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Reviewing Biochar on Soil Health and Crop Productivity

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A B S T R A C T

Soil mineral depletion is a major issue due mainly to soil erosion and nutrient leaching. The addition of biochar is a partial solution because biochar has been shown to improve soil fertility, to promote plant growth, to increase crop yield, and to reduce contaminations. The main properties of biochar are the following: high surface area with many functional groups, high nutrient content, and slow-release fertilizer. Biochar, a charcoal produced from biomass, can sequester carbon in soil for hundreds to thousands of years. Biochar is created by heating organic material under conditions of limited or no oxygen. Soil organic matter needs to be maintained and further increased to keep soil healthy. Biochar is extremely porous which allows it to retain nutrients and water and improved soil aggregate stability. The quality of biochar as a soil ameliorant depends on the feedstock and on soil type, temperature, and humidity. Converting biomass to biochar offers an excellent method for waste management and using these byproducts for the improvement of soil health and productivity.

Introduction

Biochar is the product of burning biomass, such as hardwood, rice hulls, bamboo, or even chicken litter, in a low- to no-oxygen environment. Biochar is a stable carbon compound created when biomass is heated to temperatures between 300 and 1000˚C, under low oxygen concentrations. Biochar's highly porous, black carbon skeletal-like structure can contain amounts of extractable humic-like and fluvic-like substances (Lin *et al.*, 2012). Moreover, its molecular structure shows a high degree of chemical and microbial stability (Cheng *et al.*, 2008). The physical and chemical properties of biochar are highly dependent on pyrolysis temperature and process parameters, such as residence time and furnace temperature, as well as on the feedstock type (Bruun *et al.*, 2011). A wide range of common raw materials are used as the feedstock, including wood chip, organic wastes, plant residues, and poultry manure (Sohi *et al.*, 2010). The elemental composition of biochar generally include carbon, nitrogen, hydrogen, and some lower nutrient element, such as K, Ca, Na, and Mg (Zhang *et al.*, 2015). Commonly, the carbon content increased with increasing pyrolysis temperature from 300 to 800 °C, while the contents of nitrogen and hydrogen decreased. Biochar has a high specific surface area and a number of polar or nonpolar substances, which has a strong affinity to inorganic ions such as heavy metal ions, phosphate, and nitrate (Kammann *et al.*, 2015).

Application of biochar is very imperative to increase soil fertility, enhance nutrient uptake, ameliorate polluted soils and reduce the amount of carbon produced due to biomass burning and its application can decrease the need for additional chemical fertilizer (nitrogen) and water inputs. It has the potential to increase conventional agricultural productivity and mitigate green house gas emissions from agricultural soils.

Several studies indicate that amending poor or depleted soils with biochar can have a positive impact on soil health and crop yield.

Potential Benefits of Biochar

The benefits of application of biochar in soil are included:

Increased crop yields (Jeffery *et al.*, 2015)

High porosity providing a large surface area (Yargicoglu and Reddy, 2015) for high cation exchange capacity (CEC), important for nutrient availability to crops (Liang *et al.*, 2006)

Improvement of soil water holding capacity (Basso *et al.*, 2013)

Stable microbial habitat, important for resilience of microbial populations

More diverse microbial populations, important for nutrient bioavailability (O'Neill *et al.*, 2015)

Long-term sequestration of carbon (McBeath *et al.*, 2014)

Reduction of soil density in heavy soils, improving water percolation and root development (Jeffery *et al.*, 2015)

Capture of nutrients in crop soils and riparian buffers reducing the amount of leaching and run-off from agricultural fields into waterways (Sweet, 2015)

Reduction of N_2O emissions from soil (Thomazini *et al.*, 2015)

Potential for helping to control invasive species by adsorbing allelochemicals (Kolb *et al.*, 2009)

Biochar has been shown to be effective in binding toxins and heavy metals (Wang *et al.*, 2015).

Rate of biochar application

Biochar application rate in soil varies depending upon many factors including the type of biomass used, the degree of metal contamination in the biomass, the types and proportions of various nutrients, and also climatic and topographic factors of the land where the biochar is applied.

