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Biochar: A boon for agriculture

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Abstract
Biochar is a new word for many, but the technology is a traditional one in several regions of the world. Biochar refers to a kind of charcoal made from biomass. Unlike charcoal made for fuel, biochar has properties which make it a valuable soil amendment. The decrease in biomass production, decrease in organic matter supply and increased decomposition rate are the primary factors to reduction in soil organic matter. Biochar is a stable carbon compound created when biomass is heated to temperatures between 300 and 1000 ˚C, under low oxygen concentrations**.** Biochar is attracting attention as a means for sequestering carbon and as a potentially valuable input for agriculture to improve soil fertility and sustainable production. Biochar, when utilized correctly, can be an important agricultural tool used to increase nutrients and organic resources in depleted soils. This is because the lumps of biochar are full of holes and crevices that help serve as habitats for soil microorganisms. Soil health management with biochar is evaluated globally as a means to improve soil fertility and to mitigate climate change.

Keywords: Biochar, soil health, soil fertility and green house gasses

1. Introduction

Soil health is the foundation of vigorous crop productivity with higher opportunity for income and employment which in turn provides sustainable food system. Soil health management forms the basis for sustainable system of productive agriculture as the Indian population, which increased from 683 million in 1981 to1210 million in 2010, is estimated to reach 1412 million in 2025 and to 1475 million in 2030. To feed the projected population of 1.48 billion by 2030, India needs to produce 350 million tonnes of food grains. The expanded food needs of future must be met through intensive agriculture without any expansion in the arable land. The per capita arable land decreased from 0.34 ha in 1950-51 to 0.15 ha in2000-01 and is expected to shrink to 0.08 ha in 2025 and to 0.07 ha in2030.

Plants obtain their nutrition from organic matter and minerals found in soils. As the land is farmed, the agricultural processes disturb the natural soil systems including nutrient cycling and the release and uptake of nutrients (Bot and Benites 2005) [3]. Modern agriculture is apt to mine the soil for nutrients and to reduce soil organic matter levels through repetitive harvesting of crops. This decline of the soil continues until management practices are improved, additional nutrients are applied, rotation with nitrogen-fixing crops is practiced, or until a fallow period occurs allowing a gradual recovery of the soil through natural ecological development. As the natural stores of the most important nutrients for plant growth decline in the soil, growth rates of crops are inhibited. Soil organic matter plays key role in soil fertility sustenance. In soybean-wheat system, without balanced input of nutrients, organic matter status of soil declined over a time in Alfisols of Ranchi. Whereas, balanced fertilization with NPK and NPK+FY Mim proved the organic matter status in Vertisols under soybean-wheat system at Jabalpur. It is crucial to maintain a threshold level of organic matter in the soil for maintaining physical, chemical and biological integrity of the soil and for sustained agricultural productivity. Thus, assessing soil organic carbon (SOC) sequestration under intensive cropping with different management practices plays an important role in long-term maintenance of soil quality.

Efficient use of biomass, available as crop residues and other farm wastes, by converting it to a useful source of soil amendment/nutrients is one way to manage soil health and fertility. The current availability of biomass in India is estimated at about 500 million tons/year. These residues are either partially utilized or un-utilized due to various constraints. It is estimated that about 93 million tons of crop residues are burnt in each year in India. Residue burning traditionally provides a fast way to clear the agricultural field of residual biomass, facilitating further land preparation and planting. However, in addition to loss of valuable biomass and nutrients, biomass burning leads to release of toxic gases including GHGs. In this context, biochar, a pyrolysis product of plant biomass offers a significant, multi-dimensional opportunity to transform large scale agricultural waste streams from a financial and environmental liability to valuable assets. Use of biochar in agricultural systems is one viable option that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improve the soil quality.

In India, about 435.98 million tons of agro-residues are produced every year, out of which 313.62 million tons are surplus. These residues are either partially utilized or un-utilized due to various constraints (Murali *et al*., 2010) [41]. Koopmans and Koppejan (1997) [25] estimated that about 507,837 thousand tons of field crop residues were generated in India during 1997 of which 43% was rice and 23% wheat. The estimates from Streets *et al.* (2003) [69] reveal that 16% of total crop residues were burnt. The results from Venkataraman *et al.* (2006) [72] suggest that 116 million tons of crop residues were burnt in India in 2001, but with a strong regional variation (Gupta, 2010) [16]. 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) [40]. Of this, about 93 million tons of crop residues are burned in each year (IARI 2012) [17].

