

## Biochar: Effects on Crop Productivity and Soil Properties

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**Abstract:** World food security is under challenge to a great extent due to effects of climate change, continued population growth and resource-depleting practices on agriculture (IAASTD, 2009). Presently poor farmers use either organic manure or inorganic fertilizers (Mando et al., 2005; Topoliantz et al., 2005) for maintaining soil fertility as they cannot afford to apply fertilizers as a nutrient source (Craswell and Lefroy, 2001). But the advantages of organic manure amendments are generally short-lived because of the rapid decomposition of soil organic matter under high temperature and aeration (Glaser et al., 2002). Therefore, organic amendments are applied every year to sustain soil productivity. An alternative to this practice could be the use of more stable compounds such as biochar (Glaser et al., 2002) instead of the easily degradable organic manures. The pyrolysis conversion of waste biomass into biochar is attracting international attention. Biochar is a solid carbon-rich organic material generated by heating biomass at 300–600°C under condition of limited or no oxygen (Lehmann and Joseph 2009). In the past few years, there has been growing interest in the use of synthetic biochar as an amendment worldwide for the following two reasons. Firstly, biochar can be used as a soil amendment for improving soil quality and secondly, storing biochar in soils is regarded as a means for permanently sequestering carbon (Hossain et al 2010) and enhancing agricultural productivity. Agronomic effects of biochar on crop yield and soil physico-chemical properties have been reported in many studies (Tryon, 1948; Kishimoto and Sugiura, 1985; Glaser et al., 2002; Lehmann et al., 2003; Chan et al., 2007; Rondon et al., 2007; Chan et al., 2008; Asai et al., 2009). The carbon-rich “Amazonian dark soils” (Arthrosols) are evidence, which host distinct microbial communities in comparison with adjacent carbon-poor soil, and have higher microbial biomass and diversity as well (O Neill et al 2009). The properties of biochars such as pH, nutrients, C-content, porosity, and surface area can significantly affect the biochemical and biophysical mechanisms of interaction between soil microfauna, mesofauna, and macrofauna in turn affecting soil ecosystem responses (Ameloot et al. 2013; Lehmann et al. 2011). Systematic evaluation of the use and function of various biochars in agricultural soils in terms of changes to physical-chemical and biological soil properties which are typically dictated by the type of amended biochar is a rapidly developing area of research (Jeffery et al. 2011; Barrow 2012; Meyer et al. 2011; Sohi et al. 2010; Biederman and Harpole 2013; Lehmann et al. 2011; Filiberto and Gaunt 2013). On the basis of recommendations from recent review studies (Jeffery et al. 2011; Verheijen et al. 2014; Barrow 2012; Gurwick et al. 2013; Liu et al. 2013; Sohi et al. 2010; Atkinson et al. 2010; Huang et al. 2013; Biederman and Harpole 2013; Ameloot et al. 2013), it is becoming evident that the effects of biochar feedstock and production processes on the physical-chemical and biological indicators of soil quality must be better understood to devise effective management strategies.

### PROPERTIES OF BIOCHAR

The chemical properties of biochar depend on the composition of the feedstock and by the production conditions, including heating rates, final temperatures, and duration of heating (residence time). A number of studies have investigated the influence of the type of feedstock and conversion

technology employed on biochar properties (Li and Zhang 2005; Novak et al. 2009; Lee et al. 2010; Cantrell et al. 2012; Fabbri et al. 2012; Ronsse et al. 2013). For example, increase in pyrolysis temperature from 400°C to 600°C decreased the volatile and N components of biochar, and increased ash and fixed carbon content. Thus, biochar

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prepared at 600°C will have wider C: N ratio making it more stable in soils. In addition, form and size of the feedstock may also affect the quality and potential uses of biochar.

The pH, content of volatile compounds, ash content, water-holding capacity, bulk density, pore volume, and specific surface area (Okimori *et al.*, 2003; Sohi *et al.*, 2010) are the key properties of biochars which influence the soil quality. The alkalinity and pH of the biochar generally increases with increased pyrolysis temperature and residence time in the reactor (Yuan *et al.* 2011 and Rondon *et al.* 2007). Yuan *et al.* (2011) implicated carbonates as the major alkaline components of the biochar generated at the high temperature. Biochar produced at a higher temperature which generally had alkaline pH were found to significantly affect the productivity on soils through increased phyto-availability of essential nutrients for plant growth (Biederman and Harpole 2013; Verheijen *et al.* 2010).

