Chapter 12
Multifarious Benefits of Biochar Application in Different Soil Types

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Abstract The extensive use of chemical fertilizers in agriculture have long term deleterious impact such as leading salinity, decline fertility of soil with fast growth of agricultural production and it is predicted that the fertilizer use to continue increase in the coming years. With current scenario, there has been keen interest on biochar, produced from various crop residues with multiple environmental applications such as soil amelioration, pollutants removal and carbon sequestration. Biochar has several unique properties like high alkaline pH, fixed carbon content, stability against decay, water holding capacity and cation exchange capacity, which makes it an efficient, cost-effective and environmentally-friendly material. Many study showed the effectiveness of biochar amendments in soil i.e. nutrient status improvement, increases soil porosity, soil pH, soil moisture-holding capacity and boost the growth of beneficial plant growth promoting microbial community.

Keywords Biochar · Microbial abundance · Soil physio-chemical property · Nutrient improvement

12.1 Introduction

Over the last 30 years, the huge amount of chemical fertilizers use in agriculture resulted fast growth of agricultural production, and it is predicted that the fertilizer use to continue increase in the coming decades. In country like India and China, the excessive use of chemical fertilizers is a common practice to achieve high crop yield. Though, continuous use of chemical fertilizers for the intensive cropping not only enhance soil nutrients but also decrease the soil organic carbon (C) and other negative effects on soils such as leading acidification, deplete soil structure and soil

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productivity (Ge et al. 2008). Rapid industrial development and increasing adaption of agro-chemical based crop production practices since green revolution have increased the persistent organic adulterations in the food chain. The uses of agro-chemical in soil are considerable costly and also produce a substantial amount of chemical residues. The Chinese Ministry of Agriculture has immediate stopped the over use of chemical fertilizer and proposed the plan "zero increment in chemical fertilizer until 2020" to reduce the consumption of chemical fertilizer. Therefore, the high effectiveness of fertilizer and alternate of chemical fertilizer is demanding (Singh et al. 2017a, b, 2019a, b; Vimal et al. 2018; Kumar et al. 2018; Singh 2019; Singh and Singh 2019; Vimal and Singh 2019). So, we should need to find the replacement or substitute of chemical fertilizer, which would be a cost effective, sustainable and wide range of applicability.

The actual use and management of agricultural residues, paddy or wheat straw, green manure and beneficial microbes have become a key focus of sustainable agriculture in recent years (Singh 2013, 2014, 2015, 2016; Singh and Boudh 2016; Kumar et al. 2017; Kumar and Singh 2017; Tiwari and Singh 2017). Biochar is considered as a stable form of organic carbon which improves the soil properties and also sequestrates carbon. Biochar considered as a promising solution with various valuable properties (Joseph et al. 2010; Uras et al. 2012). Biochar can be formed from a numerous of agricultural biomass comprising straw, woody leftovers, animal manure, and other waste products. Its use can make available resourceful path for agricultural waste utilization. Due to its unique structure and composition, application of biochar can potentially enhanced the carbon sequestration, improve soil health, and lead to sustainable management of organic waste (Lehmann and Joseph 2009). Biochar can also improve the soil cation exchange capacity (CEC) (Zwieten et al. 2010), nutrient absorption (which prevents subsequent nutrient run-off), water holding capacity (Laird et al. 2010; Schulz and Glaser 2012; Zhang et al. 2013), and excessive soil acidification (Karami et al. 2011).

Biochar is a promising carbonaceous material and substitute to the activated carbon to remove various organic pollutants such as agrochemicals, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), polychlorinated biphenyls (PCBs), aromatic dyes and antibiotics (Beesley et al. 2010; Teixidó et al. 2011; Xu et al. 2012; Zheng et al. 2010), and also a series of inorganic contaminants (e.g., heavy metals, ammonia, nitrate, phosphate, sulfide etc.) from aqueous, gaseous and/or solid phases (Ahmad et al. 2014; Jung et al. 2015; Oliveira et al. 2017). Biochar application to the soil gives many beneficial effects (Fig. 12.1) such as increase microbial respiration, crop yield, improve soil health, water holding capacity etc. (Marjenah 1994; Yamato et al. 2006).

