Review Article

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 CO₂ 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 up to 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 natural 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 (Srinivasaraao 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 gases 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  |    |             |         |     |    |    |   |   |     |                         |
| Paper mill waste 1-| 9.4| 50.0        | 0.48    | 104 | 6.2| 1.20| - | 0.22| 9.00| Zwieten et al., (2010)  |
| (waste wood chip)  |    |             |         |     |    |    |   |   |     |                         |
| Paper mill waste 2-| 8.2| 52.0        | 0.31    | 168 | 11.0| 2.60| - | 1.00| 18.00| Zwieten et al., (2010) |
| (waste wood chip)  |    |             |         |     |    |    |   |   |     |                         |
| Green waste (grass| 9.4| 36.0        | 0.18    | 200 | 0.4| 0.56| - | 21.0| 24.00| Chan et al., (2007)     |
| clippings, cotton |    |             |         |     |    |    |   |   |     |                         |
| trash and plant    |    |             |         |     |    |    |   |   |     |                         |
| prunings)          |    |             |         |     |    |    |   |   |     |                         |
| 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| 9.9| 38.0        | 2.00    | 19  | -  | -  | 37.42| -  | -  | Chan et al., (2008)     |
| °C)                |    |             |         |     |    |    |     |   |   |                         |
| Poultry litter (550| 13 | 33.0        | 0.85    | 39  | -  | -  | 5.81| -  | -  | Chan et al., (2008)     |
| °C)                |    |             |         |     |    |    |     |   |   |                         |
| 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 CH₄ emissions| Decrease| Porous structure, pH | Abundance of methanotrophic proteobacterial, 37 methanogenic bacteria reduced at too high or too low pH | Feng et al., (2012)              |
| N₂O 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  | 0, 2.5, 5.0 and 10        | Nil                                  | No effect                        | Feng et al., (2012)         |
|       | and sand        |                           |                                     |                                  |                             |
| 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); P2O5 (100); K2O (150)       | + 146                            | Peng et al., (2011)        |
| Beans | Oxisol          | 0, 30, 60 and 90c         | 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
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 unamended 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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