Impact of Biochar on Soil Properties

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Biochar is a dark-black-colored, partially combusted (pyrolyzed), and recalcitrant compound which helps to enrich the nutrient balance and carbon stock in the soil. It is a porous carbonaceous sorbent generally produced from materials of biological origin (crops residues) which is formed after specific thermochemical conversions (pyrolysis) under limited oxygen supply conditions. Most frequently, biochar is a product of plant and agricultural residues derived biomass carrying oxygen-containing functional and aromatic groups.

carbonaceous sorbent | contaminants | human health | nutrients | pyrolysis | soil properties

1. Properties of Biochar

The biochar has various properties, mainly depending on the feedstock type and the pyrolysis conditions. The biochar properties are governed by its composition, stability, specific surface area, pH, cation exchange capacity (CEC), porosity, decomposition capability, and contaminants level. However, the chemical composition, available nutrients, and the level of contaminants of biochars mainly depend on the composition of the used substrates/feedstock. Biochar is considered alkaline in nature and mainly has a pH > 7.0. The soil has a strong buffering capacity (resistant to changes in pH), and in case of soil with a pH > 7.5, the biochar should not be applied frequently as it may impair the fertility and nutrient availability of soils. Biochar is mainly recommended for soil that has acidic pH and low content of organic carbon. It has been reported that biochar could enrich the soil systems with divalent cations. The addition of biochar to saline-sodic soil could be a source of Ca^{2+} and Mg^{2+} and mainly responsible for salt leaching . It has been reported that the application of biochar increased the yield of *E. viminal* when grown in saline sodic soil.

Most biochars prepared from crop residues tend to exhibit neutral to alkaline properties depending on pyrolysis temperatures [1][1]. The rise in pH in biochar derived from sugarcane straw, poultry litter, corn straw, pine, and sewage sludge were reported with the increase in pyrolysis temperature [2]. The changes in pH values depend on non-pyrolyzed inorganic elements of feedstocks, pyrolysis temperature, and production duration [2]. The elevation in pyrolysis temperature could also enhance biochar specific surface areas due to micropores development (**Table 1**). The long-term stability of biochar plays a major role in carbon sequestration. It can be achieved in a wide range of production conditions .

The source of organic and inorganic contaminants in biochar is an issue of major concern. Some of these contaminants may be generated and simultaneously destroyed during the process itself, but some will remain unchanged or converted into more harmful substances. However, heavy metals present in the feedstock remain unchanged and concentrate in the biochar [3][4]. The contaminants that form during pyrolysis are represented by polycyclic aromatic hydrocarbons (PAH) and dioxins [5]. PAHs can be formed during the pyrolysis process at high temperature during secondary and tertiary reactions [6]. With the rise in temperature, pyrolysis severity rises, and PAHs production becomes significant at around 750 °C. It was found that the concentration and composition of PAHs in biochar are feedstock-dependent to some extent [7].

Biochar exhibits a high surface area, the presence of pores, and different functional groups hydroxyl (-OH), carboxylic acids (-COOH), and small alkyl chains such as methane groups (-CH_3) [8][9]. These attributes increase the nutrient retention capacity of biochar, even of the negatively charged NO_3^- and PO_4^- ions [9][10][11]. The pores of biochar serve as a secure habitat for microorganisms [12][13][14] such as bacteria (size range from 0.3–3 µm), fungi (2–80 µm), and protozoa (7–30 µm); these pores protect them from predatory microarthropods [15]. Biochar macropores (>200 nm) are the most protective habitat for bacteria because of the similar size, although biochar can store water and dissolved substances in micropores (<2 nm) and mesopores (2–50 nm) [8]. The size of the pores depends on the temperature of biochar production. At higher temperatures, pore size will be larger due to more water and organic matter volatilization [8]. It was reported that biochar produced at 500 °C using 5 feedstocks in 600 × 500 µm SEM image sugarcane bagasse, paddy straw, and umbrella tree wood biochars had mostly 10–50 µm, 20–100 µm, and 50–70 µm diameter pore sizes, respectively [16]. In 60 × 50 µm SEM images, cocopeat husk and palm kernel biochars showed 5–10 µm and 1–3 µm diameter pore sizes, respectively. The size of the pores in a biochar can also depend upon the plant part used [17]. The size and diameter of vessels increases along with decreases in density from leaves to roots.

