Plinthudult	The biochar application significantly increased the grain yield of rice by 32% in Psammaquent soil while 41% in the Plinthudult soil	Muhammad et al. (2017)
Wheat and rice straw	Pyrolysis	300, 400, 500	32–48	1% w/w	Calcareous soil	Biochar at low pyrolysis temperature can produce nutrient-rich biochar added with high CEC and low pH which is suitable for soil amendments	Naeem et al. (2017)
Mature switchgrass	Pyrolysis	350–800	–	0, 1, 2 and 10%	Calcareous soil	A slight decrease in the pH values of biochar had beneficial effects on soil micro-nutrient availability	Ippolito et al. (2016)

Table 1 (continued)

Feedstock	Preparation method	Temperature (°C)	Biochar yield (%)	Applied dose	Soil type/texture	Results	References
Pine sawdust	Fast pyrolysis	400–800	55–15.7	5%	Sandy soil	Sorghum growth and yield increased by 26 and 23% at the T-700 treatment	Laghari et al. (2016)
Eucalyptus wood	Slow pyrolysis	350 and 800	–	0, 1, 2, and 4% w/W	Loamy-sand (Ultisol) siltyclay loam (Oxisol)	Significant reduction (25%) on the biomass of *Maize* in the sandy at 800 °C produced biochar as compared to control treatments	Butnan et al. (2015)
Wheat straw and chicken manure	Slow pyrolysis	450	–	5 t dry weight ha^{-1}	Sodosols	There was no significant effect on the soil fertility or the plant productivity	David (2015)
Date palm fronds	Slow pyrolysis	400	–	0, 10, 50 and 100 g kg^{-1}	Sandy soil (94.4% (w/w)	Increased in CEC (2.5 to 6.7 meq 100 g^{-1}), decrease in pH value (− 0.5) and water retention significantly improved (up to 20%)	Khalifa and Yousef (2015)
Mixed crop straws	Slow pyrolysis	500	22	16 t ha^{-1}	Loamy soil (entisol)	Biochar with application rate of 40 t·ha^{-1} increased rapeseed and sweet potato yields by 36.02% and 53.77% as compared to control treatment	Liu et al. (2014)
Rice husk, shell of cotton seed	Pyrolysis	400	20	67.5 t ha^{-1}	Sandy loam soil	Biochar amendment in soil increased fruit yield by 20% 13% and 6% respectively, as compared with non-biochar amendment soil	Akhtar et al. (2014)

Table 2 Different production methods of biochar from water hyacinth biomass

Temperature	Methods	References
300–350 °C temperature with 30–40 min residence time	Carbonization	Masto et al. (2013)
Biomass of water hyacinth under N_2 at 250, 350, 450, and 550 °C for 1 h	Slow pyrolysis	Zhang et al. (2015)
Under N_2 temperature at 300, 450, and 600 °C for 2 h	Slow pyrolysis	Ding et al. (2016)
300, 450, and 550 °C	Pyrolysis methods	Cornette et al. (2018)
Biomass was initially heated to 100 ºC for 2 h followed by heating at rate of 5 °C per min to reach three maximum temperatures (200, 300, and 600 °C) for 6 h	Pyrolysis	Nyamunda et al. (2019)

production of biochar through carbonization process at temperature range of 450–550°C, a considerable volume of yield was obtained. So, the researchers emphasize on the temperature variations in slow pyrolysis and lignin decomposition (Cornette et al. 2018). Though the yield of biochar decreases with temperature and time variations but, the biochar carbon stability increases with temperature variations. When compared with other methods, HTC produces biochar that retained nutrients like N and P, which can be supportive in regaining soil fertility. Also, HTC proves to be advantageous over other methods in terms of reduction in O/C ratio, higher calorific value, and increased hydrophobicity (Libra et al. 2011; Gao et al. 2013).

Nevertheless, the production of biochar from plant biomass is usually triggered through energy conversion processes. Moreover, amongst the above-mentioned processes, pyrolysis and hydrothermal carbonization are most suitable and practical alternatives for the extraction of biochar as mentioned in Table 2. Even, complete combustion of plant biomass in absence of oxygen takes place in both the processes (Masto et al. 2013; Ding et al. 2016; Nyamunda et al. 2019). For both the methods, the end product is biochar along with a little amount of syngas and biofuel but, the portion of biochar is comparatively larger. However, the amount of biochar produced depends on the processing conditions such as temperature, duration, biomass sources, etc. A large variety of biomass feedstock such as wood, manure, grasses, invasive plants, crop residues, can be utilized for volarizing into biochar (Xu et al. 2020). Even, the types of biomass can also distort the efficiency and effectiveness of produced biochar (McLaughlin et al. 2009) and the characterization of biochar may be helpful for soil amendment in terms of crops and forest productivity.

