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Biochar Application Effects on Physical, Chemical and Biological Properties of Soil in Tropical Environments

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Abstract: Biochar is a carbon-rich byproduct of biomass pyrolysis under oxygen-limited environments and is intended for soil application as a means to improve agronomic and environmental benefits. It can be produced from biomass sources such as wood, crop residues and manure, as well as from organic waste streams. It is characterized by high carbon content, a stable chemical structure resistant to decay, high porosity and a high specific surface area. It improves soil quality through its effects on varied soil processes. Many of the benefits of biochar are derived from its very high surface area and porous structure. The surface area plays an important role in soil chemical reactions and porosity plays an important role in physical processes, such as water movement and creates more area for microbial colonization. Its key properties such as high pH, porosity, specific surface area and cation exchange capacity are mainly dependent on feedstock type and production process. These biochar properties affect its interactions with physical, chemical and biological components of the soil as well as its fate within the ecosystem. Biochar is used as a soil amendment to enhance soil fertility and sustain crop productivity by improving nutrient availability while simultaneously reducing leaching losses. This can decrease fertilizer needs and may even increase nutrient supplies to plants. Besides, biochar can improve soil biological properties by increasing the diversity of microbes and providing a suitable environment for soil microbial communities. Biochar has a significant role in climate change mitigation through sequestration of carbon in the soil and reduction of nitrous oxide and methane gas emissions to the atmosphere by improving uptake of the soil. The application of biochar to agricultural soils can increase soil carbon sequestration potential for global warming mitigation through the withdrawal of carbon dioxide from the atmosphere. However, biochar's ability to sequester C would depend on the composition of the stable and recalcitrant form of organic carbon from the transformation of plant organic matter into biochar. Generally, biochar can reduce the amount of greenhouse gas emissions to the atmosphere and enhance plant growth and productivity through improving soil physic-chemical and biological properties.

Key words: Biochar・Soil Biological Property・Soil Fertility・Soil Physicochemical Property

INTRODUCTION

Biochar, a mainly stable black carbon material, is derived from pyrolysis usually between 300 and 1000°C of biomass under oxygen-limited environments [1, 2]. Pyrolysis is the thermal decomposition of biomass material under oxygen-depleted conditions [3]. This thermochemical process, generally classified by the rate of reaction into slow pyrolysis, fast pyrolysis and flash pyrolysis, [4], can be used to transform organic materials into bio-oil, syngas and biochar [5]. The two major thermal conversion processes widely used in biochar production are slow and fast pyrolysis technology [6]. The slow pyrolysis, most widely used and carried out at lower temperatures and heating rates and longer residence times compared to fast pyrolysis [7], optimize biochar yields over energy production [8, 9]. The thermal conversion of biomass to biochar yields materials with greater C concentration and along with changes in the nutrient concentration and forms. Ancient Amazonian Darks Earths in Brazil also known as Terra Preta de Indio (Anthrosols) display high soil organic matter and high concentrations of exchangeable cations and available phosphorus [10] as a result of long term biochar

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application. The high concentration of nutrients and carbon in the charred materials has been suggested to be responsible for sustaining long-term C stability and promoting a high level of fertility of these soils [11]. The resultant materials from biomass pyrolysis are more chemical recalcitrant and resistant to biological decomposition than native organic matter, thereby maintaining or increasing stable soil organic C pools which can be used as a long-term carbon sequestration alternative [12-14].

Biochar application increases soil organic carbon levels [15, 16] and improves soil structure [17]. Its application improves the soil's ability to retain moisture [18, 19], prevents nutrient leaching [20-22] and increases cation exchange capacity [23-25]. The application of biochar reduces aluminum toxicity [26] and bioavailability of heavy metals [27], increases soil pH [25, 28], supplies essential plant nutrients and decreases the need for chemical fertilizers [17, 29]. Biochar improves the biological condition of soils [15, 30], increases soil microbial biomass and supports beneficial organisms like earthworms [30]. The conversion of biomass to biochar reduces greenhouse gas emissions [31, 32] and helps in sequestering atmospheric carbon into the soil [33, 34]. There has been a great deal of interest in biochar recently for many reasons, including bioenergy production, carbon sequestration, use as a soil amendment to improve productivity and as an end-use for animal manure. Thus, it is essential to transfer knowledge about the importance of biochar as a soil amendment to scientists, politicians and end-users in poor tropical countries, where improved soil management strategies in combination with new crop varieties (e.g., drought-tolerant ones) can likely maximize beneficial effects on crop yield and climate, fostering the further implementation of climate-smart agricultural practices. Therefore, this paper was reviewed with the objectives of (i) to assess the effect of biochar application on soil physical properties (ii)) to assess the effect of biochar application on soil chemical properties and (iii)) to assess the effect of biochar application on soil biological properties.

Biochar Effect on Soil Physical Properties: Depending on the starting material and process parameters (temperature, time, etc.), the biochar will obtain different physical and chemical structures that can modify the physical and chemical characteristics of the soil. Biochar can enhance plant growth by improving soil physical characteristics including bulk density, water holding capacity, permeability, particle size distribution, porosity, structure and texture [35-38]; and soil chemical characteristics (nutrient retention and availability, cation exchange capacity, surface areas and pH [39]. The large surface area of biochar and its porous nature partly explain increased retention of nutrients and water [37, 40, 41]. Besides, biochar can improve soil biological properties by increasing diversity and providing a suitable environment for soil microbial communities [30, 42]. The apparent high recalcitrance of biochar to chemical and biological processes supports its long-term agronomic and environmental benefits [43, 44]. Several soil benefits arise from the physical properties of biochar. The highly porous nature of biochar results from retaining the cell wall structure of the biomass feedstock. A wide range of pore sizes within the biochar results in a large surface area and a low bulk density. Biochar application into the soil may increase the overall net soil surface area [45] and consequently, may improve soil water and nutrient retention [46] and soil aeration, particularly in fine-textured soils [47]. The particle size distribution of biochar is highly dependent on the feedstock used. In general, wood-based biochars are coarser and of xylem structure, while biochars obtained from crop residues are finer and of recalcitrant structure [48]. Generally, biochar incorporation can alter soil physical properties such as structure, pore size distribution and density, with implications for soil aeration, water holding capacity, plant growth and soil workability [46].