Generation of crop residues is highest in Uttar Pradesh (60 million t) followed by Punjab (51 million t) and Maharashtra (46 million t). Maharashtra contributes maximum to the generation of residues of pulses (3 million t) while residues from fibre crop is dominant in Andhra Pradesh (14 million t). Gujarat and Rajasthan generate about 6 million t each of residues from oilseed crops. Among different crops, cereals generate maximum residues (352 Mt), followed by fibres (66 Mt), oilseeds (29 Mt), pulses (13 Mt) and sugarcane (12 Mt). The cereal crops (rice, wheat, maize, millets) contribute 70% while rice crop alone contributes 34% to the crop residues (Fig 1). The surplus residues i.e., total residues generated minus residues used for various purposes, are typically burnt on-farm. Estimated total amount of crop residues surplus in India is 91-141 Mt (IARI, 2012) [17]. Cereals and fibre crops contribute 58% and 23%, respectively and remaining 19% is from sugarcane, pulses, oilseeds and other crops. Out of 82 Mt surplus residues from the cereal crops, 44 Mt is from rice followed by 24.5 Mt from wheat. About three fourths of greenhouse gas (GHG) emissions from agro-residues burning were CH_4 and the remaining one-fourth was N_2O. Burning of wheat and paddy straws alone contributes to about 42% of GHGs. Hence, conversion of organic waste to produce biochar using the pyrolysis process 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, 2013) [62, 63]. Biochar has the potential to increase conventional agricultural productivity and enhance the ability of farmers to participate in carbon markets beyond the traditional approach by directly applying carbon into the soil (McHenry, 2009) [39]. Converting waste biomass into biochar would transfer very significant amounts of carbon from the active to inactive carbon pool, presenting a compelling opportunity to intervene in the carbon cycle. The use of biochar as soil amendment is proposed as a new approach to mitigate man-induced climate change along with improving soil productivity. The use of biochar in agriculture is not new; in ancient times farmers used it to enhance the production of agricultural crops. In order to sequester carbon, a material must have long residence time and should be resistant to chemical processes such as oxidation to CO_2 or reduction to methane. It has been suggested by many authors (Izaurralde *et al*., 2001; McHenry, 2009) [19, 39] that the use of biochar as soil amendment meets the above requirements; since the biomass is protected from further oxidation as compared to material that would otherwise have degraded to release CO_2 into the atmosphere. Such partially burnt products, more commonly called pyrogenic carbon or black carbon, may act as an important long-term carbon sink because their microbial decomposition and chemical transformation are probably slow.

1.1. What is biochar?

Lehmann and Joseph (2009) [29] define biochar as the carbon-rich product when biomass, such as wood, manure or leaves, is heated in a closed container with little or no available air. In more technical terms, biochar is produced by so-called thermal decomposition of organic material with limited supply of oxygen, and at relatively low temperatures (<700 °C) (Stockmann, 2011) [68]. This process often mirrors the production of charcoal, which is one of the most ancient industrial technologies developed by mankind (Barrow 2012). However, biochar can be distinguished from charcoal and similar materials in that it is produced with the intent it be applied to soil as a means of improving soil productivity, carbon (C) storage and possibly filtration of percolating soil water (to try and cut pollution of surface and groundwater bodies). The production process and the intended use, forms the basis for distinguishing biochar (Lehmann *et al*., 2006) [30, 32]. Biochar is the appropriate term where charred organic matter is applied to soil in a deliberate manner, with the intent to improve soil properties. This distinguishes biochar from charcoal that is used as fuel for heat, as a filter, as a reductant in iron making or as a colouring agent in industry or art (Lehmann *et al*., 2006) [30, 32]. Biochar is the most widely used and arguably the best term. Biochar is very variable in quality, depending on raw material, pyrolysis conditions, whether it is enriched with other compounds and how finely it is ground. The problem is that biochar is a generic term and standards have not been established but are much needed (Barrow 2012).

