Review Research

Research on Crop Ecophysiology
Vol.19/2, Issue 2 (2024), Pages: 129 - 149

The Benefits of Biochar in Agricultural Ecosystems, Soil Properties and Reducing the Harmful Effects of Drought Stress, Heavy Metals and Greenhouse Gases: A Review

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Received: 5 March 2024 Accepted: 10 June 2024

ABSTRACT

Food security is challenged by drought stress and water scarcity, especially in arid and semi-arid regions. Additionally, drought stress on agriculture and population growth exacerbate the need for food due to a decrease in water resources and drought stress on agriculture. By disrupting nutrient balance, gas exchange, and primary and secondary metabolisms, water deficiency decreases performance and plant growth. A biochar soil amendment has been proposed to increase water and nutrient efficiency and increase long-term productivity. There have been numerous studies demonstrating that biochar can improve the physical and chemical characteristics of soil, retaining organic matter and moisture. Biochar has a low density and high surface area, resulting in a high adsorption capacity, which helps retain nutrients, reduce leaching, and improve soil fertility. The porous structure of biochar can also reduce the bulk density of soil, thereby improving water retention. Therefore, this study was done in order to survey the benefits of biochar in agricultural ecosystems, soil properties and reducing the harmful effects of drought stress, heavy metals and greenhouse gases. Most of the studies on biochar have been short-term, which questions the long-term fate of heavy metals, therfore long-term studies should be done. It can be expected that due to aging processes, the ability of biochar to separate heavy metals decreases with time. Large-scale and long-term well-designed field experiments are needed to evaluate the feasibility of the proposed approach regarding the impact of biochar on vegetation, increasing soil quality, preserving the environment, and coping with drought stress. The stability of this material and its resistance to decomposition causes the long-term accumulation of carbon in the soil and reduces the intensity of greenhouse gas emissions, including carbon dioxide and nitrous oxide, and its effects on global warming and climate change. Although the stability of biochar in soil is a long-term process, environmental stresses accelerate the degradation of biochar and indicate the need to mitigate climate change. Nevertheless, the application of biochar helps to reduce adverse climatic effects and can lead to sustainable strengthening of food security.

Keyword: Drought Stress, Biochar, Organic Matter, Phytoremediation, Soil Fertilty.

INTRODUCTION

Food security is challenged by drought stress and water scarcity, especially in arid and semi-arid regions. Additionally, drought stress on agriculture and population growth exacerbate the need for food due to a decrease in water resources and drought stress on agriculture (Ansori *et al*., 2025; Nassiri Mahallati *et al*., 2022; Ghadirnezhad Shiade *et al*., 2022; Taheri *et al*., 2021; Mirzaei Heydari *et al*., 2020). By disrupting nutrient balance, gas exchange, and primary and secondary metabolisms, water deficiency decreases performance and plant growth (Al-Khazali *et al*., 2023; Delfi and Mohammad Mirzaei, 2022; Fathi *et al*., 2022; Bahamin *et al*., 2020; Iqbal *et al*., 2018). Drought tolerance is a very complex trait due to the interactions between plant growth factors and specific molecular, physiological, and morphological responses (Mirzaei Heydari *et al*., 2024; Giancarla *et al*., 2012). Drought stress prevents water absorption, as well as limiting nutrient availability and absorption; therefore, plant nutrition management in stress conditions is an important aspect of plant production (Gholami *et al*., 2024; Salehi *et al*., 2022; Waraich *et al*., 2011; Fathi & Bahamin., 2018; Rezaei *et al*., 2015). Moreover, the soil must provide a suitable growth and development environment for plants under such circumstances.

A biochar soil amendment has been proposed to increase water and nutrient efficiency and increase long-term productivity (Mhaibes *et al*., 2023; Kattan and Mirzaei Heydari, 2022; Sohi *et al*., 2010; Sarong and Orge, 2015). There have been numerous studies demonstrating that biochar can improve the physical and chemical characteristics of soil, retaining organic matter and moisture (Deenik *et al*., 2010; Van Zwieten *et al*., 2010). As a soil amendment, biochar differs from charcoal as it is a high-carbon co-product of pyrolysis of organic matter (Lehmann, 2007). Biochar has a low density and high surface area, resulting in a high adsorption capacity, which helps retain nutrients, reduce leaching, and improve soil fertility (Nartey and Zhao, 2014). The porous structure of biochar can also reduce the bulk density of soil, thereby improving water retention (Briggs *et al*., 2005; Karhu *et al*., 2011). There are potential soil factors that can change with the addition of biochar, which could lead to an increase in soil fertility and crop productivity. These factors include the physical properties of the soil (increased aeration, decreased bulk density, increased soil organic matter), chemical properties (cation exchange capacity, increased nutrient availability, decreased leaching), soil biological properties (microbial population, activity, and diversity as well as enzyme activity). In addition, plants have the ability to increase root growth and reduce the incidence of disease (Blanco-Canqui, 2017; Ding *et al*., 2016).

