EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 67 (2025): 51 - 60
Journal homepage: https://eqa.unibo.it/

published by

The effect of biochar on enhancing soil fertility, mitigating soil salinity and promoting plant growth: a review

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Article info
Received 26/12/2024; received in revised form 22/1/2025; accepted 3/2/2025
DOI: 10.6092/issn.2281-4485/20614

Abstract
Biochar (BC) is a widely recognized soil amendment, produced by pyrolysis from different biomass, its potential is determined through pyrolysis temperature and feedstock material. Biochar produced at maximum temperatures (> 500 ℃) increased bulk density and porosity to greater levels. It is produced at minimum pyrolytic temperature (< 500 ℃) had more influence on bacterial diversity, and the type of organic resources can affect soil bulk density. Application of BC to soil can enhance its quality and reduce the effects of salt, drought, and contamination as well as climate change. The addition of biochar to soil improves its physical and chemical properties, like porosity, moisture content, and water-holding capacity. BC, can enhance the fertility of soil, improve the retention of nutrients, and decrease the salinity of the soil, all of which can increase crop yields. Moreover, biochar could capture C in the soil and is an effective method to mitigate climate change, improve soil management, and promote agricultural sustainability in Semi-arid and Arid areas.

Keywords: *Biochar, feedstock, pyrolysis, soil salinity, and plant growth*

Introduction

Biochar (BC) is a carbonaceous microstructure substance that possesses various elements (H, C, O, S, and N) along with multiple-macros (Ca, Na, Mg, Fe, Al, N, and P) and microelements in trace amounts, produced by the thermochemical conversion of biomass in low-oxygen environments(Ding et al., 2016; Tan et al., 2017). Generally, biochar characteristics vary dramatically and mainly depend on the pyrolysis temperature, duration of pyrolysis, and feedstock material resulting in different microstructure, physicochemical properties, and C and ash content (Marks and Alexender, 202013). BC was documentted to improve not only soil physiochemical characteristics but as well as microbial properties. According to several reports, adding BC to soil could enhance porosity, decrease bulk density, promote aggregation, as well as enhance the water-holding capacity(Ding et al., 2016; Saifullah et al., 2018). BC can decrease Co_2 emissions, improve plant productivity and mitigate climate change, enhance soil quality, and reduce soil salinity drought stresses, and toxic material on plants. BC, can help increase organic matter in the soil, and decrease the effect of water deficit on plant growth(Majidi, 2022). Biochar impact on salt stress, nitrogen metabolism, and nodulation of soybeans. Biochar impacts salt stress, and nitrogen metabolism as well as the ability to enhance soil fertility, accelerate plant growth, boost crop yield, and minimize pollution. The physiochemical characterristics of BC are significantly affected by pyrolysis

DOI: 10.6092/issn.2281-4485/20614

temperature, process factors, and feedstock type. It can be used to promote soil fertility, improve soil physiochemical qualities, and increase soil microbial activity (Ding et al., 2016; Yuan et al., 2011b). Applying BC improved the organic carbon content, cation exchange capacity of soil, and pH; and enhanced crop yield in soil with fine and coarse texture(Singh et al., 2022). Application of BC decreases the stress of salinity and enhances plant productivity in salinity soil (Akhtar et al., 2015a), and it can reduce drought and saline stress in plants (Yang et al., 2020). Biochar can improve various plant growth parameters by observing Na+ and ameliorate salinity stress (Ding et al., 2016; Akhtar et al., 2015a), and Ding et al (2016) reported that biochar can boost plant productivity, enhance soil fertility, improve plant growth, and reduce contamination, and it's a source of fertilizer for improvement of physical and chemical parasites of soil and microbial growth. In recent years, the application of charcoal has increased in agricultural soil, environmental restoration, improvement of soil nutrients, and carbon sequestration (Liu et al., 2012). However, many problems, including low soil fertility, salty and sodic soils, water shortage, alkalinity, soil compaction, insect and disease infestations, and a lack of understanding about soil management have an impact on agricultural productivity (Omari et al., 2023). The current study aims to assist with the following aspects: 1) the physical and chemical characteristics of BC produced at different temperatures; 2) The capacity of BC to enhance soil fertility, retention of nutrients, and plant yield; 3) the utilization of biochar and its possible effects on salinity soil; and 4) the potential of biochar to sequester C in the soil and mitigate the effects of climate change. Salinity has influenced hundreds of millions of hectares of land globally, which is an existential threat to biodiversity and the world's food security.