Slow pyrolysis is said to minimize the risk of producing dioxins and harmful polyaromatic hydrocarbons, which could contaminate biochar and/or escape with exhaust gases and solid or liquid wastes. Low temperature pyrolysis gives a material with more desirable soil improvement properties than charcoal or ash that is also richer in aromatic carbon and humic substances (Barrow 2012). The pyrolysis can generate useful heat, biofuel or syngas as by-products. It may be possible to sequester more carbon dioxide in the soil than is liberated to the atmosphere during biochar pyrolysis: making it a carbon negative activity, which can enhance profitability (Fowles, 2007; Lal, 2007; Lehmann & Joseph, 2009;

Matthews, 2008b) [12, 28, 29, 38]. Sohi, Loetz-Capel, Krull, and Boll (2009) [59] noted biochar seems capable of remaining in soil without releasing carbon for centuries, even millennia and it enhances microbial activity. The mean soil carbon residence time for buried biochar is likely to be at least 1000 years, possibly longer (Nguyen & Lehmann, 2009) [43].

Some burnt materials like ash can be hydrophobic; so if added to soil they reduce moisture storage and enhance runoff resulting in poorer crops and even erosion; care needs to be exercised to ensure biochar does not have these qualities (Renner, 2007) [48]. So far the indications are that it enhances soil moisture. Beneficial applications might not need to be very frequent (compared with fertilisers, compost or manures). Ideally, biochar should have a long residence time in soil and actively support beneficial soil microorganisms. More research is needed to check these qualities. Also, successful biochar programmes will require more than technical know-how if they are to avoid unwanted socio-economic impacts; there must be political will, farmer support, organisational skills and the ability to cover the costs of raw material transportation and application to the land.

1.2. Important Feedstock for Biochar

Biochar can also be produced from manures and other animal wastes, including bone. For instance, dairy shed waste and chicken litter have been used to produce biochar (Cao & Harris 2010; Joseph *et al.* 2010; McHenry 2009) [21, 39]. There are also obnoxious weed viz. *Parthenium*, *Lantana* etc. having characteristic woody stem can be used for making biochar. Many types of manure are anaerobically digested to produce biogas (a mixture of methane and carbon dioxide) and it is possible that the remaining solid by-products could be used in pyrolysis reactions to produce biochar. When considering a potential feedstock for biochar production, biomass availability and moisture content must also be considered to ensure continual operation of the processing plant, with minimal energy input requirements. Pyrolysis of these types of waste may produce both energy and a biochar product with relatively high levels of plant nutrients, such as phosphorous, potassium, nitrogen, magnesium and calcium. Containment and use of nutrient rich manures and animal products for production of biochar may also have positive environmental effects including reduced nutrient runoff and corresponding reductions in greenhouse gas emissions, such as methane and nitrous oxide (He *et al.* 2000). Although manure and municipal waste may be used in pyrolysis, the high risk of contamination from toxic chemicals and heavy metals may limit its use on agricultural soils. The mineral content of potential biomass feed stocks must also be considered. Nik Azar *et al.* (1997) found that impregnating woody biomass with sodium, potassium and calcium increased biochar yields by up to 15 per cent. These findings are in agreement with other studies, where addition of inorganic salts (magnesium chloride, sodium chloride, iron sulphate and zinc chloride) increased production of char from 5 per cent (control feedstock; no addition of salts) to 8, 14, 17 and 28 per cent respectively (Varhegyi *et al.* 1988). However, addition of any minerals to feed stocks to increase biochar yield would, from an agricultural productivity perspective, have to be weighed against the effect of those minerals on soil structure, soil fertility and plant growth, and the cost of supplying these nutrients through other means.

Not all agricultural waste materials are suitable for biochar production for agricultural purposes (Lehmann *et al.* 2006; McHenry 2009) [30, 32, 39]. Some production conditions and feedstock types can cause the resulting biochar to be ineffective in retaining nutrients and susceptible to microbial decay (McHenry 2009) [39]. Depending on the biomass source, some biochar products, such as municipal waste, may contain high levels of toxic substances (heavy metals and organic pollutants) which must also be considered in the context of adding biochar to agricultural soils (Lehmann *et al.* 2006) [30, 32].