Agriculture is becoming increasingly dependent on biochar, which is being explored from different aspects. There has been little research on the effects of biochar on plant growth, water relations, and physiological responses to drought stress. Biochar has substantial benefits that have attracted the attention of policymakers in developing and developed countries. In this review, we study the benefits of biochar in agricultural ecosystems, soil properties and reducing the harmful effects of drought stress, heavy metals and greenhouse gases.

Novel biochar production

The characteristic of biochar pyrolysis is mainly affected by the pyrolysis temperature (Table 1). At a temperature higher than 500 °C, biochar is effective in cleaning pollutants. But the biochar obtained from a temperature lower than 500 °C has more soluble organic carbon and O-containing functional groups, C/N ratio and relatively low porosity, so it is more suitable for cleaning heavy metal pollutants (Yaashikaa *et al*. 2019). Biochar pyrolysis temperature has a very important role on the properties of the produced biochar. As the pyrolysis temperature increases, the surface area increases due to the creation of fine and coarse pores (Angin and Şensöz, 2014). Biochar created at a temperature lower than 500 °C has a higher CEC (cation exchange capacity) due to the presence of carboxylate functional groups. On the other hand, biochar below 700 °C has a lower CEC with a positive surface charge due to the presence of functional groups containing oxygen. At a temperature lower than 250 °C, the mass reduction of biochar occurs due to volatile gases and evaporation of moisture. Also at this temperature, internal structures are rearranged due to bond reorganization, moisture diffusion, and formation of CO and COOH groups (Anawar *et al*. 2015). At temperatures between 200 and 500 degrees Celsius, a large mass of biochar is reduced because the structure of cellulose and hemicellulose breaks apart at a high speed. Zhang *et al*. (2020) stated that as the temperature increased from 300°C to 700°C for cow manure biochar, the exchangeable and reducible fractions of cadmium and zinc decreased.

After reviewing the literatures, it was found that biochar produced at a temperature of less than 500 °C is the best type of biochar for the treatment of mineral spoils contaminated with heavy metals. A study conducted on copper mine tailings (n¼6) can be modified with biochar produced at 400-450°C, for silver-lead mining site (n¼7) at 500°C and for polymetallic mines (n¼19). Furthermore, no one type of mechanism, specific feedstock, or pyrolytic condition is true for all types of phytoremediation strategies in mine soils (Yaashikaa *et al*. 2019). Therefore, before the application of biochar, the pyrolysis temperature of biochar, the types of phytoremediation in mine soil, the type of raw material used and the residence time should be optimized for effective modification.

Table 1 .The effect of pyrolysis temperature and biomass type on biochar properties (Dom *et al*., 2015)

Measured variables	Coffee skin biochar prepared at 35°C	Coffee skin biochar prepared at 500°C	Maize skin biochar prepared at 35°C	Maize skin biochar prepared at 500°C
Special surface (M^2 S^{-1})	14.07	26.4	4.46	18.1
pH H2O (1:10)	9.62	11	8.15	9.44
EC (mS/cm^{-1}) (1:10)	4.29	6.44	0.89	1.81
Exchangeable calcium (me $100g^{-1}$)	50.5	61.5	37.4	48.4
Exchangeable magnesium (me $100g^{-1}$)	6.71	8.21	4.93	6.43
Exchangeable potassium (me $100g^{-1}$)	1.96	2.77	1.71	2.16
Exchangeable sodium (me $100g^{-1}$)	3.43	5.15	0.71	1.45
CEC (me $100g^{-1}$)	64.8	79.2	47.5	62
Organic carbon (%)	16.51	26.9	14	2.6
Organic matter (%)	28.4	46.4	24.1	35.5
Total nitrogen (%)	1.42	2.32	1.2	1.77
Absorbable phosphorus (mg kg^{-1})	9.79	13.9	8.55	10.8

