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Influence of biochar on soil properties, soil health and crop productivity- a review

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Abstract
India achieved a spectacular growth in agriculture since 1966, but for meeting the needs of current growing population, food grain production has to be increased at least 70 per cent by 2050. Over more the present-day agriculture is challenged to fulfill the objectives of achieving food, fodder, fibre and fuel security as well as environmental sustainability to restoring soil resources, improving water quality and mitigating climate change. Therefore, it is crucial to maintain the threshold level of organic matter for maintaining physical, chemical and biological integrity of the soil and also to perform its agricultural production and environmental functions (Segun and Oladele, 2019). For managing these issues, addition of organic amendments and biochar to mitigate climate change and ensures food production at global scale. Biochar (commonly known as agri char) is a carbon rich product derived from slow pyrolysis process of several kinds of waste biomass. Application of biochar at the rate of 5 t ha^{-1} favourably influenced the soil bulk density, pH, OC, microbial carbon and CEC in the soil and positive changes in increasing nutrient availability. Further application of biochar may offer additional carbon-negative benefits though avoiding burning in field and bioresource recycling, which have been a great concern with air pollution of Indian agriculture and climate change mitigation (Segun and Oladele. 2019). Application of biochar at low doses (3–6 t/ha) with low rate of nitrogen fertilizer (30 kg/ ha) notably improved N fertilizer use efficiency, grain biomass yield of upland rice and soil physicochemical properties.

The results of Snekapriya and Jayachandran (2018) concluded that application of 100 per cent recommended dose of NPK along with 2 t of bio-char + *Azospirillium* @ 10 kg ha^{-1} recorded higher benefit cost ratio of 1.96 for sugarcane seed cane production. The digested-enriched biochar treatments significantly improved soil quality as it provided higher soil organic matter and macronutrients. Application of green waste biochar improves soil physical properties and reduce tensile strength and increases the field capacity (Naresh Kumar *et al.*, 2018). Recent studies have demonstrated that soil pH was a main factor affecting soil microbial community and stability of biochar. Little information is available for the micro biome across different soil pH and subsequently CO_2 emission. However, the decreased bioavailability of SOC via adsorption of biochar resulted in higher abundance of oligotrophic bacteria in Phaeozems, leading to the decrease in CO_2 emission.

Keywords: biochar, climate change mitigation, environmental sustainability, carbon sequestration

Introduction

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. 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. 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. Despite high productivity, farmers see various problems associated with our intensive agricultural systems. Soil health is one of the foundations for vigorous and sustainable food system. 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. 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.

Biochar

Biochar is a solid material obtained from thermo chemical conservation of biomass in an oxygen limited environment (IBI, 2012) [5]. 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. (Amonette and Joseph, 2009) [1].

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. 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 CO2 from atmosphere, since it is chemically and biologically more stable (Lehman and Joseph, 2012) [9].

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) [4]. 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.

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 greenhouse gas levels.

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.

Table 1

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

Methods of biochar production

1. Gasification

Gasification is a process that converts organic- or fossil fuel-based carbonaceous materials into carbon monoxide, hydrogen and carbon dioxide. This is achieved by reacting the material at high temperatures (>700 °C), without combustion, with a controlled amount of oxygen and/or steam.

The resulting gas mixture is called syngas or producer gas and is itself a fuel. The power derived from gasification and combustion of the resultant gas is considered to be a source of renewable energy if the gasified compounds were obtained from biomass. Gasification can also begin with material for biochar production which would otherwise have been disposed of such as biodegradable waste.

2. Pyrolysis

The word is coined from the Greek-derived elements pyro "fire" and lysis "separating". Pyrolysis is a thermal decomposition of materials at elevated temperatures in an inert atmosphere such as a vacuum or nitrogen gas. It involves the change of chemical composition and is irreversible. Pyrolysis is most commonly applied to the treatment of organic materials. It is one of the processes involved in charring wood, starting at 200-300°C (390-570). In general, pyrolysis of organic substances produces volatile products and leaves a solid residue enriched in carbon, char.