Biochar production and application

The production of BC is frequently accomplished by thermochemical conversion. Thermochemical conversion techniques include gasification, torrefaction, hydrothermal carbonization, and pyrolysis (Yaashikaa et al., 2019), yield biochar products, which mostly contain carbon, hydrogen, and oxygen (Thuy et al., 2020). Variation in pyrolytic temperatures and feed-stocks influences the yield and nutrient composition of biochar. Pyrolysis produces distribution and their quality depends upon the process parameters. Pyrolysis parameters, temperature, residence time, and rate of heating also influence the BC yield (Tripti et al., 2017). Biochar has the potential to eliminate different pollutants from aqueous solutions, biochar-based methods have great potential for cleaning waste from agriculture from both point and spread sources, thus decreasing water requirements and increasing crop yields (Li et al., 2020). Biochar's impact on salt stress, nitrogen metabolism, and nodulation of soybeans (*Glycine max* cv. M7), and biochar treatment enhanced nodulation and nitrogen metabolism of the soybean under saline conditions (Farhangi et al., 2018). The application of BC offers multiple advantages for climate change reduction and improving soil fertility. In soil, BC can serve as a source of nutrients and a C separator. The function and content of biochar have significance for soil fertility(Majidi, 2022; El-naggar et al., 2019). The whole content of S, H, and O, the unstable form of organic C, and the acidic functional groups reduced as the pyrolysis temperature, while the ash content, electrical conductivity, PH, basic functional groups, C stability, and total content of C, P, Ca, N, Mg, and K enhanced through BC production. As the temperature rose, the rations of H/C, O.C, (O + N+S)/C tended to decrease. When applied to soil, BC produced by high-temperature pyrolysis may have a greater capacity to sequester C

Figure 1
Shows first-time biochar production in Afghanistan by using the oven and its application on agricultural plant

DOI: 10.6092/issn.2281-4485/20614

than the BC produced at moderators (Al-wabel et al., 2013; Majidi, 2022). The BC was produced through a pyrolysis process using a biochar production oven under limited oxygen conditions for 3 hours at a temperature between 300–400ºC from Oak (Quercus) biomass (Figure 1) (Majidi, 2022; Sikder, Joardar, 2019). According to Jindo et al. (2014), BC, made from wood products has a good absorption property and high C concentration. Zhang et al. (2019), documented that BC generated at 600 ºC has a much greater absorption capacity than the BC produced at 300 ºC. Singh et al. (2022), reported that BC, prepared at higher pyrolytic temperatures (> 500 ºC) improved bulk density and porosity to greater extents, and BC prepared at lower pyrolytic temperatures (<500 ºC) had more effect on microbial diversity and increased soil texture (Singh et al., 2022).

Biochar properties and its effect on soil

Microstructure of biochar

Biochar is micro-porous in structure and varies in shape and size depending upon its way of generation. Several reports have evidenced that biochar is rectangular (Tan et al., 2017; Lin et al., 2009), whereas others reported irregular (Liu et al., 2017). These micropores are both small and large and thus possess high surface area with many functional groups, which play a vital role in holding water, nutrients, and element uptake in soil. Large pores can promote soil breathability, increase water holding capacity, and provide space for microbial growth and enzymatic activities whereas, small pores can improve the adsorption of greenhouse gases, and poisonous and pernicious polyaromatic hydrocarbons (PAH) in soil (Yuan et al., 2011a; 2o11b). BC has the potential to increase soil quality and properties based on the type and quality of feedstock used for production as well as pyrolysis conditions (Table 1). An et al. (2023), reported that long term application of BC can improves soil health, enhance cation exchange capacity(CEC) and decrease soil salinity. Higher rate of BC application have negative consequences(An et al., 2023).