Experiments have found that rates between 5 to 50 t/ha (0.5 to 5 kg/m^2) have often been used successfully. Rates around 1% by weight or less have been used successfully so far in field crops (Major, 2013). Winsley (2007) suggests that even low rates of biochar application can significantly increase crop productivity.

Application to soils of higher amounts of biochar may increase the carbon credit benefit; but, in nitrogen-limiting soils, it could fail to assist crop productivity as a high C/N ratio leads to low N availability (Lehmann and Rondon, 2006).

Biochar application rates also depend on the amount of dangerous metals present in the original biomass.

Biochar as a Tool to Improve Soil Health

Biochar was reported to improve not only soil chemical and physical properties but also soil microbial properties.

Physical properties

Many studies indicated that the combination of biochar with soils could improve soil structure, increase porosity, decrease bulk density, and enhance aggregation and water retention (Baiamonte *et al.,* 2015). Tyron (1948) reported that in a sandy soil, there was a monotonic increase in the per cent of available moisture as a function of charcoal volumetric proportion with an increase of about 6 per cent available moisture per cent under any amendment amount, while the available moisture per cent in the clay soil decreased by nearly 7 per cent under a 15 volume per cent load of charcoal has been argued to enhance soil physical properties, including soil water retention and aggregation both of which may improve water availability to crops as well as decrease erosion (Glaser *et al.,* 2002). Glaser *et al.,* (2002) observed that charcoal rich anthrosols from the Amazon region whose surface area was 3 times greater than that of surrounding soils which have 18 per cent greater field capacity. Further charcoal has also been reported to form complexes with minerals as a result of interactions between oxidized carboxylic acid groups at the surface of the charcoal particles and mineral grains soil aggregate stability (Glaser *et al.,* 2002). Chan *et al.,* (2007) observed improvement in texture and behavior of a hard setting soil with significant reduction in tensile strength at higher rates of biochar application. Several studies showed enhanced soil water holding capacity (Karhu *et al.,* 2011), improved soil water permeability (Asai *et al.,* 2009), improved saturated hydraulic conductivity, reduced soil strength, modification in soil bulk density (Laird *et al.,* 2010), modified aggregate stability (Peng *et al.,* 2011). Soil amendment with biochar can result in increased soil infiltration rate and decreased bulk density, retain water in small pores and increased water holding capacity (Asai *et al.,* 2009). Most research findings point to the improvement of bulk density with biochar application (Karhu *et al.,* 2011). 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. Addition of biochar to the soil improves soil physical property, water permeability and aggregate stability. Peng *et al.,* (2011) reported that compared with fertilizer application biochar amendment to a typical soil ultisol resulted in better crop growth.

Soil chemical properties

Biochar is generally alkaline in pH and may increase soil pH (Chan *et al.,* 2007), cation exchange capacity, base saturation, exchangeable bases and organic carbon content as well as decreases in Al saturation in acid soils (Glaser *et al.,* 2002). Biochar addition can increase the pH of amended soils by 0.4 to 1.2 pH units with greater increase observed in sandy and loamy soils than in clayey soils (Tyron *et al.,* 1948).

Winsley (2007) observed that incorporation of biochar increased organic carbon and decreased nitrogenous fertilizer requirement. Similar results were also obtained with different types of feedstocks and soil (Laird *et al.,* 2010). The increase in soil carbon through biochar application is attributed to the stability of biochar in the soil which persists despite microbial action. Steiner *et al.,* (2008) 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.

Biochar has negatively charged surfaces that hold nutrients making them available for the nutrient cycling process.

Soil Biological Properties

Biochar has been shown not only to improve soil physicochemical properties but also to change soil biological properties (Grossman *et al.*, 2010). Some mechanisms may explain how biochar could affect microorganisms in soils: (1) changes in nutrient availability; (2) changes in other microbial communities; (3) alterations in plant-microbe signaling; and (4) habitat formation and refuge from hyphal grazers. These changes could make soil structure, containing increasing organic/mineral complexes (help to aggregate formation) and improve pore spaces, enhance nutrient cycles, which include the increase of nutrient retention and immobilization, as well as the decrease of nutrient leaching (Steiner *et al.*, 2008), thus promote plant growth. Besides, microorganisms, such as rhizosphere bacteria and fungi, may facilitate plant growth directly. In summary, changes in microbial community composition or activity induced by biochar may affect nutrient cycles and plant growth, as well as the cycling of soil organic matter (Liang *et al.*, 2010).

