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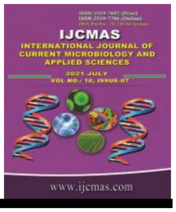

Review Article

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Biochar: A Tool for Sustainable Agriculture and Climate Change Mitigation

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ABSTRACT

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Biochar widely known as black carbon, promotes plant growth and soil fertility and limits the necessity for fertilizer and decreases soil loss through erosion. Biochar is a carbon-rich solid material produced by heating from a wide range of organic feedstocks in the absence or limited oxygen supply (pyrolysis). Biochar serves as a sink for atmospheric CO_2 in soil and retains water and nutrients in surface soil due to its highly porous nature. Biochar not only offers a lot of environmental solutions, it can also improve soil quality and crop productivity. By converting agricultural waste into a powerful soil enhancer that holds carbon and makes soils more fertile, we can boost food security, discourage deforestation and reduce fertilizer requirements.

Introduction

In India, about 93 million tonnes of crop residues are burned each year primarily to clear the fields in the form of straw and stubble after the harvest of preceding crop. The problem is severe in irrigated agriculture, particularly in the mechanized rice-wheat system in the Northern India due to unavailability of labour, high cost in removing the residues, use of combine-harvester in rice-wheat cropping system and less time for sowing of wheat after harvesting rice. Besides atmospheric pollution, burning of residues lead to loss of entire amount of C, 80% of N, 25% of P, 50% of S and 20% of K present in straw, adversely affecting soil fertility (Mandal *et al.*, 2004). In addition, burning of agricultural residues releases ozone depleting gases such as carbon dioxide, methane, carbon monoxide, nitrogen oxide, sulphur dioxide and very small particles in the air which adversely affect the atmospheric composition. Biochar has the unique ability to indirectly enhance soil fertility by encouraging the growth of soil microbial population and retain soil water and plant nutrients. The world population is currently increasing at a fast rate and is expected to reach 9 billion by 2050. To meet a growing demand for food from a growing population, we need to increase agricultural productivity up to 70%, and food production in the developing world will need to double by 2050 (FAO). Soil organic matter is the key to soil health. In wet tropical condition, organic matter is easily subjected to decomposition and mineralization. Mineralization produces CO_2 in just a few seasons and causes nutrient content to be low. Biochar significantly improve soil tilth, productivity, and nutrient retention and availability to plants via both direct slow- nutrient release fertilizing properties and indirect effects on improved water holding capacity, nutrient holding ability, and soil aggregate stability, when used as a soil conditioner along with organic and inorganic fertilizers. Moreover, increasing organic carbon in soil especially in arid regions and coarse-textured soils can enhance soil physical and chemical properties and at the same time beneficially sequester carbon and help to suppress atmospheric green house gas emissions (Busscher *et al.,* 2007). To address these issues, biochar popularly known as *black gold* in agriculture a carbon-rich product has emerged as a new opportunity with potential to resolve many of the short comings of conventional agriculture. Biochar possess many beneficial properties such as improving soil fertility, crop yield, and most importantly mitigate climate change (Abrol *et al.,* 2017).

Biochar as a soil amendment

Amazonian people added biochar along with other organic wastes over centuries to modify the surface soil horizon into a highly fertile soil called *Terra Preta* (dark earth), which is in direct disparity to the typical weathered Oxisol soils in close proximity. Due to the large amounts of biochar incorporated into its soils, this region still remains highly fertile despite centuries of leaching from heavy tropical rains. Biochar is a pyrolyzed product produced by a thermochemical decomposition process of organic materials in the absence of oxygen. Characteristic properties of biochar prepared will majorly depend on type of feedstock and pyrolysis conditions used during its preparation (Bird, 2015). Biochar can be a major boon in agriculture as soil amendment to address major issues such as climate change, future food security and agricultural residual waste management. Moreover, use of biochar as a soil additive has been proposed as a means of mitigating climate change through long-term sequestration of carbon whilst simultaneously improving soil properties and functions (Jeffery *et al.,* 2011; Kookana *et al.,* 2011; Verheijen *et al.,* 2010). Biochar as a soil amendment can change properties of soil at different levels of physical, chemical and biological status.