Table 1. *Effect of Biochar on soil properties depends on material and pyrolysis temperature*

No	Biochar Feedstock	Pyrolysis temperature	Key properties	Effects on Soil
1	Corn Straw	≥500 ºC	Low bulk density and high porosity	Enhance soil porosity, decrease bulk density, and increase nutrient retention.
2	Bamboo	400-500 ºC	High surface area and nutrient content	Enhance soil fertility and water retention
3	Olive	400-600 ºC	High C content and variable PH	Increases soil productivity, water holding capacity
4	Rice Husk	400-500 ºC	High porosity, enhances PH	Improves soil aggregation, water holding capacity
5	Chicken Manure	400-500 ºC	High cation exchange capacity	Increases plant growth through nutrient supply
6	Diary Manure	≤400 ºC	High nutrient content	Enhances nitrogen retention and improves soil fertility
7	Municipal waste	300-500 ºC	Variable nutrient content	Improve soil fertility

Biochar physicochemical properties

Organic substance is a significant soil component in improving soil physical properties and productivity of soils mainly in semi-arid zones. The effect of organic substances on soil physical properties depends upon the amount, type, and size of applied organic materials. Both the rate and type of organic resources affected the soil bulk density. Higher rates of organic material application caused lower bulk densities and hence higher soil porosities (Barzager et al., 2002).

The physical state of the soil before tillage can influence how well tillage tools work as well as the final soil's physical features. Wetting and drying are two elements that can impact the soil's physical condition before tillage (Rajaram and Erbach, 1999). A variety of soil physical attributes, such as total porosity, soil density, pore size distribution, soil moisture content, water retention capacity or plant available water content, and hydraulic conductivity, are thought to improve the application of biochar

DOI: 10.6092/issn.2281-4485/20614

(Fig. 2). There is evidence to suggest that soil porosity altered by biochar can be applied through direct pore contribution, accommodation pore formation, or enhanced aggregate stability (Hardie et al., 2014; Rajkovich et al., 2015). In recent years, application of charcoal has been increased in agricultural soils. Biochar utilization in soil affects soil porosity, sorption capacity, pH, and cation exchange capacity (Mohammad et al., 2014). Variations in soil chemical properties impact soil biota and biogeochemical processes. Measurements of soil particle's structure and basic chemical properties include pH, available phosphorus (P), calcium (Ca), and nitrate, total carbon(C) exchangeable potassium (K), magnesium (Mg), cation exchange capacity (CEC) total nitrogen (N), and soil organic matter (SOM) (Park et al., 2010). Moreover, the physical and chemical properties of biochar depend on two major components i.e. pyrolysis and raw material used for the production of BC. In general, the pH of biochar is low at lower temperatures and increases with an increase in temperature (Ding et al., 2016; Tan et al., 2017; Di et al., 2017). Tan et al. (2017) reported relatively lower pH values in BC prepared from manures as compared to lignocellulose; however, all showed pH values higher than 7. Besides, temperature also affects the CEC content in biochar and mostly it decreases with an increase in temperature (Ding et al., 2016; Rajkovich et al., 2015).
An increase in CEC enhances the sorption and retention of cations electrostatically in soil, thus biochar enhances the retention of nutrient content and plays a key role in the fertility of the soil (Liu et al., 2017). Pyrolysis of raw material results in the breakdown and

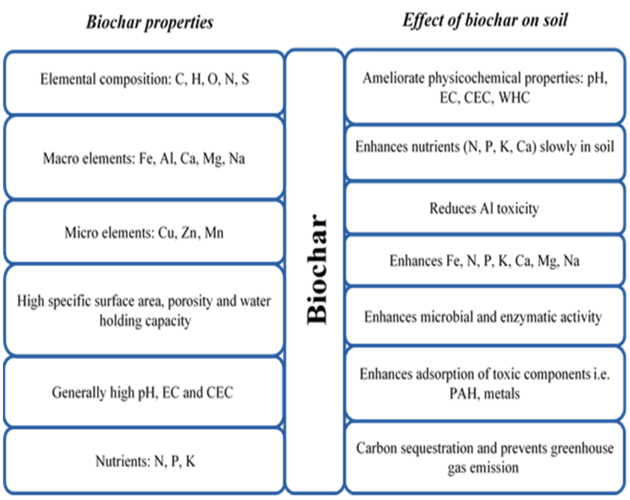

Figure 2. *General characteristics of biochar and its plausible effect on soil.*

generation of fine very fine porous structure which has a very high specific, total surface area and volume which enhances the adsorption ability. Because of the very fine structure, the WHC of the biochar is high and can retain water for a longer duration Park et al., 2010).