Soil water retention capacity is the maximum amount of water that a soil can hold or retain. It is a very important property concerning the former's point of view as well as plant growth. If the soil can hold a large amount of water it decreases the irrigation frequency of crops and also plants grow well this type of soil. It was investigated that biochar application boasts up the available water content of the soil up to 97% and saturated water contents 56% [49]. Laird *et al.* [19] described that the biochar amended soil retained 15% more moisture contents as compared to controlled treatment. There is a significantly increased in soil water retention capacity in the case of sandy soil by biochar application but there little and no increased in loamy and clay soil, respectively. Herth *et al.* [50] described experimentally that biochar application increased the water retention capacity of the soil because it increases soil porosity and also due to the adsorptive nature of biochar. Glaser *et al.* [17] observed that biochar-rich anthrosols from the Amazon region whose surface area were 3 times greater than that of surrounding soils which have 18% greater field capacity.

Further biochar has also been reported to form complexes with minerals as a result of interactions between oxidized carboxylic acid groups at the surface of the biochar particles and mineral soil aggregate stability [17]. Chan *et al*. [45] observed improvement in texture and behavior of a hard setting soil with a significant reduction in tensile strength at higher rates of biochar application. Several studies done on biochar showed enhanced soil water holding capacity [35, 51], improved soil water permeability [35], improved saturated hydraulic conductivity, reduced soil strength, modification in soil bulk density [19], modified aggregate stability [52]. Soil colloidal particles adhere together depends upon net attractive forces among them. This property is very important from a soil structure point of view. A soil that is well aggregated has a good structure and as a result, provides a good medium for nutrient and water movement into the soil and uptake by plants [53].

The intrinsic contribution of biochar on soil physical parameters such as the wet ability of soil, water infiltration, water retention, macro-aggregation and soil stability is of critical importance in tropical environments in combating erosion, mitigating drought and nutrient loss and in general to enhance groundwater quality. The studies conducted by Chan *et al*. [45] reported a noteworthy improvement in texture and behavior of a hard-setting soil, with a significant reduction in tensile strength at higher rates of biochar application. Biochar can be used as a soil amendment to increase plant growth, yield and improve water quality, increase soil moisture retention and availability to plants [18]. Chan *et al*. [45] also reported that biochar application had improved some physical soil properties, such as increased soil aggregation, water holding capacity and decreased soil strength. Increased surface area, porosity and lower bulk density in mineral soil with biochar can alter water retention, aggregation and decrease soil erosion [54-56]. An increase in saturated hydraulic conductivity of upland rice soil with biochar application has been reported [35]. Biochar-amended soils display an increase in available moisture for coarse-grained and low organic matter content sandy soils, a rather marginal to moderate improvement effect in medium-textured soils [19] and potentially a reduction in moisture retention for clayey soils [57]. Significant improvements in aggregate stability and accompanying changes in water retention have been linked to biochar application for clayey soil [58]. Water retention of soil is determined by the distribution and connectivity of pores in the soil matrix, which is largely affected by soil texture, aggregation and soil organic matter content [59]. Biochar has a higher surface area and greater porosity relative to other types of soil organic matter and can therefore improve soil texture and aggregation, which improves water retention in soil.

Soil moisture retention improvement is an indirect result of alterations in soil aggregation and structure after biochar application [60]. Biochar can affect soil aggregation through interactions with soil organic matter, minerals and microorganisms; however, the surface charge characteristics and their development over time determine the long-term effect on soil aggregation. Glaser *et al*. [17] reported that Anthrosols enriched with biochar had surface areas three times higher than those of surrounding Oxisols and had an increased field capacity of 18%. Tryon [61] studied the effect of biochar on the percentage of available moisture in soils of different textures and found a different response among soils. In sandy soil, the addition of biochar increased available moisture by 18% after adding 45% biochar by volume, while no changes were observed in loamy soil and soil available moisture decreased in the clayey soil. The high surface area of biochar can lead to increased water retention, although the effect seems to depend on the initial texture of the soil. Improved water holding capacity with biochar additions is most commonly observed in coarse-textured or sandy soils [17, 62]. The impact of biochar additions on moisture content may be due to increased surface area relative to that found in coarse-textured soils [17]. Therefore, improvements in soil water retention by biochar additions may only be expected in coarse-textured soils or soils with large amounts of macro-pores. Additionally, a large amount of biochar may need to be applied to the soil before it increases water retention. The amount of adsorbed water is directly dependent on the surface area; therefore biochars can adsorb large amounts of water. The process of water adsorption on the surface area of biochar is governed by the functional groups [63]. When added to the soil, biochar will increase the total soil surface area, which is one characteristic that is believed to be responsible to overcome the problem of too much water held in clay soils, due to increased soil aeration and increase the water content or water holding capacity in sandy soils [64].

