Sustainable Agriculture and Plant Production by Virtue of Biochar in the Era of Climate Change

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Abstract In recent years, rapid increase in population growth, improper usage of synthetic fertilizers, organic matter depletion, nutrient imbalance, and land degradation owing to several anthropogenic activities have significantly exerted considerable pressure on agriculture which negatively influences sustainable plant production. Therefore, it is necessary to sustain the most appropriate levels of organic matter in degraded soils, which supports sustainable crop production and maintains nutrient cycling in them. Biochar has been broadly used for sustainable plant production among different organic matters due to its several advantages such as mitigating global warming, excellent soil conditioner, and as a potential amendment for various environmental applications over other soil additives. Moreover, biochar additions in agricultural soils also promoted the seed germination, growth, biomass, yield, and nutritional qualities of crops grown on biochar amended soils. In addition to these benefits, biochar also supports soil microorganisms by providing them habitat due to its porous structure and releases essential nutrients from its matrix, improving microbial communities. Thus, it is suggested that biochar could play a vital role in reducing the adverse impacts of climate change and threats to sustainable crop production.

Keywords Activated carbon · Abiotic stress · Soil amendment · Crop growth · Plant nutrition · Carbon sequestration

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1 Background

In recent years, land degradation, intense agriculture, soil fertility loss, environmental stresses (heat, drought, salinity, cold, metals), and nutrient imbalance significantly decreased sustainable agriculture and plant production owing to a decline in soil organic matter. Besides, the world's population dramatically increased during the last four to five decades which exerted stress on food production (Riaz et al. 2019). Soil nutrient depletion and fertility loss are the key concerns linked with sustainable food production and food uncertainty owing to extensive land use (Agegnehu et al. 2017). The applications of inorganic fertilizers have played a crucial role in enhancing crop and plant production during the last half-century. However, the use of synthetic fertilizers alone is not a wise solution in maintaining soil fertility and enhancing crop yield because the chemical fertilizers, particularly, nitrogen (N) may result in soil degradation and other associated environmental problems such as the rapid organic matter decomposition of organic matter resulted in the reduction of soil carbon stocks (Agegnehu et al. 2017). Thus, maintaining the suitable organic matter in degraded arable lands and ensuring effective biological nutrient cycling is critical for sustainable plant production and soil management. After understanding land degradation and environmental issues, research on numerous organic additives such as composts, mulches, manures, and other carbonaceous additives e.g. biochar has evolved extensively with vital findings on agronomic benefits, greenhouse gas emissions, carbon sequestration, soil quality, and fertility as well as a potential soil amendment (Bis et al. 2018). Biochar, a carbon rich porous material produced through the slow pyrolysis and/or by the combustion, thermolysis, or gasification of various feedstock such as plant residue (Knicker 2007; Naeem et al. 2021; Preston and Schmidt 2006), anthropogenic sources (Warnock et al. 2007), forest waste, biomass from energy crops, (Agegnehu et al. 2017) forage plant biomass (Husk and Major 2011), swine manure (Ren et al. 2020; Tsai et al. 2012), sewage biosolids (Gao et al. 2020; Li et al. 2018; Zhou et al. 2017), empty fruit bunches (Abdulrazzaq et al. 2015; Yavari et al. 2016, 2019), poultry litter and manure (Abd El-Mageed et al. 2021; Sehrish et al. 2019; Wang et al. 2015; Chan et al. 2008; Jin et al. 2016), human manure (Liu et al. 2014), goat manure (Touray et al. 2014; Tayyab et al. 2018), and paper-mill waste (Hmid et al. 2015), kitchen waste (Xu et al. 2020a) and rice husks (Islam et al. 2021; Wang et al. 2020a). The physical and chemical properties of biochar entirely depend upon the feedstock type, heating rate, pyrolysis conditions, residence time, pressure, design of reaction vessel, the flow rate of inert gas, and other treatments (sieving, crushing, activation) after pyrolysis (Joseph and Lehmann 2009; Qambrani et al. 2017). For instance, wood biomass-derived biochar was relatively more resistant to biodegradation due to higher lignin content (Windeatt et al. 2014) compared to biochar derived from crop residues and animal manures (El-Naggar et al. 2018; Singh et al. 2014). The biochar derived from manure feedstock, however, is thought to be nutrient (Mg, Ca, and P) rich (Bandara et al. 2020; Cao et al. 2011) accompanied by higher cation exchange capacity (CEC) and stability (Cely et al. 2015). Previous studies revealed that biochar obtained from the chicken manure at different pyrolysis conditions exhibited dissimilar characteristics of pH, electrical conductivity (EC), N and P concentrations (Chan et al. 2008; Meier et al. 2017). Additionally, biochar is drawing attention as potential input in agriculture to support sustainable crop production and increase yield via improving soil fertility, water holding capacity, providing essential nutrients, carbon capturing benefits, simultaneously alleviating the negative consequences of numerous biotic and abiotic stresses, reducing greenhouse gas emissions and pollution (Akhtar et al. 2015; Beesley and Dickinson 2011; Lehmann and Joseph 2015). Moreover, agricultural activities also deteriorate the soil organic carbon (SOC) day by day. The resilient carbon fraction of biochar enhanced the total carbon pool in the soil, resultantly improved soil fertility (Niar et al. 2017; Lorenz and Lal 2014). This SOC plays a key role via maintaining the nutrients (P, N, K) and water retention and by providing habitat for soil microorganisms that improve soil structure and support plant growth (Kolton et al. 2011; Lorenz et al. 2007). Land use practices and extreme weather conditions (especially high temperatures) are also known to reduce SOC and soil fertility. The addition of biochar as a soil conditioner is recommended to enhance both SOC and soil fertility. Apart from this, biochar also increases carbon sequestration and reduces greenhouse gas emissions released from biomass breakdown and thus reduces the global warming issue (Qambrani et al. 2017). Likewise, biochar may also be utilized as an excellent adsorbent to remove toxic environmental pollutants from the soil or wastewater (Yu et al. 2021). The occurrence of numerous functional groups onto the surface of biochar served as excellent binding sites for the adsorption of toxic heavy metals such as lead (Pb), cadmium (Cd), and nickel (Ni) consequently prevent their accumulation in plants (Tauqeer et al. 2021).