1.3. Potential benefits of biochar

- Store recalcitrant form of carbon in soil. Compost and manures are subject to rapid microbial breakdown. Sequestration in biochar is likely to be for centuries, possibly for thousands of years.
- Enhance plant growth. Raise and sustain crop yields. Help improve good and problematic nutrient-poor soils, including acidic tropical humid and drier environment soils. (Table 2)
- Help compensate for greenhouse gas emissions associated with agricultural development.
- Biochar may improve soil moisture retention, increasing agricultural resilience and provides support to intensive sustainable agriculture which could help to cut pressure for new forest clearances and enhances biodiversity conservation benefits.
- Enable production of useful materials from uncropped land making use of unused wastes with increased adaptability to environmental change by making production more resilient.
- Reduce the need for fertiliser/manure/compost. Reduce costs of sewage and animal waste treatment and cut emissions that they would otherwise cause if held in lagoons or heaps. Application of manure or compost to the soil may stimulate bacteria and cause methane and N_2O to the atmosphere. Composting also releases greenhouse gases and compost may have a limited residence time in soil. Pyrolysis destroys microorganisms and some veterinary pharmaceuticals. It also reported by many researchers worldwide to suppress methane and N_2O (nitrous oxide gas) emission from cultivated soil thereby reduces global warming.
- Offer a more environmentally-friendly way of processing plastics and refuse if biochar is too contaminated for agricultural use for growing non-food crops or send to landfill to sequester carbon.
- Nutrient affinity i.e. retention of plant nutrients, notably retention of N on permeable soils under rainy conditions is found higher with biochar application. Biochar may play role in bioremediation by binding agrochemicals and help reduce phosphate and nitrate and agrochemicals pollution of streams and groundwater. Thus helping resolve major problems hindering sustained and improved agriculture. Reduce plant uptake of pesticides from contaminated soils (Xiang-Yang Yu. *et al*., 2009) [74].
- Reduce soil acidity/raise pH (Rodriguez *et al.* 2009) [50]. Reduce aluminium toxicity and increases cation exchange capacity (Table 1). The published data suggest that biochars from woody materials tend to provide low CEC values, while non-woody plant materials such as sugarcane trash (leaf) or tree bark tend to have higher CEC values (Yamamoto *et al*., 2006; Chan *et al*., 2007; Major *et al*., 2009; Singh and Gu, 2010; Van Zwieten *et al*., 2010) [75, 4, 37, 57, 71].

Table 1: Effect of biochar on different soil properties (Srinivasarao *et al.* 2013) [63]

Some selected soil properties	Findings	Reference
Cation exchange capacity	50% increase	Glaser *et al.*, 2002 [14]
Fertilizer use efficiency	10-30% increase	Gaunt and Cowie, 2009 [13]
Liming agent	1 unit pH increase	Lehman and Rondon, 2006 [30]
Crop productivity	20-120% increase	
Biological nitrogen fixation	50-72% increase	
Soil moisture retention	Up to 18% increase	Tryon, 1948 [70]
Mycorrhizal fungi	40% increase	Warnock *et al.*, 2007 [37]
Bulk density	Soil dependent	Laird, 2008 [27]
Methane emission	100% decrease	Rondon *et al.*, 2005 [51]
Nitrous oxide emissions	50% decrease	Yanai *et al.*, 2007 [76]

- By improving moisture retention biochar may reduce the demand for irrigation and make cropping more secure.
- Support biofuel production and reduce its carbon footprint and even enable it to move toward being carbon neutral.
- Increase soil microbial biomass and support other beneficial organism like earthworms. Support nitrogen fixation. Increase arbuscular mycorrhizal fungi in soil.
- Opportunities for poor to benefit from carbon offset market and also reduce dependency of farmers on input suppliers.
- Periurban/urban agriculture: biochar may be a useful input to counter harmful compounds like heavy metals, dioxins, PAHs (polycyclic aromatic hydrocarbons) present in sewage or refuse inputs.

1.4. Biochar and Plant Growth

Most of the currently published studies (Table 2) assessing the effect of biochar on crop yield is generally small scale, almost all short-term, and sometimes conducted in pots where environmental fluctuation is removed. These limitations are compounded by a lack of methodological consistency in nutrient management and pH control, biochar type and origin. It is not therefore possible at this stage to draw any quantitative conclusion, certainly not to project or compare the impact of a particular one-time addition of biochar on long-term crop yield. Nonetheless, evidence suggests that at least for some crop and soil combinations, moderate additions of biochar are usually beneficial, and in very few cases negative.

