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Biochar and their impacts on soil properties and crop productivity: a review

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Abstract
Biochar may be added to soils with the goal to improve the soil properties and relocate an amount of conventional fossil fuel based fertilizers, and sequester carbon. Biochar stability is critical to quantifying the impact of biochar amendments on net greenhouse gas (GHG) emissions to the atmosphere, it is not sufficient. Biochar production and incorporation in soil must play a role in climate change mitigation. 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 amendment. There is urgent need to intensify agricultural production to secure food supply for the increasing population especially in developing country like India of the tropics. But, the organic matter is mineralized at a faster rate due to high temperature (32-44 ^{0}C) throughout the year except in winter season. Biochar proponents have placed on biochar stability in soil and it also includes increased soil fertility and water holding capacity, increased crop production, and remediation of contaminated soils. The organic matter is important for sustainable agriculture in the soils. The large quantities of biomass residues, which should be considered as precious residues, are disposed or burned, and reasons unaffordable ecological issues and notable soil degradation. Application of green waste biochar improves soil physical properties of this hard setting soil in terms of reduction tinsel strength and increases in field capacity. The biochar have potential to feasibly and sustainably sequester/offset over 1 Pg of CO_2-carbon equivalents annually. Current carbon market incentives are not sufficient to rapidly increase or maximize the initiation and development of biochar implementation.

Keywords: Soil properties, biochar, soil organisms, carbon sequestration

1. Introduction
The solid product of pyrolysis, called “biochar” in the context of climate change mitigation, is highly heterogeneous material with chemical composition that varies widely depending on feedstock and pyrolysis conditions (Spokas, 2010) [41]. The bio char is a thermo-chemical process where biomass is heated in the absence of oxygen. As a result, bio-oil, synthesis gas with different energy values and black carbon (biochar) are obtained. Bio char is a fine-grained and porous substance, similar in its appearance to charcoal produced by natural burning. Biochar is sterile, odorless, high carbon solid that may be produced from a variety of organic feedstock which can be tailored to suit the crop, soil type and management system to reach maximum benefit. The highly porous nature of biochar results from retaining the cell wall structure of the biomass feedstock. The biochar incorporation can alter soil physical properties such as structure, pore size distribution and density, with implications for soil aeration, water holding capacity, plant growth, and soil workability (Downie *et al*. 2009) [12]. Therefore, the bio char application can reduce the overall total bulk density of the soil which is generally desirable for most plant growth and increased water holding capacity (Chan and Xu, 2009) [6]. The increased in surface area, porosity, and lower bulk density in mineral soil with bio char could be alter water retention, soil aggregation, and decrease (Mbagwu and Piccolo, 1997) [30]. The effect of bio char was positive additions may be on moisture content found in coarse-textured soils (Glaser *et al.* 2002) [17]. Application of biochar improved the WHC in sandy soils proved by Downie *et al.* (2009) [12]. The International Biochar Initiative (IBI) promotes ubiquitous use of bio char as a soil amendment, advocates for inclusion of provisions favorable to bio char use in national and global climate mitigation policies, promotes biochar commercialization, and aspires to a global system that sequesters 2.2 Gt C/yr by 2050.

2. Impact of bio char on soils dynamics
2.1 Soil properties
The soil properties are the effect of bio char may be improve the soil pH, bulk density, water holding capacity, or cation exchange capacity. Crop yield improvements with biochar have

been demonstrated frequently for acidic and highly weathered tropical field soils and there is new data on biochar use in temperate soils of higher fertility (Husk and Major, 2010) [18].

2.2 Carbon sequestration

When it is added to soil, biochar has beneficial for growing crops; additionally biochar contains stable carbon (C) and after adding biochar to soil, this carbon remains sequestered for much longer periods than it would in the original biomass that biochar was made from. The biochar can rapidly increase the recalcitrant soil Carbon fraction of soil. Biochar also contains varying concentrations of other elements such as Oxygen (O), Hydrogen (H), Nitrogen (N), Sulfur (S), Phosphors (P), base cations, and heavy metals (Preston and Schmidt, 2006) [35]. Nutrient availability may be affected by increasing cation exchange capacity, altering soil pH, or direct nutrient contributions from biochar. Biochar has a greater ability to adsorb and retain cations in an exchangeable form than other forms of soil organic matter due to its greater surface area, and negative surface charge (Liang *et al.* 2006) [26]. Observed that biochar has a higher sorption affinity for a range of organic and inorganic compounds as compared to other forms of soil organic matter (Nguyen *et al.* 2004) [31].