Extreme pyrolysis, which leaves mostly carbon as the residue, is called carbonization. The process is used heavily in the chemical industry, for example, to produce ethylene, many forms of carbon, and other chemicals from petroleum, coal, and even wood, to produce coke from coal. Certain uses of pyrolysis are called dry distillation, destructive distillation, or cracking. The processes involve thermal depolymerization, i.e. the breaking of chemical bonds in macromolecules to give smaller fragments. The phenomenon involves exceeding the ceiling temperature of polymers. Pyrolysis is the basis of several methods for producing fuel from biomass, i.e. lignocellulosic biomass.

Types of pyrolysis

There are three types of pyrolysis based on different pyrolysis temperature and product of pyrolysis:

- **Slow pyrolysis**

It operates at low temperature (less than 400- 500^{0}C) and it takes more time for pyrolyzed product. It yields (35%) of biochar.

- **Flash pyrolysis**

It Operates at higher temperature (450-100 ^{0}C) and achieves up to 75% of bio-oil and 12% Solid biochar.

- **Fast pyrolysis**

It takes seconds to complete the pyrolysis with temperature range of (800 ^{0}C). It Yields 60% bio-oil, 20% biochar and 20% syngas (Laird *et al.*, 2009) [7].

Feed stock for biochar

Sources of feedstock used for pyrolysis

Green waste, Sawdust, waste wood, Nut shell, Straw, Cotton trash, Rice hulls, Animal waste including poultry litter, dairy manure, and other manures.

Characteristics of biochar

Physical characterization

Pyrolysis temperature is the main regulating factor which governs characterization of biochar.

Table 2

Low temperature (400ºC & below)	High temperature (600 – 900ºC)
Surface area 120 sq. m/gm	Surface area 460 sq. m/gm
Material analogous to activated carbon	Suitable for controlling release of nutrients
Lower ash content	Higher ash content

Chemical characterization

Table 3

Low temperature (400ºC & below)	High temperature (600 – 900ºC)
Lower carbon content	Higher carbon content.
Higher amount of N, S, K & P compounds	Lower amount of N, S, K & P compounds
Lower pH, EC & extractable NO_3^-	Higher pH, EC & extractable NO_3^-
Higher extractable P, NH_4^+ and phenol	Lower extractable P, NH_4^+ and phenol

Chemical composition of different biochar

Table 4

S. No	Biochar	Recovery (%)	Bulk densiy	Particle density	Pore space (%)	Moisture content (%)	References
1.	Lantana	28.5	0.37	1.25	70.37	38.9	Sellamuthu *et al.* (2018)
2.	Dodonia	26.1	0.50	1.00	50.00	23.9	
3.	Eichornia	35.6	0.38	2.50	84.62	42.0	
4.	Prosopis	40.0	0.36	1.25	71.43	43.3	
5.	Melia	35.0	0.42	1.67	75.00	44.9	
6.	Gliricidia	30.8	0.42	1.00	58.33	39.7	
7.	Delonix	27.6	0.37	1.25	70.37	40.9	
8.	Maize	32-35	0.36-0.39	0.52-0.57	26-31	4.8-5.1	Kannan *et al.* (2016) [6]
9.	Cotton	38-46	0.40-0.43	0.61-0.65	28-31	3.6-4.1	
10.	Redgram	36-39	0.37-0.40	0.57-0.63	34-37	4.3-4.8	

Properties of biochar

High carbon content (60-95% C), Resistant to biodegradation, Significant adsorptive qualities (similar to activated carbon), Nutrients essentially lock on the structure, increases moisture holding capacity, enhance microbial biomass, 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.

Biochar impact on soil properties

Table 5

Soil properties	Findings	References
Cation exchange capacity	50% increased	Glaser *et al.*, 2002 [3]
Fertilizer use efficiency	10-30% increased	Gaunt and Cowie, 2007 [8]
Liming agent	1 unit pH increase	Lehman and Rondon, 2006
Crop productivity	20- 80% increased	
Biological nitrogen fixation	50-70% increased	
soil moisture retention	18 % increased	Tryon, 1984 [15]
Mycorrhizal fungi	40 % incresed	Warnock *et al.*, 2007
Bulk density	Soil dependent	Laird, 2009 [7]
Methane emission	80 % decreased	Rondon *et al.*, 2005 [12]

Effect of biochar on soil physical properties

1. Soil water hydraulic conductivity

Biochar additions to soils had mixed results with regard to modifying soil hydraulic conductivity (k_{sat}). Addition of biochar to a silt and sandy loam-textured soil increased the water hydraulic conductivity of soil. In contrast no significant change has been reported in k_{sat} biochar applied to loam- and clay-textured soils.