The C content in biochar produced from wood is relatively higher than that obtained from agricultural residues because of the abundance of lignin in the wood biomass (Huang *et al.* 2012). Generally, proportion of elemental C in the biochars increases with increasing pyrolysis temperature, indicating that the degree of carbonization increases because of thermochemical conversion of a more labile fraction of organic residues in the feedstock (such as fatty acids and cellulose) into highly aromatic and more stable forms of carbon (Zheng *et al.* 2010; Spokas *et al.* 2011). The stability of biochar in soil is a critical factor to ensure that the benefits associated with soil quality improvement are sustained (Budai *et al.* 2013). The amount of volatile matter decreases with increasing pyrolysis temperature. Results of some studies indicated that biochars with volatile matter higher than 80% (w/w) can be decomposed at much higher rates rendering them unsuitable for long-term carbon sequestration (Enders *et al.* 2012). The volatile matter in biochar can affect the overall microbial activity when amended to soil and in some cases, result in increased mineralization rates consequently from stimulated microbial respiration (Spokas 2014).

In general, porosity and surface area of biochars increase with the increase in the temperature (Keiluweit *et al.* 2010; Bird *et al.* 2011). In general, biochar amendment to soil increased the porosity, plant-available water, and nutrient retention capacity and decreased the soil bulk density (Lei and Zhang 2013). The distribution of pore size in biochars, which is representative of the extent of micropores, mesopores, or macropores, was found to be a critical factor that affects the sub-surface soil ecosystem (Verheijen *et al.* 2010). The incorporation of biochars with high sorption capacity to soils can additionally help capture certain toxic compounds such as pesticides, herbicides, and PAHs which can otherwise leach into the environment or be easily transported, thereby increasing the risk of subsurface pollution (Cao and Harris 2010; Verheijen *et al.* 2010).

#### AGRONOMIC EFFECTS OF BIOCHAR

Biochar has the potential to boost agricultural sustainability by increasing crop yields. Biochar improves soil productivity by favourably influencing soil properties such as holding carbon and improving soil fertility. Biochar affects crop yield indirectly by improving soil physical (e.g. bulk density, water holding capacity, soil aggregation and permeability, saturated hydraulic conductivity), chemical (e.g. nutrient retention, and availability) and biological properties, subsequently increasing the yield (Glaser *et al.*, 2002; Lehmann and Rondon, 2006; Yamato *et al.*, 2006 Chan *et al.*, 2007, Asai *et al.* 2009). As a result, application of biochar can increase agricultural sustainability especially in areas with low rainfall and in inherently low fertile soils. Also, in soils having a low cation exchange capacity application of biochar can improve the CEC (Chan *et al.* 2007, Liang *et al.* 2006) and ultimately improves crop yields (Crane-Droesch *et al.*, 2013). Biochar has been shown to boost yield under problematic soils also such as acidic soils (Masulili, 2010). Biochar can be used as amendment in degraded tropical soils (Lehmann and Rondon, 2006). Being resistant to microbial decomposition it ensures long term benefit for soil fertility (Steiner *et al.*, 2007). Biochar can increase agricultural productivity and mitigate GHG emissions from agricultural fields. The

application of biochar as a soil amendment has led researchers to produce biochar from bioresidues. In India, studies on biochar production, its characterization and its utilization as a soil amendment are lesser. Agricultural by-products such rice husk, bagasse, coconut shell, coir pith etc. are available in large quantities (Sugumaran and Sheshadri, 2009) and can be utilized in biochars production.