Biochar influenced soil physical properties

Addition of biochar triggers the physical contact of biochar/soil surface and sets-in-motion the physical-chemical interaction. The impact of biochar as an amendment depends on its properties or attributes. Biochar properties like large surface area, rich in carbon and porosity (Suliman *et al.,* 2017) contribute to the adsorptive properties of biochars and potentially alter soil's water retention, aggregation, bulk density, and penetration resistance. Studies of the effects of biochar on physical properties of soil are discussed in Table 1. Most research findings point to the improvement of soil bulk density with biochar application (Karhu *et al.,* 2011, Masulili *et al.,* 2010); water-holding capacity also increased (Karhu *et al.*, 2011). Physicochemical properties of degraded or nutrient-depleted soils may also improve by using biochar as a soil amendment. The high surface area of biochar provides space for formation of bonds and complexes with cations and anions with metals and elements of soil on its surface which improves the nutrient retention capacity of soil. Jones *et al.*, 2010 observed significantly increase in mesoporosity may also at the expense of macropores in biochar-amended soil compared to control. The higher the total porosity (micro- and macro-pores) the higher is soil physical quality because micropores are involved in molecular adsorption and transport while macropores affect aeration and hydrology. Many studied reported decreases soil bulk density, increases total pore volume and water holding capacity after application of biochar to infertile soils (Abel *et al.*, 2013; Chan *et al.*, 2007; Sharma *et al.*, 2016). Abrol *et al.*, (2016) also found decreased bulk density with the application of biochar as a soil amendment in the non-calcareous loamy sand. Zhang *et al.*, (2012) also observed in a 2-years field study decrease in soil BD from biochar application rate of 9.4 ± 2.2 and could be one of the indicators of enhancement of soil structure or aggregation, and aeration. According to Oguntunde *et al.*, (2008) bulk density on charcoal-site soils was reduced by 9% compared to adjacent field soils. Jones *et al.*, 2010 found improved WHC and water retention in biochar-amended soils with as low as 0.5% (g g^{-1}) biochar application. Biochar assist water to infiltrate from the ground surface to the top soil through the large pores after heavy rain (Abrol *et al.*, 2016). Tryon, 1948 demonstrated that biochar increased available water content in sandy soil, no effect in a loamy soil, and decreased moisture content in a clayey soil might be attributed to the hydrophobic nature of the biochar. Similarly other groups also reported increases in available water capacity by 22% (Peake *et al.*, 2014) and from 0.12 to 0.13m3m-3 (Nelissen *et al.*, 2015). Addition of biochar with manures decreased soil bulk density (BD) and crack volume, and increased infiltration rate (IR) and rice yield in sandy clay loam soil (Sharma *et al.*, 2018 and 2019). The saturated hydraulic conductivity of soils under charcoal kilns increased from 6.1 to 11.4 cm h^{-1}.