2. Biochar stability in soil

It has been predicted that the stable portion of biochar has a realised some organic acids that maintain the soil stability in sandy soil.

Effect of biochar on soil chemical properties

Nutrient availability to plants

Progressive elimination of carbon, oxygen and hydrogen during pyrolysis therefore increases the total concentration of minerals in the biochar residue. Biochar addition to soil increase exchangeable Ca, Mg, K, Na, and P in the soil by increasing CEC. Biochar has a great ability to absorb and retain cations in an exchangeable form than the other form of soil organic matter due to greater surface area and negative surface charge (Liang *et al.*, 2006) [10].

Organic carbon (g/ kg)

The resulted values of soil residual organic carbon content with respect to different integrated nutrient management strategies revealed significant variations are furnished in Table 9. The maximum soil organic carbon of 3.45 g kg of soil was obtained with the treatment T_7 (150 per cent recommended dose of NPK+ 2 t of bio-char + *Azospirillum* @ 10 kg ha). However, it was on par with T_6 (125 per cent recommended dose of NPK along with 2 t of bio-char and *Azospirillum* @ 10 kg ha) and T_5 (100 per cent recommended dose of NPK+2 t of bio-char + *Azospirillum* @ 10 kg ha) treatments. The application of recommended dose of NPK alone (T_1) recorded the lowest organic carbon content of 2.61 g /kg.

Nitrogen availability (kg/ ha)

The evaluated integrated nutrient management strategies impart significant influence on the post-harvest soil phosphorous content are furnished in Table 9. Among the treatments, the highest soil nitrogen availability was resulted with regard to the 150 per cent dose of NPK along with 2t of bio-char + *Azospirillum* @ 10 kg ha (T_7) with 227.90 kg ha^{-1}, which was comparable with the treatments T_6 (125 per cent dose of recommended NPK + 2 t of bio-char+ *Azospirillum* @ 10 kg ha) and T_5 (100 per cent dose of recommended NPK + 2 t of bio-char + *Azospirillum* @ 10 kg ha), T_2 recommended NPK + 2 t of bio-char + *Azospirillum* @ 10 kg ha) and T_1 (recommended dose NPK alone). The treatment T_3 (50 per cent dose of recommended NPK + 2 t of bio-char + *Azospirillum* @ 10 kg ha) registered lowest nitrogen uptake value of 210.70 kg ha.

Phosphorous availability (kg ha^{-1})

The evaluated integrated nutrient management strategies impart significant influence on the post-harvest soil phosphorous content are furnished in Table 9. Among the treatments, the adoption of 150 per cent dose of NPK along with 2 t of bio-char + *Azospirillum* @ 10 kg/ ha (T_7) registered the highest soil phosphorous availability of 27.36 kg/ ha which was on par with the integrated applications of 125 per cent dose of recommended NPK + 2 t of bio-char+ *Azospirillum* @ 10 kg ha (T_6) and 100 per cent dose of recommended NPK + 2 t of bio-char + *Azospirillum* @ 10 kg ha (T_5) treatments. The treatment T_3 (50 per cent dose of recommended NPK + 2 t of bio-char + *Azospirillum* @ 10 kg /ha) registered lowest phosphorous uptake value of 20.25 kg ha.

Potassium availability (kg/ ha)

The resulted values on soil residual potassium availability with respect to different integrated nutrient management showed significant variations are tabulated in Table 9. The maximum soil potassium availability of 264.22 kg/ ha was accounted significantly with the 150 per cent dose of NPK along with 2 t of bio-char + *Azospirillum* @ 10 kg/ ha which was on par with the treatment T_0 (125 per cent dose of recommended NPK 2 t of bio-char + *Azospirillum* @ 10 kg /ha) and T_5 (100 per cent dose of recommended NPK +2 t of bio-char + *Azospirillum* @ 10 kg ha) treatments. The application of 50 per cent dose of NPK+ 2 t of bio-char+ *Azospirillum* @ 10 kg ha recorded the minimum soil potassium availability of 230.42 kg ha.

Soil nutrient leaching prevention

Biochar may have the potential to reduce leaching of nutrients from agricultural soils (Lehmann *et al.*, 2007) [8]. 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) [8] *found that "cumulative leaching of mineral N, K and Mg in* the soil was only 24, 45 and 7%, respectively, to control biochar.

