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Biochar Effects on Amelioration of Adverse Salinity Effects in Soils

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Abstract

Biochar is the term given to biomass subjected to the process of change in the composition by the action of high temperatures. Advantages of biochar in soil quality have been reported, including amelioration of salinity effects. Salinity has a negative effect on soil physical properties and plant production by adversely affecting the process of plant growth, hence seed germination, nutrient uptake, and yield. Moreover, salt stress causes oxidative stress in plant and the reduction in antioxidant enzyme activities. Biochar is an amendment, which could decrease the negative effect of salt stress on crop growth and production. Application of biochar enriches mineral nutrients; improves the soil's physical, chemical, and biological characteristics such as bulk density, hydrological properties, aggregate structure, ion exchange capacity, and microbial activity; and consequently enhances plant growth. Enhancing physical properties, biochar balances water holding capacity and air porosity in soils. Biochar promotes benefits in plant growth in saline soils through reduction in oxidation stress and in osmotic stress, lower production of phytohormones, improvement in stomatal density and conductance, improvement in seed germination, and the promotion of microbial activities. Biochar amendment can contribute to reduce salt stress in plants under saline condition due to its high salt adsorption capability.

Keywords: organic residues, pyrolysis, soil quality improvement, plant growth, carbon sequestration

1. Introduction

Biochar (charcoal) is the term given to biomass subjected to the process of decomposition or change in the composition by the action of heat at high temperatures. Biochar is obtained by pyrolysis of biomass at temperatures of 300–600°C and has a great potential to mitigate possible impacts of climate change, such as periods of excessive rain or severe droughts. Because it is a thermally altered material, it degrades much more slowly, creating a large long-term carbon stock in the soil, being about 1500–2000 times more stable than non-pyrolyzed organic matter [1].

Good-quality biochar has an internal structure similar to graphite, which preserves (sequester) the carbon in the soil for hundreds and even thousands of years [1], in addition to having a reactive peripheral structure, which acts as the natural organic matter of the environment. The presence of internal organic structures similar to that of graphite contributes to the biochar recalcitrance, i.e., biochar stays for a longer period in soil, characterizing a more efficient negative carbon sequestration system [1].

The interest in using biochar as a soil amendment is increasing in the years 2000 because of the work of researchers who study the production of an organic soil-conditioning fertilizer trying to be similar to the black lands of Amazonian Indians [2]. Pre-Columbian peoples produced the black lands of Indians, but it is not known exactly whether it was an intentional process of soil improvement or a by-product of the agricultural and housing activities of these peoples. Human activity in the pre-Columbian past resulted in the accumulation of plant and animal waste, as well as large amounts of ash and coals with various chemical elements, such as P, Mg, Zn, Cu, Ca, Sr, and Ba [1].

The tailings produced by the industrialization of plant-origin products and the tailings originated from animal production can be used as inputs for agriculture and can be potential environmental liabilities, such as animal residues, rests of wood, and crop residues. The establishment of mechanisms, by which external environmental benefits can be monetized or internalized, may be important for the adoption of biochar production technologies [3].

Thus, biochar of vegetable or animal source is an alternative to act in carbon sequestration and as an organic soil conditioner. In addition, in many agricultural and forestry production systems, there is an expressive amount of produced waste, such as cut waste, dead wood, surplus seedlings, and sawmill and crop residues left in the field after harvest. Many of these residues can be used to produce biochar, which can be applied to agricultural soil both to sequester carbon and to improve crop production potential [3].

When applied to the soil, biochar acts as a soil conditioner promoting plant growth by retaining the nutrients and enhancing the physical and chemical soil properties [3, 4]. Experiments carried out in field with biochar application in the soil have presented benefits to agricultural productivity.

In this way, many functions of the biochar stand out, such as promote the structure of the soil with chemical connections between the biochar and the inorganic macromolecular structures, thus avoiding landslides during the rainy periods; retention of rainwater and irrigation to be released during dry periods; retention and release of H^+ and OH^- ions in the action of controlling soil pH; retention of nutrient metal ions from plants such as Ca, Fe, Cu, or toxic to them (e.g., Al); increase in plant growth and agricultural productivity; decrease in N_2O emissions; reduction in the need for mineral fertilizers; and increase in the organic carbon stock in the soil by sorption of labile soil organic matter onto biochar particles, thus decreasing its mineralization, for instance [5].

