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Biochar's Contribution for Enhancing Soil Properties and Crop Productivity by Alleviating Soil Acidity Stress: A Comprehensive Review

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Abstract: Soil acidity stress is a significant challenge in modern agriculture, impacting crop productivity and overall soil health. One promising solution to mitigate this stress is the use of biochar, a carbon-rich material derived from the pyrolysis of organic matter. This review aims to provide an in-depth analysis of the role of biochar in reducing soil acidity stress. It covers various aspects including the physicochemical properties of biochar, its interactions with soil components and the mechanisms through which it can effectively counteract soil acidity. The review also discusses the potential benefits and limitations of biochar application in diverse agricultural systems and highlights key considerations for its successful integration into soil management practices. Through a comprehensive examination of current research and findings, this review offers insights into the promising potential of biochar as a sustainable amendment for enhancing soil quality and crop production while addressing soil acidity stress.

Key words: Biochar · Crop Productivity · Soil Acidity Stress · Soil Properties

INTRODUCTION

Soil acidity stress is a widespread issue impacting agricultural productivity and sustainability. The key concerns of crop managements include deterioration of soil physical qualities, nutritional dis order, loss of soil organic carbon, accelerated erosion, soil degradation and a lack of incentives and regulations to adopt improved and ecologically friendly technologies [1, 2]. Excessive soil acidity negatively affects nutrient availability, microbial activity and overall soil health. Addressing this challenge is crucial for ensuring food security and environmental stability. Reclaiming acid soil related production problem is one of the best soil acidity management technologies (chemical fertilizers, organic fertilizers, lime and biochar) that not only enhance crop production but also improve the fertility and quality factors. Conserving soil organic carbon has been recognized as a strategy to reduce soil acidity and degradation.

Biochar has been recently recognized as a multifunctional material related to carbon sequestration, contaminant immobilization, greenhouse gas reduction, soil fertilization and water filtration [3]. Biochars are mainly composed of carbon. The organic portion of biochar has high carbon content and the inorganic portion mainly contains minerals such as Ca, Mg, K and inorganic carbonates, depending on its feedstock type. It stores carbon for long time so that it helps in mitigating climate change besides improving soil fertility and crop productivity. It can also improve crop biomass, N_2 fixation and enhances the efficacy of N fertilizers [4, 5] but the biochar capacity to neutralize the soil acidity depends on the biomass selection on which the biochar was prepared. In addition to the ameliorating effects of biochars on soil acidity, inhibition on soil re-acidification has been reported by different scholars. Soil pH buffer is a crucial factor determining soil acidification rate and an increase in soil pH buffer slow soil acidification process as pH buffer mainly depends on the CEC and organic C content [6].

When used as a soil amendment, biochar has been reported to boost soil fertility and improve soil quality by raising soil pH, increasing moisture holding capacity, attracting more beneficial fungi and microbes, improving cation exchange capacity, increasing soil base saturation,

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nutrient retention and availability, decreasing fertilizer needs and nutrient leaching and in soil and improving SOC, stimulation of soil microbes, increased microbial biomass and activity [7,8,9]. The material can be produced from different plant materials including wood chip and wood pellets, tree bark, crop residues, grasses, organic wastes [10]. Depending on the sources of biochar used, basic cations such as Ca, K, Mg and Si can form alkaline oxides or carbonates during the pyrolysis process. Following the release of these oxides into the environment, they can react with the H^+ and Al^{3+} and decrease exchangeable acidity [11]. In recent years, biochars have received interest as a large-scale soil amendment due to their potential for carbon sequestration, soil fertility improvement and soil restoration. Therefore, the objective of this paper was to review the effectiveness of biochar in enhancing soil properties and crop productivity by alleviating Soil Acidity Stress.

Physicochemical Properties of Biochar: Biochar exhibits diverse physicochemical characteristics based on feedstock type, pyrolysis conditions and post-production treatments. Its surface area, porosity, pH and cation exchange capacity (CEC) play pivotal roles in its interactions with soil components. These properties determine biochar's ability to adsorb and retain nutrients, buffer pH and modify soil ion concentrations. The physical properties of biochars contribute to their function as a tool for environmental management. Their physical characteristics can be both directly and indirectly related to the way in which they affect soil systems [12]. When biochar is present in the soil mixture, its contribution to the physical nature of the system may be significant, influencing depth, texture, structure, porosity and consistency through changing the bulk surface area, pore-size distribution, particle-size distribution, density and packing.