Potential utilization of *E. crassipes* biomass for valorization into biochar

E. crassipes is a nitrogen rich plant species (up to 3.2% of dry matter) and C/N ratio is 1:5 suggesting good content of organic matter in the plant (Gunnarsson and Petersen 2007). Also, it is a rich source of minerals and can serve as suitable economic feed for the production of biochar. In a study, it has been found that dry matter of water hyacinth consists of 5.2% N, 0.22% P, 2.3% K, 0.36% Ca, 280 ppm of Fe, 45 ppm of Zn, 2 ppm of Cu and 332 ppm of Mn (Lata and Veenapani 2011). Similarly, in some other studies, it was observed that the use of water hyacinth biochar enhanced the consistency of carbon, organic matter and water holding capacity of the soil (Bordoloi et al. 2018; Cornette et al. 2018; Gopal et al. 2019). In view of the above characteristics, water hyacinth emerges out as righteous choice for the production of biochar. Biochar produced through pyrolysis of water hyacinth biomass effectively removes carbon from the atmospheric carbon cycle and transfers it to long-term storage in soil as a result of which the plants have higher carbon–nitrogen percentage (i.e., 1:24.3) (Jafari 2010).

Characterization of biochar produced from water hyacinth biomass

For the production of biochar, the determining components are organic carbon, nitrogen, lignin, cellulose, hemicellulose, etc. However, the characterization of the produced biochar needs to be accomplished prior to its application into the soil as amendment for further suitability. The yield of biochar was determined as the ratio between the dry weight of *Eichhornia* and the obtained biochars (Thermo Scientific Flash 2000). As the yield decreases with elevating temperature in pyrolysis, the pH contrastingly increases from 7.98 to 11.54 with the rise of temperature from 300 to 700°C. Also, the carbon content grows from 47.17 to 51.34%, while there is a considerable decrease in oxygen, nitrogen, and hydrogen contents from 47.13 to 46.83%, 0.73 to 2.12%, and 1.10 to 3.580% respectively (Walkley and Black 1934; Pereira et al. 2011; Masto et al. 2013). Even, the surface polar functional groups curtail thereby signifying decrease in the (O + N)/C ratios with the pyrolysis temperature (Cantrell et al. 2012). Likewise, the H/C and O/C ratios of the *Eichhornia* biomass and biochar are 1.71 and 0.78 and 0.85 and 0.33 respectively, this decrease in values indicates high degree of aromaticity in resultant biochar (Feng et al. 2017). Masto et al. (2013) found that the biochar produced at 300°C is thermally more stable than that produced at 500°C, which states that loss of organic matter is quite lower for biochar at 300°C as against biochar at 500°C. For this reason, biochar at 300°C is more effective for soil amendment motive in relation to biochar produced at 500°C. Also, the puffy surfaces are clearly visible in scanning electron microscope (SEM) images. This process increases the surface area and porosity in the resultant biochar. So, considering biochar application into the soil, these two features are useful in boosting nutrient retention, improving water holding capacity, magnifying soil organisms and intensifying fertilizer use efficiency. The results of SEM–EDX (Energy dispersive X-ray analysis) of some studies reveal the composition of water hyacinth biochar particles, where, the prime elements found were C, O_2, K, Cl, P, Na, Fe, Ca, Mg and Si (Masto et al. 2013; Mosa et al. 2018; Abd et al. 2018) and varied according to the types of biomass feedstock (de la Rosa et al. 2014). In another study, the maximum contents of P, K and Mg (4.3, 9.9 and 2.8 g/kg, respectively) were detected in the biochar obtained at 500°C temperature, whereas the 400°C temperature the result was confined to maximum contents of C and N (73.6% and 1.9%, respectively) (Saletnik et al. 2016). Out of which, K has a major role in influencing biochar formation as it promotes dissolution of cellulosic compounds and also affects the thermal stability (Zhou et al. 2009). Bottezini et al. (2021) characterized water hyacinth biochar using 13C and 31P NMR spectroscopy and found that the formed extractable phosphorus, mainly orthophosphate at 400°C, contains 60 mg kg^{-1} of extractable P, and 0.83% of total P. They have also found that aromaticity of produced biochar increased from 52 to 79% with pyrolysis temperature which is very promising for a soil P-supplier.