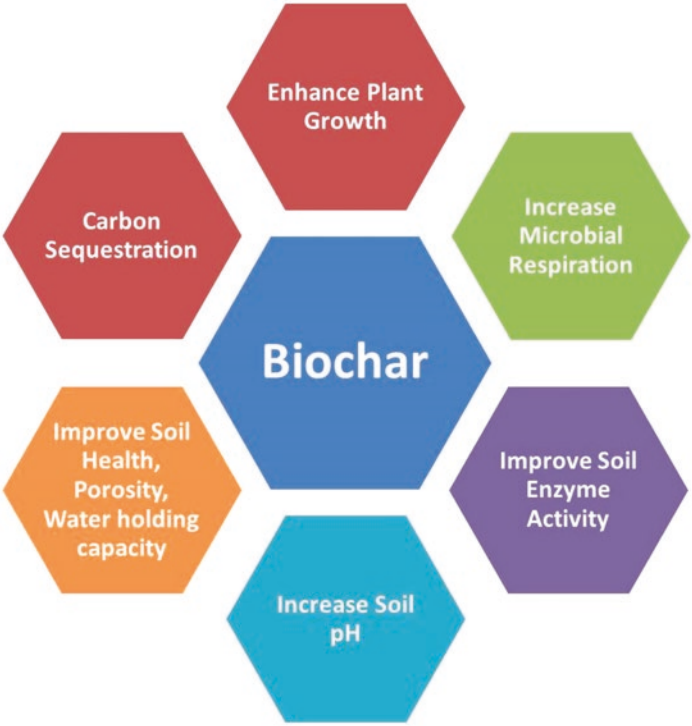

Fig. 12.1 Multi-benefits of biochar application into poor physico-chemical property soil

12.2 Biochar Production from Organic Residue

Generally, biochar was produced in a muffle furnace that was equipped with a digital temperature regulator (detection accuracy <5 °C). Biochar was obtained from slow and/or fast pyrolysis of organic residue (manure, organic waste, bioenergy crops, crop residues) at around 400–600 °C for 8–12 h in oxygen-free or low-oxygen environment. After pyrolysis of the biomass, an average the production yield was approximately 25–50% of the original biomass C remains in the biochar (Lehmann 2007). Under the pyrolysis process most of the Ca, Mg, K, P, and plant micronutrients, and about half of the N and S in the biomass feedstock are separated into the biochar fraction.

Major thermochemical technologies for biochar production include slow and fast pyrolysis, gasification, torrefaction, and hydrothermal carbonization (Kambo and Dutta 2015). Biochar yield greatly depends on adaption of pyrolysis type. Slow pyrolysis performed at longer residence time and at a moderate temperature

Table 12.1 Properties of different biochar from the various organic residues

Biochar type	pH	Density (g cm^{-3})	Ash content (%)	Fixed carbon (%)	References
Rice straw	9.0	0.13	23.0	51.8	Li-li et al. (2017)
Bamboo	8.6	0.56	11.9	69.0	Li-li et al. (2017)
Swine manure	8.4	–	32.5	17.7	Cantrell et al. (2012)
Mulberry wood	10.2	–	7.5	37.5	Zama et al. (2017)
Maize straw	9.8	0.40		59.1	Luo et al. (2017)
Peanut shell	7.0	–	7.0	32.5	Zama et al. (2017)
Oak biochar	10.2	–	3.49	68.2	Teutscherova et al. (2018)

(350–550 °C) in absence of O_2 results in higher yield of biochar (30%) than the fast pyrolysis (12%) or gasification (10%) (Inyang and Dickenson 2015). The various factors affecting the physicochemical properties of biochar during production are discussed in the following section.