The biochar structure is amorphous, containing local crystalline structures of joint aromatic compounds [65]. The carbon skeleton formed during the pyrolysis of organic matter results in a high porosity of biochar, due to its sponge-like structure [66]. The pore space or porosity of soil is defined as the ratio of the pore volume to total soil volume. It is a very important soil attribute affecting plant growth. There are three types of pores present in soil (macro, meso and micropores) classified based on size. The voids are formed as pores present as macro- (>50 µm), meso- (2-50 µm) and micropores (<2 µm). The large proportions of micropores (<2 x 10-3 µm in diameter) is responsible for the increased surface area, which can reduce the mobility of soil water [64]. These are important for aeration, movement and retention of nutrients as well as water and also provide refuge to microbes inside the soil. The overall porosity of soil increased by the application of biochar but this increase in porosity was dependent on the type of biochar used and soil type where biochar was applied [50]. The relative contribution of three types of pores varies in a total increment of soil porosity depending upon biochar and soil type [67]. This increase in soil porosity was due to the highly porous nature of biochar [68]. Biochar has high porosity, which allows high water-holding capacity. However, it is hydrophobic as it is dry due to its high porosity and light bulk density. Laird *et al.* [19] reported that, compared with chemical fertilizer application, biochar amendment to a typical Ultisol resulted in better crop growth. Biochar has high porosity which allows high water holding capacity. However, it is hydrophobic as it is dry due to its high porosity and light bulk density. The high porosity results in a low bulk density, which when incorporated into the soil in sufficient concentrations can reduce the total bulk density of the soil [19]. Most biochar exhibits a large surface area, depending on the base material and treatment. For biochar obtained from pyrolysis, surface areas range from 20 m^2 g^{-1} [69] up to 3000 m^2 g^{-1} [70]. The large surface area of biochar will increase the ion exchange capacity and the sorption of nutrients [64].

Bulk density is a measurement of how tightly soil particles are pressed together. It is a ratio of the mass of oven-dry soil to bulk volume (volume of soil particles + volume of pore spaces). Bulk density of soil has a significant effect on soil properties as well as on plant growth e.g. a soil having high bulk density (>1.6 Mg cm^{-3}) has less capacity to absorb water and provide great penetration resistance to plant root into the soil ultimately soil characteristic, as well as plant growth, will be affected [71]. Most research findings point to the improvement of soil bulk density with biochar application [51]; water-holding capacity also increased [51]. According to Mukherjee and Lal [68] biochar application decreased the soil bulk density because the porosity of biochar is very high and when it is used in the soil it significantly decreases bulk density by increasing the pore volume. Githinji [67] concluded that by increasing the rate of biochar application bulk density was also significantly decreased. Biochar has a relatively high surface area and has been reported to influence biochar interactions with soil solution substances as well as to provoke a net increase in the total soil-specific surface of biochar-amended soils [72]. Biochar has a bulk density much lower than that of mineral soils (~0.3 Mg m^{-3} for biochar compared to typical soil bulk density of 1.3 Mg m^{-3}); therefore, application of biochar can reduce the overall total bulk density of the soil which is generally desirable for most plant growth [59]. Biochar bulk density, ranging from 0.08 g cm^{-3} to 0.43 g cm^{-3} [73] depending on feedstock biomass and process conditions, is lower than that of mineral soil ranging from 1.16 to 2.00 g cm^{-3} [74]. Therefore, a reduction in soil bulk density [19, 75] is anticipated due to biochar's low bulk density and its highly porous structure [46]. Biochar not only improves soil water movement but also soil water retention characteristics [76] because of its highly porous structure [35, 51] as production processes induce loss of volatile matter [77]. Soil amendment with biochar can result in decreased bulk density and soil penetration resistance and increased water holding capacity. Most research findings point to the improvement of bulk density with biochar application [51].

Biochar Effect on Soil Chemical Properties: Biochar application to the soils is considered a soil amelioration technique, enhancing plant growth by supplying more nutrients and providing other functions such as improving the physical and biological properties of the soil. Biochar is generally alkaline in pH and may increase soil pH, cation exchange capacity, base saturation, exchangeable bases and organic carbon content as well as decreases in Al saturation in acid soils [17]. Several studies have shown that biochar can increase soil pH, cation exchange capacity (CEC), total N, available P, exchangeable Ca, magnesium, etc. and can reduce Al availability [78]. The application of biochar can reduce ammonia volatilization and increase the immobilization of inorganic N [16]. Widowati *et al.* [79] reported that biochar application decreased N fertilizer requirement. They also found that organic carbon was increased by biochar application. Similar results were seen with different types of biochar and soil in various regions [19, 76, 80]. The increase in soil carbon through biochar application is attributed to the stability of biochar in the soil, which persists despite microbial action. By using isotopes, Steinbeiss *et al*. [81] reported that the mean residence time of biochar in the soil varied between 4 and 29 years, depending on soil type and quality of biochar. Biochar additions may positively affect the soil C sequestration and, thus, act as a sink and long-term storage of C due to its long residence time in the soil ranging from 100 to 1000 years [48]. In soils regularly managed by biochar amendments, the increasing aromatic carbon content is likely to affect soil properties.