Effects of biochar on properties of soil

Soil physics

After incorporation into soil, biochar increases soil physical properties, including aggregation, soil structure, and water holding capacity due to its high porosity and high organic carbon content. With the addition of biochar, more macroaggregates were formed and the saturated hydraulic conductivity improved slightly (Jangir *et al*., 2017). Biochar amendment has increased the content of saturated water and decreased the content of residual water due to changes in soil structure. Also. it significantly caused changes in soil water retention function (Jangir *et al*., 2017). Biochar may affect the physical and hydraulic properties of a porous medium, including water retention, bulk density, hydraulic conductivity, porosity and penetration resistance. By maintaining biochar in degraded soils, soil fertility can be preserved, erosion susceptibility can be reduced, and water retention, holding capacity, and hydraulic conductivity can be increased (Jangir *et al*., 2017; Fischer and Glaser, 2012). It has been reported that contaminated soils can be improved by applying biochar by increasing water retention, total porosity, and bulk density (Mcbeath *et al*., 2014; Spokas *et al*., 2012). In addition, biochar can improve soil structure by influencing root area processes and soil microbe activity through plant growth and aboveground and structure-building processes (Yuan *et al*., 2019). As a result of increased calcium content in the soil, biochar improved its accumulation in the cropland and increased its saturated hydraulic conductivity. In degraded soils, biochar's physicochemical properties vary depending on the soil, the raw material, the application amount, and the age of the biochar (Obia *et al*., 2016). The amount of water available to the plant is one of the most important physical parameters of soil. According to recent studies, biochar increases water retention (Martinsen *et al*., 2014; Basso *et al*., 2013). A high specific surface of biochar has resulted in an increase in available water due to the change in particle size distribution and soil porosity caused by the addition of biochar (Sun *et al*., 2014). Biochar causes decrease in the bulk density (Laird *et al*., 2010; Chen *et al*., 2011).

Soil chemistry

After biochar amendment, soil chemical properties may change. The extent of this effect, however, is strongly differentiated by factors such as soil type and primary characteristics, application amount, raw material, preparation conditions, and biochar production process (Ding *et al*., 2016; El-Naggar *et al*., 2019). Inyang *et al*. (2016) found that soil pH increased with increasing rice straw biochar addition rate, with delicate rice straw biochar increasing soil pH more effectively than coarse rice straw biochar. In contrast to the control treatment, bamboo biochar did not significantly alter soil pH. According to these researchers, rice straw has a higher pH, ash content, and surface alkalinity than bamboo biochar. According to Hossain *et al*. (2010), biochar significantly increases soil electrical conductivity, especially when combined with fertilizer. In spite of this, plant growth is not negatively affected.

By increasing the CEC, biochar can significantly improve soils with low fertility (Bilias *et al*., 2021). According to Ghorbani *et al*. (2019), the CEC of the loamy sand soil increased by 20% and 30% when biochar was added at 1% and 3%, respectively, while the CEC of the clay soil increased by 9% and 19%. A biochar system reduces denitrification potential, lowers N2O emissions, and controls nitrogen leaching and nutrient availability, thus improving the efficiency and availability of water, nutrients, and plant growth (Panwar *et al*., 2019). Moreover, it increases soil fertility by modulating soil acidity and increasing water-holding capacity as well as increasing cation exchange (Panwar *et al*., 2019). Biochar generally decreases buffer capacity and soil acidity, raises dissolved and total organic carbon, increases CEC, retains water, increases nitrogen availability, and decreases bulk density (El-Naggar *et al*., 2019; Lehmann & Joseph, 2015). There is evidence that biochar increases microbial activity, accelerates nutrient cycling, and reduces nitrogen leaching and volatilization (Lehmann & Joseph, 2015).

The effect of biochar on plant yield

In most cases in the studies, biochar improves the soil fertility by changing the physical, chemical and biological characteristics of the soil and ultimately increases the growth and performance of the plant. The effect of biochar on plant performance depends on various factors, including the initial soil fertility status, soil texture, preparation temperature, physical and chemical properties of biochar, and even the type of plant, and it can increase or decrease plant performance. Several studies have shown the positive and negative effects of biochar on soil fertility and plant performance. Tood Revell (2011) investigated the effect of biochar on soil properties and plant growth. The results of this study showed that the consumption of about 1% of biochar increased the germination of lettuce, which was attributed to the increase in water retention by biochar. The results obtained by Major *et al*. (2010) showed a 140% increase in yield and an increase in the absorption of calcium, magnesium, potassium, copper and manganese compared to controls. The study by Zang *et al*. (2012) showed a 7.5% and 15% increase in corn yield due to the use of biochar. On the other hand, some researchers not only did not observe an increase in yield, but some biochars caused a decrease in plant yield. For example, Wu *et al*. (2013) reported the lack of effect of wood and corn biochar on plant yield. The researchers reported that the reason for the lack of effect of biochar on increasing yield is the inherent fertility of the soil and the insufficient level of biochar consumption. Herath *et al*. (2013) using three type of wood biochar, they concluded that the use of this type of biochar in the first year had little effect on corn yield, and in the second year, its effect on grass yield was less, and in the third year, it increased plant yield. Dume *et al*. (2015) They observed less soybean growth in soils treated with biochar containing a high amount of volatile substances (35%) and increased growth in soils treated with biochar containing a low percentage of volatile substances (11%). Therefore, the use of biochar can have positive and negative effects depending on the characteristics of the soil. The use of biochar in the soil can increase the yield of the plant by 60% or decrease it by about 30%, and this increase or decrease of the product depends on the type of soil. In addition, the type of biochar has an effect on soil properties and plant performance. In a specific area, the consumption of different biochars caused different responses. Some of the biochars increased the yield by 100% and some caused the plant to die (Rajkovich *et al*., 2012).