During pyrolysis the organic agricultural residue (e.g. lignin, cellulose, hemicellulose, fat, and starch) is thermally combusted and yielding three main products (i) biochar (solid fraction), (ii) bio-oil (partly condensed volatile matter), and (iii) non-condensable gases such as carbon monoxide (Co), carbon dioxide (CO_2), methane (CH_4) and hydrogen (H_2) (Suliman et al. 2016). Furthermore, in biochar varying ratio of O/C and H/C is achieved by specific elimination of different elements (C, H, O) into gases and other volatile compounds (Brewer et al. 2012). Essentially, in biochar the ratio of O/C and H/C is directly correlates with aromaticity, biodegradability, and polarity, which are extremely necessary properties for the exclusion of organic pollutants (Crombie et al. 2013). For example, while a biochar formed at higher temperature have lower H/C and O/C ratios as compared to lower temperature, demonstrating a steady increase in aromaticity and lower in polarity with increasing temperature (Suliman et al. 2016; Chen et al. 2016). Van Krevelen diagram is widely used to understand the selective loss of elements (during dehydration and carbonization reactions) by comparing atomic ratios of H/C and O/C. Most of the biochars derived from various sources of feedstock's have decrease ratios of the H/C and O/C due to the removal of H and O atoms during pyrolysis. However, the stability of any biochar depends on high aromaticity and carbon content (Windeatt et al. 2014). Besides, atomic ratios some other factors like pH and temperature also have a major effect on biochar properties. Some researchers had established the relation of biochar high pH with increasing pyrolysis temperature (>500 °C) due to the enrichment of ash content (Table 12.1); greater hydrophobicity and aromaticity, and higher surface area (Windeatt et al. 2014; Keiluweit et al. 2010). Above mentioned all the properties of biochar make a good candidate for highly responsive for removal of organic pollutants. Biochar is act as a zwitterionic which comprises of both positively and negatively charged surfaces (Tan et al. 2017). The negatively charged surface is attracting the cations and influencing the cation exchange capacity (CEC) of soils (Lawrinenko 2014). When pyrolysis was done below 500 °C temperature aids incomplete carbonization resulted smaller pore size biochar formed, lower surface area and greater O-containing functional groups (Lu et al. 2014), which make biochar highly responsive for elimination of inorganic pollutants due to enlarged ionic interactions through interface with O-containing functional groups.

12.3 Effect of Biochar on Soil Microbial Abundance

Microorganisms are present in environment (soil, water, air) and interact with human, plant, animal and neighbouring organism. These microbes also regulate the soil nutrients mobilization, uptake and plant metabolisms. So, it is essential attention to truthfully profiling and also compares the composition of the populations they form. The one of the most important approach for microbial community profiling is by classification of PCR amplicon sequences from the small subunit ribosomal RNA gene (i.e., the 16S rRNA gene of bacteria and archaea). This method is also useful to introduce biases in microbial composition estimation due to variations in 16S rRNA gene copy numbers per genome. The other most common approach for determination of soil microbial abundance and community composition is phospholipid fatty acid (PLFA) analysis (Zhang et al. 2015). The quantitative realtime PCR and Illumina MiSeq sequencing method outcomes revealed that the bacterial abundances and diversity increased with biochar addition (Chen et al. 2013; Yao et al. 2017). A study revealed that the abundance of microbial PLFAs (Gram-positive bacteria, Gram-negative bacteria, actinobacteria and fungi) in biochar amended soil was higher as compared to un-amended soils. The ratios of bacteria/fungi and monounsaturated/branched PLFAs were significantly correlated with the volumetric soil water content, porosity, or computed effective oxygen diffusion coefficients under biochar amended soil.

Several reports are available in which the biochar has both positive and negative impact on microbial community and abundance. Biochar can significantly influencing the soil microbial communities and abundance (Grossman et al. 2010; Jindo et al. 2012; Lehmann et al. (2011), possibly varying the activity of advantageous soil microorganisms and nutrient cycles (Bruun et al. 2014). One of the advantageous aspects that biochar pores are provide habitat for microorganisms such as mycorrhizae and bacteria that also obtain their metabolic needs from these micro-habitats (Lehmann et al. 2011). Biochar surface contained the labile soil organic matters which favours the microbial growth and activity, consequently lead to microbial abundance, microbial activity and mineralization (Wardle et al. 2008; Ameloot et al. 2013). Valuable effects of biochar amendment on crop yield have been documented (Yamato et al. 2006; Jeffery et al. 2011), however broad analysis is needed on soil microbial community and abundance because soil microorganisms play a key role in nutrient cycling and provide thus an important ecosystem service (Costanza et al. 1987). Due to biochar pore size is very small below 5 mm in diameter (Glaser 2007) it protect microorganism from predator such as nematodes, mites, protozoan, collembolans and maintained the microbial diversity (Warnock et al. 2007; Swift et al. 1979; Wright et al. 1995). Contrary to this, some reports are present the negative effect of biochar on microorganism (Graber et al. 2010) due to reduction in reproduction rate. Arbuscular mycorrhizal fungi (AMF) plays a major role in soil aggregation, provide essential nutrient phosphorus to the plant, sequestration of soil carbon and nitrogen under different stress condition like droughts and saline or sodic soil (Wilson et al. 2009). However, some reports are described the AMF abundance decreased with the addition of biochar (Warnock et al. 2010; George et al. 2012) while, others reports reflects had no significant role of AMF and microbial abundance and biomass (Chan et al. 2008; Durenkamp et al. 2010). Zheng et al. (2016) also found that biochar addition increased the bacterial diversity and changes in bacterial community composition in drylands, while under paddy soil it did not alter the microbial community structure (Tian et al. 2016). However, until now, few reports have been available on the changes in the soil microbial community with biochar addition. The possible reason behind no changes in microbial abundance and biomass is biochar were not equally spread across different functional groups and allow to dominate or diminish soil environment might cause some microorganisms to become competitively dominant only specific group of microorganisms (Kuppusamy et al. 2016). Another logic given by Warnock et al. (2010), that organic pyrolytic product (phenolics and polyphenolics) are responsible for the reduction in microbial community and their abundance. Biohar and soil type is also responsible for increasing and/or decreasing the microbial community (Jones et al. 2012; Galvez et al. 2012; Lehmann et al. 2011). One of the important property of biochar is explored by Qui et al. (2009), in which harmful chemical secreted by plant or other organisms (allelochemicals) are detoxify by application of biochar consequently improved the plant growth promoting rhizobacteria (*Paenibacillus* sp., *Rhizobium* sp., *Bradyrhizobium* sp., *Pseudomonas* sp. etc.) and mycorrhizae (mainly arbuscular, ericoid and ectomycorrhiza) growth. Biochar have many O-bearing functional groups which involve in sorption of dissolved organic compounds, simple organic compounds, and ammonium ions, provide favorable microbial habitat (Thies and Rilling 2009; Wardle et al. 2008) and responsible for necessary changes in microbial activity.