There is high variability among the characteristics of different biochars, but in the case of pH, biochars are usually alkaline (pH>7) [64]. An increase in soil pH by increasing biochar application rate might be due to the presence of alkali elements (Ca, Mg and Na) and the presence of -OH ions in biochar [82]. An increase in soil pH following biochar application is frequently reported across many soil types [17]. The results, therefore, indicate that biochar could be used as a substitution for lime materials to increase the pH of acidic soils. A similar increase in pH and electrical conductivity (EC) was found by Bhattarai *et al*. [83]. There are several studies showed that soil pH was increased due to biochar amendments especially in acidic soil [84, 85]. The increase in soil pH attributed to the integration of the highly alkaline nature of biochars, high base cation concentration which in turn released protons into the soil solution and the acidity reduced through proton consumption reaction and higher availability of $CaCO_3$. Another study indicated that incorporation of biochar to soil improves NH_4^+ immobilization and subsequently decreases nitrification which in turn conquer the discharge of H^+ concentration to the soil and relieve soil acidification [86]. However, ameliorating ability of biochar are depends on Pyrolytic parameter (higher pyrolytic temperature i.e. > 400°C help to produce alkaline pH), feedstock and soil properties [87]. In a Similar way to feedstock and pyrolytic temperature, the alkalinity nature of biochar was a key factor that affecting the liming potential of the acidic soil [9].

According to Novak *et al*. [76] presence of -OH ions in the biochar enhanced its pH and ultimately the soil in which biochar is applied [88]. Yuan and Xu [25] also noted the similar type of results on the soil pH when they applied the biochar in their experiment as a soil amendment. Biochar addition can increase the pH of amended soils by 0.4 to 1.2 pH units with a greater increase observed in sandy and loamy soils than in clayey soils [61]. Novak *et al*. [76] observed that the incorporation of biochar increased organic carbon and decreased nitrogenous fertilizer requirement. Similar results were also obtained with different types of feedstocks and soil [19, 76, 80]. The increase in soil carbon through biochar application is attributed to the stability of biochar in the soil which persists despite microbial action. Lehmann *et al*. [89] reported that the use of biochar can improve the efficiency of nitrogen fertilizer, as biochar can reduce the loss of nitrogen and potassium that occurs through leaching [79]. In addition to this, Glaser *et al*. [17] concluded that the biochar may be more than just a soil conditioner, but may act as a fertilizer itself, as seen also in the results of Chan *et al*. [90]. Lehmann *et al*. [89] reported that the application of biochar improved soil fertility status, as soil organic carbon, cation exchange capacity, available phosphorus, exchangeable potassium, calcium and magnesium of the sandy soils in Lombok, Indonesia. Since biochar is highly porous and has a large specific surface area, its impact on soil cation exchange capacity and other nutrients that correlate with cation exchange capacity is very important. Biochar amendment significantly decreased extracted Cd in the soil by 17 to 47 percent. Some types of biochar also appear to reduce the mobility of heavy metals such as Cu and Zn.

There is small variability for the pH between biochars, with typical values above seven [48]. The pH and EC for biochars are higher with higher temperatures. Gundale and De Luca [73] concluded that the higher pH with higher pyrolysis temperatures might occur due to the accumulation of oxides of alkaline metals. The high pH of biochar will have a liming capacity when incorporated into the soil [91]. Exchangeable acidity is the measure of the concentration H^+ and Al^{3+} ions reserved on soil colloid after the active acidity is measured. A study indicated that biochar application decreased the exchangeable acidity of the soil [90]. According to Chan *et al*. [90] who indicated that biochar application increases soil pH which in turn decreased acidity by precipitates exchangeable Al^{3+} into insoluble hydroxyl Al species. Apart from the increase in soil pH, Yuan *et al*. [25] reported that amendments of biochar can release their base cations into acidic soil this can contribute to exchange reactions and replace the exchangeable Al^{3+} and H^+ on the soil surface and lessening the soil exchangeable acidity. When the exchangeable acidity of the soil is high with a subsequent low pH, it affects the soil condition and many processes in the soil. In an acidic condition, aluminum fixes phosphorus causing its deficiency in plants, the bioavailability of iron, aluminum, or manganese can be very high and may reach toxic levels at lower pH [92]. Biochar can serve as a liming agent resulting in increased pH and nutrient availability for several different soil types [17, 92]. Concentrations of carbonates can vary from 0.5 to 33% [45] depending on starting conditions. The carbonate concentration of biochar facilitates liming in soils and can raise soil pH of neutral or acidic soil [26]. Mbagwu and Piccolo [56] report an increase in pH of various soils and textures by up to 1.2 pH units from pH 5.4 to 6.6. Hardwood biochars are reported to have substantial carbonate concentrations and prove more effective in reducing soil acidity, therefore having a larger influence on soil fertility [18]. The liming of acidic soils decreases Al saturation while increasing cation exchange capacity and base saturation [56, 93].

Cation exchange capacity (CEC) is a measure of soil capacity to retain key exchangeable cations in the soil and has been seen to mitigate leaching losses [10]. The application of biochar in agricultural soils has been shown to increase CEC over time due to biochar surface oxidation and the abundance of negatively charged surface functional groups [94]. Most biochars have a strong surface area charge and thereby a high CEC having both cation and anion exchange capacity [95]. Mukherjee *et al*. [96] stated that the surface properties of biochar lead to its potentially useful properties, such as contaminant control and the release and retention of nutrients. The possible reason for the increase in CEC due to the amendments of biochar might be high surface area, high porous, possesses organic materials of variable charge that have the potential to increase soil CEC and base saturation when added to soil [17]. The biochar application significantly increased exchangeable cations (Ca^{2+}, Mg^{2+} and Na^{+}) and CEC. According to Lima and Marshall [97] the release of Ca, K, Mg and Na ions by biochar increases the EC of soil. Joseph *et al*. [98] found that when the volatile matter is removed from the biochar then the rest biomass of biochar contains a sufficient amount of Ca, Mg and inorganic ions in it that become the part of ash contents. Shenbagavalli and Mahimairaja [99] reported the presence of Ca and Mg ions in the biochar at sufficient levels that can make biochar a liming agent. According to Amonette and Joseph [100] Biochar contains a significant proportion of Ca, Mg and Na that become part of soil solution through ion exchange mechanism. Biochar has a high surface area, highly porous, variable charge organic material that has the potential to increase soil CEC, surface sorption capacity and base saturation when added to soil [17]. Because pH increases are related to CEC increases, this benefit can be interrelated to biochars effect on soil pH. Plants that are cultivated in biochar treated soils respond better in growth through modifications in soil CEC and nutrients retention [101].