Biochar influenced soil chemical properties

Chemical properties of soil include several aspects such as its inorganic and organic matter content, colloidal properties of soil particles and soil reactions and buffering action both in acidic and basic soils. The chemical properties of soils largely depend on the soil collides. It is, therefore, important to know about the soil colloids and their nature to have an insight into their influence on various chemical properties of soils. Further, pH is another important parameter to determine types and the rate of reaction occurring in soil. When soil is added with any foreign material, all the above parameters will interplay affecting the chemical reactions occurring in soil depending on the property of the material. Therefore, soil amendment material needs to be thoroughly studied before its administration to understand its possible effect on quality of soil. Biochar as a soil amendment is not a new concept, but its scientific interests and understanding is at infancy stage to unveil possible implications of its use on major environmental concerns of climate change, food security and residual management. In terms of chemical properties of biochar, it is not a pure carbon, rather mix of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in different proportions (Masek, 2009). Moreover, chemical content of a biochar depends majorly on the type of biomass used for its preparation. For instance, biochar prepared from *Lantana camara* at pyrolysis temperature of 300 °C contained phosphorous (P), potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) in available concentrations of 0.64 mg kg^{-1}, 711 mg kg^{-1}, 1145 mg kg^{-1}, 5880 mg kg^{-1}, and 1010 mg kg^{-1}, respectively (Masto *et al.,* 2013). Similarly, two other groups reported that fresh biochar have potential of nutrient availability and could release large amounts of nitrogen (N) and phosphorous (P) within the concentration range of 23–635 mg kg^{-1} and 46–1664 mg kg^{-1}, respectively (Mukherjee and Zimmerman 2013; Zheng *et al.*, 2013). Inyang *et al.,* (2010) also reported that bagasse biochar addition significantly enhanced the exchange capacity of cations and anions of soils and improved their nutrient holding capacities. Cheng and Lehmann, 2009 found that high reactivity of the surfaces of the biochar particles is partly attributed to the presence of a range of reactive functional groups, some of which are pH – dependent. Biochar ageing causes an increase in hydroxyl groups and carboxyl groups (Lehmann and Joseph, 2015), while aging of biochar in soils causes development of quinine functional groups (Mukome *et al.*, 2014). Thus, biochar aging creates oxygen − containing functional groups on the surface. While describing these properties, aromaticity on account of H:C ratio and oxidation state on account of O:C ratios are considered very important. Specific surface area is one of the important physical properties of biochar that affects the sorption capacity (Rajapaksha *et al.,* 2016), water holding capacity and habitat for microbes (Ng *et al.,* 2014). In addition to the direct effects, Steiner *et al.*, (2008) reported that the use of biochar can improve the efficiency of nitrogen fertilizer, as biochar can reduce the loss of nitrogen and potassium that occurs through leaching (Widowati *et al.*, 2011, 2012) (Table 2). Thus, it is evident that biochar based soil amendment results into beneficial chemical changes supported by combination of characteristic physical features of both soil and biochar.

Biochar influenced soil biological properties

Many studies reported increase plant growth and carbon sequestration after addition of biochar (Baronti *et al.*, 2010; Vaccari *et al.*, 2011; Jones *et al.*, 2012; Viger *et al.*, 2015; Lehmann *et al.*, 2006; Major, 2010; Mao *et al.*, 2012), possibly related to altered abiotic characteristics including increased pH, CEC and improved soil water content (Verheijen *et al.*, 2010; Jeffery *et al.*, 2011; Jones *et al.*, 2012). The soil physico-chemical changes induced by biochar addition may also play a pivotal role in determining soil bacterial biodiversity (Fierer & Jackson, 2006) (Table 3). Shifts in microbial communities may result from a wide range of biochar-mediated interactions, including variations in microbial signalling through sorption of the molecules themselves (Masiello *et al.*, 2013), increased transfer of electrons, resulting in augmentation of biological processes (Cayuela *et al.*, 2013), shifts in microbial N cycling (Harter *et al.*, 2014) and decreased abundance of fungi relative to bacteria (which could utilize biochar substrates for growth; Gomez *et al.*, 2014). Soil amended with biochar show an increase the abundance of bacteria and archaea oxidizing ammonia to nitrates and nitrites (Prommer *et al.*, 2014), increase *Bradyrhizobiacea* and *Hyphomicrobiaceae* populations in short-term pot experiment on ryegrass (Anderson *et al.,* 2011). It was demonstrated by Steiner *et al.*, 2008 and Warnock *et al.*, (2007) that addition of biochar increase in number of mycorrhiza colonies because of its porous nature and high surface area provides a suitable habitat for microbes (Gomez *et al.*, 2014). Graber *et al.*, (2010) have found that, with increasing rate of biochar application, there were more culturable colonies of general bacteria, *Bacillus* spp., yeasts and *Trichoderma* spp. but decreasing culturable filamentous fungi *Pseudomonas* spp. and *Actinomycetes* spp.