Effects of drought stress on plant growth and development

plant growth

Water absorption by the root system is significant. Extensive and deep root systems can absorb moisture from the lower parts of the soil. Therefore, the development of the root system increases the productivity of water absorption from the soil under drought stress conditions (Setayesh-Mehr and Ganjeali, 2013). Under drought stress conditions, the absorption of nutrients by the roots and the transfer of these substances to the stem is reduced due to the limitation in the rate of transpiration, the reduction of membrane permeability, and damage to active transport (Fathi *et al*., 2022). However, the absorption of nutrients from the soil in drought stress conditions is correlated with the soil moisture level, so the diffusion flow of nutrients from the soil to the surface of the roots decreases with a decrease in the soil moisture level (Arndt *et al*., 2001). In drought stress, the root/stem ratio increases, mainly due to the reduction of the aerial part compared to the root.

Furthermore, two essential plant responses to drought stress are increasing the root/stem ratio and decreasing the leaf area. Access to water plays a vital role in leaf structure, so in drought stress, the response of the leaf surface is greater than that of the root and stem (Setayesh-Mehr and Ganjeali, 2013). Wilting, falling, twisting of leaves, and closing of stomata can be the reason for the reduction of leaf surface under stress conditions (Fathi *et al*., 2022). During drought stress, the lack of water prevents cell elongation in the leaf. Decreased leaf area reduces water absorption from the soil, and transpiration decreases (Thinley and Dorji, 2021; Mohammadi *et al*., 2021).

Quantitative and qualitative performance

Under drought stress conditions, reactive oxygen species' activity causes damage such as the inactivation of enzymes, changes in the structure of proteins, and the loss of chlorophyll pigments (Kheiri Sis *et al*., 2021). Leaf chlorophyll content, photosynthesis rate, stomatal conductance, carboxylation efficiency, and transpiration rate decreased under drought stress conditions (Khalvandi *et al*., 2021). Drought stress reduces leaf water by reducing vacuole water and cell size. Because the moisture available to the plant and root is low, plant root growth increases to increase water uptake. It cannot supply the water leaving the plant. As a result, leaf water is reduced. These processes prevent the photosynthesis of plants, cause changes in chlorophyll content, and damage to photosynthetic structures (Anjum *et al*., 2017; Per *et al*., 2018).

Drought stress affects the activity of many physiological processes that determine plant performance. Therefore, it is difficult to interpret how plants accumulate, combine and display the changing and complete physiological processes during the crop life cycle for drought stress (Fathi *et al*., 2022; Umair Hassan *et al*., 2020). When faced with drought stress, the plant creates a balance between transpiration and water absorption in the first stage by absorbing water and changing the water potential, and with the continuation of the stress, with a change in root growth and an increase in the root-to-stem ratio, the water holding capacity of the tissue increases.

Leaves are the main photosynthesizing organ in the plant, so increasing the leaf surface index creates a sufficient physiological source to use the received light as much as possible and provide the growth materials necessary to fill the seed and increase the yield (Maleki *et al*., 2020). The severe decrease in yield and its components under severe drought stress conditions can be attributed to the severe reduction in photosynthesis and the cessation of chlorophyll formation, the decrease in the activity of nitrate-reducing enzymes, and the increase of hydrolyzing enzymes (Maleki et al., 2020). Drought stress causes a significant reduction in the growth process, yield components, dry matter, and quantitative and qualitative yield in different types of dry crops. Researchers have stated that drought stress causes yield reduction in crops such as wheat 64%, barley 50%, corn 63-87%, rice 53-92%, soybean 46-71%, peas 55-65%, and sunflower 60%(Hussain *et al*., 2019). The availability of nutrients in the soil decreases under the influence of drought stress. Therefore, the effect of stress on each of the constituents of crop plant performance can lead to a decrease in yield, and in the absence of sufficient water, not only the growth of the plant decreases due to the lack of water, but also due to the lack of absorption of available nutrients (Ezati *et al*., 2020).