The uses of biochar cannot be limited only to increasing crop productivity and carbon sequestration, as biochar also reduces other important greenhouse gas emissions. Thus, studies reported by [6] show that a decrease in methane emissions was verified with additions of 30 g kg^{-1} of biochar to the soil, as well as a significant reduction in nitrous oxide emissions. According to the author, such facts may be due to the improvement of soil aeration, reducing the occurrence of anaerobic conditions and possibly decreasing the nitrogen cycle by increasing the soil's C/N ratio. In addition, biochar can alter the rates of nitrogen cycling in soil systems by influencing nitrification and denitrification, which are key sources of the greenhouse gas nitrous oxide. According to Liu et al. [7], biochar can potentially reduce N_2O emission in soil by affecting ammonia- and nitrite-oxidizing bacteria, and these effects depended on the biochar application rate in soil.

It is estimated that the world population is expected to increase to 9.7 billion by 2050, and in 2100, it is expected to reach 10.9 billion people, which will inevitably lead to an increasing demand for food [8]. According to [9], to feed more people and better feed them, in a scenario with higher prices, inputs that are more

expensive, and increasingly limited resources, and, at the same time, fight against climate change is an unprecedented challenge for humankind.

In this sense, the application of biochar as a sustainable soil corrective has been proposed as an attractive approach to mitigate greenhouse gas emissions due to its contribution to carbon sequestration and to improve crop productivity [3]. Thus, Woolf et al. [10] estimated that the annual net emissions of CO₂, N₂O, and CH₄ could be reduced by 12% with the implementation of biochar, without endangering food security, habitat, or soil conservation.

The potential of biochar in increasing crop productivity has been demonstrated in a large number of studies on tropical agricultural products [11–13]. It has been found that treatments with biochar increased crop yields averaged 10%, with larger effects observed in acid soils and thick texture [14].

Although the detailed physiological mechanisms remain unclear [15], the favorable effects of biochar on crop productivity are due to the high specific surface area and cation exchange capacity and depend on pyrolysis conditions and microporosity [13]. In addition to improving water and nutrient retention in the soil, these properties shown by biochar also allow adsorbing a wide range of potentially toxic materials, including heavy metals [16], pesticides [17], and other contaminants [16, 18, 19]. In saline conditions of soils, biochar improved soil conditions for plant growth [20].

Soil salinity is one of the factors that affect the crop yield. In arid and semiarid regions, salinity constitutes a serious problem, limiting agricultural production and reducing crop productivity to uneconomic levels. In these regions that are characterized by low rainfall and high evapotranspiration, inadequate irrigation management, quality of irrigation water, and conditions of insufficient drainage contribute to accelerating the soil salinization process [21].

Soils affected by salts, also known as soils halomorphic or saline and sodium soils, are soils developed in imperfect drainage conditions, which are characterized by the presence of soluble salts, exchangeable sodium, or both, in horizons or layers close to the surface. Salt-affected soils are generally classified as saline, sodic, or saline-sodic, which is mainly based on their electrical conductivity (EC), sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP) of the saturated paste extracts [21].

Among saline soils, saline-sodic soils are highly degraded and least productive which is mainly due to the effect of both salinity and sodicity on soil properties, and if these soils are dispersed, then water infiltration and hydraulic conductivity are reduced, which negatively affect the plant growth [22]. Salinity stress negatively correlates with soil properties such as organic matter and C/N ratio [23]. Soil salinity reduces the microbial activity and biomass and alters the microbial community structure in the soil [24].

Increasing the concentration of soluble salts in the soil affects plant growth due to increased osmotic tension of the soil solution, which reduces the absorption of water by plants, the accumulation of toxic amounts of various ions, and disturbances in the ion balance. On the other hand, the saturation of the exchange complex for Na⁺ results in physical conditions highly unfavorable to plant growth, besides causing nutritional disturbances [20].

The high capacity to activate carbons in order to adsorb a variety of salts has been observed, and for this reason, the biochar has been used in industrial processes such as desalination [25]. However, the potential use of biochar as a soil amendment to mitigate the stress induced by salt in the plant has received little attention [26].

In addition, some studies have also shown that the application of organic amendments improved the physicochemical properties of saline soil; however, little data are available on the effect of biochar on the saline soil properties [27–30].

Thus, the objective of this chapter was to approach the role of biochar on amelioration of adverse salinity effects in soils.

2. General considerations about biochar production

Biochar is produced by heating any kinds of organic waste materials (crop residue, animal, or poultry manure) at high temperature through the process of pyrolysis (fast and slow). In addition, rotating kilns, vertical silo-type reactors, gasification, hydrothermal carbonization, and pyrolysis are common techniques used for biochar production [31].

A great amount of waste such as forest waste and crop residues is left in the field after harvesting in several agricultural and forest production. Many of the agricultural and forestry waste can be used to produce biochar, a product that when applied to agricultural land can both sequester carbon and improve crop production potential. Moreover, animal wastes can also be converted to biochar [3, 32–34]. In many cases, these residues have little value, and their disposal incurs costs.

The characterization of biochars is hard to be specified due to the large variety of potential biomass to be used for its production. In addition, the carbonization conditions applied for the conversion of biomass into biochar also interfere in the final product characterization [25].

