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Biochar: A Way to Combat Climate Change by Improving Soil Health

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Abstract

The application of bio-char (charcoal or biomass-derived black carbon (C)) to soil is proposed as a novel approach to establish a significant, long-term, sink for atmospheric carbon dioxide in terrestrial ecosystems. Apart from positive effects in both reducing emissions and increasing the sequestration of greenhouse gases, the production of biochar and its application to soil will deliver immediate benefits through improved soil fertility and increased crop production. Biochar has many important properties: high surface area with many functional groups, high nutrient content, and slow-release fertilizer. We discuss the influence of pyrolysis temperature, feedstock, pH, effect on different soil types.

Keywords

Bio-char; Ecosystems; Greenhouse gases; Fertilizer.

Introduction

Sustainable development necessitates major changes in agriculture development to improve weak rural economies. The main concern in global agriculture is loss in fertility and increased erosion which is due to long term cultivation of soil (Jianping, 1999). Further, decrease in soil organic matter decrease the aggregate stability of soil. Conservation agriculture (CA) contributes to environmental conservation as well as to enhanced and sustained agricultural production by conserving, improving and making more efficient use of natural resources (Joshi *et al*., 2018). Biochar being a renewable resource and economic and environmental benefits is an important resource for soil fertility management. Biochar as a source of nitrate, ammonium and phosphate can be used as a slow release fertilizer to increase soil fertility (Schmidt *et al*., 2015). Biochar can be an important tool to increase food security and cropland diversity in areas with severely depleted soils, scarce organic resources, and inadequate water and chemical fertilizer supplies.

Biochar increases soil retention of nutrients and agrochemicals by improving water quality and quantity for plant and crop utilization. More nutrients stay in the soil instead of leaching into groundwater and causing pollution. Biochar application to the soil has been shown by different

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studies to have significant impacts on several soil quality parameters (Barrow, 2012). Amendment of biochar have positive impact on soil which include: (i) reduce leaching loss of nutrients with increase in capacity of soil sorb plant nutrients (Cheng *et al*., 2008); (ii) decrease in soil bulk density results in more root growth and water permeability (Laird *et al*., 2010); (iii) increasing the soil cation exchange capacity (Steiner *et al*., 2008); (iv) increasing soil microbial activity and diversity (Lehmann *et al*. 2011); (v) increasing plant available water retention (Karhu *et al*. 2011); and (vi) increasing crop yields (Kimetu *et al*. 2008).

Land application of bio-char is not a new concept. For example, certain dark earths in the Amazon Basin (so-called Amazonian Dark Earths or "terra preta") have received large amounts of charred materials, the residues from biomass burning (Sombroek *et al*. 2003). These applications were most likely a result of both habitation activities and deliberate soil application by Amerindian populations before the arrival of Europeans (Erickson *et al*. 2003). Even after hundreds and thousands of years of abandonment, biochar derived C stocks remain in these soils today in large amount. The typical values of total C storage is 100 Mg C $ha^{-1}m^{-1}$ in Amazonian soils which is less than total C storage value of 250 Mg C $ha^{-1}m^{-1}$ as derived from similar parent material (Glaser *et al*. 2001). Such C storage in soils far exceeds the potential C sequestration in plant biomass even if bare soil were, theoretically, restocked to primary forest containing about 110 $MgCha^{-1}$ above ground (Sombroek *et al*. 2003).

Biochar is the by-product of biomass pyrolysis in an oxygen depleted atmosphere which contains porous carbonaceous structure and many functional groups (Lehmann and Joseph 2009). Biochar is highly porous 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. Biochar's physical and chemical properties depend on pyrolysis temperature and process parameters, such as residence time and furnace temperature, as well as on the feedstock type (Bruun *et al*. 2011). Common raw materials used for feedstock are wood chip, organic wastes, plant residues, and poultry manure (Sohi *et al*. 2010). Biochar elemental composition generally includes hydrogen, carbon, nitrogen, and also nutrient element, such as K, Ca, Na, and Mg (Zhang *et al*. 2015). The carbon content increased with increase in 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 non-polar substances, which has a strong affinity to inorganic ions such as heavy metal ions, phosphate, and nitrate (Schmidt *et al*. 2015). In recent years, an increasing interest in applying biochar is focused on the amendment of nutrient-poor soil for soil ecological restoration including sequestering carbon (Jiang *et al*. 2012). To increase plant nutrient availability various mechanisms have been suggestd in nutrient limited agroecosystems such as (1) the initial addition of soluble nutrients contained in the biochar (Sohi *et al*. 2010) and the mineralization of the labile fraction of biochar containing organically bound nutrients (Lehmann *et al*. 2009); (2) reduction of nutrient leaching due to biochar's physicochemical properties (Liang *et al*. 2006); (3) lower escapable N losses by ammonia volatilization and N_2 and N_2O from denitrification (Cayuela *et al*. 2013); and (4) with the increase in biological activities or community shifts, more retention of associated N, P, and S.