2.3 Mineralization and Immobilization

Once added to the soil, abiotic and biotic surface oxidation of biochar results in increased surface carboxyl groups, a greater negative charge, and subsequently an increasing ability to sorb cations (Cheng *et al.* 2008) [9]. It also exhibits an ability to sorb polar compounds including many environmental contaminants (Yu *et al.* 2006) [52]. A small fraction of nutrients in the feedstock, apart from N, are retained in biochar in a potentially extractable form. The readily available nutrients and small amounts of labile C retained in biochar could promote mineralization process (Wardle *et al.* 2008) [47], especially in nutrient-limited environments. Biochar can serve as a liming agent resulting in increased pH and nutrient availability for a different soil (Lehmann *et al.* 2006) [25]. Attribute the increased plant growth responses observed to greater plant uptake with increased biochar application in sandy loam soil (Lehmann *et al.* 2003) [24]. The biochar application improved soil fertility status in sandy loam soils, especially soil O.C. CEC, available P, exchangeable K, Ca, Mg and increased nutrient uptake and maize yield (Sukartono *et al.* 2011) [43]. Biochar has been found to decrease nutrient leaching thus enhancing nutrient availability (Chan *et al.* 2007) [7]. Higher nutrient availability for plant is the result of both the direct nutrient addition by the biochar and greater nutrient retention (Lehmann *et al.* 2003) [24]. Biochar may supply a source of plant-available nutrients once applied to the soil (Sohi *et al.* 2010) [40].

2.4 Nitrogen recovery

The nitrogen recovery may be improved by biochar application to sandy loam but not silt loam soil suggesting soil textural effect in the effectiveness of biochar application for soil productivity (Yeboah *et al.* 2009) [51]. The availability of nutrients was greater with biochar and soil pH increased, attribute the greater crop yield and nutrient uptake primarily to the 77-320% greater available Ca and Mg in soil where biochar was applied (Major *et al.* 2010) [18]. Much greater yields in plant growth are observed with fertilizer additions plus biochar, as opposed to fertilizer additions alone (Blackwell *et al.* 2009) [4].

2.5 Fertilizer use efficiency (FUE)

Studies that reported loss of nutrients, for example via leaching or gaseous emissions, from soils amended with biochar. This apparent increase in fertilizer use efficiency with biochar is attributed to decreased bulk density, increased water holding capacity (Chan and Xu, 2009) [6]. Biochar applied was found to improve soil fertility and to reduce greenhouse gases emission and also to improve soil carbon sequestration (Lehmann *et al.* 2003) [24] but in case of application of biochar without fertilizer, it may cause N immobilization due to high C: N ratio. The efficiency of carbon conversion of biomass to biochar is highly dependent on the type of feedstock (Lehmann *et al.* 2006) [25].

2.6 Biochar feed stocks and Pyrolysis

The biomass pyrolysis and gasification are well established technologies for the production of biofuels and syngas. However, commercial employment of biochar as a soil amendment is still in its infancy. The effect of biochar as a soil amendment on crop productivity is variable due primarily to interactions and processes that occur when biochar is applied to soil, which are not yet fully understood. The pyrolysis process affects the qualities of the biochar produced and its potential value to agriculture in terms of soil performance or in carbon sequestration. The temperature and time the biomass is in the pyrolysis kiln, along with various feedstock types determines the nature of the product. Feedstock and process condition affect the characteristics of the biochar produced. The thermal profile and feed choice in addition to the geographic variations in soil type and climate are some of the chief sources of variability when looking to benefits of biochar as a soil amendment. Feed stocks currently used at a commercial scale or in research facilities include wood waste, crop residues (including straw, nut shells, and rice hulls), switch grass, bagasse from the sugarcane industry, chicken litter, dairy manure, sewage sludge and paper sludge. Biomass energy crops processed by slow pyrolysis such as cereals and wood along with agricultural wastes including wheat straw and peanut shells result in a char suitable for soil amendment. Green waste as plant prunings and grass clippings and waste water sludge has also been employed as soil amendments. A key differentiation between biochar feed stocks can be made between biochars made from nutrient rich feed stocks such as animal manures or sewage sludge, and biochars produced from lignin rich plant biomass feed stocks.