Some studies have reported the differences in results of biochar applications in saline soils according to the method used for obtaining it [31]. In a study carried out by [35], reduction in plant growth was observed when eucalyptus wood-derived biochar produced at high temperature (800°C) was applied in a sandy ultisol, whereas biochar produced at lower temperature (350°C) enhanced plant growth. According to Almaroai et al. [30], characteristics such as duration and temperature of pyrolysis as well as the application rate of biochar are highly variable according to soil characteristics (fertility level, for instance) and soil biological activities.

According to Qayyum et al. [36], the use of biochar is a practice for achieving multiple benefits of sustainable agriculture. Biochars are characterized with a high concentration of total organic carbon (30–70%) depending on the pyrolysis conditions (temperature, aeration, and time), high mineral contents (Na, K, Mg, Fe, etc.), high pH, high electrical conductivity, and a low concentration of ash and volatile matter [36]. However, the feedstock type significantly affects the biochar properties [37].

The sophisticated techniques of characterization include the quantification and identification of surface functional groups, aromatic compounds, polycyclic aromatic hydrocarbon, active surface area, and scanning electron microscopy. Thus, biochars should be carefully analyzed prior to their utilization [38].

In a study carried out by Hansen et al. [39], the authors applied two kinds of biochar: straw gasification biochar and wood gasification biochar in sandy soil for evaluating the shoot and root growth of barley (*Hordeum vulgare* L.). They observed that straw gasification biochar was more effective compared to the application of wood gasification biochar in soil, since straw gasification biochar presented considerable potential for enhancing crop productivity in coarse sandy soils by increasing soil water retention and improving root development.

Two biochar materials produced from maize using two different pyrolysis techniques, heating at 600°C for 30 min and batch-wise hydrothermal carbonization at 210°C, were used in a study carried out by Almaroai et al. [30]. The results of this study demonstrated positive synergistic effects of biochar amendments on plant growth, plant nutrient uptake, soil nutrient contents, and soil biological properties

in sandy loam soil, with a more significant effect on the measured biological indicators for the biochar produced by batch-wise hydrothermal carbonization at 210°C. According to these authors, different methods of producing biochar from the same source (maize) play a critical role in the expression of soil ecological effects, which underpin the assumption of a link between chemical and physical properties of biochar and enhanced plant nutrient acquisition, symbiotic performance, and plant stress tolerance.

3. Application of biochar in saline soils and improvement of plant growth

Mineral salts are an important plant stress factor, having adverse impacts on crops particularly in arid and semiarid regions. High soil salinity and/or sodicity affects an estimated 1.1 Gha or more than 7% of the world's total land area [40]. Salinity changes the water absorption and uptake of nutrients, as well as the permeability of membranes. These changes reflect in the water and nutrient balance of the plant and cause changes in metabolism, hormonal balance, gas exchange, and production of reactive oxygen species (ROS) [41]. All these changes compromise the growth and division of cells, vegetative and reproductive growth and acceleration of leaves senescence, resulting in the eventual death of the plant [42].

Salt stress adversely affects the process of plant growth, since seed germination, nutrient uptake, and yield. Moreover, salt stress causes oxidative stress in plant and the reduction in antioxidant enzyme activities [43]. Salinity reduces crop growth by affecting several processes that depend on salt accumulation in shoots [44]. The independent processes reduce shoot biomass predominately by closing stomata and inhibiting leaf expansion. Plant initial responses to salt stress are generally the reduction in leaf expansion and partial/full closure of stomata to conserve water resource. These responses are coordinated by an increased accumulation of stress hormones, particularly abscisic acid (ABA). An increased level of ABA in xylem stream is an indication of plant roots facing osmotic stress [43].

The application of biochar in saline soils favors the increase of soil organic matter and nutrients, also increasing the cation exchange capacity and replacing Na from exchange sites by providing Ca in soil solution, improving the stabilization of soil structure. Therefore, by enhancing physical properties, biochar balances water holding capacity and air porosity in soils. In addition, biochar works as habitat for many soil microorganisms that can help improve salt-affected soils [45, 46].

Biochar can also hasten salt leaching and thus decrease the time required for reducing salt concentration to a level suitable for growing plants [47]. Moreover, biochar adds soil organic C and increases the stability of organic molecules that would help bind soil aggregates for long periods compared to easily degradable molecules from other organic amendments [48].

Several studies observed that the application of biochar has been shown to be effective in reducing salinity stress by improving soil physicochemical [49, 50] and biological [50, 51] properties directly related to Na removal such as Na leaching, Na adsorption ratio, and electrical conductivity, as reported by Saifullah et al. [52].