Surface Area: Surface area is a very important soil characteristic as it influences all of the essential functions for fertility, including water, air, nutrient cycling and microbial activity. The limited capacity of sandy soil to store water and plant nutrients is partly related to the relatively small surface area of its soil particles. High organic matter contents have been demonstrated to overcome the problem of too much water held in a clay soil and also increase the water contents in a sandy soil [13, 14].

Porosity: The pore-size distribution of activated carbons has long been recognized as an important factor for industrial application. It is logical that this physical feature of biochars will also be of importance to their behaviour in soil processes. The relationship between total surface area and pore-size distribution is logical. Micro-pores contribute most to the surface area of biochars and are responsible for the high adsorptive capacities for molecules of small dimensions such as gases and common solvents [15-17]. In the past, when biochars and activated carbons were assessed mainly for their role as adsorbents, macrospores (>50nm diameter) were considered to be only important as feeder pores for the transport of adsorbate molecules to the meso- and micro-pores. Macropores are also relevant to the movement of roots through soil and as habitats for a vast variety of soil microbes [18-20].

Particle Size Distribution: The particle sizes of the biochar resulting from the pyrolysis of organic material which dependent upon the nature of the original material. Due to both shrinkage and attrition during pyrolysis, particle sizes of the organic matter feedstock are likely to be greater than the resultant biochar. In some cases, particles may agglomerate; therefore, increased particle sizes are also found. Depending upon the mechanical intensity of the pyrolysis technology employed a degree of attrition of the biomass particles will occur during processing. This is especially true in the post-handling of the material as the biochar is significantly more friable than the original biomass.

Density: Two types of density of biochars can be studied: the solid density and the bulk or apparent density. Solid density is the density on a molecular level, related to the degree of packing of the C structure. Bulk density is that of the material consisting of multiple particles and includes the macro porosity within each particle and the inter-particle voids. Often, an increase in solid density is accompanied by a decrease in apparent densities as porosity develops during pyrolysis. The relationship between the two types of densities, in this respect [21-24] reported that apparent densities increased with the development of porosities from 8.3 to 24 per cent at pyrolysis temperatures up to 800°C.

Elemental Rations: The H/C ratio of unburned fuel materials, such as cellulose or lignin, is approximately 1.5 and used molar H/C ratios of 0.2 to define 'black carbon'.

Graetz and Skjemstad [25] concluded that temperatures during biomass burning are predominantly greater than 400°C and that chars formed during these temperatures are likely to have H/C ratios of 0.5. Consequently, biochar production is often assessed through changes in the elemental concentrations of C, H, O and N and associated ratios. Specifically, H/C and O/C ratios are used to measure the degree of aromaticity and maturation, as is often illustrated in van Krevelen diagrams [26].

Macro-Elements: Macro-elements are the most important nutrients for plants. They occur naturally in the soil to some extent and can be supplemented with fertilizers, manure and compost. Legumes are able to bind nitrogen. The macro-elements are calcium, magnesium, potassium, sulphur, phosphate, nitrogen sodium.

Trace Elements: Trace elements are nutrients that plants need in small doses. The trace elements are boron, copper, manganese, cobalt, silicon, zinc, iron and molybdenum. Signs of shortage occur when the disappearance of trace elements through the crops is not compensated adequately with supplements by means of fertiliser, manure or compost, or when the availability of certain elements is limited by the pH or mineral imbalance in the soil. It is difficult to solve a lack of trace elements in the plant at source, as many shortages are the result of a shortage or surplus of another mineral in the soil.

Benefits of Biochar on Soil Properties

Soil Physical Characteristics: Biochar not only influence soil chemical properties but also affects soil physical structure. Biochar is a low density material that reduces soil bulk density [27], thereby increasing water infiltration, water holding capacity, root penetration and soil aeration [28-30]. Numerous studies report positive effects of biochar application on soil physical properties. Glaser *et al.* [31] observed that water retention in Terra Preta soils was 18% higher than in adjacent soils where the amount of charcoal was lower or absent. Ghorbani *et al.* [32] applied biochars derived from wood residues to rice cultivation. They found improvements on soil water permeability, water holding capacity and plant water availability. More recently, Herath *et al.* [33] found that corn stover biochar application on two different soils improved significantly the aggregate stability and the porosity of both soils considered, ameliorating their hydraulic properties. The enhancement of soil water retention properties depends on biochar mineral and organic content [34,35] as well as its porous nature (predominantly ìm sized pores) that reflects the cellular structures of the original feedstock [36].

Despite the possible positive effects, the application of char to different soils should be carefully investigated since it could also have detrimental effects. For example, Diatta *et al*. [37] suggested that biochar effects on water retention will be particularly positive in sandy soils (due to their typical large porosity), neutral in medium-textured soils and potentially detrimental in clay soils.