Thus, this chapter aims to collect information about the potential applications of biochar for sustainable plant production after its incorporation into agricultural soils.

2 Benefits of Biochar Additions in Soils

2.1 Soil Quality Improvement

The addition of biochar in soils has a remarkable influence on numerous physical characteristics of soil such as porosity, texture, depth and structure, surface area, particle and pore size distribution, and bulk density. This improvement in the physical traits of soil consequently has a positive influence on water availability at deeper depths and aeration in the root zones which support plant growth (Chan et al. 2008). Additionally, the different merits of biochar additions in agricultural soils significantly raised interest in its utilization as a soil conditioner due to an increase in physical and biological traits of soils such as water and nutrient retention which further improved plant growth (Riaz et al. 2019). For instance, among nine numerous sorts of biochar each produced from various feedstock (500 °C), miscanthus feedstock biochar significantly enhanced soil fine and medium pores, EC, available water content, CEC and reduced pH, bulk and particle density, and soil-wide pore (Khan et al. 2017) (Table 1).

2.2 Soil Physical Properties

The biochar addition in soils increases water-holding capacity (WHC) and decreases bulk density. This rise in WHC capacity could be attributed to the larger surface area as well as the highly porous structure of biochar which enhanced water uptake capacity and hence improved plant growth (Kinney et al. 2012; Laghari et al. 2016). For example, the biochar derived from pine sawdust feedstock at numerous pyrolysis conditions (400, 500, 600, 700, and 800 °C) were added in desert soil, a significant improvement in sorghum yield by 32% and 19% was observed at 700 and 400 °C, accordingly, over control. Additionally, WHC of the desert soil was improved by 16% and 59% which enhanced water use efficiency by 52% and 74% as well as total soil carbon stock, CEC, and plant nutrient content under 400 and 700 °C treatments (Laghari et al. 2016) (Table 1).