The interaction effects of biochar and salinity on growth and yield of wheat significantly decreased wheat production through increase in soil salinity as the produced biochar while the grain yield and straw dry weight were declined by application of biochar. Therefore, under dry condition, biochar can be used as an appropriate level, as it could store more water compared to treatments without biochar [42].

It was reported that incorporation of biochar into salt-affected soil could alleviate salinity stress in potatoes [48] mainly because of its high salt (Na^+) adsorption potential. In another study, Akhtar et al. [53] examined the effect of different levels of salinity and biochar on wheat yield. The results showed that biochar application positively influenced growth and yield of wheat under saline condition. However, Thomas et al. [28] noticed high salt adsorption potential of biochar, some studies have reported negative effect of biochar on crop productivity, but these were generally restricted to specific type of biochar [54].

Biochar could improve the soil physicochemical and biological properties under conditions of abiotic stresses [55]. Biochar poultry manure compost (BPC) with pyroligneous solution (PS) in the saline soil increased microbial biomass carbon and the activities of urease, invertase, and phosphatase in bulk soils and rhizosphere soils under maize cultivation, according to Lu et al. [56]. Similarly, Bhaduri et al. [57] concluded that the effects of biochar on soil enzyme activities in saline soil vary with the applied rate of biochar, incubation time, and soil enzyme types.

The biochar application in salt-stressed soil (30 g m^{-2}) did not affect the soil pH but increased the soil electrical conductivity as compared to the control [28]. Similarly, a biochar produced by furfural (a colorless liquid used in synthetic resin manufacture, originally obtained by distilling bran) in saline soil decreased pH, while increasing the soil organic carbon, cation exchange capacity (CEC), and available P in the soil [31].

When applied in saline soils, composted biochar increased the soil organic matter content and CEC and decreased the exchangeable Na and soil pH [58]. These studies showed that biochar addition in saline soils could improve the plant growth by improving the soil biological activity and physicochemical properties.

The accumulation of Na and impairment of K nutrition are major characteristics of salt-stressed plants [59]. Thus, improved K/Na ratio through enhancing K availability is considered a useful tool to increase plant growth and yield under saline soils [60, 61]. Biochar, depending upon feedstock, may increase K concentration in soils, and this increase in salt-affected soils counteracts the adverse impacts of Na, being considered one of the major benefits associated with biochar application in saline soils [52].

Corroborating [52], a study carried out by Lin et al. [62] reported that the biochar application in saline soil improved wheat and soybean yields by increasing the exchangeable K concentration (by 44% over control) and increasing the K/Na ratio in plants, improving plant salt tolerance. According to Lashari et al. [63], a considerable increase in K concentration and K/Na ratio in the leaf sap of corn under salt stress and an increasing supply of K were suggested as major mechanisms responsible for the alleviation of salt stress to plants.

The benefits of biochar in plant growth in saline soils observed in several studies cited by Saifullah et al. [52] also include reduction in oxidation stress through degradation of O_2^- and H_2O_2 concentration reduction in osmotic stress through improving water holding capacity and thus availability of water; lower production of phytohormones; improvement in stomatal density and conductance; improvement in seed germination and the promotion of microbial activities; and a bacterial community shift toward the beneficial taxa in the rhizosphere.

Plants under salinity stress produce abscisic acid (ABA), and it is a good indicator of the osmotic stress, acting as a long-distance signal molecule to close stomata under water deficit conditions [64]. Thus, decreased production of ABA could be attributed to a biochar-induced improvement in water availability to plants, which would result ultimately in increased stomatal conductance. Further, enhanced availability of water and nutrients with biochar application under saline conditions could improve seed germination.

However, Thomas et al. [28] affirm that the biochar impact on the growth of plants in salt-affected soils is species dependent. Biochar application significantly improved the growth of salt-sensitive plant species; however, salt-tolerant species did not show any growth improvement with biochar amendment.

On the other hand, Luo et al. [58] reported significant improvement in the growth and yield of two salt-tolerant species grown in biochar manure compost-amended salt-affected soils.

4. Conclusions

The interaction of biochar with soils with salinity conditions is essential for determining any contrasting effects, which also depend on the physicochemical properties of biochar and the raw material used for biochar production. Elucidating the effect of biochar type on plant growth and development and soil biochemical properties provides important guidance on the selection of feedstock type and production technology, which could be applied under specific environmental conditions.

Different methods of producing biochar from the same source play a critical role in the expression of soil ecological effects, which underpin the assumption of a link between chemical and physical properties of biochar and enhanced plant nutrient acquisition, symbiotic performance, and plant stress tolerance.

Although there is an increasing number of studies about biochar and its effects in saline soils for improvement of plant growth, the results obtained until the present are still not conclusive given the diversity of raw material and methods for biochar production. It is still necessary to conduct more investigations in order to better use biochar for ameliorating the adverse salinity effects in soils.

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