The addition of biochar to soil alters important soil chemical qualities; soil pH increased towards neutral values [102], typically increased soil CEC. Biochar has a greater ability to absorb and retain cations in an exchangeable form than other forms of soil organic matter due to its greater surface area and negative surface charge [103]. Once added to the soil, abiotic and biotic surface oxidation of biochar results in increased surface carboxyl groups, a greater negative charge and subsequently an increasing ability to sorb cations [94, 104]. It also exhibits an ability to sorb polar compounds including many environmental contaminants [94]. CEC of biochar is highly variable depending upon the pyrolysis conditions under which it is produced. Cation exchange capacity is lower at low pyrolysis temperatures and significantly increases when produced at higher temperatures [33]. Freshly produced biochars have little ability to retain cations resulting in minimal CEC [33, 104] but increase with time in soil with surface oxidation [104]. This supports the findings of high CEC observed in Amazonian Anthrosols [103]. One potential mechanism for enhanced nutrient retention and supply following biochar amendment is increasing CEC by up to 50% as compared to unamended soils [56, 103]. Laird *et al*. [19] indicated that the biochar treatments significantly increased CEC by 4 to 30 % compared to the controls. Similarly, the CEC of the highly weathered soil was increased from 7.41 to 10.8 cmol kg^{-1} after biochar treatment. Available evidence also suggests that the intrinsic CEC of biochar is consistently higher than that of whole soil, clays, or soil organic matter [10]. Studies have also revealed the increase in soil CEC after the application of biochar [90].

Biochar has the potential to increase nutrient availability for plants [89]. Nutrient availability can be affected by increasing CEC, altering soil pH, or direct nutrient contributions from biochar. Glaser *et al*. [17] observed an increasing trend of bio-available P and base cations in biochar applied soils. Studies have shown significant increases in the availability of all major cations [17, 89]. Cheng *et al*. [94] found biochar to exhibit an anion exchange capacity at pH 3.5, which decreased to zero over time as it aged in soil. The optimal biochar combining fertilizer and carbon storage function in soils would activate the microbial community leading to the nutrient release and fertilization and would add to the decadal soil carbon pool. The increase of CEC with the application of biochar has also been shown by Liang *et al*. [103]. Novak *et al*. [76] showed that the application of biochar in the acidic coastal soil increase soil pH, soil organic matter, Mn and Ca and decrease S and Zn. Biochar application boosts soil fertility and improves soil quality by raising soil pH, increasing moisture-holding capacity, attracting more beneficial fungi and microbes, improving CEC and retaining nutrients in soil [33, 92]. Another major benefit associated with the use of biochar as a soil amendment is its ability to sequester carbon from the atmosphere-biosphere pool and transfer it to soil [105, 106]. Biochar addition significantly improved soil fertility in acid and highly weathered soils and it has the potential for widespread application under various agro-ecological situations by mobilizing and improving the complex of chemical, physical and biological properties of soil systems.

Biochar addition to agricultural soils has been proven as an effective and unique opportunity for soil fertility improvements and nutrient-use efficiency [107]. Biochar application induces changes in soil chemical properties including an increase in soil pH, cation exchange capacity and nutrient contents [94, 103]. Biochar has the potential to increase soil pH with an accompanying decrease in the amount of exchangeable Al^{3+} [77]. Biochar application has been also reported to reduce the mobility of toxic elements in acid soils [84, 85] as well as enhance K and P availability [1, 35]. These biochar effects have been reported to reduce lime application needs and to increase crop production in highly weathered infertile tropical soils [108]. Glaser *et al.* [17] found that applied biochar can also directly provide readily available nutrients for plant growth. Biochar's porous structure, large surface area and negative surface charge [46] increase the CEC of the soil and allow for the retention of nutrients [19]. Crop fertilizer requirements can be decreased due to an increase in nutrient use efficiency with biochar addition [64, 107]. Most benefits for soil fertility were obtained in highly weathered tropical soils but also higher crop yields of about 30% were obtained upon biochar addition in temperate soils. Furthermore, enhanced water-holding capacity can also cause higher nutrient retention because of a reduced percolation of water and the herein dissolved nutrients [17]. However, since biochar has only low nutrients contents in general, plant nutrients must be supplied externally.

