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Effect of Biochar on Soil Health and Crop Productivity: A Review

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ABSTRACT

Biochar has been recently proposed as a management strategy to improve crop productivity and global warming mitigation. 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 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 ever increasing population especially in developing country like India of the tropics. 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 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.

Key words: Biochar, Carbon sequestration, Soil amendment, Soil organisms, Soil properties.

Soil health is the foundation of a vigorous and sustainable food system. As the land is farmed, the agricultural process disturbs the natural soil systems including nutrient cycling and the release and uptake of nutrients (Skjemstad *et al.,* 2002; Lal, 2004). 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 (DeLuca *et al.,* 2006; Glaser *et al.,* 2001). Biochar is a potential soil amendment and carbon sequestration medium. It also reduces farm waste and improves the soil quality.

The key role of agriculture now and in future is to provide safe and quality food for ever growing population. But agriculture is of more significance to global climate change and its effects on soil health and crop productivity. High yields often come from the use of improved crop varieties, fertilizers, pest control measures and irrigation, which have resulted in food and nutritional security (Lehmann *et al.,* 2011). Despite high productivity, farmers see various problems associated with our intensive agricultural systems. It emphasizes the integration of biological, chemical and physical measures of soil quality that affect farmers profit and the environment. Efficient use of crop residue based amendment in soil is an important strategy to improve the soil fertility and productivity in rainfed areas.

Annually 500 Mt crop residues are generated in India, out of which 141 Mt is surplus. These residues are either partially utilized or un-utilized due to various constraints. Surplus and unused crop residues when left unattended, often disrupt land preparation, crop establishment and early crop growth and therefore are typically burnt on farm which causes environmental problems and substantial nutrient losses (Kannan Pandian *et al.* 2016). Efficient use of huge amount of biomasses, available as crop and agro forestry residues and other farm wastes by converting it in to a useful source of soil amendment. In this concern, biochar is an organic soil amendment, has emerged as a potential strategy to mitigate climate change, to maintain soil health and ensure the sustainable food production at the global scale.

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Biochar

Biochar is a solid material obtained from thermo-chemical conservation of biomass in an oxygen limited environment (IBI, 2015). Biochar is a fine-grained, carbon-rich, porous product remaining after plant biomass has been subjected to thermo-chemical conversion process (pyrolysis) at temperatures (~350-600°C) in an environment with little or no oxygen. (Ameloot *et al*., 2015). The word Biochar is derived from Greek word. Bios means life; char means charcoal (product of carbonization of biomass). The term biochar was invented by Peter Read (lobbyists for biochar plantations). Biochar is a carbon material made by a process called pyrolysis and it is used as a soil amendment (Krull *et al.,* 2006). It is the black carbon rich material derived by heating biomass with limited supply of oxygen. Unlike the original biomass, it contributes to long term removal of CO_2 from atmosphere, since it is chemically and biologically more stable.

Need of biochar research in India

a. Reduce the crop residue burning in the field

Open field burning of crop residues is an age old practice to boost soil fertility in terms of P and K, but it often leads to a loss of other nutrients such as N and S, organic matter and microbial activity required for maintaining better soil health (IARI, 2012). But maintenance of threshold level of organic matter in rainfed soil is crucial to sustain soil physical, chemical and biological health. For more effective management and disposal of the crop and agro forestry residues, their conversion into biochar through thermo-chemical process (slow pyrolysis) is an alternative way of managing unusable and excess crop residues, examples of crop residues are given in Table 1.

b. To improve organic carbon in soil

Biochar contains organic matter and nutrients, its addition increased soil pH, EC, Organic carbon in soil and thereby improves the soil fertility.

c. To reduce CO_2 rise in atmosphere

The burning and natural decomposition of biomass and in particular agricultural waste adds large amounts of CO_2 to the atmosphere. Biochar is a stable way of storing carbon in the ground for centuries, potentially reducing or stalling the growth in atmospheric green house gas levels.

Table 1: Loss of nutrients through crop residues.

Crop residue	Loss of nutrient Mt/y			Total
	N	P	K	
Rice	0.236	0.009	0.200	0.45
Wheat	0.079	0.004	0.061	0.14
Sugarcane	0.079	0.001	0.033	0.84
Total	0.394	0.014	0.295	1.43

d. Environmental degradation

Biochar helps in improving environmental quality by reducing soil nutrient leaching losses, reducing bioavailability of environmental contaminants, sequestering carbon, reducing GHG emissions and enhancing crop productivity in highly weathered or degraded soil.