2.7 Crop productivity and biochar application rates

Studies that reported responses, such as yield or nutrient status, of plants grown on soils amended with biochar. Along with improved soil health, increased crop yield is generally reported with application of biochar to soils. However, many of the published experiments are highly variable and dependent on many factors, mainly the initial soil properties and conditions and biochar characteristics. Positive crop and biomass yield was found for biochar produced from wood, paper pulp, wood chips and poultry litter. Liu *et al.* (2013) reviewed published data from 59 pot experiments and 57 field experiments from 21 countries and found crop productivity was increased by 11% on average. Liu found benefits at field application rates typically below 30 tons/ha field application and reported that increases in crop productivity varied with crop type with greater increases for legume crops (30%), vegetables (29%), and grasses (14%) compared to cereal crops corn (8%), wheat (11%), and rice (7%). Biederman and

Harpole (2013) [3] analyzed the results of 371 independent studies. This meta-analysis showed that the addition of biochar to soils resulted in increased aboveground productivity, crop yield, soil microbial biomass, rhizobia nodulation, plant K tissue concentration, soil phosphorus (P), soil potassium (K), total soil nitrogen (N), and total soil carbon (C) compared with control conditions. The yield gains were attributed to the combined effect of increased nutrient availability (P and N) and improved soil chemical conditions resulting from the bio solid based amendment. However, there exists the concern of heavy metal contamination from biochars produced from sewage sludge. The inconsistency of sewage sludge might contain differing amounts of toxic metals which limit the land application due to food chain contamination. However, there appears to be an upper limit on the application of biochar additions and crop productivity.

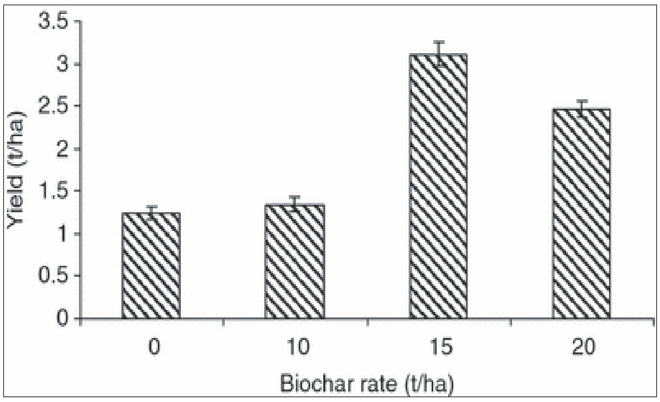
2.8 Movement of conventional (Fossil Fuel Based)

The fertilizer one of the reasons for the observed increase in crop yield with biochar application is the increase of nitrogen utilization from the applied fertilizer. This is the result from the decrease of nitrogen lost due the increase of soil CEC with biochar application or because of the ability of biochar to inhibit nitrate transformation by fertilizer. As biochar applications provide greater nutrient retention, this implies that less conventional fertilizers need to be applied to achieve a given crop yield. Because the vast majority of nitrogen fertilizer is derived from natural gas (CH_4) via the Haber-Bosch process, Gaunt and Cow in an assessment of biochar ability to reduce greenhouse gases, have estimated a 10%-30% reduction of nitrogen fertilizer use. Zhang *et al.* (2013) [53] estimate that for approximately every ton of N fertilizer manufactured and utilized, 13.5 tons CO_2 is emitted. Additionally, Sohi *et al*. (2009) [39] have suggested the concept of using syngas from the pyrolysis process to replace the natural gas to produce nitrogen. Combining the biochar and nitrogen that is produced in the same process can create a powerful carbon and nitrogen.

3. Impact of biochar on soil properties

3.1 Physico-chemical properties

The physio-chemical properties are soil pH, bulk density, water holding capacity, or cation exchange capacity of soils amended with biochar. Application of biochar at 10, 15 and 20 t ha^{-1} mixing rates significantly increased water use efficiency (WUF) increased by 6, 139 and 91 per cent, respectively as compared to control in sandy soil. Nutrient uptake by maize grain was significantly increased with higher biochar applications. Application of cow manure biochar improved the field-saturated hydraulic conductivity of the sandy soil, as result net water use efficiency also increased. Results of the soil analysis after the harvesting indicated significant increase in the soil pH, total C, total N, Olson-P, exchangeable cations and cation exchange capacity, Uzoma *et al.* (2011) [45]. Biochar increased green biomass growth of the maize on the fertile soil in absence or presence of bio-digester effluent and in the sub-soil when effluent was applied. Soil pH was increased from 4.0-4.5 due to addition of biochar, Rodriguez *et al.* (2009) [36].