2.3 Soil Chemical Properties

Biochar application also improved the chemical traits of soil such as CEC, soil pH, soil fertility, and nutrient uptake by the plants (Lehmann and Joseph 2015). Likewise, the oxidation process occurring onto biochar surfaces and the abundance of different negative charge sites increased the CEC of the soil which increases nutrient retention and subsequently supports plant growth (Cheng et al. 2008; Laird et al. 2010). In contrast, biochar additions to agricultural soils also increased anion exchange capacity (AEC) of the soil owing to the presence of oxonium functional groups which reduced the leaching of anionic nutrients (NO_3^-, PO_4^{3-}) from the soil (Lawrinenko and Laird 2015).

2.4 Soil Biological Properties

Soil microorganisms such as fungi, bacteria, algae, nematodes, actinomycetes, archaea, protozoa, and bacteriophages perform a crucial role in maintaining soil functions such as soil structure formation and improvement, nutrient cycling, suppression of pathogens and diseases, organic matter decomposition, secretion of plant growth supporters, and mineralization of organic toxicants (Gorovtsov et al. 2019). The presence of biochar in agricultural soils elicits the diversity and functioning of these microorganisms owing to the overall improvement in physicochemical traits of

Table 1 The influence of biochar applications on different traits of soil and plant

Feedstock type	Results	References
Cow-bone derived biochar (application rate = 2.5, 5 and 10% w/w Pyrolysis conditions = 500 °C and 800 °C).	Increased total N, total dissolved organic carbon, and total P. The application of 2.5 and 5% biochar (500 °C) improved the activities of alkaline phosphatase and β-glucosidase, over control. Moreover, a significant improvement in maize growth, polyphenol oxidase (PPO), lipid peroxidase (POD), phenylalanine ammonia-lyase (PAL), chlorophyll, and carotene contents were observed, over control	Azeem et al. (2021)
Spartina alterniflora feedstock	The sole and combined application of biochar with effective micro-organisms promisingly improved seed germination rate, stem diameter, plant height, total biomass, and nutrient uptake by *Sesbania cannabina.* Moreover, a remarkable reduction in salt content and improvement in total carbon, available P, total N, and available K, soil NO_3^- and NH_4^+, microbial biomass carbon, soil enzymes, and soil fertility was recorded in the sole and combined treatments of biochar and effective micro-organisms. Overall, the integrated use of biochar at 3% and effective micro-organisms could be an effective approach for the management of coastal saline-alkali soil	Cui et al. (2021)
Peanut shells derived biochar	Biochar utilization in aluminum (Al) and acid-toxic soil improved nutrients availability, exchangeable cations (Mg^{2+}, $Ca^{2+,}$ K^+), soil organic matter, N use efficiency, and overall soil quality. Further, an improvement in the root and shoot biomass of maize by 44% and 89%, respectively, were recorded over control. Results suggested that biochar may use to improve soil quality and support plant production through alleviating Al toxicity	Xia et al. (2020)
Woodchips derived biochar	The utilization of biochar (at 1%) promisingly improved *Arenosols* health, various microbial groups, and populations, maize biomass especially root biomass, and the activities of antioxidants grown on poorly humus sandy soil	Kocsis et al. (2020)
Cassava straw	Applications of N fertilizers coupled with biochar improved soil quality, morphological traits of roots and photosynthesis resultantly increased the yield and yield-related traits of noodle rice	Ali et al. (2020)

(continued)

Table 1 (continued)