The role of biochar in the growth and development of plants under drought stress conditions

There are many studies reporting that biochar increases plant productivity, with an average yield of 10%–42% (Joseph *et al*., 2021), though adverse effects have also been reported (Jeffery *et al*., 2017; Macdonald *et al*., 2014; Ye *et al*., 2020). The researchers found that biochar incorporation prevented soybean seedlings from being negatively affected by water deficit conditions (Gullap *et al*., 2022). Researchers have also reported that biochar applications increase soil water content at field capacity (Abel *et al*., 2013) and influence soil water and nutrient retention. In several plants grown under drought, biochar applications from different sources have been shown to positively affect plant growth and yield (Agbna *et al*., 2017; Langeroodi *et al*., 2019; Li *et al*., 2020). Biochar amendment improved soil physical and chemical properties and plant nutrient availability to alleviate drought stress on crop growth and yield (Trupiano *et al*., 2017). Chlorophyll content in different crops is mitigated by biochar amendments (Youssef *et al*., 2018; Zhang *et al*., 2020). It has also been reported that biochar enhances photosynthetic activity. According to Kammann and Graber (2015), increased soil water holding capacity, porous structure, and high biochar surface area are all contributing factors to the increased chlorophyll content of soybean leaves under drought stress.

Under drought stress conditions, biochar has been reported to improve crop growth and yield (Akhtar *et al*., 2015; Ramzani *et al*., 2017). Akhtar *et al*. (2015) showed that biochar significantly enhances tomato leaf water use efficiency, stomatal conductance, chlorophyll content, and photosynthesis under drought conditions. Moreover, quinoa grown under water-scarce conditions performed better in terms of growth, soil water content, water use efficiency, leaf water potential, photosynthesis, and transpiration when amended with biochar (Kammann and Graber, 2015). In crops, biochar application strengthens the defense mechanism against drought by increasing the activity of protective enzymes and electron transfer, thus minimizing the damage caused by drought on the photosynthetic apparatus (Lyu *et al*., 2016).

A lack of water and poor soil fertility have been identified as critical factors affecting crop production (Ray *et al*., 2013; Faloye *et al.*, 2019). It is, therefore, becoming increasingly crucial for scientists to develop strategies that improve the chemical and physical properties of soils in areas with low soil fertility, improve soil water retention, and improve plant water use efficiency (Oki and Kanae, 2006; Faloye *et al*., 2019). Biochar increases soil water retention and available water capacity (Novak *et al*., 2009; Ajayi and Horn, 2016). It usually occurs in soils with coarse textures or soils with large macropores, although the amount of biochar required to increase water retention varies with soil types (Glaser *et al*., 2002). Based on a meta-analysis, biochar generally increases available plant water by 28.5%, but its positive effects are primarily observed on coarse-textured soils (Edeh *et al*., 2022). This finding is supported by Razzaghi *et al*. (2020) and Blanco-Canqui (2017). It has also been shown that biochar's effectiveness varies based on location, application rate, soil type, and biochar feed (Jeffery et al., 2011, 2017; Akhtar *et al*., 2014; Martí *et al*., 2021). It has been suggested that biochar may increase crop productivity by conserving more water from rainfall in dry areas whereas less water is needed for irrigation in irrigated areas (Haddad *et al*., 2022). According to Novak *et al*. (2012) and Liu *et al*. (2021a, b), biochar improved the water relations in semi-arid soils. Consequently, combining biochar with limited irrigation strategies can lower water consumption while increasing crop productivity (Haddad *et al*., 2022).

Reduction of wilting in tomato after biochar application in sandy soils under drought stress has been reported (Mulcahy *et al*. 2013). Abideen *et al*. (2020) in a study applied biochar fertilizer to soils under drought stress and they reported increased soil moisture and plant performance (increased water use efficiency, plant biomass, photosynthesis rate, antioxidant activity and chlorophyll content) under stress conditions. The use of rice husk biochar increased chlorophyll, improved plant-water relations, plant biomass, plant height and yield in corn plants affected by drought (Mannan and Shashi 2020). Li and Tan (2021) used biochar produced from rice straw to identify the processes involved in reducing drought stress in the soil-plant system. They reported that although biochar can improve soil water retention (activated by high porosity and hydrophilic surface functional groups, mainly -OH and -COOH), they also stated that the small particle size of biochar facilitates higher surface and pave the way for increased WHC (water holding capacity) of amended soils. Hardie *et al*. (2014) stated that soil porosity can be improved with biochar application. Application of biochar produced from Camara lantana increased stomatal conductance, water use efficiency and photosynthesis (Batool and Rashid, 2015). The amount of osmotic potential and transpiration in corn affected by stress, increased after modification by biochar (Haider *et al*. 2015). But the use of biochar increased the water ratio, photosynthetic pigments, overall plant growth and antioxidant activity in corn (Sattar *et al*. 2019). Application of biochar improved plant biomass, crop yield, water use efficiency, and other biochemical and physical traits in wheat plants under drought stress (Haider *et al.* 2020). In another investigation, they stated that the use of biochar fertilizer improved antioxidant enzyme activity, physiological characteristics, and plant performance (Abbas *et al*. 2018). In another study, biochar from poultry litter increased the accumulation of proline (indicator of water deficit stress) and water and reduced the amount of chlorophyll degradation in soybean plants (Mannan et al. 2017). Nevertheless, Afshar et al. (2016) reported no changes in chlorophyll content and gas exchange when using biochar derived from maple wood for thistle plants.

