CHAPTER

11

Biochar for Sustainable Agriculture: Nutrient Dynamics, Soil Enzymes, and Crop Growth

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11.1 INTRODUCTION

With the increasing demands of the ever-changing global population, a pragmatic approach to viable agricultural practices has become necessary. Sustainable agriculture (SA) is an area of growing interest as it focuses on plausible means to produce crops in an environmentally friendly, socially fair, and economically beneficial manner that can be sustained long term (Hester and Harrison, 2005).

Implementation of biochar amendment in agriculture serves to enrich the sustainability of soils in numerous ways. Biochar has the ability to act as a reservoir of macro- and micronutrients. It can also act as a short-term source of highly available nutrients instigating an acceleration of nutrient cycling processes long term (DeLuca et al., 2015). Nutrient dynamics are influenced by altering physiochemical properties and microbial community composition of the soil. Biochar has become a more cost-effective alternative for commercially available, slow-release nutrient sources such as coated- and nanofertilizers. In addition, the long-term stability of biochar in soil avoids the need for multiple periodic applications (Laird et al., 2010b; Novak et al., 2009).

From the perspective of community, creating and applying an organic-based amendment such as biochar can be easily taught to farmers. Any toxic effects that can result as a consequence are minimized by enabling the delivery of high-quality foods to the public (Atkinson et al., 2010).

Environmentally friendly effects result from biochar use in place of artificial amendments as it prevents nutrient leaching from soil. If leached into water ways, it can eventually lead to eutrophication (Laird et al., 2010a). The biochar production itself is a carbon-negative process, sequestering the carbon present in waste biomass that would otherwise have being released back into the atmosphere (Lehmann and Joseph, 2015).

This chapter focuses on how biochar benefits two key aspects of a soil ecosystem—nutrient dynamics and soil enzyme dynamics—that show how biochar can play a key role in sustainable agricultural practices (Lehmann et al., 2011; Rillig and Thies, 2012).

11.2 EVOLUTION OF SUSTAINABLE AGRICULTURE

11.2.1 Malthusian Catastrophe and Green Revolution

The British scholar Thomas Malthus in 1798 developed a concept to express the salient effects growing food demands have on agricultural production. Malthus predicted a population decline to an optimal state once the increasing food demand which is resulted by the population growth would surpass the agricultural production, later called the Malthusian catastrophe. (Maltus, 2006). Despite the threat predicted by the Malthusian catastrophe, the lucrative initiatives taken by the agricultural technology toward a green revolution, which expanded its scope during the 1930s and 1960s increased agricultural production globally, saving the world for over a century from catastrophe (Cullather, 2004). Adoption of new technologies including the utilization of chemical fertilizers and pesticides, the engineering of irrigation systems, the introduction of high-yielding and pest-resistant varieties along with the large-scale agricultural operations supported by mechanization can also be considered as significant attributes of the green revolution (Cullather, 2004).

However, one major drawback of commercial farming is the continuous removal of plant nutrients from farm lands requiring regular application of synthetic fertilizers to prevent the depletion of soil fertility and to improve soil health (Laird et al., 2010b). Leaching of applied nutrients from soils can have adverse effects on the quality of ground and surface water causing deleterious impacts on surrounding aquatic ecosystems. The excessive application of fertilizer can also result in increased cost of crop production (Laird et al., 2010a).

The drawbacks of the green revolution set the stage for a new concept called SA, creating a marriage between traditional agricultural systems and modern technology schemes. The SA movement began in the latter part of the 20th century and while there are many different definitions of it and its systems, it is an economically viable, environmentally safe, and socially fair form of agriculture production (Lichtfouse et al., 2009; Abubakar and Attanda, 2013).

11.2.2 Role of Biochar in Sustainable Agriculture

The idea of SA does not imply a strict deviation from technological developments, but rather includes the practices of (1) integrating natural processes in soil and plants that includes soil regeneration, nitrogen fixation, nutrient cycling, competition, predation, and parasitism into agricultural operations; (2) reducing nonrenewable inputs that are harmful to the environment; and (3) substituting expensive external inputs by human capital by enhancing the knowledge and skills of farmers (Pretty, 2008; Hester and Harrison, 2005).

Biochar is a renewable, environment friendly, low-cost material that can be used in agricultural soil amendments (Ahmad et al., 2014). Incorporation of biochar in agriculture has proven to be an excellent method of reaching sustainability as a result of its potential to (1) increase the ability of soils to retain and recycle nutrients (Biederman and Harpole, 2013); (2) increase carbon sequestration (Lehmann and Joseph, 2015); (3) enhance cation-exchange capacity (CEC) in soil (Liang et al., 2006); (4) act as a reservoir of macro- and micronutrients (Gaskin et al., 2010); (5) stimulate microbial activity and potentially contribute to enzyme dynamics in soil (Lehmann et al., 2011, Warnock et al., 2007); and (6) reduce nitrous-oxide and methane emissions (Cabeza et al., 2018). However, the productivity of soil amendments depends on various characteristics of the biochar such as the surface charge at operating pH, surface functionality and morphology, CEC, ash content, etc. (Herath et al., 2015). A rich science lies behind biochar application since these properties are heavily dependent on feedstock type, pyrolysis conditions, and the age of the biochar (Peiris et al., 2017). Thus biochar-based agronomy research has become a popular research topic in the past decade.

