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Biochar A Source of C Sink and Soil Health-A Review

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A B S T R A C T

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 quality and productivity.

Introduction

Biochar refer to the carbon-rich materials (charcoal) obtained from the thermo-chemical conversion of biomass in an oxygen- limited environment (pyrolysis). Biochar was first found in the Central Amazon basin. Applying biochar to agricultural soils is considered to improve carbon sequestration and decreased greenhouse gas emissions from agriculture. Recently, biochar has gotten attention of researchers because of its capacity to improve water-holding capacity and nutrient-holding ability of soil because of its porous structure, high specific surface area, and CEC. Use of biochar can increase soil nutrient availability in the long term (Lehmann *et al.*, 2003; Rondon *et al.*, 2007; Steiner *et al.*, 2008). The use of biochar can enhance soil pH and soil CEC (Liang *et al.*, 2006) and increase in soil water retention capacity and decrease in soil strength (Chan *et al.*, 2007). Adoption of biochar management does not require new resources but makes use of locally available and renewable materials in a sustainable way. Biomass can include forestry and agricultural waste products, municipal green waste, biosolids, animal manures, some industrial wastes such as peppermill wastes. Soil organic matter is the key to soil health. In wet tropical condition, organic matter is easily subjected to decomposition and mineralization. Mineralization produces CO_2 in just a few seasons and causes nutrient content to be low.

Biochar significantly improve soil tilth, productivity, and nutrient retention and availability to plants via both direct slow-nutrient release fertilizing properties and indirect effects on improved water holding capacity, nutrient holding ability, and soil aggregate stability, when used as a soil conditioner along with organic and inorganic fertilizers. The world population is currently increasing at a fast rate and is expected to reach 9 billion by 2050. To meet a growing demand for food from a growing population, we need to increase agricultural productivity upto 70%, and food production in the developing world will need to double by 2050 (FAO). The main challenge facing the future of agricultural production is to produce almost 50% more food up to 2030, and double production by 2050.

Crop residues management: a burning issue

The management and utilization of crop residues is essential for the improvement of soil quality and crop productivity. Viable option is to retain residue in the field; burning should be avoided. India, with a long history of agricultural activities, produces vast amounts of unusable crop residues at about 500 million tons/year (2010-2011). Studies sponsored by the Ministry of New and Renewable Energy (MNRE), Govt. of India have estimated surplus biomass availability at about 120–150 million tons/annum (MNRE, 2009). Of this, about 93 million tons of crop residues are burned in each year (IARI 2012). Direct incorporation of crop residues into agricultural soil to conserve soil moisture and nutrients can cause considerable crop management problems. However, long-term field research has confirmed that adding crop residues to agricultural soils leads to large increases in soil C stocks in the short term but minimal increases in the long term due to na1tural decay. For more effective management and disposal of the crop residues, conversion of organic waste to produce biochar is one viable option that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improve the soil quality (Srinivasarao *et al.,* 2012).

Biochar for waste management

"Biochar" is a relatively new term, yet it is not a new substance. It actually comes from the study of very old soils in the Amazon Basin. The so-called "*Terra preta de Indio*", or "black soil of the Indians" was formed by indigenous peoples centuries to thousands of years ago when they accumulated charcoal and other fire residues, and also nutrient-rich waste such as animal and fish bones, in waste piles near dwellings. Over time these wastes resulted in black colored human-modified soils which are up to two meters deep, while the surrounding soils are reddish to yellowish.

Biochar is a charcoal based, soil amendment that can be designed to help reclaim and improve marginal soils by increasing soil water holding capacity and enhancing fertility, while also generating high-value renewable energy co-products during its production. Biochar is not a pure carbon, but rather mix of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in different proportions (Masek, 2009). The central quality of biochar and char that makes it attractive as a soil amendment is its highly porous structure, potentially responsible for improved water retention and increased soil surface area. Biochar is created by heating organic material under conditions of limited or no oxygen. Production of biochar generally releases more energy than it consumes, depending on the moisture content of the feedstock. Heat, oil, and gas that are released can be recovered for other uses, including the production of electricity. Biochar and its byproducts can be produced from a wide variety of feed stocks such as organic farm waste, waste treatment plant slurry, and woods with high cellulose/lignin content. After pyrolysis, the solid byproduct is a porous network of carbonates and/or aromatic carbon. Different feedstocks used lead to different properties (Table 1).

Biochar as a source of C sink

Fossil fuels are carbon positive; they add more carbon dioxide (CO_2) and other greenhouse gasses to the air and thus exacerbate global warming. Ordinary biomass fuels are carbon neutral; the carbon captured in the biomass by photosynthesis would have eventually returned to the atmosphere through natural processes like decomposition. Sustainable biochar systems can be carbon negative by transforming the carbon in biomass into stable carbon structures in biochar which can remain sequestered in soils for hundreds and even thousands of years.