Mechanism of heavy metal remediation

After studying the literatures related to the modification of heavy metals using biochar, it was found that half of the studies used wood biochar, 21% of agricultural waste and 21% of sludge. The most common materials for making biochar include wheat straw and rice husk (Li *et al*. 2019), manure waste (Gasco *et al.* 2019), weeds (Ghosh *et al.* 2020) and wood waste (Khan *et al.* 2020). The effect of biochar on the availability of heavy metal depends on the raw materials, as well as the types of heavy metals and the type of substrate (Yaashikaa et al. 2019). For example, surveys of the copper mine site in Touro (Spain), Rodríguez-Vila *et al.* (2015) used oak biochar while Forján *et al.* (2016) used biochar from acacia to remediate heavy metals. Holm oak biochar reduced the concentration of extractable copper with calcium by 98%. Acacia biochar reduced the concentration of calcium-extractable copper by 60%. Dai *et al.* (2018) also used biochar obtained from rice straw to remediate contaminated coal mine soils, and showed that the concentration of zinc, copper, and cadmium decreased by 51.37, 57.26, and 42.04 percent, respectively, compared to the control samples. Zhan *et al*. (2019) applied rice straw biochar to the soil of a lead-zinc mine and stated that the application of biochar reduced the concentration of lead by 23.6% compared to the control treatment. Hodgson *et al*. (2016) also used biochar produced from 6 types of plant raw materials to investigate their effect on adsorption performance on mine-water effluent. They stated that Lolium’s biochar has a higher Zn adsorption potential than biochar from Picea (54-64%) and Miscanthus (41-51%).

The characteristics of biochar fertilizer such as pH, organic carbon, CEC, porosity, functional groups, specific surface area, mineral content and aromaticity are affected by pyrolysis conditions and raw materials. The bioavailability and mobility of plant remediation depends on the characteristics of soil and biochar, in which biochar fertilizer is used for soil improvement (Hu *et al*. 2019). The process related to plant treatment by biochar fertilizer is electrostatic interactions in which the negative surface charge of biochar causes electrostatic attraction between metal cations and soil particles, the p-p electron interaction between the p-p electron acceptor and the p-electron rich biochar. Positively charged phytoremediation cations with graphene surface and p-p-electron-deficiency-charge immobilize them. Ion exchange where CEC over biochar releases divalent magnesium and calcium cations that exchange with phytoremediation ions present on biochar surfaces (Liu *et al*. 2019).

Application of biochar increases plant-soil remediation complex and affects soil properties. When phytoremediation increases, a large negative charge occurs on the surface of biochar fertilizer, which affects the adsorption of phytoremediation on the biochar surface and ionic strength. According to the mentioned article, the ionic strength by which biochar absorbs ions depends on the plant treatment (Ahmed *et al*. 2014). Due to the alkaline conditions, the use of biochar fertilizer increases the absorption capacity of the soil, which leads to the remaining plant treatment and the transformation of oxidizing parts (Ahmed *et al*. 2014). Characteristics such as microbial biomass carbon, enzyme activities, soil respiration and mycorrhizal growth can be used as indicators to measure the success of biochar amendment. Investigations based on biochar modifiers are categorized as direct and indirect methods, considering the substrate that is indirectly contaminated by mining activities, mine spoils (Norini *et al*., 2019).

Biochar for pollution control

In higher plants, cadmium (Cd) and the metalloid arsenic do not have physiological and biochemical functions, but they could cause serious toxic effects (Williams and Salt, 2009; Pan *et al*., 2019). Heavy metal(loid) contamination of arable soils in the world is mainly caused by human activities (mining, wastewater irrigation, and industrial activities) (Sun 2004; Roberts *et al*. 2010). In addition to endangering food safety and causing grain yield losses, metalloid contamination of arable soils threatens the long-term sustainability of agriculture (Khan *et al*., 2010; Pan *et al*., 2019). In contrast to organic pollutants, heavy metals (loid)s are persistent and non-degradable once introduced into soil (Li *et al*., 2016). Since biochar is environmentally friendly, widely used, and inexpensive, it is highly recommended for inactivating heavy metals (Wang *et al*., 2016; Liu *et al*., 2017).