2. Impact of Biochar on Soil Properties

The application of biochar is more effective for soils with low OC content and low soil pH. The application of biochar to the soil results in better aeration and higher water holding capacity, porosity, nutrient holding capacity, and microbial population [18][19][20][21][22]. This section mainly focuses on how biochar amendment could influence different soil properties, especially pH, EC (Electrical Conductivity), CEC (Cation Exchange Capacity), O:C ratio, NPK, soil organic matter, and soil biological activity.

2.1. Soil Physicochemical Properties

The literature reported increases in soil pH after applying various types of biochar [23][24]. The alkaline biochar addition could increase acidic soils' pH by 0.1 to 0.2 units [25]. However, at high biochar application rates, acidic soil's pH could rise up to 2.0 units [26]. The biochar application is mainly recommended based on the properties of soils. The soil with low OC content, acidic pH, and poor soil physical properties has the most effective response to biochar. The buffering capacity of the soil generally resists the change of soil pH. There are some other reasons for an increase in soil pH after applying biochar such as the activity of negatively charged phenolics, carboxyl, and hydroxyl groups on biochar surfaces. These groups bind H^+ ions present in the soil solution and reduce their concentration in the soil solution, resulting in the rise of soil pH value. This feature can be vital to decreasing the uptake of contaminant by crop plants, as the plants possess H+ efflux pumps and the root exudates are acidic in nature. Simultaneously, too-high soil pH could lead to adverse effects, such as reducing phosphorus, magnesium, and molybdenum bioavailability.

The application of biochar to soil could alter soil EC and CEC. The EC value of soil increases due to the elevated concentration of soluble salts in biochar [27][28]. A sudden increase in EC from 0–2 dS/m may have a harmful effect on the soil due to extensive accessibility of soluble salts, which increases the osmotic pressure of soil solution, resulting in a reduced availability of water and nutrients from the soil. Alteration in soil CEC after the application is a collaborative effect of biochar's feedstock, pyrolysis temperature, and biochar degradation in soil. Application of wood biochar increases the CEC of soil to a more considerable extent than crop residue biochar [29]. This increase in CEC of soil may be due to the oxidation of specific functional groups such as phenolic, carboxylic, lactone, pyranone, and amine on the biochar's surface [30]. Biochar behaves as a cation exchange resin that may retain or exchange different cationic species [31][32]. It also increases soil CEC and helps in long-term carbon sequestration [33]. Increased plant growth followed by increased crop productivity are a possible response to increased CEC [34][35].

The wood-based biochar has a longer-lasting effect due to more carbon and being more resistant to decomposition in the environment. Such products have a potential capacity to sequester the carbon in the soil for a very long time. The dry wood may be converted to biochar before decaying and can be potentially used for energy and soil improvement [36]. Different properties of biochar such as the surface area and O:C ratio are also important in understanding the biochar interaction with organo-mineral complexes, i.e., the first step of aggregate formation and stabilization. The main electron shuttling and redox-active moieties are quinones, which are responsible for the two-way direct linkage between mineral or organic surfaces or the indirect linkage through a non-biochar organic matter cross-linking agent that binds biochar to mineral surfaces in a three-way linkage [37][38].

Biochar produced with slow pyrolysis (400–600 °C) has a positive influence on soil aggregation in a wide variety of soils [39][40][41]. However, biochar produced at high temperature (700 °C) with a low O:C ratio did not show any significant results [42], which may be because of the lower amount of organic matter content in this biochar. It was found that straw derived biochar increased soil macroaggregate by 17.77–18.87% and 33.55–50.87% in 0–20 and 20–40 cm soil layers in a rice–wheat rotation system, respectively [43].