12.4 Effect of Biochar on Soil Enzyme Activity

Soil enzyme activity is considered as a most important indicator of soil health. The biochar application had significant long and short term impact on soil enzyme and nutrient cyclic were reported. Biochar is influence the intra and extracellular enzymes activity of the organism in the different soil system like normal and stressed soil. One of the intracellular enzyme i.e. dehydrogenase in a soil have role in respiratory processes and strongly correlated with organic carbon availability (Teutscherova et al. 2018). Though, biochar had pH enhancing property it affects the activity of soil dehydrogenase enzyme by adding labile carbon for neutralizing the acid pH under degraded acid soil. Likewise, β-glucosidase is known for the catalyzing cellulose degradation in the final step of glucose release. On addition of biochar the β-glucosidase enzyme activity observed higher and/or decreased. The other hydrolases enzymes such as β-glucosaminidase, phosphatase and urease are involved in soil organic carbon transformation and nutrient cycling (Teutscherova et al. 2018). Urease enzyme have role in the transformation of soil organic nitrogen into available inorganic nitrogen and had no significant relation with biochar application because the feedstock type, pyrolysis conditions, production method, application rate, and soil types are the governing factors that will influence the nitrogen cycling and urease activity in the soil (Zheng et al. 2019). Invertase enzyme also plays crucial role in improving soluble nutrients in the soil, providing sufficient energy for the soil organisms and increased the activity with addition of biochar. The possible mechanism is biochar increases enzyme activity by enhancing the soil organic matter, microbial activity, and microbial biomass or through co-location of enzymes and their interaction with biochar surface (Zheng et al. 2019).

12.5 Effect of Biochar on Soil Physico-chemical Properties

Soil physico-chemical properties play an important role in plant and microbial growth and development. Biochar amendments can changes soil physico-chemical and biological properties such as reduce bulk density increased water holding capacity (retain plant available water), cation exchange capacity and favour the soil microbial activities. The changes in physical properties of soil are also depends on feedstock type, rate of application, type of biochar and interaction time of biochar with soil (Chaganti et al. 2015). It was well documented that the biochar had high porosity, high inner surface area and large number of micropores, which create a better environment for plant root growth, nutrient capture and air porosity (Zheng et al. 2019). Biochar application efficiently improves the soil fertility and crop productivity and also directly related to improvements in soil characteristics due to the high cation exchangeable capacity, surface area, and nutrient contents of biochar (Major et al. 2010). Under sandy loamy soil, biochar application considerably reduced clay dispersion and aggregate disintegration and increased in filtration rate (Abrol et al. 2016). Additionally, biochar also support the building processes of the soil structure via indirect mechanism, such as providing habitat for soil microorganisms and enzyme activities. The effects of biochar on the growth, nutrient uptake and soil properties are summarized in Table 12.2. On the other hand, under salt affected soil biochar is reduces the Na toxicity to the plant because the accumulation of sodium (Na^+) and also improved the K^+: Na^+ ratio through enhancing potassium (K^+) availability to plant (Saifullah et al. 2018).