Effect of biochar on soil biological properties

The application of biochar helps in the growth of different beneficial microorganisms in the soil. They not only improve water retention in the soil but the pores provide humid space for the growth of microorganisms, which results in improved aggregate formation in soil. Biochar also absorbs nutrients and thus releases slowly but constantly for the soil flora. Additionally, they promote the exudation of nitrogen and dissolved organic C from roots, which are essential for microbial breakdown and constitute the majority of microbial biomass (Norton et al., 1996). BC reduces the salinity and sodicity stress and offers a rich source of C for microbes (Zheng et al., 2017; Gul et al., 2015; Saifullah et al., 2018). The presence of salinity in soil results in poor physical and chemical conditions along with decreased nutrient content. Thus, saline soil could harmfully impact the soil microbial activity, growth, and diversity. To overcome the toxicity, lack of water retention, and breakdown of soil aggregate it is important to regain the microbial community. Microbial biomass is thought to serve as a gauge for variations in the organic C content and breakdown of soil. Biochar can help in retaining water, and air spaces for microbial growth, improve aggregate formation of soil, release nutrients to the soil, and promote the release of dissolved organic C and N from the roots, which are applied in microbial metabolism, and constitute the majority of microbial biomass, and give microorganisms a large amount of C (Norton et al., 1996; Saifullah et al., 2018; Bhaduri et al., 2016; Jalali and Ranjbar, 2009).

Effect of biochar on plant growth and productivity

Several researchers have reported that the application of BC in fixed concentrations can help to improve plant growth and development. The micro and macronutrients such as Ca, K, N, P, and Zn present in biochar are being slowly released into the soil thus taken up by the plants and increasing their productivity and yield (Thomas et al., 2013; Hammer et al., 2014; Darke et al., 2016). However, the percentage of application of biochar varies from plant to plant.

DOI: 10.6092/issn.2281-4485/20614

Moreover, it not directly, but indirectly biochar absorbs the toxic organic and inorganic components from the soil through adsorption on its highly porous surfaces. Moreover, high porosity and water-holding capacity enhance the chance of growth of biological microorganisms (Thomas et al., 2013). Studies conducted in laboratories and on plants in the field revealed that adding BC to salt-affected soils significantly reduced salt stress and enhanced plant growth by releasing vital macro and micronutrients such as Ca, K, N, P, and Zn into the soil to help counteract the negative effects of salts. Decrease of osmotic stress through increasing water retain capacity and thus water obtainability (Akhtar et al., 2014; Ali et al., 2017; Rizwan et al., 2018), enhancement of conductance and stomatal density (Thomas et al., 2013; Abbas et al., 2017). It was found that by enhancing the phosphorus, and C levels of the soil and exchanging connected microbial populations, BC can increase the quantity and biomass of lettuce leaves (Lebrun et al., 2020; Lin et al., 2015). Tripti et al. (2017) documented that the use of BC resulted in a higher yield of tomato and its plant biomass with an increase in enzyme activity of dehydrogenase.

Biochar mitigates soil salinity

Salinity has affected hundreds of millions of hectares of land globally, which is an existential threat to biodiversity and the world's food security. Applying organic additions to salt-impacted soils is a good method for reducing challenges brought on by salinity (Gunarathne et al., 2020; Majidi, 2022; Akhtar et al., 2015b; Yang et al., 2020; Ghafoor et al.,2004; Lakhdar et al., 2009; Saifullah et al., 2018).