High crop yields were obtained by amending the soil with biochar produced from wood, paper pulp, wood chips and poultry litter (Jeffery *et al.* 2011). Asai *et al.* (2009) reported that biochar application resulted in higher grain yields at sites with low P availability and enhanced the response to N and NP fertilizer treatments but reduced leaf SPAD values, possibly through a reduction in available N, indicating that biochar application should be coupled with N fertilization in soils with low N supply. Higher agronomic nitrogen use efficiency (91.0 kg grain/kg N) was recorded with application of biochar (6.0 t/ha) coupled with NPK (Venkatesh *et al.*, 2012). Suppadit *et al.* (2012) studied the effect of quail litter biochar on soybean yield attributes and yield in pot experiment in sandy soil and reported significant that yield increase with biochar application. The highest number of nodes per plant and the tallest plant were obtained from 98.4 g quail litter biochar per pot mixture. Abewa *et al.* (2013) reported that application of 12 t/ha eucalyptus biochar significantly increase the yield of teff compared to 4 t/ha. Nigguse *et al.* (2012) studied the effect of maize stalk biochar on nutrient uptake of lettuces and reported higher N, P and K uptake with application of biochar. While Zhang *et al.* (2010) studied the effect of wheat straw biochar and n fertilization on rice yield and reported that application of 10 t/ha biochar coupled with 300 kg/ha N produces on par yield with application of 40 t/ha biochar alone. Milla *et al.* (2013) compared the effect of wood biochar and rice husk biochar on plant growth parameters and reported that with application of rice husk biochar, significantly higher number of leaves, leaf width, number of stems and root size are produced compared to wood biochar.

Application of rice husk biochar significantly increased number of tillers and yield in rice

compared to unamended control (Masulili, 2010). In maize application of biochar at 15 and 20 t D ha significantly increased maize grain yield by 150 and 98%, respectively compared to the control. Major *et al.* (2010) also reported improvement in yield of maize. Uzoma *et al.* (2011) have also reported increased maize yield by application of cow manure biochar. Yield increase in cowpea by 100% has been reported by Glaser *et al.* (2002). Liu *et al.* (2013) performed meta-analysis of literature data and reported that biochar soil amendment resulted in positive crop productivity response in field (9.1% on average) though the response was higher in pot experiments (11.1 % on average) though in the pot experiments crop yield increase was not significant compared to control. The increase in crop productivity was higher for dry land crops compared to paddy. Biederman and Harpole (2013) also performed meta-analysis of literature data and reported that addition of biochar to soils resulted, on average, in increased aboveground productivity, crop yield.

## EFFECT OF BIOCHAR AMENDMENTS ON SOIL PROPERTIES

### Physical properties

The chemical and physical properties such as high charge density and its particulate nature along with specific chemical structure, and high microbial and chemical stability, all contribute to greater nutrient retention and resistance to microbial decay than other organic matter (Atkinson *et al.* 2010). As a consequence of particle surface oxidation of biochar, the adsorption of organic matter and its charge density (CEC per unit surface area) increased (Atkinson *et al.* 2010). When added to soil, biochar appears to divide rapidly into particles of silt size or less due to abrasion, shrink-swell, and other physical weathering processes (Brodowski *et al.* 2007). Incorporation of biochar influences soil structure, texture, porosity, particle size distribution, and density. Biochar is considered to be biologically inert but it may also contain key mineral elements, the quantities of which can be directly related to the levels of these components in the feedstock prior to burning. Glab *et al.* (2016) indicated that biochar

application significantly improved the physical properties of the sandy soil. It was found that the basic soil physical parameters, such as bulk density and total porosity, were not only dependent on the rate but also on the size of the biochar. Small particles of biochar reduced the volume of soil pores in diameter below 0.5  $\mu\text{m}$  but increased the volume of larger pores with a diameter 0.5–500  $\mu\text{m}$ . Biochar application increased the available water content (AWC), especially when the finest fraction was used (0.064  $\text{cm}^3 \text{cm}^{-3}$ ). Andrian *et al.* (2016) reported that biochar, compost and co-composted biochar COMBI organic amendments improved soil properties including soil water content. Deng *et al.* (2016) studied the effects of biochar on soil physical properties on a silt loam soil and reported that field capacity and available water content increased significantly. Devereux *et al.* (2013) showed that pore size is significantly affected by biochar concentration. Increasing biochar is associated with decreasing average pore size, which is likely to impact heavily on hydraulic performance. At the end of the experiment, average pore size had decreased from 0.07  $\text{mm}^2$  in the 0% biochar soil to 0.046  $\text{mm}^2$  in the 5% biochar soil. Increased biochar concentration also significantly decreases saturated hydraulic conductivity and soil bulk density. Increased water retention was also observed at low matric potentials, where it was shown that increased biochar is able to retain more water as the soil dried out. Aslam *et al.* (2014) concluded that application of biochar at 1–2% decreases soil bulk density, increases soil porosity and infiltration rate by increasing the total porosity. In the same way biochar application increases water holding capacity of soil but it varies with respect to soil texture. Jien and Wang (2013) found that biochar application decreased bulk density from 1.4 to 1.1  $\text{Mg m}^{-3}$ , increased  $K_{\text{sat}}$  by 1.8 times and increased the mean weight diameter (MWD) of soil aggregates from 2.6 cm to 4.0 cm. Incorporating biochar into the soil significantly reduced soil loss by 50% and 64% at 2.5% and 5% application rates, respectively, compared with the control.