Table.1 Impact of biochar on soil physical properties

Properties	**Biochar**	**Feedstock**	**Pyrolysis temperature**	**Soil type/texture**	**References**
Bulk density	Reduced	Rice husk		Non-calcareous/ loamy sand	Abrol *et al.,* (2016)
//	Decrease	Municipal green waste	450 °C	Residue sand	Jones 2010
//	Decreases	Peanut *(Archis hypogaea)* Pecan (*Carya illinoensis*) Poultry litter Switchgrass (*Panicum virgatum*)	400 °C 350 °C 350 °C 250 °C-500 °C	Norfolk loamy sand	Novak *et al.,* (2012)
Porosity & surface area	Increases	Jarrah woods (*Eucalyptus marginata*)	600 ° C	Sandy soil	Dempster *et al.,* (2012)
//	Increasing	Peanut hulls (*Arachis hypogaea*)	500°C @1 h	Loamy sand	Githinji.,2013
//					
Water stable aggregates	Increased	Corn stover	350 and 550°c	Typic fragiaqualf (alfisol), typic haplud and (andisol)	Herath *et al.,* (2013)
//	No effect	Rice straw	250 to 450°C @ 2-8 hours	Typic Plinthudult (Ultisol)	Peng *et al.,* (2011)
//	Increased	Rice hulls	400°C @ 2 hours	Typic Eutrudept (Inceptisol)	Hseu *et al.,* (2014)
//	Increased	Birch	400°C @ 2.5h	Silt loam	Karhu *et al.,* (2011)
Water holding capacity	Increases	Ponderosa pine (*pinus ponderosa*)	450 °c	Sandy loam	Briggs *et al.,* (2012)
//	Increased	Birch mixed wood	400°C @ 2.5 hours	Silt loam	Karhu *et al.,* (2011)
Infiltration rate/ saturated hydraulic conductivity	Increased	Wood		Haplic acrisol	Oguntunde *et al.,* (2008)
//	Increased	Maize and beechwood	750°C (maize) 550°C (beechwood)	Haplic Luvisol / loamy sand	Abel *et al.,* (2013)
//	Increased	Rice husk	620°C	Non-calcareous/ loamy sand Sandy clay loam	Abrol *et al.,* (2016) Sharma et al. (2019)
Penetration resistance	Reduces	Hydrochar	220 °c	Albic luvisol	George.,(2012)
//	Reduces	Pecan shells	700 °C	Norfolk loamy sand:	Busscher *et al.,* (2011)
//	Reduces	Organic wastes		Sandy Clay Loam	Negiş *et al.,* (2019)

Table.2 Impact of biochar on soil chemical properties

Properties	Biochar	Feedstock	Pyrolysis Temperature	Soil type/ Texture	References
pH	Increased	Red gram, cotton, maize stalk and mesquite wood.	250 @ 450°C;	Acidic/red soil	Pandian *et al.*, (2016)
//	Increased	Rice husk	900 & 1100 °C	Acidic/sandy loam	Carter *et al.*, (2013)
//	Increase	Waste biomass	450 ◦C & 550 ◦C	Forest soils	Karim *et al.*, (2020)
	Increased	Poultry litter	450°C & 550°C	Alfisol	Chan *et al.*, (2008)
Soil organic carbon (SOC)	Increased	Rice husk	500 °C for 6 h	Acid purple soil	Chan *et al.*, (2007)
//	No effect Increased	Eucalyptus wood biochar	550 °C	Ultisol	Fungo *et al.*, (2017)
Total carbon	Increased	Poultry litter	450°c & 550°c	Alfisol	Chan *et al.*, (2008)
Total phosphorus, available phosphorus, Available potassium	Increased	Rice husk	500 & 700°c	Acid purple soil	Li *et al.*, (2020)
//	Increased	Hardwood	500°C @ 12 hours.	A sandy loam Alfisol	Adekiya *et al.*, (2020)
, Carbon/nitrogen ratio	Increased	Wheat straw	450°c	Black chernozem	Hu *et al.*, (2014)
Mineralization of O.C	Increased	Eucalyptus saligna wood, E. Saligna leaves, poultry and cow manure	400 & 550°C	Vertisol	Singh and Cowie (2012)
Soil microbial biomass carbon	Increased	Liter from coppice woodland	550°c	-silty loam	Utigliano *et al.*, (2011)