Feedstock type	Results	References
Miscanthus and wheat straw biochar	The provision of wheat straw biochar improved bacterial abundance, actinomycetes, soil enzymes, soil fertility index, the geometric mean of enzyme activities index which resultant in an overall improvement in the soil quality	Mierzwa-Hersztek et al. (2017)
Cotton gin trash (pyrolyzed at 450 °C)	Biochar promisingly improved SOM, the contents of Ca, P, Mn and K, and EC in clay loam and sandy loam soils in comparison to the rest of the biochar treatment	Zhang et al. (2016)
Wood and manure-derived biochar treatments	Increased water content in the soil and plant water use efficiency. Additionally, improved CEC and total N while reduced NH_4-N leaching	Ajayi et al. (2016); Abel et al. (2013)
Wood, peanut shell −chicken manure −wheat chaff	Enhanced the availability of P up to 208% while reducing AMF abundance in the soil	Madiba et al. (2016); Warnock et al. (2007)
Wheat straw	Improved soil pH, the contents of SOC, N, and reduced N_2O release	Li et al. (2015)
Eucalyptus logs, maize Stover	Biochar applications significantly enhanced the contents of total N in the soil from the atmosphere	Güereña et al. (2015)
Acacia whole tree green waste	Improved porosity of the soil and aggregate stability	Hardie et al. (2014)
Different biochar prepared from various feedstock	Improved pH, microbial biomass, microbial habitat, and the contents of P, N, K, and total carbon.	Thies et al. (2015); Biederman and Harpole (2013)

soil as well as the porous structure of biochar which serves as habitat and also prevent them from predation (Khan et al. 2020; Palansooriya et al. 2019; Warnock et al. 2007). Moreover, biochar additions to soil also increased carbon-to-nitrogen (C:N) ratios, dissolved organic carbon (C), and K^+ concentrations which support numerous microbial community structures (Wong et al. 2019). Likewise, biochar also enhanced the activities of soil enzymes which increase microbial communities and improved overall soil health (Ramzani et al. 2017; Khan et al. 2020) (Table 1).

2.5 *Provision and Retention of Essential Nutrients*

Biochar also supports sustainable plant production by providing essential mineral nutrients to plants as well as microorganisms. Though, biochar increases soil pH which influences the availability of micronutrients. However, biochar slowly released micronutrients from its matrix and makes them available for plants

(Ahmed et al. 2016). Moreover, biochar additions remarkably promoted the grain quality and yield of *Zea mays* after Mg and Ca uptake (Major et al. 2010). Likewise, the application of acidified biochar produced from maize cob (350 °C) promisingly improved the growth, yield, physiological, chemical, and biochemical traits, antioxidants, and anti-nutrients in *Chenopodium quinoa* grown on drought, salt and Ni stressed soils. The results suggested that the acidified biochar effectively increased the bioavailability and aerial transport of nutrients and subsequent accumulation in quinoa seed (Ramzani et al. 2017).

2.6 CO_2 Sequestration and Reduction of Greenhouse Gas Emission

Agriculture contributes its share in releasing the substantial magnitudes of greenhouse gases which is an alarming and universal global warming and climate change issue (Burney et al. 2010). Usually, CO_2 is released into the atmosphere by the microbial decay or burning of agricultural by-products as well as through the breakdown of organic matter (Smith et al. 2010). Carbon emissions from the soil are considered as one of the prime signals of land degradation which is a challenging task for sustainable plant production, biodiversity conservation, and acclimatizing to climate change (Barrow 2012; Mchunu and Chaplot 2012). The presence of vegetation cover is a natural and effective method of CO_2 captured from the air via photosynthesis. The efficacy of this practice for carbon sequestration is inadequate owing to the instability of captured carbon which returned into the environment as CO_2 through respiration or decomposition (Semida et al. 2019).

As mentioned earlier, biochar additions to agricultural soils may mitigate greenhouse gas emissions and combat climate change through a range of mechanisms (Mohammadi et al. 2020). For instance, inhibition of CO_2 and CH_4 (particularly from rice fields), reduced nitrous oxide (N_2O) released from agricultural soils, consequently decreased the use of artificial fertilizers. The improvement in crop yield are the additional key benefits of biochar applications in agro-ecosystem due to the improved soil aeration (Mohammadi et al. 2020; Qambrani et al. 2017; Rogovska et al. 2011; Zhang et al. 2012).