Table 2: Effects of biochar on plant growth and yield

Crop	Experimental summary	Findings	Reference
Pea	Char @ 0.5 t/ha	biomass increased by 160%	Iswaran *et al.*(1980) [18]
Mungbean		biomass increased by 122%	
Soybean	Crops were grown on volcanic ash loam, Japan with char @ 0.5, 5, 15 t/ha	Char @ 0.5 t/ha increased yield by 151% whereas, Char at 5 t/ha and15 t/ha decreased yield by 63% and 29%, respectively	Kishimoto and Sugiura (1985) [24]
Sugi trees	Crops were grown on clay loam, Japan Wood charcoal, bark charcoal and activated charcoal at 0.5 t/ha	increased biomass by 249, 324 and 244%, respectively	
Bauhinia trees	Crops were grown on Alfisol/Ultisol	Charcoal application increased biomass yield by 13% and height by 24%	Chidumayo, (1994) [8]
Cowpea	Grown on xanthicferralsol char @ 67 and 135 t/ha	Char @ 67 and 135 t/ha increased biomass by 150% and 200%, respectively	Glaser *et al.* (2002) [14]
Cowpea	Planted in pots and rice crops in lysimeters, Brazil	Soil fertility and nutrient retention. Biochar additions significantly increased biomass production by 38 to 45%	Lehmann *et al.* (2003) [34]
Maize	Comparison of yields between is used charcoal production sites and adjacent fields, Ghana	Grain and biomass yield was 91 and 44% higher on charcoal site than Control	Oguntunde *et al.* (2004) [45]
Maize, cowpea and peanut	Trial in area of low soil fertility Acacia bark charcoal plus fertilizer	Increased in maize and peanut yields but not cowpea	Yamamoto *et al.* (2006) [75]
Radish	Pot trial on heavy soilusing commercial green waste biochar (three rates) with and without N	Biochar at 100 t/ha increased yield 3 times; linear increase 10 to 50 t/ha, butno effect without added N	Chan *et al.* (2007) [4]
Beans	Enhanced biological N_2 fixation (BNF) by common beans through biochar additions, Colombia	Bean yield increased by 46% and biomass production by 39% compared to control at 90 and 60 g biochar/kg, respectively	Rondon *et al.* (2007) [52]
Four cropping cycles with rice (*Oryza sativa* L.) and sorghum (*Sorghum* *bicolor* L.)	Charcoal amended with chicken manure amendments	Charcoal amended with chicken manure amendments resulted in the highest cumulative crop yield (12.4 t/ha)	Steiner *et al.* (2007) [67]
Maize	Mitigation of soil degradation with biochar. Comparison of maize yields in degradation gradient cultivated soils in Kenya	Doubling of maize grain yield in the highly degraded soils from about 3-6 t/ha	Kimetu *et al.* (2008) [22]
Rice	Pot experiment in alluvial soil with rice husk biochar @ 0, 4, 8 and 16 t/ha	Non-significant increase in the grain yield and dry matter accumulation due to biochar application	Singh 2013 [56]
Rice	Pot experiment in alluvial soil with rice husk biochar @ 5 and 10 t/ha	Dry matter increased by 11 and 17% as compared to control @ 5 and 10 t/ha, respectively	Rani 2013 [47]

1.5. Biochar and GHGs emission

Burning of residues emits a significant amount GHGs. For example, 70, 7 and 0.66% of C present in rice straw is emitted as CO2, CO and CH4, respectively, while 2.09% of N in straw is emitted as N2O upon burning. One ton straw on burning releases 3 kg particulate matter, 60 kg CO, 1460 kg CO2, 199 kg ash and 2 kg SO2. This change in composition of the atmosphere may have a direct or indirect effect on the radiation balance. Besides other light hydrocarbons, volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) and SOx, NOx are also emitted. These gases are important for their global impact and may lead to a regional increase in the levels of aerosols, acid deposition, increase intropospheric ozone and depletion of the stratospheric ozone layer.