Effects of water hyacinth biochar on soil and plant productivity

Utilization of *Eichhornia* biomass for making of biochar is proved to be low-cost and environment-friendly biotechnological application (Lahori et al. 2017). The biochar is applied for various purposes such as soil quality improvement, wastewater treatment, climatic chaos mitigation, waste minimization and management (Lehmann and Joseph 2009; Li et al. 2017; Wang et al. 2017; Mosa et al. 2018). However, biochar can enhance the soil properties along with soil fertility and nutrient contents, especially by reducing the leaching of nitrate, phosphate and other anionic nutrients, improving the soil structure and soil–water capacity and enhancing the soil microbiological properties (Wilson 2014; Petersen-Rockney 2015; Blanco-Canqui 2017). Meanwhile, the greater availability of nutrient to crops can be made more efficient, if the biochar is supplemented with various types of soil amendments like compost, manure, cow dung, press mud or synthetic fertilizer. Masto et al. (2013) reported that application of water hyacinth biochar substantially increased soil microbial activity (around three times in active biomass) as well as soil respiration. Similar kind of results were also observed by Gorovtsov et al. (2019) where they found that large fungal colonies were developed after the application of biochar into the soil. According to Jafari (2010) water hyacinth biomass can be used as an efficient soil amendment because it contains up to 75.8% organic matter, 1.5% nitrogen, and 24.2% ash, as well as 28.7% K_2O, 1.8% Na_2O, 12.8% CaO, 21.0% Cl, and 7.0% P_2O_5.

The application of biochar in soil has a great potential to improve soil quality as well as sequester carbon at the same time (Verheijen et al. 2009). Many studies showed that application of biochar increased crop productivity, improved water quality, minimized nutrient leaching rate, reduced soil acidity, increased water holding capacity and minimized the use of fertilizers. However, all these conditions are favorable for better plant growth and productivity, as described in Table 3. Masto et al. (2013) reported that application of biochar derived from water hyacinth biomass aids in salubrious growth of *Zea mays* seedlings. Oladele (2019) in his observation found that using *Eichhornia* biochar on rice cultivation at 3–6 tons ha^{-1} significantly ($P < 0.05$) increased grain yield by 46% and straw yield by 47%. Similarly, Najmudeen et al. (2019) in their study observed higher yield in crops cultivated in the soil applied with 4% of *Eichhornia* biochar than in controlled conditions. Along with higher yield, there was remarkable increase in the growth of plant shoots and roots. Biochar derived from water hyacinth also regulates heavy metal pollution in soil, paving the way for large-scale utilisation of water hyacinth resources (Yin et al. 2016). Likewise, *Eichhornia* biochar can be used as a soil amendment to reduce heavy metal and phytotoxicity because of its high surface area, broad surface functional group, and interlocking patterns of its particles (Xu et al. 2020). Bordoloi et al. (2018) examined the efficacy of water hyacinth biochar for improving soil fertility and metal adsorption.

Comparison of *E. crassipes* biochar with other plant biomass biochar

E. crassipes is an invasive plant, thus there is need of advance research in this field to control its growth and management of its biomass that includes production of biochar for soil as well as water remediation, and use as catalyst in restoration of environmental issues (Zheng et al. 2016). With recent technological advancements, it is possible to convert the biomass of this aquatic weed into biochar, biomethane, biohydrogen, and absorbent for remediation of pollutants crack propagation (Feng et al. 2017; Zheng et al. 2016; Bordoloi et al. 2019). The application of water hyacinth biochar for soil remediation, of oil and and other pollutants retains more water than soil not amended with biochar under both saturated and drought conditions. In a study, Muigai et al. (2021) found that the biochar made from water hyacinth, yellow oleander, and sugarcane bagasse can also be used as an additional carbon source in agronomy, increasing soil mineral content and maintaining pH. They have suggested that biochar derived from water hyacinth can be used as a supporting matrix for the synthesis of-stable bio-composites due to its increased surface area. Besides, the gradual addition of biochar to soil subsequently decreases the crack intensity factor (CIF) potential from 7 to 2.8% in soil (Bordoloi et al. 2018). Yin et al. (2016) observed that biochar derived from water hyacinth, when incorporated at 2% (w/w) showed substantial and persistent reduction of cadmium mobility from soil (used for paddy cultivation) in comparison with biochar made from rice straw. Hence, many studies have proven that biochar obtained from water hyacinth biomass can be effective in mitigating several issues of soil and environment.