Biochar is known for its potential in carbon sequestration along with considerable improvement in soil functions [44]. The application of rice husk biochar increased the carbon content in soil due to its recalcitrant nature [31][45]. Thus, the biochar could stabilize soil organic matter and increase respiration and decomposition [46].

Biochar contains many carbonaceous compounds that are useful for improving soil fertility [47][48][49][50].The various types of biochars contain high percentages of carbon, for example, in chicken manure-derived biochar contains 51.7% C and green waste-derived biochar contains 77.5% C when prepared at 550 °C [46] and 70–85% from the wood of different tree species, depending on the pyrolysis temperature [51][52]. The lowest percentages of carbon (29–50%) were found in rice husk and straw as compared to woody biochars [52]. Organic matter, inorganic salt, and humic substances such as humic acid, fulvic acid, and humin can serve essential functions in plant nutrition [53]. The biochar produced from *Acacia saligna* at 380 °C and sawdust at 450 °C contained humic-like (17.7%) and fulvic-like (16.2%) substances [51].

The application of biochar to soil might address the problem of climate change and also improve soil fertility. However, the positive priming of biochar on the decomposition of native soil organic matter and the abiotic release of CO_2 from the reaction of carbonates in the biochar after the amendment to acidic soil were identified [54][55]. The main source of the increase in CO_2 emissions from a biochar amended soil seems to be microbially mediated decomposition of labile biochar constituents [56][57]. The CO_2 emission in biochar-applied soil appears to be a short-lived effect [58].

2.2. Soil Biological Properties

Biochar has a profound influence on soil biological properties. The mechanisms of this influence are diverse and can be both direct and indirect through the alteration of soil properties after the application of biochar. Direct mechanisms include the influence of biochar on soil microorganisms, which can be positive and negative.

The positive influence of biochar on soil microorganisms includes creating a new habitat for colonization due to biochar's porous structure [59][60]. Pore size has a significant effect on the pace of biochar colonization by the microorganisms: larger pores are colonized more rapidly, but they do not provide a shelter for soil microfauna [61]. The aging of biochar is also important for microbial colonization. Fresh biochar releases organic substances that microorganisms can utilize as a carbon source, supporting the bacterial growth and promoting colonization [62]. At the same time, fresh biochar can release toxic substances, and it has been demonstrated that aged biochar increases soil microbial activity, while fresh biochar suppressed it [63]. Another positive effect on microorganisms is that biochar can serve as a mineral nutrient source that can originate from pyrolyzed ash or concentrated on the biochar surface through sorption from soil solution. The enhanced microbial activity can also be connected with the increased CEC from biochar application [59][64]. Biochar granules are also capable of holding water that positively influences the microbial communities and allows them to recover more quickly after the commencement of drought conditions [64].

The incorporation of biochar amendments can stimulate the growth and development of plants, along with significant improvement in microbial populations [65], and can also affect the abundance of microbes (bacteria, ratio of fungi, community structure) [66][67][68].

Azeem et al. [69] reported that the sole application of biochar does not influence (non-significant) on microbial population, while compost alone and with the conjoint use of biochar significantly boosts the enzymatic activity. They also reported that the application of 5 cm green waste compost and of 12.5 t ha^{-1} biochar and 5 cm compost resulted in 6%, 54%, and 54% increases in urease, dehydrogenase, and β-glucosidase activity, respectively, as compared to a control. It was also reported that green waste compost (5 cm) and 12.5 t ha^{-1} biochar and 5 cm compost significantly improved the fungal and bacterial respirations by 426% and 346% and 88% and 161%, respectively, compared to the control soil.