Biochar production does emit carbon dioxide and other greenhouse gases but combined with waste disposal or biofuel production it appears to offer a practical way to mitigate global warming. Soil is a significant source of nitrous oxide (N_2O) and both a source and sink of methane (CH_4). These gases are 23 and 298 times more potent than carbon dioxide (CO_2) as greenhouse gases in the atmosphere. Biochar is reported to reduceN_2O emission could be due to inhibition of either stage of nitrification and/or inhibition of denitrification, or promotion of the reduction of N_2O, and these impacts could occursimultaneously in a soil (Berglund *et al*., 2004; DeLuca *et al*., 2006) [11]. Biochar potential is attracting much attention asa safe, practical, technically simple, and affordable method of sequestration, which has a chance of spreading fast enough to have real effect. If enough farmers, larger agricultural enterprises, biofuel producers, and waste treatment plants a are established it could become an important means of carbon sequestration. This potential is a little better researched than biochar agricultural value; although, there is insufficient data on biochar-burial soil carbon mean residence times. However, according to Sohi *et al.* (2010) [58], no peer-reviewed studies documenting suppression of nitrousoxide emissions in field experiments have been reported. There are, however, conference proceedings and laboratory-based peer-reviewed studies reporting reductions in nitrous oxide emissions (Clough & Condron 2010) [9]. Rondon *et al.* (2005) [51] found that adding biochar significantly reduced net methane and nitrous oxide emissions when infertile Colombiansavannah soils were amended with biochar at a rate of up to 30 grams per kilogram of soil. Researchers found that nitrous oxide and methane emissions were reduced by up to 50 and100 per cent respectively, at an optimal application rate of 20 grams of biochar per kilogram of soil (Rondon *et al.*2005) [51]. Similarly, Spokas *et al.* (2009) [60] found suppression of both methane andnitrous oxide at levels up to 60 per cent inclusion rates in laboratory trials (corresponding to720 tonnes biochar per hectare). Yanai *et al.* (2007) [76] also found that addition of biochar up to 10 per cent reduced nitrous oxideemissions by 89 per cent, but only when the soil was rehydrated with 73 to 78 per cent water filled pore space. However, biochar added to soils rehydrated at 83 per cent water-filled pores pace significantly stimulated nitrous oxide emissions compared with the control (Yanai *et al.* 2007) [76]. Increased soil aeration from biochar addition reduces denitrification and increases sink capacity for CH4. Biocharaddition induces microbial immobilization of available N in soil, thereby decreasing N_2Osource capacity of soil. Increased pH from biochar addition drives N_2 formation from N_2O.When applied to the soil, biochar can lower GHG emissions of cropland soils by substantially reducing the release of N_2O (Lehmann *et al.*, 2003) [34]. Reduction of N_2O and CH_4 emission asa result of biochar application is seen to attract considerable attention due to the muchhigher global warming potentials of these gases compared to CO_2 (Steiner, 2010) [64]. Rondon *et al.* (2005) [51] reported a 50% reduction in N_2O emissions from soybean plots and almost complete suppression of CH_4 emissions from biochar amended acidic soils in the Eastern Colombian Plains. Yanai *et al.* (2007) [76], however, reported an 85% reduction in N_2O emission from re-wetted soils containing 10% biochar, compared to soils without biochar. Biochar from municipal bio waste also caused a decrease in emissions of nitrous oxide in laboratory soil chambers (Yanai *et al.* 2007) [76]. Spokas *et al.* (2009) [60] also found a significant reduction inN_2O emission in agricultural soils in Minnesota; while Sohi *et al.* (2010) [58] found an emission suppression of only 15%. Additions of 15 g biochar/kg of soil to a grass and 30 g/kg of soil to a soil cropped with soybeans completely suppressed methane emissions (Rondon *et al.* 2005) [51].