Soil Chemical Characteristics: During pyrolysis, most of the mineral nutrients that are present in biomass are concentrated into the biochar fraction. Therefore, soil application of this carbonaceous material could be a convenient mean of recycling those nutrients to agricultural lands [38]. Several studies have shown significant agronomic benefits, such as increased crop production, in soils amended with biochar. The improvements in soil fertility were related to an increase in: soil nutrient retention [39], soil water permeability and plant water availability [40], soil cation exchange capacity [41] and the neutralization of phytotoxic compounds [42]. Furthermore, char affects soil microbial community and may have a positive impact on plant resistance to disease due to its suppressive effect on soil pathogens [43]. All these effects are due to biochar elemental composition that can directly modify soil chemical properties and provide a chemically active surface able to change nutrients dynamics, as well as to catalyze useful reactions.

An important issue for a sustainable cultivation is to find the correct equilibrium between the supply of sufficient nutrients for a healthy plant growth (especially N and P) and the reduction of nutrient leaching. The loss of nutrients from agricultural soils has several negative effects: depletion of soil fertility, drop of crop yields, soil acidification, increase of the fertilizer costs for farmers, reduction in the quality of surface and ground waters by eutrophication [44-46]. The use of a soil amendment able to retain nutrients could help to solve this problem.

Several investigators +reported an increase in soils ability to retain plant available nutrients and a decrease in the leaching of nutrients and agricultural chemicals when char was used as soil amendment. For example, Laird *et al.* [47] Bradley *et al.* [48] found a significant decrease in total amounts of P, Mg, Si and N leaching using biochar, despite the simultaneous addition of swine manure. By contrast, total amounts of leached K and Ca increased.

Beck *et al.* [49] observed that the soils containing biochar had an increased retention of nitrate, total nitrogen, phosphate, total phosphorus and total organic carbon compared to the control without biochar. These positive effects are mainly related to biochar high surface area, high surface charge density, negative surface charge [50] and to biochar capacity to stimulate soil microbial activity. In more details, due to its high porosity as well as the presence on its surface of both polar and non-polar functional groups, biochar can efficiently adsorb organic molecules and nutrients [51]. After its soil inclusion, char surface undergoes oxidation leading to the formation of phenolic and carboxylic functional groups which represent negative pH-dependent charges [52].

Soil Microorganisms: Soil amendment with biomass-derived black carbon (biochar) determines changes in soil microbial community and soil biogeochemistry. Several studies documented the stimulation of indigenous arbuscular mycorrhizal fungi by biochar and this has been associated with enhanced plant growth. The main mechanisms that could explain how biochar influences the abundance and/or the activity of soil biota and plant roots are: Increase of nutrients (i.e., N, P and metal ions) amount and availability, affecting both plants and microorganisms [53-55]. Biochar labile components have the potential to stimulate microbial activity [56]. Moreover, an increase in soil nutrient retention and availability results in enhanced host plant performance and elevated tissue nutrient concentrations which allow higher colonization rates of the host plant roots by microorganism [57].

Microbial abundance increases due to the sorption of compounds that would otherwise inhibit microbial growth. For example, Zhu *et al.* [58] found that high temperature corn stover biochar has a high adsorption capacity for catechol, which is toxic to microorganisms. Most of the pores within biochar are large enough to accommodate soil microorganisms (including bacteria and fungi), excluding their larger predators. Thus, char pore structure offers a physical protection from soil predators and allows a better attachment to various microorganisms. The latter makes them less susceptible to leaching in soil and determines an increase in bacterial growth rates. As reviewed by Lehmann *et al*. [59], the effects of biochar on soil biota are highly variable and not always positive. Consequently, further evaluations are needed to better understand the impacts that the application of different kind of chars can produce on different soils.

Sorptive Capacity: In addition to retain nutrient elements in a plant-available form, biochar also has an affinity for both inorganic and organic compounds and may sorb toxic by-products from soils and wastewaters. Several studies have been conducted to investigate how charcoal can effectively retain polar compounds, e.g. polar organic pesticides [60] and hydrophobic molecules, such as polycyclic aromatic hydrocarbons [61]. The adsorptive capacity of biochar depends both on its physical (i.e., its porous structure) and chemical (i.e., presence of specific surface functional groups) properties. High surface area and the presence of surface polar groups on wheat biochar were determinant in the uptake of neutral organic contaminants, such as benzene and nitrobenzene. Prelac *et al.* [62] related the ability of wood-biochar to adsorb large molecules, such as phenolic compounds, to the presence on its surface of a large number of macropores. In addition to organic compounds, char can also effectively bind inorganic molecules.