Table.3 Impact of biochar on soil biological properties

Biochar	**Feedstock**	**Pyrolysis Temperature**	**Soil type/Texture**	**References**
Increase bacteria and archaea oxidizing ammonia to Nitrates & nitrites	Hardwood	500°C @ 2 hours	-	(Prommer *et al.*, 2014)
Increase *Bradyrhizobiacea* and *Hyphomicrobiaceae* populations	*Pinus radiata*		Silt-loam soil	(Anderson *et al.*, 2011)
Increase nitrification, nitrogen fixing, nitrite reduction	Switchgrass (*Panicum virgatum*)	350°C	Aridic subsoil	(Ducey *et al.*, 2013)
Increase Rhizobacteria (S and P mobilizing bacteria)	*Miscanthus giganthus*	600 °C @ 15 min;	Poorly drained gley /loamy	(Fox *et al.*, 2014).
Increase Bacteria: *Bacillus* spp. yeasts and *Trichoderma* spp, decrease in culturable filamentous fungi *Pseudomonas* spp, *Actinomycetes* spp.	Citrus wood		-	Graber *et al.*, (2010)
Enhance PSM activity, significantly improved the crop	Lignin-rich wood	350–500° C	Fine textured/silt loam	(Deb *et al.*, 2016).
Increase in nitrogen fixation in legumes.	*Eucalyptus deglupta*	350°C @ 1 h	Typic Haplustox (oxisol)/ clay–loam	Rondon *et al.*, (2007)
Improved microbial abundance	Eucalypt green waste	650–750 °C	Acidic black/clay loam, Dermosol/loamy red, Kurosol/brown sandy loam	Abujabhah *et al.*, (2016)
Decline of arbuscular mycorrhizal fungal (AMF), Abundance in roots	*Pinus contorta* Douglas	600°C;	-	Warnock *et al.*, 2010

Wood biochar and phosphorous solubilizing microbes (PSM) enhance PSM activity for P mobilization in phosphate rich soils, but significantly improved the crop yield in P deficient soils (Deb *et al.*, 2016). The positive influence of biochar on soil biological fertility occurs through increasing activity of soil microorganisms (Steiner *et al.*, 2008).

In another study Rondon *et al.*, (2007) observed that biochar increases nitrogen fixation in legumes. Further, biochar pores may provide physical protection for soil microorganisms. Microbial abundance, diversity and activity are strongly influenced by pH (Rousk *et al.*, 2010).

The buffering capacity, that is, the ability of the soil solution to resist changes in pH imparted by biochar CEC may also help maintain appropriate pH conditions and minimize pH fluctuations in the microhabitats within biochar particles (Rousk *et al.*, 2010; Sparkes and Stoutjesdijk, 2011). Studies have shown that biochar and fertilizer application increased microbial biomass compared to mineral fertilizer (Birk *et al.*, 2009; Burger and Jackson, 2003). Microbial immobilization is an important mechanism to retain N in soils affected by leaching (Burger and Jackson, 2003). Increased C availability stimulates microbial activity resulting in greater N demand, promoting immobilization and recycling of nitrate. Biochar addition has also increased crop yield, soil microbial biomass, plant tissue K concentration, total soil C and N, soil P and K (Biederman and Harpole, 2013; Galvez *et al.*, 2012), nodulation and BNF by common beans (Rondon *et al.*, 2007), red clover (Mia *et al.*, 2014), soybean (Mete *et al.*, 2015) and faba bean (Van Zwieten *et al.*, 2015).