Effect of biochar rate on maize grain yield. (Uzoma *et al*. 2011) [45]

Experiment on cowpea (*Vignaunguiculta* L. Walp) with added charcoal in *Anthroso* land they noticed that the increased biomass production and nutrient uptake are mainly as a result of direct nutrient additions with the added charcoal, especially of K, but also of P, Ca, Zn and Cu. The nutrient losses were relatively low. The cation exchange capacity of soil increased up to 50% by added charcoal from both hardwood and softwood, Lehmann *et al.* (2003) [24]. Chan *et al.* (2007) [7] observed that the significant effect of biochar and nitrogen fertilizer interaction. The higher yield of radish increases were observed with increasing rates of biochar application in the presence of N fertilizer, highlighting the role of biochar in improving N fertilizer use efficiency of the plant. Significant increases in pH, organic carbon and exchangeable cations were also observed in *Alfisol.* Application of cow manure biochar @ 15 and 20 t ha^{-1}was significantly increased total maize grain N uptake 67.14 and 63.42 kg ha^{-1}. Similarly, P uptake by grain increased by 49, 215 and 175 percent in cow manure biochar @ 10, 15 and 20 t ha^{-1}, respectively as compared with control in sandy soil, Uzoma *et al.* (2011) [45]. Jin-Hua *et al.* (2011) [20] revaluated that the alkalinity of the biochar from legume straw was greater than that from non-legume straws (P<0.05), thus the incorporation of legume biochar decreased soil exchangeable acidity and increased soil exchangeable base cations and base saturation, thus improving soil fertility. Matsubara *et al.* (2002) [29] reported that greenhouse experiment the soil pH of treatments receiving biochar increased from 5.4 to 6.2 (10% biochar by volume) and 6.3 (30% biochar by volume).

3.2 Biological properties

Studies that described or reported changes in soil microbes, fungi, earthworms, or other soil fauna on biochar or in soil amended with biochar. The major effects of biochar addition were the same in forest and arable soil types and depended only on the biochar type. While the addition of glucose-derived biochar rarely changed the composition of the soil microbial community, the yeast- derived biochar strongly promoted fungi in both soils (Steinbeiss *et al*. 2009) [42]. The application of grass derived biochar and oak derived biochar in unburned increased the bacterial population (118.7±121.0 and 87.7±4.4 CFUs are per gram of soil, respectively) as compared to control (31.8 ± 1.4 CFUs are per gram of soil) application of biochar (Khodadad *et al.* 2011) [22]. Biochar was added to an agricultural field at 0, 25 and 50 t ha^{-1} and planted with maize (year 1) and grass (year 2 and 3). The year 2 effect of biochar @ 50 t ha^{-1} on bacterial growth that was stimulated by about 80%, from 47.6 ± 6.9 pmolLeu h^{-1} g^{-1} in the control soil to 85.5 ± 10.8 pmolLeu h^{-1} g^{-1} in the presence of biochar. Similarly, the rate of fungal growth was also stimulated, if too a smaller extent, by about 21% from 3.9 ± 0.3 pmolLeu h^{-1} g^{-1} in the control soil to 4.7±0.2 pmol Ac h^{-1} g^{-1} in the presence of biochar (Jones *et al.* 2011) [21]. Yeboah *et al.* (2009) [51] observed that application of biochar @ 3 t ha^{-1} plus 120 kgN ha^{-1} significantly higher biomass root yield of maize in sandy loam soil as compared to silt loam soil. The results show that biochar enhanced crop growth better in a sandy loam soil compared to the silty loam soil suggesting soil textural effect in the effectiveness of biochar application for crop growth. Prenderast-Miller *et al.* (2011) [34] observed that application of biochar @ 20, 60 t ha^{-1} significantly increased the root length ratio (root length/plant biomass) 17.03 and 13.55%, respectively in sandy loam soil of wheat crop over to control. It indicates the biochar treatment at 20 and 60 t ha^{-1} produced larger root, thus increasing surface area and soil contact, this may be the biochar mechanism behind the increase N content within the rhizosphere of biochar.

3.3 Effect on biochar on root colonization by mycorrhizal fungi

The porous structure of biochar gives it a good habitat for microbes (Shoi *et al.* 2009) [39]. The biochar properties may enhance soil microbial communities and create microenvironments that encourage microbial colonization. Biochar pores and its high internal surface area and increased ability to adsorb OM provide a suitable habitat to support soil microbiota that catalyzes processes that reduce N loss and increase nutrient availability for plants (Winsley, 2007) [49]. There are improved in root colonization by mycorrhizal fungi with biochar (Warnock *et al.* 2007) [48]. Matsubara *et al.* (2002) [29] showed that a fresh organic amendment had fairly similar effects as biochar in increasing AMF mediated host plant resistance against fusarium and that the asparagus plants reached similar mycorrhizal colonization levels with both additions. Xie *et al.* (1995) [50] and Cohn *et al.* (1998) [10] stated that *Rhizobium sp.* and *Bradyrhizobium sp.* can produce compounds that induce flavonoid production in nearby plants (legumes) that may ultimately increase root colonization of plant roots by AM fungi.