Various microorganisms produced CH_4 under anoxic conditions via methanogenesis. Approximately CH_4 is considered 20 times more powerful than CO_2 in absorbing thermal radiation in the earth's lower troposphere and increased global warming (Watson et al. 2000). It was observed that after adding biochar in the soil, a remarkable reduction in CH_4 emission was observed (Rondon et al. 2005a). This reduction in CH_4 emission could be due to the porous characteristics of biochar which increased aeration and reduced the favorable anaerobic environments causing methanogenesis (Verheijen et al. 2010). In another study, biochar utilization also reduced CH_4 and CO_2 emissions from the rice field (Liu et al. 2011). Thus, biochar from animal manure may help in this context.

Nitrous oxide is also an important gas having over 300 times more potential than CO_2 in absorbing thermal radiation in the troposphere and causing global warming (Watson et al. 2000). Primarily, N_2O is produced in the soil by numerous microorganisms via denitrification and nitrification. The presence of moisture content in the soil significantly influenced the production of N_2O. For instance, higher moisture (>70%) levels support anoxic conditions, which promote denitrification, while reduced moisture (<50%) levels stimulate nitrification. It was reported that the higher moisture level (up to 80%) produced 8–23 times more N_2O in contrast to lower moisture levels (40%) (Bruun et al. 2011). Similarly, the findings of a study revealed that the utilization of biochar in the form of charcoal significantly declined N_2O release up to 89% (Yanai et al. 2007). Moreover, over 80% decrease in N_2O emissions from biochar amended soil was observed in the greenhouse, and field trials in Columbia (Renner 2007) consequently reduced the applications of synthetic fertilizer. This reduction in N_2O emission from the soil could be due to the adsorption of nitrate (NO_3^-) onto the large surfaces of biochar. Additionally, biochar applications also influence the N transfer and N dynamics which reduced N_2O release (DeLuca et al. 2006; Rondon et al. 2007; Yanai et al. 2007). The presence of biochar in agricultural soils also supports biological stabilization of inorganic N, resultantly reduced ammonia volatilization owing to the higher C: N ratios and lower N content in biochar (Taghizadeh-Toosi et al. 2011).

Likewise, a recent field study (24 months) was conducted in Moso bamboo forest to evaluate the effectiveness of various biochar application rates (0, B5, and B15 Mg ha^{-1}) on SOC stocks, greenhouse gas emissions, and vegetation carbon stocks. Results suggested that the maximum SOC stocks were increased up to 66%, while the greenhouse gas emissions increased by 21%, respectively, in B5 and B15 treatments over control. Moreover, the addition of biochar remarkably reduced N_2O release by 24% in B15, whereas increased CH_4 emission by 16% in B5, respectively, over control. Overall, biochar utilization improved the total ecosystem carbon stock of the moso bamboo forest by 486% and 252% for B5 and B15 treatments and is recommended as an excellent and effective approach for the management of forest soils (Xu et al. 2020b). A recent two-year field study also investigated the potential of biochar as a soil conditioner to combat climate change in sandy loam soil under the influence of drip irrigation with mulch. Biochar was prepared from the corn residue and applied in the soil at various rates (Bo, B15, B30, and B45 t ha^{-1}). The average CH_4 reduction by 124% and 132% was observed in B15 and B30 treatments, respectively over control. Likewise, B30 and B45 treatments improved SOC in the top upper layer (15 cm) by 19% and 37% during the first growing season and by 12% and 15% during the second growing season. Among all applied rates, B30 was efficient in reducing CH_4 and N_2O emissions and improved corn yields (Yang et al. 2020).

Moreover, the applications of rice straw, bamboo, and wood chip-derived biochar promisingly reduced CO_2 emissions from the paddy (Liu et al. 2011) as well as silt loam soil (Spokas et al. 2009). Previously, it was observed that the amending soybean cropland and *Brachiaria humidicola* grass stands with biochar (at 20 g kg^{-1}) eliminate CH_4 releases whereas reduced NO_2 emissions by 50% and 80% (Rondon et al. 2005b) (Table 2).