Biochar role in carbon sequestration and green house gas mitigation

Soils contain 3.3 times more carbon than the atmosphere and 4.5 times more than plants and animals on earth. This makes soils an important source of greenhouse gases but also a major sinks which helps to sequester more carbon. Agriculture generates around a fifth of the world's greenhouse gas emissions (FAO, 2016). To overcome the negative effects of climate change without compromising on productivity and incomes of farmers, adoption of climate-smart practices are urgently needed.

Conversion of biomass C to biochar leads to sequestration of about 50% of the initial C compared to the low amounts retained after burning (3%) and biological decomposition (< 10–20% after 5–10 years), therefore yielding more stable soil C than burning or direct land application of biomass (Lehmann *et al.*, 2006).

Further, biochar sequester CO_2 into the soil and reduce water pollution through enhancing soil nutrient retention (Lehmann *et al.*, 2006; Shackley *et al.*, 2010). Applying wheat straw biochar in paddy soil (hydroagric Stagnic Anthrosol) indicated that CH_4 emission increased by 31 and 49% while N_2O emission decreased by 50 and 70%, at application rates of 10 and 40 Mg $ha^{-1,}$ respectively (Zhang *et al.*, 2012) attributed to increased soil aeration, sorption of NH_4^+ or NO_3^-, or presence of microbial inhibitor compounds such as ethylene. Spokas *et al.*, (2009) observed reduced emission of CO_2 from a silt loam soil amended with wood chip biochar compared to un-amended control, at a rate of >20% (w/w).

However, some studies have documented minimal impacts or no significant differences in the net GHG fluxes under field trials or laboratory incubation studies. Emissions of greenhouse gasses such as CO_2 and N_2O,which is more than 300 times as potent as CO_2, was suppressed significantly from soils (Felber *et al.*, 2012; Lentz *et al.*, 2014; Martin *et al.*, 2015; Mukherjee *et al.*, 2014). Woolf *et al.*, (2016) indicate that biochar could play an important role in removal of carbon from the atmosphere. Biochar helps reduce the leaching of nitrogen into groundwater, while reducing the need for fertilizers that are the source of excess nitrogen (Glaser *et al.*, 2015; Lehmann, 2007; Zhang *et al.*, 2016).

Biochar and crop productivity

Application of biochar not only improve soil productivity by improving physical, chemical and biological soil conditions but also to decrease the environmental effect on soil and water resources (Glaser *et al.*, 2007, Lehmann *et al.*, 2003, Chan *et al.*, 2007, Sharma *et al.*,2018). Improvement in soil structure increase in soil water retention and decrease in soil strength have been reported by Chan *et al.*, (2007) conducted a study on Australian soil. Lehmann *et al.*, (2003) compared soil fertility and leaching losses of nutrients between an Anthrosol and an adjacent unammended Ferralsol. The Anthrasol showed significantly higher P, Ca, Mn and Zn availability than the Ferralsol, and an increased biomass of both cowpea and rice by 38–45% without fertilization. The application of paper mill waste biochar, combined with inorganic fertilizer, showed higher soybean and radish biomass compared with sole application of inorganic fertilizer (Van Zwieten *et al.*, 2010). Application of chicken manure and city waste biochar increased maize biomass (Widowati *et al.*, 2012). This higher biomass production is attributed to biochar increasing the soil pH and CEC (Liang *et al.*, 2006). Biochar has the potential to improve soil fertility, microbial abundance, carbon sequestration and crop productivity and also abbreviated as black gold for agriculture (Abrol and Sharma, 2019, Sharma *et al.*, 2018). If the fertility or nutrient status of soil is increased, it leads to increase the crop production and also helps in maintaining soil health. Efficient use of biomass by converting it as a useful source of soil amendment is one way to improve soil health and crop productivity.

In India, about 435.98 million tons of agro-residues are produced every year, out of which 313.62 million tons are surplus and crop residues in fields can cause considerable crop management problems. Efficient use of biomass by converting it as a useful source of soil amendment is one way to manage soil health and fertility.

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