Biochar as a source of nutrients

Organic matter and inorganic salt, such as humic-like and fluvic-like substances and available N, P, and K, can serve as fertilizer and be assimilated by plants and microorganisms. Large amounts of N (23–635 mg kg^{-1}) and P (46–1664 mg kg^{-1}) could be released from fresh biochar (Mukherjee and Zimmerman 2013). The actual availability of N, P, and K not reflected by total N, P, and K in biochars, (Spokas *et al*. 2012), the available N, P, and K (e.g., ammonia (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}) and K^+) may be associated with the amounts of total N, P, and K. For example, the decrease of available N was contributed from loss of total N in higher temperatures biochars (Koutcheiko *et al*. 2007). Besides, the available K content significantly increased with the increase of total K amount (Zheng *et al*. 2013).

Nutrient contents in biochars were determined greatly by feed stock source and pyrolytic temperature. For example, N losses began at about 400° C, then half of the N was lost as volatiles at about 750° C in three woody and four herbaceous biochars (Lang *et al*. 2005). Contrasted to total N content in biochars, total P content significantly increased from 0.12 to 0.17% with the increase of temperature from 300 to 600° C (Zheng *et al*. 2013). However, available P in biochar produced at higher temperature was lower than produced at lower temperature. Additionally, the total K content increased from 3.7% at 300°C to 5.02% at 600°C, while the available K (water-soluble) content increased with the increase of pyrolysis temperature (37% at 300°C and 47% at 600°C) (Zheng *et al.* 2013). Nutrient availability of biochar is affected by pH of the soil (Silber *et al.* 2010). The release of PO_4^{3-} and NH_4^+ were pH-dependent while the release of K+ and NO_3^- were not (Zheng *et al.* 2013). Further more, with the increase of pH values from 2–7, K^+ remained relatively stable whereas the content of PO_4^{3-} and NH_4^+ released from the biochars would be decreased (Zheng *et al.* 2013). Higher pyrolysis temperature may increase the availability of K while lower pyrolysis temperature and pH may increase the availability of N and P.

Biochar influence on properties of soil

Biochar may also be used as a sustainable amendment to enhance soil chemical properties (Lehmann *et al.* 2011). For example, the content of ash in biochars ranged from 0.35 to 59.05%, which were rich in available nutrients, especially cationic elements, such as K (0–560 mmol kg^{-1}), Ca (3–1210 mmol kg^{-1}), Mg (0–325 mmol kg^{-1}), and Na (0–413 mmol kg^{-1}) (Rajkovich *et al.* 2012). Besides the direct amendment of biochar on soil's properties, biochar can also alter microbial and nutritional status of the soil within the plant rooting zone through changing soil physical properties (e.g., bulk density, porosity, and particle size distribution). Overall, the improvement of soil properties is highly contributed to the increased of both nutrient and water use efficiency and crop productivity.

Effect on 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. The increase in soil carbon through biochar application is attributed to the stability of biochar in the soil which persists despite microbial action (Table 1).

Effect on soil physical properties

Little research has been published on the effects of biochar on physical properties. 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 percent greater field capacity. Due to interactions between oxidized carboxylic acid groups at charcoal particles surface and mineral grains soil aggregate stability, it forms complexes with minerals (Glaser *et al.*, 2002). Soil amendment with biochar can result in decreased bulk density and soil penetration resistance and increased water holding capacity (Abrol *et al.*, 2016). 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. Peng *et al.*, (2011) reported that compared with fertilizer application biochar amendment to a typical soil ultisol resulted in better crop growth.

Effect on 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; Liang *et al.* 2010). The 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). Joshi *et al.*, 2017 reported that maximum nitrogen content and uptake in brahmi was recorded in sole brahmi (3 hand weedings at 30, 45 and 60 DAP) treatment followed by alternate (1:1) ratio along with pendimethalin fb cyhalofop-butyl fb one hand weeding at 45 DAS during both the years, which denotes that medicinal crop has good effect on soil properties.

Domene *et al.* (2014) indicated that microbial abundance could increase from 366.1 (control) to 730.5 μgCg^{-1} after an addition of 30*t* ha^{-1} biochar. At preincubation times (2–61 days), with the increase in corn stover biochar rates (from 0 to 14%), microbial abundance increased by 5–56% (Domene *et al.* 2015). Some possible reasons may be responsible for the increase of microbial abundance, such as higher availability of nutrients or labile organic matter on biochar surface (Bruun *et al.* 2012), less competition (Lehmann *et al.* 2011), the enhanced habitat suitability and refuge, the increased water retention and aeration (Schimel *et al.* 2007), or positive priming (Zimmerman *et al.* 2011). With the increase of pH up to values around 7, bacterial populations were possible to increase, whereas, no change in fungi abundance was observed (Rousk *et al.* 2010). Similar to nutrient and C changes, the pre-existing soil pH, the direction, and magnitude of change will also largely affect the level of pH changes.