Restoring the carbon balance in the atmosphere

It removes net carbon from the atmosphere. When a green plant grows, it takes CO_2 out of the air to build biomass. All of the carbon in the plant came from CO_2 taken out of the air, and returns to the air when the plant dies and decomposes. When the biomass is pyrolyzed—heated in the absence of oxygen—over 40% of the total carbon from the waste biomass is retained in biochar and sequestered in the soil for thousands of years, effectively removing that carbon from the atmosphere. The carbon in 1 ton of biochar is equivalent to about 3 tons of CO_2 removed from the atmosphere.

Biochar as a soil amendment

Biochar application to soil leads to several interactions mainly with soil matrix, soil microbes, and plant roots (Lehmann and Joseph, 2007). The types and rates of interactions depend on different factors like composition of biomass as well as biochar, methods of biochar preparation, physical aspect of biochar and soil environmental condition mainly soil temperature and moisture.

Soil chemical properties

Biochar is generally alkaline in pH and may increase soil pH (Chan and XU, 2009), 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). Widowati *et al.,* (2012) 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 (Rondon *et al.*, 2007, Novak *et al.*, 2009, 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. Lehmann *et al.,* (2003) and 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 (Widowati *et al.,* 2011). In addition to this, Glaser *et al.*, (2002) concluded that the charcoal 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.*, (2008). Sukartono *et al.*, (2011) reported that 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 the increasing aromatic carbon is likely to affect soil properties.

Table.1 Properties of biochar used in different experiment

Materials used for	**pH**	**Total C**	**Total N**	**C:N**	**Ca**	**Mg**	**P**	**K**	**CEC**	**Reference**
Producing biochar		**(%)**					**(cmol/k g)**			
Paper mill waste 1- (waste wood chip)	9.4	50.0	0.48	104	6.2	1.20	-	0.22	9.00	Zwieten *et al.*, (2010)
Paper mill waste 2- (waste wood chip)	8.2	52.0	0.31	168	11.0	2.60	-	1.00	18.00	Zwieten *et al.*, (2010)
Green waste (grass clippings, cotton trash and plant prunings)	9.4	36.0	0.18	200	0.4	0.56	-	21.00	24.00	Chan *et al.*, (2007)
Eucalyptus biochar	-	82.4	0.57	145	-	-	1.87	-	4.69	Novak *et al.*, (2009)
Cooking biochar	-	72.9	0.76	96	-	-	0.42	-	11.19	Novak *et al.*, (2009)
Poultry litter (450^{o}C)	9.9	38.0	2.00	19	-	-	37.42	-	-	Chan *et al.*, (2008)
Poultry litter (550^{o}C)	13	33.0	0.85	39	-	-	5.81	-	-	Chan *et al.*, (2008)
Wood biochar	9.2	72.9	0.76	120	0.83	0.20	0.10	1.19	11.90	Major (2013)
Hardwood sawdust	-	66.5	0.3	221	-	-	-	-	-	Singh *et al.*, (2010)
Mixed wood	8.13	88.9			50.9			14		Abrol *et al.*, (2016)

Table.2 Effect of biochar addition on soil properties

Property	Effect	Biochar property	Mechanism	Reference
Soil Organic matter	Increased	High C content	Increased carbon concentration	Zhang *et al.*, (2012)
Water-holding capacity	Increased	Porous structure	Increased macro porosity and hydrophilicity	Herath *et al.*,(2012), Atkinson *et al.*,(2010)
Porosity	Increased	Porous structure	Dilution effect and formation of macro aggregates	Herath *et al.*, (2013)
Plant Crop yield	Increased	Soil organic matter, pH, bulk density, CEC, high porosity	Due to the positive effect of soil quality; chemical, physical, microbial and nutrient availability	Zhang *et al.*, (2012)
Environment CH_4 emissions	Decrease	Porous structure, pH	Abundance of methanotrophic proteobacterial, 37 methenogenic bacteria reduced at too high or too low pH	Feng *et al.*,(2012)
N_2O emissions	Decreased	Recalcitrant, porous structure	Enhanced aeration and stable carbon, increased microbial activity and immobilization of N	Zhang *et al.*, (2012)
Carbon sequestration	Increased	Recalcitrant or stable C; Recalcitrant or stable C;	Long-term storage of stable carbon in soil	Kameyama *et al.*,(2010),Matovic *et al.*,(2011)
Nutrient leaching	Decreased	Porous structure, surface area and negative surface charge	Enhanced CEC facilitates retention of nutrients	Biederma and Harpole (2012)