Therefore, the highest remediation potential of biochar depended on the presence of a large amount of specific surface functional groups that serve as adsorption sites for heavy metals. Indeed, a relatively high concentration of surface acidic groups can allow the formation of chelates with metal ions and help the binding of positively charged ions [63]. In conclusion, biochar sorptive capacity can be effectively used to mitigate diffuse pollution from agriculture and to immobilize potentially toxic organic and inorganic compounds, thereby reducing contamination from soils or wastewater

Soil Fertility and Crop Production: Biochar effects on soils physicochemical properties also influence soil fertility and crop production. Presently, many studies demonstrating significant agronomic benefits due to char application to soils have been conducted. Early researches from 1980s and 1990s showed marked favorable impacts of low charcoal additions (0.5 t ha-1) on various crop species, but growth inhibition at larger rates [64]. Ishii and Kadoya [65] applied char as a soil conditioner on citrus cultivation reporting an increase in the fresh weights of roots, shoots and the whole tree. Further works conducted on different crops and soil types demonstrated that adding charcoal to soil increased significantly seed germination, plant growth and crop yields. Biochar amendments result promising especially in combination with fertilizers. For example, Yamato *et al.* [66] found an enhancement of maize and peanut yields in Indonesian soils where bark charcoal was applied together with N.

However, some studies showed no significant effects of char applications on crop yield and some other adverse dose-dependent effects. Indeed, some chars have unfavorable properties which cause long-term alterations in soil chemistry and can inhibit permanently woody plants growth. Rondon *et al*. [67] studied the effects of the addition of increasing amount of biochar on Phaseolus vulgaris cultivation. They found that biomass production and plant total N uptake decreased as biochar applications were increased. Deenik *et al*. [68] reported an enhanced soybean plant growth for soils amended with a low volatile matter (11%) biochar, but significantly lower plant growth for soils amended with a high volatile matter (35%) biochar. These findings suggest that the extent of biochar effects on crop productivity is very variable due to the high variability of the potential biophysical interactions and processes that occur when it is applied to soil. A better knowledge of the relevant properties of a high variety of charred materials and how these properties influence field responses, is essential to identify the best char to be applied to a particular kind of soil and for a specific crop.

Biochar interactions with Soil Components: Acidity is a measure of the concentration of free hydrogen ions (H^+). A high concentration in the soil signifies a low pH, whilst a low concentration equals a high pH. Soils and other substances with a pH below 6 are called acidic, whilst those with a pH above 6 are known as base or alkaline.

Biochar-soil interactions involve complex processes influenced by electrostatic forces, surface chemistry and microbiological activity. The application of biochar can alter soil pH by releasing alkaline compounds and enhancing soil buffering capacity [69]. Furthermore, biochar's interactions with soil colloids and organic matter influence nutrient retention and availability. The salt level is the sum of all the mineral salts that are present in the soil. They can originate from the soil itself, fertiliser and organic manure. When the concentration levels in the soil are higher than in the cells of the plant roots, the moisture is drawn from the roots and the fine hair roots die off [70-72]. Over time this impedes the moisture and nutrients absorption by the plant and causes reduced growth or death of the plant. Crops vary in the extent to which they tolerate nutrient concentration and the salt levels at which they can still provide a good yield. Some crops grow well in salty soil.

The form in which macro- elements and micro-elements occur in the soil depends on the pH. This means that the pH exercises a significant influence on the availability of nutrients for plants, as plants cannot absorb macro-elements and micro-elements in all their forms. Soil-life activity and consequently the mineralization of organic matter are limited in that situation. Monitoring biochar-soil interactions and their impacts on the environment is crucial to ensure sustainable

Challenges and Considerations: Biochar application offers numerous benefits, such as improved soil structure, enhanced water retention and increased nutrient-use efficiency. However, challenges like feedstock variability, application rates and long-term effects require careful consideration. Monitoring biochar-soil interactions and their impacts on the environment is crucial to ensure sustainable implementation.

CONCLUSION AND RECOMMENDATIONS

The review underscores the promising role of biochar in addressing soil acidity stress, enhancing soil properties and ultimately increasing crop productivity. Its multifaceted benefits make it a valuable tool in sustainable agriculture, offering solutions to some of the pressing challenges facing modern farming. However, continued research, field trials and best practices are essential to maximize the positive impact of biochar while minimizing potential drawbacks. Overall, biochar holds great potential in the pursuit of more resilient and productive agricultural systems. Governments and other responsible bodies should create awareness to the farmers concerning the importance of using biochar technology to ameliorate soil acidity and improve quality of soil and also should promote and support research activities on the use of biochar for maximizing productivity and maintaining soil fertility especially under acidic environment.

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