An experiment with 1.5% bamboo biochar, for example, significantly decreased Cd's acid-soluble/exchangeable fraction. When cabbage and maize plants were harvested, it increased the reducible and oxidizable fractions of Cd in the soil (Mohamed *et al*., 2015). The exchangeable Cd fraction in paddy soil decreased with the addition of wheat straw biochar, while the residual Cd fraction increased (Cui *et al*., 2016). According to Irfan *et al*. (2021), the highest reduction in Pb (lead), Cd, and Cr (chromium) in maize plants was recorded at the highest biochar application rate. The concentration of Pb, Cd, and Cr in maize plants was also consistently reduced by incremental biochar and compost rates. Maize plants were more affected by biochar than compost when it came to reducing Pb, Cd, and Cr concentrations. In addition to Phyto-stabilizing heavy metals in maize plant shoots, biochar reduces phytotoxicity in contaminated soil (Irfan *et al*., 2021). Similarly, Yang *et al*., (2017) found biochar's application reduced heavy metal uptake and improved heavy metal fixed fractions.

Biochar and emission of greenhouse gases

The researchers stated that the use of biochar in agricultural lands that had a drip irrigation system increased the efficiency of water use and yield and significantly reduced the amount of greenhouse gas emissions. Xiao *et al*. (2018) stated that by using rice straw biochar along with saving water, methane emissions and water consumption have been reduced. Biochar also increased water use efficiency and rice yield. Likewise, biochar application increased water use efficiency by 15.1–42.5% and reduced CO2 emissions by 2.22% and improved rice yield by 9.35–36.30% (Yang *et al*. 2018). Biochar fertilizer prevented CO2 emissions (Jones *et al*. 2011). In addition to stopping methane emissions, the use of biochar fertilizer reduced nitrogen oxide emissions through abiotic and biotic mechanisms. Various processes include adsorption of soil ammonium and nitrate ions, increasing soil acidity, ammonia-oxidizing bacteria, and improving soil aeration (Zhang *et al*, 2020). Basalirwa *et al*. (2020) suggested the importance of using palm biochar to reduce greenhouse gases (including nitrate oxide and carbon dioxide) in their review. Zhu *et al*. (2022) stated in their review that biochar fertilizer obtained from straw has a great potential in increasing soil acidity and maintaining oxygen in the soil, which limits the release of nitrate oxide in the soil. Also, these researchers observed an increase in the emission of nitrate oxide gas in soils that were amended only with straw. Edwards *et al*. (2018) also stated that the use of biochar fertilizer is able to increase the emission of nitrogen oxide in the early stages. Sánchez-Garcia *et al*. (2014) also reported a 76% reduction in NOx (nitrogen oxides) emissions in haplic pheozems and a 54% increase in emissions in haplic calcisols. Also, a meta-analysis was conducted by Shakoor *et al*. (2021) stated that the addition of biochar reduced NO emissions by 19.7%.

The simultaneous use of microorganism biochar and biochar is very useful in increasing the absorption of nutrients and supporting plant performance in drought. The porosity of biochar provides a suitable place for microorganisms to multiply and colonize, which indicates that biochar is a suitable carrier for microorganisms along with protecting them from adverse environmental conditions (toxicity, inappropriate pH, salinity). The use of biochar fertilizer combined with bradyrhizobium under stress conditions reduced the amount of damage and increased nutrient absorption, biological performance, growth and nodulation in Lupinus angustifolius (Egamberdieva *et al*. 2017). The porosity of biochar fertilizer retains moisture, improves aeration, and significantly increases the supply of nutrients to microorganisms for proper reproduction in the soil-plant system. Microorganisms located in the rhizosphere of the plant dissolve minerals that provide phosphorus, nitrogen, magnesium and potassium to plant roots for optimal growth and therefore improve the harmful effects of stress. Nevertheless, the application of biochar fertilizer obtained from birch wood along with Rhizophagus irregularis bacteria reduced the leaf area, nutrient absorption and water use efficiency in potato under drought stress (Liu *et al*. 2017). Reasons for such a process probably included (1) the limited adsorption capacity of biochar fertilizer for P-N, (2) phytotoxic effects of biochar fertilizer due to the release of phenolic compounds derived from lignin in biomass or phytohormones such as ethylene and (3) improving soil acidity due to the low dose of biochar. Application of biochar fertilizer improves the physicochemical and biochemical properties of drought-stressed soils (Baronti *et al*. 2014), mainly due to good EC, alkaline pH, high WHC (Water holding capacity) in grain formation, and low BD (bulk density) of biochar (Kumar and Bhattacharya 2020).