Biochar application to soil influences various soil physicochemical properties. Due to the high specific surface area of biochar and because of direct nutrient additions via ash or organic fertilizer amendments, nutrient retention and nutrient availability were reported to be enhanced after biochar application [17, 109]. Higher nutrient retention ability, in turn, improves fertilizer use efficiency and reduces leaching [7]. Knowledge on the link between biochar function and its interaction with nutrient elements and crop roots may throw light on understanding fertilizer use efficiency. The enhanced nutrient retention capacity of biochar-amended soil not only reduces the total fertilizer requirements but also copes with the climate and environmental impact on crops. Biochar significantly increases the efficiency and reduces the need for traditional chemical fertilizers with sustainable crop yields. Biochar helps to improve soil resources by increasing crop yields and productivity by the way of reducing soil acidity and reducing the need for some chemical and fertilizer inputs [110]. The immediate beneficial effects of biochar additions on nutrient availability are largely due to higher potassium, phosphorus and zinc availability and to a lesser extent of calcium and copper [89]. Longer-term benefits of biochar application on nutrient availability mainly due to a greater stabilization of organic matter, concurrent slower nutrient release from added organic matter and better retention of all cations due to a greater CEC. High rates of biochar addition in the tropical environment have been associated with increased plant uptake of P, K, Ca, Zn and Cu [12]. Biochar also adds some macro (P, K, N, Ca and Mg) and micronutrients (Cu, Zn, Fe and Mn) which are needed for sustainable agriculture [85]. It may significantly affect nutrient retention and play a key role in a wide range of biogeochemical processes in the soil, especially for nutrient cycling. A beneficial impact of biochar on the plant-available P has been observed in soils enriched with biochar, which in contrast to ammonium, is not a characteristic generally associated with soil organic matter [18, 33].

Iron and Manganese are associated and largely retained during biochar formation [100]. Biochar application increases Fe and Mn while Zn decreases and Cu was not significantly affected. The study carried out by Gaskin *et al.* [13] suggested that poultry litter biochar had the highest amount of Fe whereas pine chip biochar has significantly lower Fe. The study conducted by Novak *et al.* [76] showed that extractable Zn marginally decreases with an increase in the addition of biochar concentration. This demonstrates that the biochar has a high sorption capacity for Zn whereas Cu concentration was not significantly affected by biochar addition. The effect of biochar on HCO_3^- and Cl^- was significantly higher. These ions developed liming ability in biochar and make it a preferable amendment for soil reclamation. Similar types of results were also noted [76]. Besides the direct/indirect effect of biochar on soil fertility characteristics, the application of biochar contributes to the interaction of soil with microelements such as lead and cadmium. Biochar amendment significantly decreased extracted Cd in the soil by 17-47%. Some types of biochar also appear to reduce the mobility of heavy metals such as Cu and Zn. Novak *et al.* [76] reported that most soil micronutrient concentrations were not influenced by biochar addition; however, biochar application decreased exchangeable acidity, S and Zn.

Concerning potential nutrient sources, only C and N can be produced in situ via photosynthetic organisms and biological N fixation, respectively. All other elements, such as P, K, Ca and Mg must be added for nutrient accumulation [110] which can be best achieved by adding organic fertilizers such as manure or compost [26]. The application of paper mill waste biochar, combined with inorganic fertilizer, showed higher soybean and radish biomass compared with the sole application of inorganic fertilizer [26]. Application of chicken manure and city waste biochar increased maize biomass [79]. This higher biomass production is attributed to biochar increasing the soil pH. Novak *et al.* [76] stated that, after 67 days and two leaching events, biochar addition to the Ultisols of Norfolk soil increased soil pH. The findings of Van Zwieten *et al.* [26] suggest that while biochar may not provide a significant source of plant nutrients, it can improve the nutrient assimilation capability of the crop by positively influencing the soil environment. Novak *et al.* [76] reported that the application of biochar improved soil fertility status, especially soil organic C, CEC, available P, exchangeable K, Ca and Mg of the sandy soils. Since biochar is highly porous and has a large specific surface area, its impact on soil CEC and other nutrients that correlate with CEC are very important. In the short term, biochar may supply a source of plant-available nutrients once applied to the soil [10]. A small fraction of nutrients in the feedstock, apart from N, are retained in biochar in a potentially extractable form. It is uncertain whether these soluble nutrients are released instantaneously once added to the soil environment, or if they are released over time [10], but will likely depend on the starting soil physical properties. The rapid introduction of readily available nutrients and small amounts of labile C retained in biochar could promote mineralization of soil organic matter [111], especially in nutrient-limited environments.

The chemistry of biochar is highly dependent on the biomass used, the temperature during pyrolysis and residence time. However, all biochars are composed of condensed aromatic ring structures that become larger and even more condensed with increasing pyrolysis temperature. Biochars obtained by maize, mineralized more rapidly than wood biochar and concluded this to be due to wood biochar having greater aromatic carbon content. Studies on the effect of pyrolysis temperature on biochar chemistry found that faster mineralization occurred in biochars produced at 400°C than in biochars produced at 550° [112]. Biochars can adsorb ammonia-N (NH_3) due to the presence of acidic functional groups and to CEC sites on the biochar [104]. The adsorbed N can subsequently be available to plants [113, 114]. Studies have shown that biochar in the soil can reduce NH_4^+ and NO_3^- leaching [115]. The mechanisms proposed for the effects of biochar amendments on soil N transformations are increased adsorption of NH_3, improved soil aeration status and the presence of volatile organic matter affecting N nitrification and denitrification [115, 116].

The high value of organic carbon (OC) in biochar amended soil indicates the recalcitrance of OC in biochar. Biochar application increases soil OC [26, 76]. The biochar application can increase N availability to crops [69] and therefore high levels of soil OC accumulation can enhance N efficiency and increase crop production [103]. Biochar increases the available P in soils as biochar increases the soil pH, which makes immobile phosphorus available. The micro-and macronutrient composition of biochar depends upon the nature of the feedstock used and the treatment conditions. For example, will biochars produced from feedstocks with high initial potassium content (animal litters) also have greater potassium content in the biochar product compared to biochar made of wood residues (high carbon content) [117]. The high variability of parameters, including carbon (C) and phosphorus (P) for different feedstock biochars have been found to range between 172 to 905 g kg^{-1} and 2.7 to 480 g kg^{-1}, respectively [64]. Liang *et al.* [103] found that the C content was significantly higher in biochars produced at high temperatures compared to the same biochar produced at low temperatures due to a release of hydrogen, resulting in an enhancement of C. Moreover, the C content is dependent on the feedstock used. The study observed lower C contents in manure-based biochars, compared to agricultural residue-based biochars and concluded this to be due to the greater mass of minerals in manure. The stable form of C in biochars is suggested to be resistant to oxidation and therefore inhibiting the formation of CO_2, decreasing the release of CO_2 [103].