Impact of biochar on soil properties

Soil physical and chemical properties

The physio-chemical properties are soil pH, bulk density, water holding capacity, or cation exchange capacity of soils amended with biochar are positively increased. Khaled *et al.,* (2019) conducted the field experiment in sandy soils with application of different rates of biochar *viz.*,10, 15 and 20 t ha^{-1} and concluded that the significantly increased water use efficiency (WUF), Crop Growth and Water Retention by 50 to 90 per cent, respectively as compared to the control like without biochar applied treatment, because the positive effect of BC treatments on water retention in the soil increased with increasing time of incubation and was greatest for the low pyrolysis temperature BC (BC300). This indicated that, as BC ages in soil, it can be more effective in promoting water retention, especially the low pyrolysis temperature. Patel and Yadav (2018) conducted the experiment in sandy soils in application of RDF along with Maize stover char @ 10 t ha^{-1} application recorded the significantly lower bulk density (1.05 g cm^{-3}) and also increasing the Water holding capacity of the soil all so positively significant of 28.27 per cent, these results are confirmed with the (Castaldi *et al.,*2011). Besides, the decrease in bulk density of biochar-amended soil could be one of the indicators of enhancement of soil structure or aggregation and aeration and could be soil-specific (Atkinson *et al*., 2010).

Kannan Pandian *et al.* (2016) conducted a field experiment in Alfisol of Semi-Arid tropics and the results are reported that soil application of red gram biochar improved the field-saturated hydraulic conductivity of the sandy soil, as result net water use efficiency also increased. At the same time chemical properties of soil also alter like soil pH, total C, total N, Olson P and cation exchange capacity, because the applied biochar have more number of functional groups that are easily adsorbed the cation are strongly and increasing the nutrient availability of soils (Hong *et al.,*2014). Snekapriya and Jayachandran (2018)

Table 2: Summary of impact of biochar application on soil properties changes.

Soil properties	Findings	References
Cation exchange capacity	50% increased	Glaser *et al.,* 2002, Liang *et al.,* 2006
Fertilizer use efficiency	10-30% increased	Lehmann *et al.* 2007
Crop productivity	20-80% increased	Rangaswami *et al.* 2020
Biological nitrogen fixation	50-70% increased	
soil moisture retention	18% increased	Kannan Pandian *et al*., 2016
Mycorrhizal fungi	40% incresed	Snekapriya and Jayachandran (2018)
Bulk density	Soil dependent	Patel and Yadav 2018
Methane emission	80% decreased	Segun *et al.,* 2019

conducted a research trial in sugar cane crop with application sugarcane trash biochar @ 2 t ha^{-1} along with grade levels fertilizer application and results are concluded that the long-term effect on biochar, the soil properties are positively increased because the biochar will be take time to mineralization and slowly released the nutrients and then crop will be easily increased uptake and availability of soils also increased the same findings also reported by Supriya *et al*., (2019) and Jin-Hua *et al.* (2011). Some important soil properties changes are given in Table 2.

Soil biological properties

Biochar pores and its high internal surface area which increased ability to absorb organic matter act as refuge for soil microbiota from predators and desiccation. The population of bacteria, actinomycetes and arbuscular mycorrhizal fungi increased due to application of biochar and this microbiota reduce N loss and increase nutrient availability for plants. The chemical stability of a large fraction of a given biochar material means that microbes will not be able to readily utilize the carbon as an energy source or the nitrogen and possibly other nutrients contained in the carbon structure.

Snekapriya and Jayachandran (2018) conducted a research trial on sugar cane with different grades of NPK (50, 75, 100, 125, 150 per cent along with Biochar @ 2 t ha^{-1}) and with biofertilizers (PSB and *Rhizobium*) in sandy soil and the results are reported that maximum microbial population was bactriea (33.16 cuf), fungi (10.25 cuf) and actinomycetes (17.44 cuf) observed in application of 150 per cent dose of NPK along with 2 t of biochar + biofertilizer @ 10 kg ha^{-1}.Segun *et al*., (2019) tried with different levels of rice straw biochar application (0, 3, 6 and 12 t ha^{-1}) in sandy loam soil at Nigeria and observed that 12 t ha^{-1} of biochar application treatment significantly increasing higher soil enzyme activities. The increase in soil biological activity has been reported by Rondon *et al.* (2007) for nitrogen fixation in *Phaseolus vulgaris* and by Chan *et al.* (2008) for earthworm and microbial biomass. Biochar application to soil has long tradition provided evidence that it has positive effects on the abundance of mycorrhizal fungi.