Table.3 Effect of biochar application on crop yield

Crops	Soil type	Biochar treatment (t·ha-1)	Fertilizer treatment (kg·ha-1)	Yield increase over control a (%)	Reference
Wheat	Ferrosol	0 and 10	1.25g Nutricote® per 250g soil b	+ 250	Van Zwieten *et al.*, (2010)
Radish	Alfisol	0, 10, 25 and 50	N (100)	+ 320	Chan *et al.*, (2008)
Radish	Alfisol	0, 10, 50 and 100	N (100)	+ 95 to + 266	Chan *et al.*, (2007)
Maize	Fine sand loam and sand	0, 2.5, 5.0 and 10	Nil	No effect	Feng *et al.*, (2012)
Wheat	Silt loam	0 and 9	Nil	No effect	Karhu *et al.*, (2011)
Maize	Oxisol	0, 8 and 20	Lime (dolomite) (2.2); N (156 – 170; P (30 – 43); K (84 – 138)	+ 28 (2004) + 30 (2005) + 140 (2006)	Major (2010)
Maize	Ultisol	0 and 2.4	N (150); P_2O_5 (100); K_2O (150)	+ 146	Peng *et al.*, (2011)
Beans	Oxisol	0, 30, 60 and 90[c]	Lime (300); N (20); P (20)	+ 39	Rondon *et al.*, (2007)

a Control indicates that no biochar was used and + and – signs indicates if yields increased or decreased.
b Nutricote® contains 15.2% N, 4.7% P, 8.9% K, 3.3% Ca, 1.1% S, and micronutrients.
c Fertiliser applied was in g/kg (pot trial).

Since biochar is highly porous and has a large specific surface area, its impact on soil cation exchange capacity and other nutrients that have correlation with cation exchange capacity is very important. Biochar amendment significantly decreased extracted Cd in the soil by 17 to 47 per cent. Some types of biochar also appear to reduce the mobility of heavy metals such as Cu and Zn

Soil physical properties

Little research has been published on the effects of biochar on physical properties. Studies showed biochar effects on parameters such as bulk density, porosity, water holding capacity and aggregate stability (Table 2). 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 (Asai *et al.,* 2009, 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 (Busscher *et al.,* 2010, Peng *et al.,* 2011). Soil amendment with biochar can result in decreased bulk density and soil penetration resistance and increased water holding capacity (Abrol *et al.,* 2016). 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 (Table 2). Peng *et al.,* (2011) reported that compared with fertilizer application biochar amendment to a typical soil ultisol resulted in better crop growth.

Soil biological properties

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. In the long term experiments, application of biochar had no significant influence on basal application rates compared with the control. Graber *et al.,* (2009) reported that with increasing rate of biochar application maximum number of culturable colonies of general bacteria, *Bacillus* spp., yeasts and Trichoderma spp. were found. However 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 enhanced biological nitrogen fixation (Rondon *et al.,* 2007), improved colonization of mycorrhizal fungi, earthworms showed preference to biochar amended soils (Van Zwieten *et al.,* 2010), increased methane uptake (Karhu *et al.,* 2011), potential catalyst in reducing nitrous oxide to nitrogen (Van Zwieten *et al.,* 2009)

Crop productivity

The response of different crops to various biochar application levels is summarized in table 3. Application of biochar can enhance soil productivity by improving the physical, chemical and biological soil conditions (Glaser *et al.,* 2007, Lehmann *et al.,* 2003, 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. Lehmann *et al.,* (2003) compared soil fertility and leaching losses of nutrients between an Anthrosol and an adjacent unamend Ferralsol. The Anthrasol showed significantly higher P, Ca, Mn and Zn availability than the Ferralsol, and an increased biomass of both cowpea and rice by 38–45% without fertilization. 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). Application of chicken manure and city waste biochar increased maize biomass (Widowati *et al.,* 2012). This higher biomass production is attributed to biochar increasing the soil pH and CEC (Liang *et al.,* 2006). Crop yields of soybeans were also reported to increase by a factor of 1.5 after an application of 0.5 Mg charcoal/ha (Kishimoto and Sugiura, 1985).

Results showed that the application of biochar to soil has been shown to improve soil quality and crop yields which could be due to direct or indirect effect. Biochar is able to play a major role in expanding options for sustainable soil management by improving upon existing best management practices, not only to improve soil productivity but also to decrease the environmental impact on soil and water resources. Future long term field studies are necessary to evaluate the effect of biochar on soil properties and C sequestration for sustainable crop production.

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