11.3 INFLUENCE OF BIOCHAR ON SOIL NUTRIENT DYNAMICS

SA is influenced by the effectiveness with which nutrients are cycled in the environment, and is critical for plant productivity. Both biotic factors such as community composition of plants, microbes, and soil fauna, and abiotic factors such as climate, soil type, and organic matter (OM) affect nutrient dynamics. Biochar can influence nutrient dynamics by increasing bioavailable nutrients, altering physiochemical properties of soil, and affecting soil ecosystems (Eviner and Firestone, 2007).

Continuous application of nutrients to soil in the form of synthetic fertilizer, manure, or other fertility amendment techniques enable the replacement of nutrients lost due to the harvesting of crop residues (Laird et al., 2010b). However, inorganic fertilizers have reduced retention in the soil as a consequence of the low nutrient-holding capacity of infertile soils (Glaser et al., 2001). This issue has been addressed by methods such as using slow-release forms of nutrients, multiple fertilizer applications, and by covering crops that maintain integrated root systems during the offseason despite the high cost associated with these methods (Laird et al., 2010a).

Currently, biochar is gaining acceptance as a relatively inexpensive and efficient alternative due to its high nutrient value that is made available to plants directly or indirectly. The direct contribution is by providing its labile nutrients to the plant whereas the indirect contribution is by improving soil quality that in turn increases the efficiency of fertilizer use (Xu and Chan, 2012; Xu et al., 2013).

11.3.1 Direct Nutrient Values of Biochar

Biochar is capable of enriching the soil nutrient pool by acting as a source of both macro- and micronutrients. Nutrient-rich biochar can function as a slow-release fertilizer (Ding et al., 2016). The production temperature of biochar is a critical factor for determining its nutrient content as a certain fraction of elements in the feedstock can be excessively lost by volatilization. The lowest volatilization temperatures (VTs) are reported in N (VT ~ 200°C) and S (VT ~ 375°C) while P and K have moderate VTs (~700–800°C). Nutrients such as Ca, Mg, and Mn are said to be thermally stable at typical biochar production temperatures (VT > 1000°C) (DeLuca et al., 2015; Laird et al., 2010b). At higher pyrolysis temperatures, the carbon content lost is increased, leaving a higher percentage of thermally stable nutrients behind. For instance, sludge based BC contains P mainly in the form of thermally stable inorganic salts creating a direct relationship between the P percentage and the pyrolysis temperature up to 800 °C. The K content in sludge-based biochar also increases with pyrolysis temperature due to inorganic associations (Hossain et al., 2011).

It is also important to note that only a small fraction of the total nutrient content of biochar is available to plants since a considerable fraction usually exists in recalcitrant forms (Gaskin et al., 2010; Laird et al., 2010b; DeLuca et al., 2015). As an example, the total S content of biochar exists partly as labile inorganic sulfates and partly as organic S, which is not bioavailable (Knudsen et al., 2004; Freney et al., 1975). The pyrolysis temperature can also affect labile and recalcitrant fractions of nutrients in a biochar. For instance, high-temperature biochar contains high ash content where nutrients exist mainly as soluble salts that can be readily liberated in soil (Ding et al., 2016; Zheng et al., 2013b; Irfan et al., 2017). It has been reported that the bioavailable amine-N fraction such as amino acids and amino sugars in the biomass can be lowered during high-temperature pyrolysis (> 700°C) due to formation of N-heterocyclic aromatic compounds (Gaskin et al., 2010; Novak et al., 2009). A study by Zheng et al. reported significant enhancement of P content when the pyrolysis temperature was increased from 300 to 600°C. However, biochar produced at 300°C contained a low fraction of crystallized P-associated minerals with higher bioavailability than the highly crystallized P found in high-temperature biochar (Zheng et al., 2013b).

The direct supply of nutrients is reported to be higher in fresh biochar generated from nutrient-rich feedstock (DeLuca et al., 2015). Multiple studies have reported high bioavailable nutrient content of newly prepared biochars and their capabilities to release increased amounts of N and P (Mukherjee and Zimmerman, 2013; Zheng et al., 2013b). Biochar produced from animal waste such as sewage sludge, manure, and broiler litter are reported to contain higher amounts of P and N than plant-based biochar (Xu and Chan, 2012; Irfan et al., 2017). Furthermore, the N content of swine manure biochar was found to be significantly higher than the biochar produced from giant cane at identical pyrolysis temperatures (400°C) (Ding et al., 2016). According to studies reported by Chan et al., increased levels of N, P, S, Na, Ca, and Mg have been detected in radish plants grown in poultry litter biochar-amended soil whereas only P, K, and Ca have been increased in plant-based biochar-amended soil (Chan et al., 2008b, 2008a).