Impact of biochar on soils dynamics

Fertilizer use efficiency (FUE)

Biochar function and its interaction with nutrient elements and crop roots may throw light on understanding fertilizer use efficiency. The enhanced nutrient retention capacity of biochar-amended soil not only reduces the total fertilizer requirements but also copes up the climate and environmental impact on crops (Chan and Xu, 2009). Biochar significantly increases the efficiency and reduces the need for traditional chemical fertilizers with sustainable crop yields. Biochar helps to improve soil resources by increasing crop yields and productivity by the way of reducing soil acidity and reducing the need for some chemical and fertilizer inputs (Yeboah *et al.* 2009). Longer-term benefits of biochar application on nutrient availability mainly due to a greater stabilization of organic matter, concurrent slower nutrient release from added organic matter and better retention of all cations due to a greater cation exchange capacity. High rates of biochar addition in the tropical environment have been associated with increased plant uptake of P, K, Ca, Zn and Cu (Lehmann *et al.,* 2007).

Biological nitrogen fixation by common beans was increased from 50 to 72% of total nitrogen uptake with increasing rates of biochar additions (0, 31, 62 and 93 tC ha^{-1}) to a low-fertility Oxisol (Rondon *et al.,* 2007). Biochar also adds some macro (P, K, N, Ca and Mg) and micronutrients (Cu, Zn, Fe and Mn) which are needed for sustainable agriculture (Major *et al*., 2010). It may significantly affect nutrient retention and play a key role in a wide range of bio-geochemical processes in the soil, especially for nutrient cycling. A beneficial impact of biochar on the plant-available phosphorus has been observed in soils enriched with biochar, which in contrast to ammonium, is not a characteristic generally associated with soil organic matter (Lehmann *et al*., 2007; Steiner *et al*., 2007).

Soil nutient leaching prevention

Biochar has been found to decrease nutrient leaching thus enhancing nutrient availability (Chan *et al.* 2007). Higher nutrient availability for plant is the result of both the direct nutrient addition by the biochar and greater nutrient retention. Biochar may supply a source of plant-available nutrients once applied to the soil. This possibility is suggested by the strong adsorption affinity of biochar for soluble nutrients such as ammonium, nitrate, phosphate and other ionic solutes. Lehmann *et al*. (2007) found that "cumulative leaching of mineral N, K and Mg in the soil was only 24, 45 and 7%, respectively, to control biochar (Krishna Veni *et al.,* 2017). Results of the column leaching experiment showed that biochar addition significantly influenced Na^+, K^+, Ca^{++} and Mg^{++} concentrations in the leachate. For Na+ concentration, no significant difference was found with biochar amendment under non-saline irrigation compared to respective non-biochar control.

Modification of soil

Biochar is commonly alkaline. The pH values of biochar at different pyrolysis temperature ranged from slightly alkaline (8.2) to highly alkaline (11.5) across a wide variety of feedstocks. Biochars shows positive effect in the case of acidic soils compared to alkaline soils (Biederman and Harpole, 2013). Biochar addition can reduce the bio-availability of toxic forms of Al, Cu and Mn and increase the availability of essential nutrients such as Na^+, K^+, Ca^{++}, Mg^{++} and Mo, thereby rendering a favourable environment for plant growth (Atkinson *et al.* 2010, Naresh Kumar *et al.,* 2018). Among different treatments 60 g kg^{-1} of biochar application treatment was recorded the lowest exchangeable acidity this was followed by lime application @ 4 g kg^{-1} of soil and the control recorded highest exchangeable acidity of without biochar and lime application. This might be due to the soluble and exchangeable Al_3^+ precipitates as insoluble hydroxyl Al-species at higher pH condition. Apart from increasing the incorporation of biochar to acidic soil can release their base cations which can participate in exchange reactions and replace the exchangeable Fe^{3+}, Al^{3+} and H^{+} on the soil surface and decrease the soil exchangeable acidity. Biochar can serve as a liming agent resulting in increased pH and nutrient availability for a different soil (Lehmann and Joseph 2007).