Based on the experimental evidence, biochar has symbiotic relationship with the mycorrhizal system. The four mechanisms by which biochar could improve mycorrhizal abundance (40%) and functioning as through

Alteration of soil physic-chemical properties,

Indirect effects on mycorrhizae through effects on other soil microbes,

Plant-fungus signaling interference, and

Detoxification of allelochemicals on biochar.

There are 50 to 72% increases of soil biological nitrogen fixation (BNF) through biochar application (Lehman and Rondon, 2006). Biochar has positive effects on soil biology. It provides microbial habitat and refugia for microbes where they are protected from grazing. Both bacteria and fungi are hypothesized to be better protected from grazers or competitors by exploring pore habitats in biochars (Thies and Rillig, 2009). Earthworms have been shown to prefer some soils amended with biochar to those soils alone. Due to biochar's ability to improve retention of nutrients in bio-available form, it has significant implications for growers who use methods that rely heavily on continual synthetic inputs, and for crop land that has been degraded of structure, organic matter, and a healthy microbiome.

Effect of biochar on crop productivity

The different forms of biochar *viz.*, dust, fine particles, coarse grain and the method of soil application *viz.*, surface application, top dressing, drilling are the important aspects to study the effect of biochar on soil health as well as crop productivity. Hill *et al.*, (2007) clearly explained that even small quantities of biochar added to seed coatings may in some cases be sufficient for a beneficial effect. Effect of biochar on the different growing environments in rice viz., (i) a double-cropped irrigated lowland, (ii) a mono-cropped rain-fed upland, and (iii) a monocropped rain-fed lowland are evaluated by Haefele (2008) and the grain yield variation between the sites was identified. Initially, the effect will be non-significant but significant improvement was shown in last three seasons. Lehmann *et al.*, (2003) reported increasing crop yields with increasing biochar applications of up to 140 t C ha^{-1} on highly weathered soils in the humid tropics, and Rondon *et al.*, (2007) found that the biomass growth of beans rose with biochar applications up to 60 t C ha^{-1}. The application of biochar on soil has significant effect on net primary crop production, grain yield and dry matter production (Spokas *et al.*, 2009). Purakayastha (2010) clearly explained that application of biochar prepared from wheat straw (1.9 t/ha) along with recommended doses of NPK at 180:80:80 kg ha^{-1} significantly increased the yield of maize in Inceptisol of IARI farm and this treatment was superior to either crop residue incorporation or 30 crop residue burning.

Application of biochar can enhance soil productivity by improving the physical, chemical and biological soil conditions (Glaser *et al.*, 2007, Chan *et al.*, 2007). Improvement in soil structure increase in soil water retention and decrease in soil strength have been reported by Chan *et al.*, (2007) conducted a study on Australian soil. The application of paper mill waste biochar, combined with inorganic fertilizer, showed higher soybean and radish biomass compared with sole application of inorganic fertilizer (Van Zwieten *et al.*, 2010).

The soil health concept has increased awareness among agriculturist and horticulturist regarding the importance in maintaining soil fertility, crop productivity and environmental quality over a long term period. The application of biochar into soils has great potential for improving soils fertility and promoting plant growth. Biochar has positive effects on the physico-chemical and biological properties of soil, which means soil health directly and indirectly. Moreover, biochar has huge surface area, well developed pore structure, amounts of exchangeable cations and nutrient elements, and plenty of liming. Because of these properties, soil properties could be improved after biochar treatment. For instance, the huge surface area and well developed pore structure may increase the water holding capacity and microbial abundance. The cation exchange capacity and availability of nutrients could be increased due to the amounts of exchangeable cations and nutrient elements. Therefore, improvements of soil physical, chemical, and biological properties promote the productivity of plant through increasing the amount of nutrient elements, enhancing availability of nutrient elements, reducing nutrient leaching, and mitigating gaseous nutrients losses. Biochar can be a novel and feasible fertilizer directly or indirectly. This is not only because of the biochars' fertility but also their environmental and economic benefits.

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