The formation of macro-aggregates in the biochar-amended soils is the critical factor to improve soil erosion potential. Based on these

results, a 5% application rate of biochar is considered as suitable for highly weathered soil because this application rate efficiently improves soil physicochemical properties and reduces soil loss. Nelissen *et al.* (2014) reported that the effects of biochar on bulk density, porosity and soil water retention curves were non-consistent over time, possibly due to interaction with tillage operations.

### Chemical properties

Bayu *et al.* 2016 showed that the addition of biochar improved pH, electric conductivity (EC), cation exchange capacity (CEC), organic carbon (OC), organic matter (OM), total nitrogen (TN), exchangeable cations and available phosphorous of the soil. Sequential extraction of Pb showed that application of biochar at 15 t/ha (4.2 g/kg), resulted in transformation of the exchangeable form of Pb carbonate bound, Liu *et al.* (2016) showed that both bamboo biochar and rice straw biochar (RB) significantly increased soil pH and soil organic carbon compared to control, whereas their effects on total N were either very small or non-significant. Application of RB significantly increased soil available P and K in both years, and the increases relative to control. Andrian *et al.* 2016 observed that biochar, compost and co-composted biochar improved soil properties including significant increases in CEC, K, Ca,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$  and soil carbon content. However, increases in soil nutrient content and improvements in physical properties did not translate to improved yield. Jiang *et al.* 2015 reported that in soils with higher C contents (i.e., >1.5 %), biochar decomposition rates appeared to slow down after initial fast decomposition; while biochar decomposition rates followed one-pool model for soils with lower C. Study by Deng *et al.* 2016 showed that biochar significantly increased soil C, exchangeable K contents but reduced soil exchangeable Ca and effective CEC, and had no effect on soil pH. Jien and Wang (2013) evaluated the influences of biochar made from the waste wood of *Leucaena leucocephala* on the physicochemical properties of long-term cultivated, acidic Ultisol. Experimental results indicate that applying biochar improved the physicochemical properties of the highly weathered soils, including significant

increases in soil pH from 3.9 to 5.1, cation exchange capacity from 7.41 to 10.8 cmol (+) kg<sup>-1</sup>, base cation percentage from 6.40 to 26.0%. Gundale *et al* (2006) studied the effect of wildfire produced charcoal on soil N dynamics and in particular, nitrification from ponderosa pine (*Pinus ponderosa* Laws) forests. The addition of NH<sub>4</sub><sup>+</sup> did not affect nitrification demonstrating that this process is not substrate limited. The amendment of these soils with charcoal significantly increased the nitrification potential, net nitrification and gross nitrification. However, charcoal had no effect on nitrification in grassland soils that had naturally high rates of nitrifier activity. The increase in gross nitrification in forest soils and lack of effect on grassland soils suggests that charcoal may alleviate factors that otherwise inhibit the activity of the nitrifying microbial community in forest soils. Schomberg *et al* (2012) reported reduced N leaching with the incorporation of five biochar materials 127 days after incubation, which was not due to greater N retention, but rather biochar addition elevated soil pH which promoted the losses of NH<sub>3</sub>. Shenbagavalli *et al* (2012) reported that concentrations of NH<sub>4</sub>-N and NO<sub>3</sub>-N decreased significantly with the increase in the rate of biochar. From another study, Case *et al* (2012) reported that biochar amendment did not affect the NH<sub>4</sub>-N and NO<sub>3</sub>-N concentration in soil. This was due to the increased immobilization of NO<sub>3</sub>-N with in microbial biomass as a result of increased C: N ratio of the soil amended with biochar. Nelson *et al* (2011) evaluated the effect of three rates of biochar and addition of N and P on N availability over a 56-day period. Biochar application at 20 g kg<sup>-1</sup> increased NH<sub>4</sub>-N concentration by 1.1 to 4.8 mg/kg during the first 10 days and consistently decreased NO<sub>3</sub>-N recovery by 5 to 10 mg kg<sup>-1</sup>. Yao *et al* (2012) determined the effect of thirteen biochars amendment on sorption and leaching of NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> in a sandy soil. They reported that most of the biochars showed little or no ability to sorb NO<sub>3</sub><sup>-</sup>. However, nine of the biochars could remove NH<sub>4</sub><sup>+</sup> from aqueous solution. Mizuta *et al* (2004) who found that bamboo biochar manufactured at 900 °C had a high NO<sub>3</sub><sup>-</sup> adsorption capacity. Marchetti *et al* (2012) observed that addition of biochar prepared from dried swine manure solids increased N mineralization after three months of incubation