Impact of biochar on nutrient condition of salt-affected soils

The salt-rich soils are generally deficient in nutrient content with low microbial activity. Moreover, the physical, chemical, and biological properties are also stressed and thus toxicity is likely to be common inside this soil (Saifullah et al., 2018; Qadir and Schubert, 2002). Extreme soluble salts and exchangeable Na in the soil can have an impact on ions capacity to compete with one another directory or on the mass flow of mineral nutrients to the root by increasing the osmotic pressure of the solution (Saifullah et al., 2018; Rengasamy, 2010; Fageria et al., 2011), Lack of organic matter and plant biomass results in low P, K, and in such soils (Lakhdar et al., 2009). As a result, salinity and sodicity harm soil microbial communities, which in turn have an impact on how nutrients are transformed and made available to plants. It also affects the nitrogen availability through leaching. Application of BC helps in the addition of organic matter to the soil which has high porosity and enhances water-holding capacity thus reducing nutrient leaching and allowing microbes to grow in a better environment. Moreover, its application helps in increasing micro and macronutrients and thus enhances the nutrient status of the soil. The latest findings showed that salt-stressed soil treated with BC had significantly higher nutrient content, particularly in the Mg, Ca, N, K, and P categories (Akhtar et al., 2016a; Saifullah et al., 2018; Kim et al., 2016; Abbas et al., 201; Rengagamy and Olsson 1991).

Role of Biochar in improving the physical characteristics of salt-affected soils

Poor physical conditions are seen in both saline and sodic soils (Rengagamy and Summer, 1998). As the Na ion concentration in these soils is high, they can break down soil aggregates as swelling, slaking, and spreading of clay (Ghafoor et al., 2004). Consequently, the hard crust development on the soil surface has a negative impact on hydraulic conductivity and infiltration (Rengagamy and Summer, 1998). The high concentration of electrolytes in the soil solution could result in a significant yield decrease because of the reduced water available and poor emergence and growth of the seedlings (Wong et al., 2010). Reduced soil organic C inputs due to decreased growth of plants in salt-affected soil could result in poor soil formation (Amini et al., 2016). Such soil can be maintained physically degraded through cultivation (which breaks up hardpans and aids in mixing soil layers to promote internal drainage for salt leaching) Na and raising Ca from soil colloids, by raising soil organic C, and by boosting biomass from microbes and plants. Recent research demonstrates that BC improves the physical characteristics of salt-impacted soil (Sun et al., 2017; Eynard et al., 2005). It is reported that Ca helps in the aggregation of soil and increases the leaching of Na thus biochar helps in improving the physical properties of salty areas (Saifullah et al., 2018). Although BC is highly porous with high water holding capacity and bulk density, the main effect depends upon the feedstock and pyrolysis condition. Moreover, the amount of BC added to the soil is also a very crucial factor in the mitigation of sodic and saline soil. Salinity soil in which an excessive amount of three different kinds of salts li-

DOI: 10.6092/issn.2281-4485/20614

mits plant development (Saifullah et al., 2018; Qadir and Schubert, 2002).