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. Biochar's shows positive effect in the case of acidic soils compared to alkaline soils (Biederman and Harpole, 2013). Biochar addition can reduce the bioavailability 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) [2].

Effect of biochar on crop productivity

Biochar improves soil quality and crop productivity in a variety of soil. The improvements in crop productivity were related to increased nutrient retention, alleviation of Al toxicity in highly acidic soils, increased soil water permeability and plant water availability, Increased soil cation exchange capacity, enhanced cycling of P and S and neutralization of phytotoxic compounds in the soil. 189 percent increase in aboveground biomass measured 5 months after application of 23 Ton per acre Biochar support plant health by improving their establishment and provide resistance to disease. The improved nutrient retention and enhanced soil fertility results in the production of high crop yield relative to adjacent soil (Lehmann *et al*., 20012) [9].

Carbon sequestration

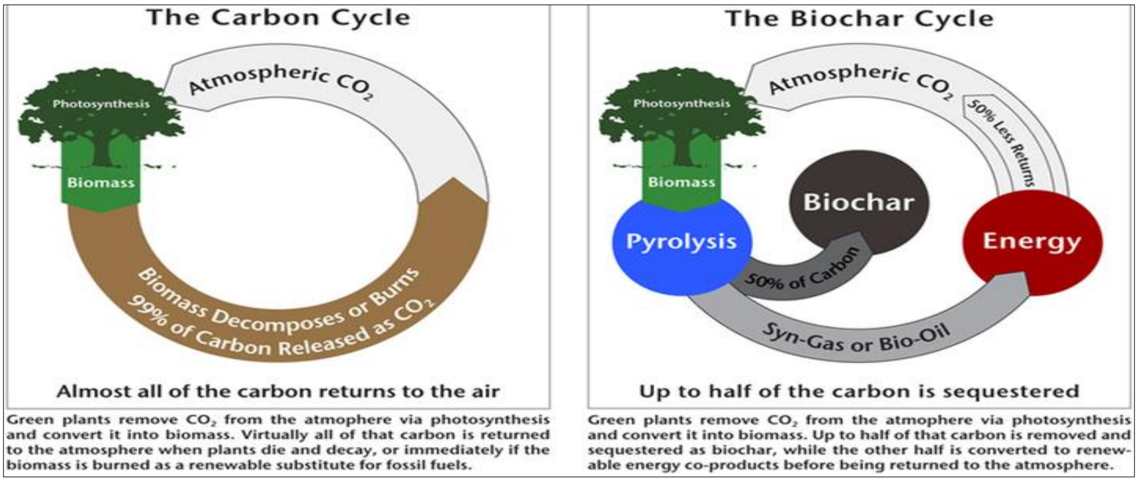

Fig 1

Negative effects of biochar

Some of the negative effects were reduces the availability of resources because of sorption of water and nutrients by biochar. Inhibit germination in clay texture soils, Sorption of pesticides and herbicides by the biochar can reduce the efficacy, Biochar can act as a source of contaminants, such as heavy metals, VOC, PAHs and DOC. Fine ash associated with biochar is the perfect source for dust, leads a risk for respiratory diseases. In high pH soils, an increase in soil pH is not desirable as crops only tolerate a certain range of soil pH.

Present challenges in biochar research

Low cost biochar pyrolysis equipment, Municipal solid waste disposal through biochar production. Standardization of biochar based nutrient fortification and nutrient releasing pattern, Optimization of biochar application for different agricultural crops. Long term carbon sequestration potential of biochar in different ecosystem, Acid soil reclamation capability of biochar induced microbial dynamics and its role in nutrient availability Biochar induced systemic resistance in plant disease and pest control.

Conclusion

Biochar has very promising potential for the further development of sustainable agriculture production systems. Biochar production provides a great potential for worldwide climate change mitigation that goes beyond its uses in agricultural production alone. It also makes soil cleaner and healthier through decontamination effect. Promotes better CO2 absorption through improved crop stand and helps in C sequestration. Survey of many literatures reviewed that application of biochar shows positive responses in low pH coarse textured soils and shows negative responses in few cases in fine texture high pH soils. So, biochar is good for coarse textured low pH soils for enhancing crop production and productivity.

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