compared to the control. Harris *et al* (2013) showed that no N was mineralized from either of the two biochars, indicating that plant-based biochar should not be considered a source of N for plant growth. Feng *et al* (2014) found that Olsen-P was not affected by biochar treatment. Galvez *et al* (2012) showed that soil amendments increased available P over no amendment. Mau and Utami (2014) studied the interactive effects of cow dung biochar and arbuscular mycorrhizal fungi (AMF) inoculation on P availability in a calcareous soil. Yu *et al* (2009) reported that the biochar derived from crop straw addition resulted in 254% increase in Olsen-P compared to control treatment in a calcareous. Zhai *et al* (2015) reported that application of 8% (w/w) biochar substantially increased soil Olsen-P from 3 to 46 mg kg<sup>-1</sup> in Red earth and from 13 to 137 mg kg<sup>-1</sup> in Fulvo - aquic soil after 42 days of incubation. The increase was mainly due to high concentrations of P in the ash fraction.

### Biological properties

Gasco *et al* 2016 reported that two pig manure biochars prepared at 300°C (BPC300) and 500°C (BPC500) at a rate of 8 wt% increased dehydrogenase, phos-phomonoesterase and phosphodiesterase activities, while that prepared at 300 °C resulted on a positive effect on dehydrogenase activity. In contrast, biochar prepared at 500 °C did not exhibit a positive effect on soil enzyme activity. Jiang *et al* 2015 showed that soil microbial composition significantly changed at 10 or 20% addition rate after 30 months, which was correlated with the increase in soil C/N. Tender *et al* 2016, reported that biochar addition had no effect on rhizosphere microbiology. Xu *et al* 2016 reported that maize-straw biochar increased both net N mineralization and respiration rate of the soil. Bacterial diversity increased in biochar-amended soil and was positively correlated with the addition ratio of biochar. On an overall basis biochar increased water holding capacity, enhanced microbial biomass and changed bacterial community structure of the soil which may all have contributed to the reduction of nitrogen leaching. Oleszczuk *et al.* (2013) studied the effect of biochar and pesticides (2, 4-D and dicamba) on the

enzymatic activity and ecotoxicity of soils. Biochar stimulated the activity of enzymes in almost all experimental treatments. In addition, it also reduced the negative effect of pesticides on the enzymatic activity.

## CONCLUSIONS

Biochar has the potential to boost agricultural sustainability by increasing crop yields. Soil quality improvement is the most commonly reported benefits of biochar amendment of soils. The effects on soil quality depended on, rate and nature of biochar and soil properties, whereas causative mechanisms are related to various characteristics of biochar. Biochar prepared from feedstock rich in nutrients, such as manure and poultry litter helps in soil quality improvement because of the higher N and P content. Biochar produced at a higher peak temperature usually have a higher SA and could be used as an adsorbent. Increase of pyrolysis temperature results in increase of the aromatic carbon structure which enhance the resistivity to microbial decomposition. However, biochar pyrolysed at relatively lower temperatures show better activity in soil and have higher surface affinity for water because of the higher molar O=C ratio. Coarse textured soils amended with biochar exhibit more improvement in soil quality as compared to fine textured soils.

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