Herat *et al*. (2013) also stated the increase of interpore space, WHC of soils with different textures and reduction of BD after using biochar fertilizer. Increasing the amount of WHC is very important in improving stressed soils and is supported by improving soil stability even with very limited water supply (Baiamonte *et al*. 2015). WHC varies with production technique, biochar heat treatment conditions, biomass type, and application amount (Brantley et al. 2015). High CEC increases soil porosity and surface area, and the surface area of biochar and therefore increases its WHC (Carvalho et al. 2014). The use of biochar fertilizer increased the water content in the vineyard field (Baronti *et al.* 2014). A very important point is that the biochar fertilizer amendment is very useful for soils under tropical conditions compared to temperate conditions which are mainly activated by prominent liming effects and fertilization in tropical conditions (Jeffery *et al*. 2017). These researchers also stated that the alkaline nature of temperate soils limits higher fertility and the use of biochar fertilizer in temperate conditions to some extent. In a different study, although cocoa husk biochar improved corn yield, the positive effects were greatly reduced in the fifth planting season (Cornelissen *et al*. 2018). These researchers stated that the gradual leaching of alkalinity associated with biochar reduced the positive effects on corn yield. Also, Griffin *et al*. (2017) stated that walnut shell biochar showed short-term effects on corn yield, which was due to the reduction of calcium, exchangeable phosphate and potassium after the application of biochar from the second year. Gao *et al*. (2020) also stated that irrigation plays a major role in increasing onion productivity instead of biochar fertilizer. In contrast, the importance of biochar consumption was highlighted by Tian *et al*. (2021), and suggested that very high application dose leads to low soil fertility.

CONCLUSION

Large-scale and long-term well-designed field experiments are needed to evaluate the feasibility of the proposed approach regarding the impact of biochar on vegetation, increasing soil quality, preserving the environment, and coping with drought stress. Non-consumable wood residues such as pruning residues are known to be high in holocellulose and lignin, which leads to the production of better quality biochar. For this reason, more studies are needed to measure the differences between different methods of using biochar for the interactive mechanisms involved in plant and biochar relationships.

Phytoremediation with the help of biochar depends on the characteristics of biochar and soil and plant species that are used as aggregates. Biochar can help plants with shallow root systems if applied to the appropriate depth, while biochar application to a greater depth is needed for trees and plants with wider and stronger root systems. Most of the studies on biochar have been short-term, which questions the long-term fate of heavy metals, so long-term studies should be done. It can be expected that due to aging processes, the ability of biochar to separate heavy metals decreases with time.

The stability of this material and its resistance to decomposition causes the long-term accumulation of carbon in the soil and reduces the intensity of greenhouse gas emissions, including carbon dioxide and nitrous oxide, and its effects on global warming and climate change. By modifying physical characteristics such as soil structure and grain size, it prepares the physical conditions of the soil for plant growth as much as possible and therefore increases soil fertility. In addition, by increasing the capacity of water and food elements, the efficiency of chemical fertilizer consumption increases and the productivity of chemical fertilizers improves. The consumption of this biological material in the soil increases the microbial population of the soil and its enzyme activity, and as a result, it improves the cycle of nutrients and the use of the soil's own capacity to provide nutrients, and it can reduce the consumption of chemical fertilizers. Therefore, according to the beneficial effects of this substance on the physical, chemical and biological properties of soil in different regions, it is suggested to carry out experiments to investigate the effects on the properties of calcareous soils and product performance.

The use of biochar reduced the harmful effects of drought stress by improving water retention capacity, improving soil fertility and nutrient elements, and the relationship between source and sink in crops. The application of biochar increases physiological parameters, improves growth, related to water and yield in control and drought conditions. Biochar is a suitable alternative to increase soil productivity and plant growth. Biochar fertilizer increases the tolerance of plants against drought, desertification, high temperature, and soil salinity. Adverse effects can be ameliorated by beneficial properties of biochar (sufficient EC, alkaline pH, increased WHC, additional porosity, and abundance of nutrients). In general, biochar fertilizer absorption efficiency of nutrients, photosynthetic activity (chlorophyll content and stomatal conductance), antioxidant enzyme activity, product quality, stem length, water use efficiency, plant biomass, root length, plant height, yield, and improves weather conditions tolerance. Also, biochar reduces the percentage of exchangeable sodium, and increases stress-fighting hormones.

Biochar fertilizer increases microbial activity by improving enzyme activity (phosphatase, β-glucosidase and arylsulfatase), creating habitat e.g. microbial habitat, supporting soil-plant systems, increasing the availability of nutrients and increasing resilience against adverse weather conditions. In addition, it increases porosity, WHC, organic matter and CEC. Although the stability of biochar in soil is a long-term process, environmental stresses accelerate the degradation of biochar and indicate the need to mitigate climate change. Nevertheless, the consumption of biochar helps to reduce adverse climatic effects and can lead to sustainable strengthening of food security in the world.

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