1.6. Biochar and Soil Biota

Biochar has been described as a possible means to improves oil fertility as well as other ecosystem services and sequester carbon (C) to mitigate climate change (Lehmann *et al*., 2006; Lehmann, 2007a; Laird, 2008; Sohi *et al*., 2010) [30 32, 27, 58]. The observed effects on soil fertility have been explained mainly by a pH increase in acid soils (Van Zwieten *et al*., 2010a) [71] or improved nutrient retention through cation adsorption (Liang *et al*., 2006) [36]. However, biochar has also been shown to change soil biological community composition and abundance (Pietikäinen *et al*., 2000; Yin *et al*., 2000; Kim *et al*., 2007; O'Neill *et al*., 2009; Liang *et al*., 2010; Grossman *et al*., 2010; Jin, 2010) [46, 77, 22, 44, 35, 15, 20]. Such changes may well have effects on nutrient cycles (Steiner *et al*., 2008b) or soil structure (Rillig and Mummey, 2006) [49] and, thereby, indirectly affect plant growth (Warnock *et al*., 2007) [37]. Rhizosphere bacteria and fungi may alsopromote plant growth directly (Schwartz *et al*., 2006; Compant *et al*., 2010) [54]. Changes in microbial community composition or activity induced by biochar may not only affect nutrient cycles and plant growth, but also the cycling of soil organic matter (Wardle *et al*., 2008; Kuzyakov *et al*., 2009; Liang *et al*., 2010) [36]. The material properties of biochar are very different from those of uncharred organic matter in soil (Schmidt and Noack, 2000) [53], and are known to change over time due to weathering processes, interactions with soil mineral and organic matter and oxidation by microorganisms in soil (Lehmann *et al*., 2005; Cheng *et al*., 2008; Cheng and Lehmann, 2009; Nguyen *et al*., 2010) [33, 42, 6, 5, 42]. However, the relationships between biochar chemical and physical properties and their effects on soil biota and potential concomitant effects on soil processes are poorly understood. The chemical stability of a large fraction of a given biochar material means that microorganisms will not be able to readilyutilize the C as an energy source or the N and possibly other nutrients contained in the C structure. However, depending on the type of biochar, a fraction may be readily leached and therefore mineralizable (Lehmann *et al*., 2009) and in some cases has been shown to stimulate microbial activity and increase abundance (Steiner *et al*., 2008a) [65].

Many soil microorganisms are specialists living in microhabitats that provide resources for their specific metabolic needs. Forinstance, aerobic microbes live at the surface of soil aggregates, while denitrifiers and semi-aquatic species dwell within the moist interior of soil peds (Sexstone *et al*., 1985) [55]. Organic matter decomposition rates are higher at the surface of soil aggregates than in the core of aggregates due to higher influx of resources at the surface(organic matter, moisture, and O_2). This is evident from depleted C concentrations and C-to-N ratios, as well as the oxidation of ligninphenols and the accumulation of microbial polysaccharides at the aggregate surface relative to the aggregate core (Amelung and Zech, 1996) [1]. Similarly, the exterior surfaces of biochar particles in the soil are significantly more oxidized than the particle interior or core (Lehmann *et al*., 2005; Liang *et al*., 2006; Cheng *et al*., 2008) [33, 36, 6]. This is due to sorption of organic matter on the biochar surface and the oxidation of the biochar C itself (Liang *et al*., 2006) [36], both biotically and abiotically mediated via reactions with O_2 (Cheng *et al*., 2006, 2008) [7, 6]. Similar to soil aggregates, the preferential oxidation of the biochar particle surface relative to the particle interior impliesa limited diffusion of O_2 to the interior of biochar particles. Such differential redox conditions not only influence organic matter oxidation but also metal transformation.

2. Conclusion

Application of biochar to agricultural land for soil amelioration and agricultural productivity improvements is not a new phenomenon. A number of benefits have been identified within the literature; biochar has been found to improve agriculturally significant soil parameters such as soil pH, cation exchange capacity and soil water holding capacity. Researchers have found the increase in these performance parameters has improved nitrogen use efficiency and therefore crop productivity in limited field trials. Further, biochar has the potential to reduce greenhouse gas emissions through carbon sequestration, as well as potentially decreasing methane and nitrous oxide emissions from the soil. However, the variable application rates, uncertain feedstock effects, and initial soil state provide a wide range of cost for marginally improved yield from biochar additions, which is often economically impracticable. Long-term field research focusing on an optimal combination of nutrient use, water use, carbon sequestration, avoided greenhouse gas emissions, and changes in soil quality and crop productivity is needed before large-scale biochar application to soils. The need for further clarity on optimizing biochar application to various crop yields is necessary if it is to gain widespread acceptance as a soil health manager.

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