Biochar Effect on Soil Biological Properties: Biochar provides a suitable habitat for a large and diverse group of soil microorganisms. Higher retention of microorganisms in biochar amended soils may be responsible for greater activity and diversity due to a high surface area as well as surface hydrophobicity of both the microorganisms and biochar. A strong affinity of microbes to biochar can be expected since the adhesion of microorganisms to solids increases with higher hydrophobicity of the surfaces [118]. Biochar helps plants' grow, raise productivity and contribute to sustaining the quality of the soil. It is well supported that biomass-derived biochar affects microbial populations and soil biogeochemistry. Both biochar and mycorrhizal symbiotic association in the terrestrial ecosystem are potentially important in various ecosystem services provided by the soil viz., contributing to sustainable plant production, ecosystem restoration, soil carbon sequestration and mitigation of global climate changes [119]. Greater microbial biomass was reported in forest soils in the presence of biochar by Zackrisson *et al*. [120] and higher microbial activity (CO_2 production as well as organic matter decomposition) was found in soils exposed to black carbon aerosols derived from biochar making [121]. The increase in soil biological activity has been reported by Rondon *et al*. [80] for nitrogen fixation in Phaseolus vulgaris and by Chan *et al*. [122] for earthworm and microbial biomass. Biochar application to soil has long tradition provided evidence that it has positive effects on the abundance of mycorrhizal fungi [123]. According to Ogawa [124], biochar is generally characterized by a proliferation effect for several symbiosis microorganisms due to its porous structure providing appropriate habitat for soil microbes. Steiner *et al*. [125] observed a significant increase in microbial activity and growth rates by applying biochar to a Ferralsol. Furthermore, an increase of soil microbial biomass and a changed composition of soil microbial community was also observed after biochar amendments [126]. While microbial reproduction rates after glucose addition in soils amended with biochar increased, soil respiration rates were not higher [125]. Based on these possible stimulating factors, biochar promotes the propagation of useful microorganisms such as free-living nitrogen-fixing bacteria [80, 124]. Biochar amendment generally seems to stimulate soil fungi which seems logical as biochar is a complex matrix being degradable only by soil fauna and soil fungi [126].

The biochar product is believed to be resistant to microbial decomposition [103]. The variety of different biochars, with varying chemical and physical properties, in conjunction with varying soil environments likely causes the wide range of microbial responses to biochar, amended soils. Biochar is considered recalcitrant due to its resistance to microbial decay [127]. However, the high porosity can provide additional niches for microorganisms [109]. Depending on the biochar and soil type, biochar may also reduce changes within the microbial community structure and function [128], have no effect on species richness or diversity [129], or increase microbial abundance [38]. Biochar application has also been found to increase the number of bacteria with decreased fungi abundance [75] or by increasing k-strategist microbial biomass and increasing species richness [19]. It may also increase plant root colonization by ectomycorrhizal fungi and arbuscular mycorrhizal fungi [119] or shift the microbial community to one that prefers aromatic C [130]. Incorporation of biochar reduced tensile strength by 50% and 72% at an amendment rate of 50 and 100 ton ha^{-1} respectively compared to the initial value of 64.4 kpa [45]. Thus the reduction in soil tensile strength (i) makes the plant root and mycorrhizal nutrient excavating more effective (ii) makes it physically easier for invertebrates to move through the soil (iii) altering predator/prey dynamics [127]. Additionally, biochar can affect the activity of soil enzymes by inhibiting or increasing the contact with soil organic matter [131].

Biochar has a role in changing soil microorganism abundance [19, 132]. Thus changes have a direct effect on nutrient cycles and an indirect effect on plant growth [119]. Sorption of compounds to biochar that would otherwise inhibit microbial growth may increase microbial abundance. Compounds such as catechol that are toxic to microorganisms were found to be strongly sorbed to comparatively high-temperature biochars produced from ash-rich corn stover. This is due to the surface of biochars which contain several chemically reactive groups, such as COOH, OH, ketone, that give biochar a great potential to adsorb toxic substances, such as Al, Mn in acid soils and arsenic (As), cadmium (Cd) in heavy metal contaminated soils. Thus, biochar could be used to rehabilitate environments that may be hostile to plant growth. Periodic drying of soil leads to stress and, ultimately, to dormancy or mortality of microorganisms. The large surface area of biochars [46, 103] helps to increase the water-holding capacity of the soil and promote the growth of microorganisms. Moreover, biochar, containing a well-developed pore structure, may provide a living environment for microorganisms. Both bacteria and fungi are hypothesized to be better protected against predators or competitors by exploring pore habitats in biochar. In general, it is hypothesized that the large porosity of biochar provides surfaces for soil microbes to colonize and grow, where their predators cannot access them. Furthermore, the fact that these surfaces sorb inorganic nutrients well as organic substances and gases might provide ideal environments for microbes. Biochar properties may enhance soil microbial communities and create microenvironments that encourage microbial colonization. Biochar pores and their high internal surface area and increased ability to adsorb OM provide a suitable habitat to support soil microbiota that catalyzes processes that reduce N loss and increase nutrient availability for plants [105]. The pores are suggested to serve as a refuge by protecting microbes from predation and desiccation while the organic matter adsorbed to biochar provides C energy and mineral nutrient requirements [119]. In temperate ecosystems with wildfire-produced biochar, N mineralization and nitrification are enhanced [73] by creating favorable microenvironments that enhance colonization by microbes [109, 119].