4. Guidelines and recommendations ofbiochar application

4.1 Application rate

Recommended application rates for any soil amendment must be based on extensive field testing. Biochar materials can differ widely in their characteristics, thus the nature of a specific biochar material (e.g. pH, ash content) also influences application rate. Several studies have reported positive effects of biochar application on crop yields with rates of 5-50 tonnes of biochar per hectare, with appropriate nutrient management. This is a large range, but often when several rates are used, the plots with the higher biochar application rate show better results (Major *et al.* 2010b) [28]. Since the C content of biochar materials varies, it may be appropriate to report application rates in tonnes of biochar-C per hectare, as opposed to tonnes of bulk biochar material. A 10 t/ha application of poultry manure biochar contains much less C (and more ash) than an equivalent application of wood waste biochar. However, "high-ash" biochar can constitute a source of various plant nutrients, and these should be taken into consideration when managing soil fertility at the field level. Most biochar materials are not substitutes for fertilizer, so adding biochar without necessary amounts of nitrogen (N) and other nutrients cannot be expected to provide improvements to crop yield. Instances of decreasing yield due to a high biochar application rate were reported when the equivalent of 165 t of biochar/ha was added to a poor soil in a pot experiment (Rondon *et al*. 2007) [37].

4.2 Frequency of application

Due to its recalcitrance to decomposition in soil, single applications of biochar may be provide beneficial effects over several growing seasons in the field (Major *et al*. 2010b) [28]. Therefore, biochar does not need to be applied with each crop, as is usually the case for manures, compost, and synthetic fertilizers. Depending on the target application rate, the availability of the biochar supply, and the soil management system, biochar amendments can be applied in increments. However, it is believed that beneficial effects of applying biochar to soil improve with time, and this may need to be taken into consideration when splitting applications over time.

5. Effect of biochar application

5.1 Adverse effect

At this high application rate, yields decreased to the level of the unamended control. This is a very large amount that is unlikely to be practically feasible in the field, at least for a one-time amendment. However, Asai *et al*. (2009) [2] working in Laos reported greater upland rice yields with 4 t/ha biochar, but when 8 or 16 t/ha were applied, yields were not different from the unamended control. A more recent field study on a poor, acidic soil of the USA showed that peanut hull and pine chip biochar applied at 11 and 22 t/ha could reduce corn yields below those obtained in the control plots, under standard fertilizer management (Gaskin *et al*. 2010) [14].

5.2 Residual effect

The residual effect of biochar and mineral fertilizers was assessed using a mycorrhizal bioassay for soil collected from the field trial 2 years after application of biochar. Biochar and both fertilizers increased mycorrhizal colonisation in clover bioassay plants. Deep-banded biochar provided suitable conditions for mycorrhizal fungi to colonise plant roots (Sdaiman *et al.* 2010) [38]. The application of biochar @ 0, 5, 10 and 20 g kg^{-1} soil with and without 5 g kg^{-1} of dried swine manure and results show that a significant decrease in the total amount of N, P, Mg and Si that leached from the manure amended columns as biochar rates increased but among columns receiving manure, the 20 kg^{-1}biochar treatments reduced total N and total dissolved P leaching by 11% and 69%, respectively (Laird *et al.* 2010) [23].

6. Conclusion

The present study was concluded the biochar behaviour in soil properties and stability of crop production. The biochar production and application affects whole-system GHG balance. The emissions associated with biochar production, transportation, and application to soils; the extent to which biochar amendment stimulates ("primes") decomposition of soil organic matter; the influence of biochar on non-CO_2 trace gas emissions; and the amount of energy captured during biochar production. The promise and limitations of biochar production and amendment to field soil should be evaluated against a range of biomass management options, including burning biomass for energy and leaving dead wood in place. The potential long-term benefits of biochar-based carbon sequestration come at a cost of short-term CO_2 pulses into the atmosphere and, consequently, near-term acceleration of climate change. There is insufficient empirical evidence to support assertions that biochar amendment to soil mitigates climate change significantly of overall environmental benefits.

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