Adsorption and retention of nutrients by biochar

Many studies showed that biochar had the potential to sorb nutrients. Biochars effectively sorb phosphate by 3.1%, nitrate by 3.7%, and ammonium by 15.7% (Yao *et al.*, 2012). Biochar greatly influence the adsorption capacity of nutrient, including pH, surface acidic groups, and ion exchange capacity (Yao *et al.* 2012; Morales *et al.* 2013). Chemisorption by hydrophobic bonding (Zhang *et al.* 2013), π-π electron donor-acceptor interactions resulting from fused aromatic carbon structures, and weak unconventional H-bonds are the mechanisms which influence the adsorption capacity of polar and apolar compounds (Conte *et al.* 2013). The influencing factors, which affect nutrients desorption, such as soil types, feedstocks, pyrolysis conditions, and biochar application rates, are needed to be considered. For biochar application rates at 0, 1, 5, and 10% in black soil, the average percentage of desorbed P were 36, 37, 39, and 41% (Xu *et al.* 2014).

Table 1: Properties of biochar used in different experiments

Materials used for producing biochar	pH	Total C	Total N	C:N	Ca	Mg	P	K	CEC	Reference
Green waste (grass clippings, cotton trash and plant prunings)	9.4	36	0.18	200	0.4	0.56		21	24.00	Chan *et al.*, (2007)
Eucalyptus biochar	–	82.4	0.57	145			1.87		4.69	Novak *et al.*, (2007)
Cooking biochar	–	73.9	0.76	96			0.42		11.19	Novak *et al.*, (2009)
Poultry litter (450°C)	9.9	38	2.00	19			37.42			Chan *et al.*, (2008)
Wood biochar	9.2	33	0.76	120	0.83	0.20	0.10	1.19	11.90	Chan *et al.*, (2008)
Hardwood sawdust	–	66.5	0.3	221						Major (2013)
Mixed wood	8.13	88.9	–	–	50.9			14		Abrol *et al.*, (2016)
Soyabean straw	7.66	576	12.7	45			2.7	–		Yuan *et al.* (2011)
Bagasse	9.3						0.005	0.026		Lee *et al.* (2013)
Paddy straw	10.5	86.28	3.25				0.034	0.213		Lee *et al.* (2013)
Peanut straw	8.6	537	26	21			6.3			Yuan *et al.* (2011)
Corn straw	9.37	536	14.4	37			2.5			Yuan *et al.* (2011)

Desorption of activated biochar was less than NH_4^+ in biochars and ranged from 18% for biochar (made at 600°C) at 2.7 mg L^{-1} to 31% for biochar (made at 450°C) at 5.1 mg L^{-1} (Zhang *et al.*, 2015). Desorption of $NO^{3\,-}$inactivated biochar treatment (4–5 mgL^{-1}) was higher than that of biochars (0–4 mgL^{-1}) (Zhang *et al.* 2015). This may be caused due to differences of the soil pH and the activity or availability of cations (Al^{3+}, Fe^{3+}, and Ca^{2+}) which interact with nutrients in biochars. Therefore, biochar has great potential as slow-release fertilizer. Research should be carried on the methods which can measure availability of nutrients of desorbed nutrients from biochar or by isotope analysis for the maximum bioavailability of soil nutrients.

Rondon *et al.* (2005) reported that 50% reduction of N_2O emissions was found under soybean systems while 80% decrease of N_2O emissions was found for grass systems. Similarly, biochars treatment could decrease N_2O emissions from 1768 to 45–699 μgN_2O-N m^{-2} h^{-1} (Wang *et al.* 2013) and suppress N_2O emissions between 21.3 and 91.6% (Stewart *et al.* 2012). Feedstocks, biochar application rates, fertilizer, and soil types should also be considered as noticeable factors for changing stabilization of nutrients. When urea and fertilizers were applied, N_2O emissions were decreased in all biochar treatments compared to the control with an average of 53% (from 618 to 295 μg N kg^{-1}) and 84% (from 3356 to 529 μg N kg^{-1}), respectively (Nelissen *et al.* 2014). These results demonstrated that the influence of fertilizer types on nutrients' fixing cannot be neglected.

Conclusion

Soil fertility and plant growth can be improved with the application of biochar. Various biomass materials could be used feedstock of biochar and they could be pyrolyzed at different temperatures. The main properties of biochar are well developed pore structure, huge surface area, amounts of exchangeable cations and nutrient elements, and plenty of liming. The productivity of plant is increased with the amount of nutrient elements and availability of nutrient elements, by reducing nutrient leaching, and mitigating gaseous nutrients losses with improvement of soil physical, chemical and biological properties.

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