2.7 Heavy Metal Immobilization and Food Safety

In recent years, a lot of research work has been done so far on biochar and its numerous applications as a potential amendment especially for the removal of heavy metals and other environmental toxicants from the soil and water owing to its majestic properties such as alkaline nature, higher CEC, and porosity (Khan et al. 2020; Tauqeer et al. 2021). Results revealed that the combined application of lignin-derived biochar and arbuscular mycorrhizal fungi (AMF) significantly improved barley grain and was safer for human consumption grown on Pb contaminated soil (Khan et al. 2020). A recent study conducted by (Zubair et al. 2021) revealed that the textile waste biochar coated with chitosan remarkably reduced Cd distribution in roots and shoots of *Moringa oleifera* L while improving the overall growth, dietary parameters, antioxidants as well as soil enzymes over control (Table 3).

3 Sustainable Plant Production under the Influence of Biochar

This section provides selected studies on the usage of biochar as a potential soil additive and its influence on sustainable plant production.

3.1 Seed Germination and Plant Growth

Up till now, limited research work on the influence of biochar from different feedstocks either on improvement or inhabitation of seed germination has been conducted so far (Semida et al. 2019). For instance, among nine different biochars (poultry manure, rice straw, vegetable waste, neem leaves, cotton sticks, wheat straw, domestic waste, citrus leaves, and eucalyptus leaves), the addition of vegetable waste-derived biochar at 2% w/w significantly improved seed germination of maize (Qayyum et al. 2015). Amending soil with biochar (0.5, 2.5 kg m^{-2}) enhanced *Amaranthus palmeri,* seed sprouting but no influence on *Senna obtusifolia* and *Digitaria ciliaris* (Soni et al. 2014). Similarly, the addition of biochar in sandy soil increased maize growth by improving leaf osmotic potential and relative water content as well as photosynthesis. The possible mechanism for this enhanced seed germination and improved growth is due to the overall improvement in soil quality,

Table 2 The influence of biochar incorporation on carbon sequestration and greenhouse gas emissions

Biomass feedstock	Application rate	Results				References
		CO_2 emissions	Soil carbon	N_2O emission	CH_4 emission	
Fir sawdust (650 °C)	20 mg ha^{-1}	Significant decline in forest soil while no influence on orchard soil under 55%, 100% moisture levels.	No influence	No influence	Completely utilized in both orchard and forest soil at 100% moisture level	Walkiewicz et al. (2020)
Wheat straw (500 °C)	4% (w/w) in 100 g soil	Decreased by 7–9% over control.	Increased dissolved organic carbon and total dissolved nitrogen	Reduced up to 36–44%	No influence	Wang et al. (2020a, b)
Bamboo derived biochar (800 °C)	10, 30 t ha^{-1}	No noteworthy variation	No influence	No influence	No influence	Zhou et al. (2017)
Sawdust and chicken manure derived biochar (400 °C)	24 t ha^{-1}	No influence	No influence	No substantial modification	No substantial modification	Zhibin et al. (2017)
Douglas-fir derived biochar (420 °C)	1, 10% (w/w)	Significantly enhanced CO_2 emission	No influence	Addition of 1% biochar had no influence while the 10% addition enhanced N_2O emission by 191%.	Reduced	Hawthorne et al. (2017)
Douglas-fir slash (420 °C)	20 t ha^{-1}	Enhanced by 6%	No influence	No influence	Reduced by 8%	Johnson et al. (2017)
Bamboo leaf derived biochar (500 °C)	5 t ha^{-1}	No influence	No influence	Reduced emission by 20%	No influence	Xiao et al. (2016)
Combined spruce sawdust and maple (350–450 °C)	5 t ha^{-1}	No influence	No influence	No influence	No influence	Sackett et al. (2015)

Sugar maple wood as a feed-stock (500 °C)	5, 10, and 20 t ha^{-1}	Significantly enhanced	No influence	No influence	No influence	Mitchell et al. (2015)
Bamboo leaf derived biochar (500 °C)	5 t ha^{-1}	No influence	No influence	No influence	No influence	Wang et al. (2014)
Cornstalk	24 t ha^{-1}	No influence	Enhanced dissolved organic carbon	No influence	Reduced by 61% Reduced by 63%	Feng et al. (2012)
Bamboo	2.50%	No change	No influence	No influence	Reduced by 63% 51	Liu et al. (2011)