Table 12.2 Multifarious role of biochar application under different soil type

Type of biochar application	Soil type	Advantage	References
Corn stalk	Silty clay	Reduce the nitrogen contamination of ground water. Changes in microbial community	Sun et al. (2018)
Holm oak	Acrisol Calcisol	Enhance dehydrogenase & urease activity Enhance aggregates stability	Teutscherova et al. (2018)
Manure compost	Salt affected soil	Increases in nutrient content (especially Ca, Mg, K, N & P)	Lashari et al. (2015)
Peanut shell	Salt affected soil	Improve soil organic C	Bhaduri et al. (2016)
Hardwood	Sodic soil	Reduce sodium uptake by Plants	Akhtar et al. (2015)
Beech, hazel, oak, birch	Saline/ sodic	Reduce Na^+ uptake, & leaching of K^+ and NH_4^+	Di Lonardo et al. (2017)
Peanut shell	Salt affected soil	Improve soil health Enhance nutrient availability Elevated bacterial activities & abundances related to nutrient transformations	Zheng et al. (2017)

12.6 Biochar for Improvement of Soil Nutrient Status

Nutrient retaining in soil for long time become a great interest of researchers because nutrient runoff, erosion and the leaching not only degrade soil quality but also adversely impact the quality of water in streams and reservoirs. Biochar have unique physical property to retain various nutrients in their pores and returns most of nutrients to the soils from which they came. Biochar also have the capability to increases the capacity of soils to adsorb essential plant nutrients (Liang et al. 2006; Cheng et al. 2008) thus reducing runoff or losses of nutrients. During formulation of biochar (pyrolysis) the most of essential plant nutrient such as Ca, Mg, Zn, K, P, and about half of the nitrogen and sulphur in the biomass feedstock are partitioned into the biochar fraction. Indeed, many reports are presented on biochar amendment increased the crop yield simultaneous improve the water holding capacity and nutrient use efficiency (Iswaran et al. 1980; Kishimoto and Sugiura 1985; Marjenah 1994; Yamato et al. 2006). The mechanisms of nutrients immobilization by biochars include (1) physical trapping of nutrients within pores of biochars, (2) direct electrostatic interactions between cationic nutrients and negatively charged carbon surfaces, (3) ionic exchange between nutrients ions and ionisable protons at the surface of acidic carbon, (4) specific binding of nutrients by surface ligands (functional groups) abundant on biochar surfaces, (5) reaction with mineral impurities (ash) and basic nitrogen groups (e.g. pyridine) of carbonaceous materials, (6) forming hydroxides, carbonates and/or various phosphate-involved precipices and (7) redox reactions with biochar along with sportive reactions (Li et al. 2018). In contrast, some reports found a decrease in microbial activity after biochar application (Qin et al.

Table 12.3 Influence of soil pH on addition of different types of biochar

Type of biochar application	Changes in soil pH		Percent increase (%)	References
	Initial	Final		
Bamboo	4.68	4.95	5.7	Li-li et al. 2017)
Mixture of Beech, Hazel, Oak and Birch	5.23	6.76	29.2	Rutigliano et al. (2014)
Oak and Hickory	6.33	7.23	14.2	Laird et al. (2010)
Maize straw	7.89	8.19	3.8	Xiao et al. (2016)

2010). These contrasting results could be related to changes in soil moisture, pH, and nutrient dynamics caused by the chemical components of the different types of biochar used (Table 12.3). Biochar had also good impact on soil respiration and soil microbial biomass (Zheng et al. 2019).

12.7 Conclusions

The problem of the depletion of agricultural land as a result of the pressure caused by the ever-growing population necessitated the sustainable practice of crop production. Biochar application is a unique sustainable approach, which has a significant potential to address number of environmental issues and good way to reduce chemical fertilizer use. Under field condition the biochar is a suitable candidate for the improvement of soil physio-chemical properties, microbial abundance and composition. However, biochar amendment to agricultural land had various effects on soil nutrient composition; changes in soil pH significantly, improving soil fertility, input of organic carbon and nitrogen contents. Several reports available on biochar application significantly reduced the soil bulk density, increased water holding capacity, cation exchange capacity, surface area, and the retention of various essential nutrients like N, P, K, Mg, Ca and several other plant nutrients.

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