Biochar has the potential to stimulate the activity and diversity of soil microbial community [125, 127] through its porous structure, high CEC and high sorption capacity. Biochar's intrinsic properties may enhance nutrient retention and availability to microorganisms and also influence the interactions between soil, plant and microorganism components [127]. The application of biochar at high rates has been reported to stimulate changes in soil microbial community composition towards a bacteria-dominated microbial community compared to fungi. This change in the microbial community could be explained by the liming potential of biochar and the addition of labile organic C in the soil leading to wider C/N ratios [134]. Furthermore, biochar-amended soils have been found to enhance microbial abundance and growth due to the sorption of toxic compounds to biochar. Biochar effects on soil biological processes are not well understood [127]. This has resulted in high variability in the response of soil microbial biomass to biochar additions reported in the literature [132]. Biochar amendments have been shown to increase microbial biomass due to the presence of labile C fractions and un-pyrolyzed feedstocks [135]. Other studies have reported that biochar does not affect soil microbial biomass as a result of its recalcitrance [136]. Dempster *et al*. [137] reported that biochar amendments reduced soil microbial biomass induced by a toxicity effect.

Evidence supporting enhanced microbial abundance and the build-up of recalcitrant soil C comes from studying biochar-amended Anthrosols and wildfire biochar. While many studies suggest biochar additions are beneficial for increasing microbial activity and increase C storage, others have reported accelerated decomposition of soil OM after fresh biochar additions. Liang *et al*. [19] report high stabilization of organic material added to soils from a tropical environment containing aged biochar. They reported 25.5% less mineralization of added OM to Anthrosols compared to unamended adjacent Oxisols. While the biochar-amended Anthrosol had more than two times the amount of microbial biomass than adjacent soils, carbon dioxide (CO_2) respiration was lower compared to unamended adjacent soils. This suggests that the microbial biomass associated with biochar additions has higher metabolic efficiency [19]. Similar findings supporting microbial proliferation and decreased soil respiration have been reported in mineral soil amended with varying rates of maize-derived biochar [138]. Conversely, the potential for biochar to cause or accelerate the decomposition of soil surface OM has been reported in a 10-year study of litter bags in the boreal zone [111], where a more rapid loss of humus in the presence of biochar was demonstrated. Similarly, Steinbeiss *et al*. [81] showed that homogeneous biochars with or without N could stimulate the loss of soil organic C (between 8-13%) in both agricultural and forest soils. There is also evidence to suggest that the availability of soil N is a controlling factor for the priming effect of biochar [73]. Whether biochar application stabilizes soil OM and soil C or results in priming is still under speculation and warrants further investigation [111].

The soil biota is vital for the functioning of soils providing many essential ecosystem services. The addition of biochar to the soil is likely to have different effects on the soil biota. Graber *et al*. [65] reported that with the increasing rate of biochar application maximum number of culturable colonies of general bacteria, Bacillus spp., yeasts and *Trichoderma* spp. were found. However, a minimum number of culturable colonies of filamentous fungi Pseudomonas spp. and Actinomycetes spp. were found in the soil. The positive effects have been reported to enhance biological nitrogen fixation [80], improved colonization of mycorrhizal fungi, earthworms showed preference to biochar amended soils [26], increased methane uptake [51], potential catalyst in reducing the nitrous oxide to nitrogen [26]. Biological nitrogen fixation by common beans was increased from 50 to 72% of total nitrogen uptake with increasing rates of biochar additions (0, 31, 62 and 93 t C ha^{-1}) to a low-fertility Oxisol [80]. The effects of biochar on soil microbial activity can influence N transformations [133]. Biochars have been shown to accelerate soil net N mineralization, increase nitrification and enhance denitrification. Biochar amendment can also influence other N transformations such as biological N fixation [80]. Biochar application rates and soil type also affected response soil microbial biomass [127]. Explanations for soil microbial biomass change in response to additions of biochar include enhanced available soil nutrients (dissolved organic matter, P, Ca and K), adsorption of toxic compounds and improved soil water and pH status, all of which can influence the activity of soil microorganisms [127]. The internal porosity of biochars may help soil microorganisms avoid grazers [109] and store C substrates and mineral nutrients [119].

CONCLUSION

Most studies show that biochar can increase soil productivity, but some do show decreased productivity. This is almost certainly due to the wide variety of biochars that can be produced and the variability between soils. Biochar can increase soil productivity through either the application of the nutrients and lime it contains or through improving soil properties. Minerals present in the feedstock are concentrated in the biochars produced, but much of the nitrogen and sulfur are lost during pyrolysis. Therefore, supplemental nitrogen will generally be needed when using biochars as a nutrient source. The primary benefits of biochar to soil quality are thought to be through increasing the active surface area that can retain nutrients and increasing the water-holding capacity. Biochar is not like fertilizer, which generally needs to be applied annually. As biochar is stable in soils, it could be built up to an optimum level which will then remain constant indefinitely. Currently, we do not know what these optimum rates are, but some studies have reported adding biochar up to 20 percent of the soil by volume. Biochar production holds great promise for bioenergy, a value-added manure product and a soil conditioner. However, as there are so many variables in feedstock and biochar production, many details remain to be refined. As this new and exciting technological advances, the role of biochar in agricultural systems will probably increase.

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