Table 3 Some selective studies on the immobilization of heavy metals by the virtue of biochar

Feedstock type	Pollutant type	Results	References
Cow-bone derived biochar (applied at 0%, 2.5%, 5% and 10%, w/w, pyrolysis temperature 500 °C and 800 °C)	Cd and Zn in mine−smelters contaminated soil.	The addition of biochar significantly reduced Zn and Cd concentrations in the roots and shoots of maize over control	Azeem et al. (2021)
Chitosan-coated textile waste biochar	Cd-polluted soil	Amending Cd polluted soil with the textile waste-derived biochar coated with chitosan resulted in the significant improvement in growth, biomass, nutritional quality, and soil enzymology while reducing Cd in roots, shoots, and in the soil over control	Zubair et al. (2021)
Lignin-derived biochar	Pb-acid batteries	The utilization of lignin-derived biochar coupled with arbuscular mycorrhizal fungi (AMF) reduced labile Pb concentrations over control. Additionally, Pb concentrations in barley grain were found below the critical limit and fit for human consumption	Khan et al. (2020)
Manure waste	Cu-mining	Promisingly reduced the accumulation and uptake of different heavy metals and support *Brassica napus* by producing excessive biomass	Gascó et al. (2019)
Cymbopogon flexuosus waste-derived biochar	Coal mining	Biochar treatment improved soil health and alleviate soil acidity which supports plant productivity	Jain et al. (2020)
Eucalyptus wood and sewage sludge biochar	Zn mining	Significantly reduced labile fractions of Zn, Pb, and Cd	Penido et al. (2019)
Miscanthus derived biochar and zeolite	Ni-polluted soil	A significant reduction in Ni bioavailability and its accumulation in wheat, sunflower, and maize were observed over control	Shahbaz et al. (2018a, b, 2019)
Eucalyptus wood biochar	Zn mining	Results revealed that biochar additions improved soil pH and support plant establishment via improving germination	Martins et al. (2018)

(continued)

Table 3 (continued)

Feedstock type	Pollutant type	Results	References
Biochar obtained from the quercus ilex wood	Cu-mining	Remarkably reduced the bioavailability of heavy metals and their uptake by the plants	Forján et al. (2018)
Dairy manure	E-waste recycling site	Reduction in the bioavailability of Zn, Cu, Pb, and Cd was observed due to the improvement in CEC, pH, and available P	Chen et al. (2018)
Pine needles, soybean Stover, wheat straw	Military shooting range soil	The addition of both biochar treatments reduced the labile fractions of Pb and Cu over control but the results were more prominent in soybean straw biochar treatment.	Ahmad et al. (2016)
Rice hull	Arable land within the surrounding of the abandoned mining area.	The increase in soil pH was observed subsequently decreased NH_4NO_3 fractions as well as accumulation in lettuce	Kim et al. (2015)
Wheat straw	Electroplating area	Biochar significantly immobilized heavy metals in the soil	Gan et al. (2012)
Rice husk, straw, and bran	Agricultural area-mining site	Promisingly reduced the concentrations of Zn, Cd, and Pb by 83%, 98%, and 72% in pore water	Zheng et al. (2012)

structure, moisture availability as well as the reduction in bulk density (Haider et al. 2015). Thus, biochar addition as an amendment may evoke poor emergence and crop establishment owing to poor soil conditions.

3.2 *Improvement in Physiological Characteristics of Plants*

Reportedly, the improvement in crop productivity and growth after biochar addition reflects the overall enhancement in the physiological traits of plants. For example, an increase in P availability and its uptake by maize was observed when biochar was applied with Arbuscular mycorrhiza fungi over other plants (Mau and Utami 2014). Likewise, an increase in stomatal conductance, chlorophyll fluorescence, and photosynthetic rate of *Abutilon theophrasti* was recorded when grown on soil amended with mixed biochar (Seehausen et al. 2017). The combined applications of biochar with zeolite (BC75% + ZE25%) considerably improved the physiology, grain yield, biochemistry, biomass, antioxidant activities in maize and sunflower (Shahbaz et al. 2018b). In another study, the up-gradation in plant water use efficiency, stomatal pore aperture, membrane stability index, stomatal density, relative water content, photosynthetic rate, and stomatal conductance were increased in tomato plants grown in sandy loam soil amended with biochar (Akhtar et al. 2014).