Role of biochar in enhancing the chemical properties of salinity soils

Salinity soil in which an excessive amount of three various types of salts limits plant growth: 1) "salt-affected soil in which electrical conductivity is > 4 dSm ⩾ 1. 2) Sodic soils in which the exchangeable sodium percentage (ESP) is > 15. 3) Saline–sodic in which the electrical conductivity is > 4 dSm ⩾ 1 and ESP is > 15". Estimates of the zone of salt-affected soils vary widely, ranging from 6 % to 10 % of the earth's land region, and 77 million hectares (Mha) of irrigated lands(Chaganti et al., 2015). The main chemical properties, that play an important role in salt-rich soil, are pH, electrical conductivity, cation exchange capacity, and sodium absorption rate (SAR) or ESP. It is widely reported that the addition of biochar increased the pH of the soil. Since most of the biochar has a high pH when prepared at high pH. However, they vary based on feedstock type and retention time. Nevertheless, some recent studies reported application of biochar led to a reduction in the pH of the soil-affected area. Although the process is currently poorly understood, high ESP may be the cause, and using BC to reduce ESP in the soil may be one of the mechanisms causing the pH of soils to crop (Saifullah et al., 2018; Lashari et al., 2015; Hinsinger et al., 2003). Another reason for the pH drops in soil treated with BC might be due to the maximum CEC of BC encouraged plant absorption of cations (Ca^{2+}, $Mg^{2+,}$ and K^{+}) which led to the release of H^{+} from roots to balance charge (Yue et al., 2016). Since biochar is released slowly in the environment and remains for a long time, studies are necessary to understand the mechanism behind the change in pH in saline soil. Several studies showed that BC can enhance soluble salt leaching to lower soil electrical conductivity (Lashari et al., 2013; Luo et al., 2017). There are some inconsistencies, as a result of BC's ability to absorb Na, decrease saline water rising to the surface of the soil, reducing the accumulation of salt. Furthermore, the amount and age of the BC, its kind, its starting salt concentration, the soil, irrigation water, and the condition of the experiment (with or without leaching) all influence its overall ability to change the EC of saline soils. Several studies have shown the advantageous effect of BC on reducing the ESP/ SAR of sodic and saline soils (Darke et al., 2016; Kim et al., 2016; Sun et al., 2017; Eynard et al., 2005). Depending on the characteristics of the soil, plant, and BC, a drop in the ESP could be caused by a variety of processes, such as a direct exchange of Na and Ca on the colloidal substance of soil substances (Lashari et al., 2015; Hinsinger et al., 2003; Luo et al., 2017), through a rise in the surface charge density (caused by organic carbon) (Zheng et al., 2017; Kim et al., 2016; Jaafar et al., 2014). Leaching of Na owing to increased BC porosity hence lowering SAR and ESP (Di et al., 2017), Furthermore, adding BC as a natural supplement might raise the rhizosphere's partial Co^{2} pressure, this would facilitate the mobilization of Ca from calcareous soils to replace sodium from soil substances (Qader and Schubert, 2002; Jalali and Ranjbar, 2009).

Biochar's advantages and disadvantages

Biochar is a recognized soil amendment, produced by pyrolysis from various biomasses. Because of its complex interplay of advantages and disadvantages, it has attracted significant attention in field and laboratory studies. Advantages of biochar: some studies have shown the advantageous effect of BC on reducing the ESP/ SAR of sodic and saline soils as well as it can improve soil properties (nutrient, pH, electrical conductivity) which are essential for plant growth and development (Darke et al., 2016; Kim et al., 2016; Sun et al., 2017; Eynard et al., 2005). The effects of BC vary depending on feedstock material, and it can enhance soil cation exchange capacity and organic C content. Additionally, the long-term application of BC can decrease greenhouse gases (Trippe et al., 2015; Santi, 2024; Biedermen and Harpole, 2013). According to Sparrevik et al (2013), the advantages of BC in agricultural systems are sensitive to local environmental variables. Moreover, adding BC as a natural supplement might raise the rhizosphere's partial Co^{2} pressure, this would facilitate the mobilization of Ca from calcareous soils to replace sodium from soil substances (Qader and Schubert, 2002; Jalali and Ranjbar, 2009). Disadvantages of biochar: according to Smith (2016), the disadvantages of using BC cannot be overlooked, BC has complicated interactions with greenhouse gasses that change depending on the kind of soil and environmental situations. In some, conditions, BC can reduce nitrous oxide emissions while enhancing methane emissions. Hung et al (2022), expressed worries regarding the unpredictability in the efficiency of BC, noting that its effect on ammonia volatilization from manure can depend on the feedstock of biochar.

DOI: 10.6092/issn.2281-4485/20614

This shows that not all BCs are equally helpful and their effects can vary significantly based on feedstock materials and production methods (Smith, 2016; Hung et al; 2022).

Conclusions

Biochar is a carbonaceous organic substance formed by pyrolysis, affected by factors such as feedstock material and temperature. BC has essential elements and properties that make it beneficial for soil fertility, mitigating climate change, and pollutant elimination. BC can increase physiochemical characteristics such as porosity and water-holding capacity. The review highlights the significant influence of BC on increasing soil fertility, reducing soil salinity, and promoting plant growth. The evidence presented underlines the potential of BC as a useful and sustainable soil improvement in agriculture. Continued study and practical uses of BC could significantly contribute to improving soil health, enhancing crop yields, and mitigating environmental problems in the future. Biochar is a promising tool for the management of Arid and Semi-arid areas and for mitigating soil salinity.

Acknowledgment

The author thanks the referees for reviewing the article.

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