In a recent study, it has been shown that the metabolic activity of the soil microbial communities increases when biochar is applied in drought conditions, and the aging of biochar increased its positive effects [70]. However, biochar can also exhibit suppressive effects on the soil microbial communities, and these effects largely depend on the feedstock, pyrolysis conditions, and the mode of biochar application. The adverse effects on microorganisms originate from byproducts of pyrolysis, such as volatile organic compounds (VOCs) and PAHs. The majority of studies report strong toxic effects of VOCs: the inhibition of nitrification [71], suppression of *Bacillus mucilaginosus* [72], and toxicity to *Cyanobacterium Synechococcus* [73]. The influence of biochar on soil microorganisms has been summarized in several recent reviews [60][74].

The incorporation of Co-biochar into the soil not only significantly increased growth and development but also the microbiota and the enzymatic activity (Azeem et al. 2019). It was noted that the incorporation of biochar amendments could enhance plant growth as well as microbial populations (bacteria, ratio of fungi, community structure, enzymatic activity) [75][69][76][77]. Recently, it was also observed that the combined application of wheat straw and wheat straw biochar improves soil's physicochemical and biological properties [76]. Other authors found that the co-application of wheat straw and of wheat straw biochar with the addition of nutrients at 1% and 2% doses significantly increased C and N contents in soil along with their dissolved organic carbon and dissolved organic nitrogen, post-harvest soil properties, i.e., pH value and C and N content, and concluded a positive effect of biochar and nutrients application on the microbial population in soil. It was also noticed that green waste compost (5 cm) and 12.5 t ha^{-1} biochar and 5 cm compost significantly improved the respiration (i.e., fungal—426% and 346%; bacterial— 88% and 161%) compared to the control soil [69]. The addition of biochar on the organic fraction of municipal solid waste (OFMSW) in real conditions found significant changes in carbon, nitrogen, organic matter, respiration activity, moisture content, as well as the microbiocenotic composition of microorganisms [78]. This addition of biochar reduced the compost toxicity and retained nitrogen during composting but did not appear to increase the rate of composting, enhance the moisture %, lower waste density, retain N, or lower the pathogenic microorganisms during the composting. During composting, the maximum abundance of mesophilic bacteria (1704.5–2198.1 104 CFU g^{-1} d.m.), endospores bacteria (84.9–298.9 104 CFU g^{-1} d.m.), and actinomycetes (0–19.5. 104 CFUg^{-1} d.m.) were found after 7 days of composting with the addition of biochar [78].

Biochar can also influence soil enzymatic activity by various mechanisms. Firstly, the impact on soil biota influences the synthesis of enzymes and their release into the soil. Secondly, the shifts in pH can both stimulate and inhibit the existing enzymes. Thirdly, the enzymes can be directly adsorbed by biochar particles, influencing their activity [79]. Dehydrogenase activity with the addition of wheat straw, wheat straw biochar, and nutrient addition was 1.6–4-fold higher compared to the control in soil [76]. However, the sole application of biochar did not influence the soil microbial population, while compost alone and in conjunction with biochar significantly boosted the enzymatic activity. The application of 5 cm green waste compost and 12.5 t ha^{-1} biochar and 5 cm compost showed 6%, 54%, and 54% increases in urease, dehydrogenase, and β-glucosidase activity, respectively, as compared to control [69].

Several other mechanisms can be involved, including the adsorption of metal ions, limiting the metalloenzymes activity, generating reactive oxygen species (ROS) that can inactivate the enzymes, and others. Due to the involvement of many different mechanisms, the impact of biochar on enzymatic activity is somewhat controversial. Different reactions were demonstrated for various soil enzymes following the biochar application. For example, biochar application increased soil urease activity, which may be attributed to the increased pH of soil solution [80]. Simultaneously, the beta-glucosidase and beta-glucosaminidase activities were decreased when biochar produced at 300–550 °C was applied [81].

To conclude, the biological properties of soil are altered by the addition of biochar to a great extent, and the type of biochar determines whether this effect will be positive or negative. Many adverse side effects of biochar can be avoided if the biochar is aged or co-composted before its application to the agricultural soil.

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