3.3 Crop Yield

Biochar applications in agricultural soils increased crop yield however, this increase mainly depends on several factors such as soil type, soil pH, fertilizer application, dosage, and feedstock of biochar and crop species (Jeffery et al. 2011). It was observed that the application of biochar at various rates (10, 15, 20 t ha^{-1}) not only improved the maize grain, water use efficiency, nutrient uptake, and yield when grown on arid sandy soil (Uzoma et al. 2011). Likewise, the yield components of sunflower were remarkably increased under the influence of biochar addition (Furtado et al. 2016). This improved yield could be due to several factors associated with biochar such as the increase in soil specific surface area, CEC, water and nutrient retention on to the large surfaces of the biochar, porosity as well as liming behavior which overall support plant growth (Zubair et al. 2021). Moreover, overall improvement in soil features resulted in the enhancement of spinach biomass, antioxidants enzymes in spinach leaves, soil enzymes, and sandy soil health (Khan et al. 2017).

3.4 Stress Alleviation by the Virtue of Biochar

During the last decades, numerous studies have proven that biochar not only enhances crop yield under ordinary circumstances but also supports plant establishment under adverse environments such as drought, salinity, heat, and pollution (Haider et al. 2015; Pressler et al. 2017; Shaaban et al. 2018). It has been reported that biochar addition alleviates drought stress and improved plant growth by increasing WHC consequently promote plant growth (Hafeez et al. 2017; Haider et al. 2015; Liu et al. 2016). Likewise, biochar can also nullify the adverse effects of salt stress by adsorbing Na^+ thereby promote crop production (Akhtar et al. 2015; Kim et al. 2016). Additionally, when biochar was used as an additive for decreasing the bioavailability of heavy metals and their accumulation by different plants, significant results were found (Shahbaz et al. 2018a, b; Shahbaz et al. 2019). Biochar additions remarkably reduced Pb, Ni, and Cd concentrations by adsorbing them onto its larger inner surfaces, or via ion exchange resultantly support plant production under heavy metal stress (Khan et al. 2020; Shahbaz et al. 2018a, b, 2019; Zubair et al. 2021). Apart from this, biochar is also known to improve and support plant establishment under heat stress by increasing WHC which increases plant water uptake and alleviates heat stress from the plants (Busscher et al. 2011; Karhu et al. 2011). Additionally, biochar also provides essential mineral nutrients by releasing them from its matrix and make available them for plant uptake which further improved nutritional quality and crop production (Taghizadeh-Toosi et al. 2012).

4 Conclusion and Way Forward

In recent years, biochar applications have myriad benefits such as increased soil pH, CEC, overall soil structure, and SOC, which significantly improved crop production, their nutritional quality under various biotic and abiotic stresses. Similarly, biochar additions to agricultural soils also reduced the transport of toxic pollutants via binding them onto its larger surfaces which support plant growth and enhance crop yield from degraded soils. Moreover, biochar also controls greenhouse gas emissions and increases carbon sequestration from the atmosphere, resultantly supports plant production under changing climatic conditions. Thus, biochar has a strong potential as an amendment and a soil conditioner that supports plant production from degraded soils. Besides these advantages, we provide some additional guidelines for future studies on exploring the potential of biochar in agricultural soils. Reportedly, biochar utilization promisingly influences the structure and diversity of microbial diversity in soil. However, scarce literature is available concerning the influence of biochar additions on particular functions performed by microorganisms and their gene functions linked with nitrogen and carbon cycling. Though, biochar addition significantly improved various traits of soil that support plant growth. However, it requires a lot of biomass to produce biochar for long-term field-scale experiments that potentially support plant production. Thus, it is necessary to study the interaction of biochar with other suitable mineral fertilizers to prevent the depletion of organic matter in the soil.

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