Biochar application on crop yield

Biochar on crop yield depend largely on the amount of biochar application and soil types. It is a positive effect on crop yield in general and it is more effective when applied to low to medium fertile soils (Chen *et al.,* 2019). Liu *et al.* (2017) 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 t ha^{-1}, 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%). Combination of higher biochar application rates with NPK fertiliser increased crop yield on tropical Amazonian soils (Steiner *et al.,* 2007) and semi-arid soils in Australia (Ogawa, 1994). Major *et al.,* (2010) conducted a multiyear experiment in a maize - soybean rotation system and found that the maize yield was increased by 28 to 30 per cent in two years continuously cultivation. Several authors are confirmed the biochar application on crop yield will be increased are given in the Table 3.

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 (Segun *et al.*, 2019). The application of biochar had significantly influenced the soil OC content after 3 years of experiment in Alfisol, at the end of the experimentation control soil had only 3.6 g kg^{-1} OC, whereas the soils that received different sources of biochar had soil OC content ranged between 4.4 and 4.8 g kg^{-1}. Increase in the levels of biochar increased the content of OC, WSC (73%) and BMC (37%) in studied soil. (Kannan Pandian *et al.,* 2016).

Biochar addition seems to generally enhance plant growth and soil nutrient status and decrease N_2O emissions. Its amendment reduced CO_2 production for all amendment levels tested (2, 5, 10%, 20, 40 and 60% weight by weight basis; corresponding to 24 to 720 t ha^{-1} field application rates). The recalcitrance of the biochar suggested that it could be a viable carbon sequestration strategy and might provide substantial net GHG benefits with long lasting

Table 3: Summary of impact of biochar application on crop yield .

Crops	Soil type	Biochar ($t\ ha^{-1}$)	Fertilizer rate ($kg\ ha^{-1}$)	Yield / biomass	Additional information	References
Wheat	Ferrosol	10	N (100)	250	Similar response was observed for biomass yield of Soybean and radish.	Zwieten *et al.* (2010)
Radish	Alfisol	100	N (100)	266	In the absence of nitrogen fertilizer application of Biochar did not increase the dry matter production of radish even at higher rate (100 t/ha).	Chan *et al.* (2007) Chan *et al.* (2008)
Rice	Inceptisol	30	Nil	294	Sole effect of biochar and interaction effect of earth worms.	Noguera *et al.* (2010)
	Oxisol	88	Nil	800		
Maize	Oxisol	20	N (156), P (36), K (83)	28 (1st year) 30 (2nd year) 140 (3rd year	In the first year after biochar application. No significant effect on crop yield was observed.	Major, (2010)
Rice	Ferrosol	11	N (30), P (36), K (50)	+29 (stover) +73 (grain)	While charcoal addition alone did not affect crop production, a synergistic effect occurred when both charcoal and inorganic fertilizer were applied.	Steiner *et al.* (2008)
Groundnut	Alfisol	15	N (10), P (10), K (45)	+55 (pod)	Biochar addition mainly influence soil moisture eretention their by enhance the nutrient .	Kannan *et al.* (2012)

reductions in N_2O production. Biochar has potential to mitigate climate change as maximum of 1.8 mt of CO_2 equivalents per year without affecting food security and ecosystem. This is equivalent to 12% of current anthropogenic CO_2 emissions annually (Woolf *et al.,* 2010). The extent of this stimulation varies according to different estimates, being larger up to 60% in forest and smaller about 14% for pastures and crops. To assess the carbon sequestration potential of adding biochar to soil, we must consider four factors *viz*., the longevity of char in soil; the avoided rate of GHG emission; how much biochar can be added to soils and how much biochar can be produced by economically and environmentally acceptable means.

Effect of biochar application

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) working in Laos reported greater upland rice yields with 4 t ha^{-1} biochar, but when 8 or 16 t ha^{-1} 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 pinechip biochar applied at 11 and 22 t ha^{-1} could reduce corn yields below those obtained in the control plots, under standard fertilizer management (Gaskin *et al*. 2010).

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). 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 ha^{-1} biochar treatments reduced total N and total dissolved P leaching by 11% and 69%, respectively (Laird *et al.* 2010).

Conclusion

The soil health concept has increased awareness among agriculturist and horticulturist regarding the importance in maintaining soil fertility, crop productivity and environmental quality over a long term period. Biochar has positive effects on the physico-chemical and biological properties of soil, which means soil health directly and indirectly influenced with the application of biochar. The positive gains of biochar application in the soils include: retaining nutrients and cation exchange capacity, decreasing soil acidity, improving soil structure, nutrient use efficiency, water holding capacity, decreasing release of non-CO_2 green house gases (CH_4, N_2O), increased number of beneficial soil microbes.

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