Conclusion and future perspectives

From the aforementioned debate, it is quite evident that the conversion of *E.crassipes* (water hyacinth) biomass into biochar could possibly be a good alternative in managing and utilizing the biomass of such invasive weed. Water hyacinth is a well-suited candidate for fabrication of biochar due to its higher content of C-N and rich source of minerals like Fe, Cu, Mn, K, P, Zn, etc. Valorization of water hyacinth biomass into biochar, and its application to agricultural ecosystems possesses several benefits and strengthens the economy for longer run. Even, in several parts of the globe this invasive species is widely being employed for the biochar production and management of soil quality. As suggested by many researchers, water hyacinth is considered as a good phytoremediator species and has great potential in accumulation of heavy metals and other toxic substances from the contaminated habitats (Singh and Kalamdhad 2012; Jain et al. 2019). Biochar made from *E. crassipes* proves to be a propitious adsorbent for the treatment of wastewater as well as contaminated soil, which can successively convert one environmental conundrum to a modern cleaning technology (Li et al., 2016a, b; Chaiyaraksa et al. 2019, 2020). The proper management of biochar residues containing higher number of toxic substances also requires to be researched upon. For example feedstock rich in heavy metals can result in their biomagnification in the food chain, when applied to soil for the enhancement of crop productivity. So, the future researches can be more focused on proper characterization and management of biochar produced form aquatic weeds like water hyacinth. Also, a very limited number of studies have estimated the changes in microbial activity in soils after addition of biochar and further

Table 3 Effects of *E. crassipes* biochar on soil and plant productivity

Biochar	Amount/dose	Findings	References
Rice straw (RS), rice hull (RH), water hyacinth (WH) and mahogany flower receptacles (MFR)	–	Application of this biochar as a soil amendment showed positive effects on soil porosity, acidity, CEC, water holding capacity and nutrient retention which improves soil fertility and plant growth	Villegas-Pangga (2021)
Water hyacinth (WHB), chicken manure (CMB) and wood biochar (WB)	5 and 10%	The highest water retention i.e. 2.6–7.55% found in 10% WHB prepared at 300 °C as compared with CMB and WB	Huang et al. (2021)
Water hyacinth, saw dust, peanut shell and poultry litter biochar	5 and 10%	The plant-based biochar has higher potency to increase the ductility of soil as compared with animal-based biochar	Bora et al. (2021)
Water hyacinth	1, 2, 3, 4 and 5%	Enhanced the specific growth rate of *O. mossambicus* at 1% concentration and highest growth of *pokkali* was observed 4% biochar-soil mixture in comparison to the control	Najmudeen et al. (2019)
Water hyacinth	0, 5 and 10%	The result showed that increase in the amount of biochar reduced the infiltration rates and enhanced the soil retention capacity	Gopal et al. (2019)
Water hyacinth	0, 2, 5, 10 and 15%	Biochar increased the soil–water retention capacity, contraction of the soil particles and enhanced the soil fertility	Bordoloi et al. (2018)
Water hyacinth	0, 1, 3, 5, 10 and 20 g kg^{-1}	The biochar increased the soil enzymes and enhanced the *Zea mays* seedling growth at 20 g kg^{-1}	Masto et al. (2013)

research is required in this area. As a result, the study on use of biochar to improve crop production with simultaneous microbial inoculation can be important. Biochar from water hyacinth had a significant role in maintaining the soil permeability which allows successive inflows of materials within the soil that promotes plant and microbial growth (Garg et al. 2021); however, a limited number of studies have been done to explore the long-term effects of biochar amendment on soil properties. Therefore, studies on water hyacinth biochar must be done for the diverse aspects which can transform a tough challenge to a potential opportunity in the future.

Declarations

Conflict of interest There is no any conflict of Interest.

Informed consent I ensure that all the authors mentioned in the manuscript have agreed for authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

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