The same type of feedstock can produce biochar with varying nutrient contents despite their identical pyrolysis conditions. As an example, the bioavailability of P in sludge-based biochar depends on the amount and the type of stabilizers applied during sludge treatment (Hossain et al., 2011). Significant variations of total N contents were reported in two biochars made from different poultry litters under the same conditions (Lima and Marshall, 2005).

However, multiple studies have reported a decline in the nutrient values of biochar after 1 year of application, making the unavailability of nutrients for long-term crop growth a major drawback of its direct application (Gaskin et al., 2010; Wu et al., 2011). It has currently become a challenging task to determine the pattern of nutrient bioavailability in the long term. As reported by Ding et al. knowledge of the long-term nutrient availability of biochar is insufficient as the majority of the studies reported are based on short-term column leaching experiments (Ding et al., 2016).

11.3.2 Indirect Nutrient Values of Biochar

Biochar is capable of indirectly influencing the different physiochemical properties of soil such as total organic carbon, pH, CEC, and soil bulk density leading to an elevation of its inherent quality and health (DeLuca et al., 2015).

Cation-exchange capacity: The CEC of soil, which is a measure of the total cations that can be retained by soil-exchangeable sites, is a key contributor of soil quality. This parameter is mainly governed by the mineral content and the soil organic carbon. In soils where aforementioned factors are low, reduced CEC is exhibited-leading to the deleterious consequence of nutrient leaching (Masulili et al., 2010). There are several reports of noteworthy augmentation in the CEC of soils subjected to biochar amendment (Laird et al., 2010b; Jien and Wang, 2013). Enhanced cationic nutrient retention of metal ions such as K, Ca, Na, and Mg in soil upon biochar amendment has also been reported occasions (Wang et al., 2014; Gaskin et al., 2010).

The CEC is mainly due to the negative surface charge on the biochar that arises from both OM and oxygenated surface functional groups (O-SFGs) (Atkinson et al., 2010; Novak et al., 2009). The fulvic and humic substances present in biochar constitute the OM that acts as exchangeable sites for cations (Atkinson et al., 2010). The functional groups present on the biochar surface vary depending on the pyrolysis conditions incorporated. Low-temperature-produced biochar consists of numerous lactonic and carboxylic groups on its surface that get deprotonated in soil to produce negatively charged anions capable of binding to cations via electrostatic attractions. In comparison, high-temperature-produced biochar is low in such O-SFGs, yielding low CECs (Ippolito et al., 2015).

Smaller and highly charged cations in soil show higher affinity toward exchangeable sites in biochar. For instance, Novek et al. reported increased retention of multivalent cations such as Ca, Mg, Zn, and Mn compared to monovalent cations such as Na and K in biochar-amended soil (Novak et al., 2009). Bioavailable nitrogen can exist in ammonium and nitrate forms. Soil CEC is mainly responsible for the retention of NH_4^+-N whereas anion-exchange capacity (AEC) and porefilling mechanisms govern the retention of

$NO_3^- - N$ (Trindade et al., 1997). In comparison with $NO_3^- - N$, higher retention of $NH_4^+ - N$ is often observed by biochar application due to higher CEC of biochar compared to its AEC (Zheng et al., 2013a). Phosphate retention is analogous to nitrate retention. However, ligand exchange reactions can also contribute to the sorption capacity of anions (Novak et al., 2009).

Total organic carbon: Total organic carbon in soil is a validated parameter to judge the condition of a soil. A soil's productivity is dependent on its capacity to retain water and nutrients as well as on its CEC and soil structure. However, lack of OM in the soil can lead to the decline of afore mentioned facets regardless of the application of synthetic fertilizer as soil amendment (Laird et al., 2010b).

The harvesting period is a time during which much of the OM is removed from the soil. To compensate for this, use of manure and biochar has proven to be effective. However, one of the drawbacks of manure application is its rapid decomposition (Laird et al., 2010b; Jeffery et al., 2011). In Venezuelan rain forests, for example, the average lifespan for the OM applied is less than 4 years. Decomposition of soil OM is accelerated as a result of high temperatures, which leads to increased bacterial degradation of the organic amendments applied. The humidity that results as a consequence of increased rainfall can also be a contributing factor. Manure has minimum stabilizing agents in its structure to confer resistance to degradation and thereby contributes to the lifespan of these organic particulates (Glaser et al., 2001).

Biochar, in contrast, is reportedly more stable than manure due to its carbonaceous structure (Laird et al., 2010b; Downie et al., 2009). For instance, Laird et al. (2016b) reported significant enrichments of total organic C in soil upon biochar amendment when compared to manure application (Laird et al., 2010b). It is important to note that biochars produced at extreme temperatures ($> 800°C$) with more graphitized structures are less stable in soil than low-temperature biochars that are generally disordered and recalcitrant in nature (Downie et al., 2009; Rajapaksha et al., 2014).

The C:N ratio: The C:N ratio is another important parameter when considering soil nutrient availability as it serves as a measure of the amount of nitrogen immobilized (Laird et al., 2010b). As reported in the literature, a ratio of greater than 32:1 in organic residues is justification for significant nitrogen immobilization in the soil (Alexander, 1977). In biochars, this parameter can take on values ranging from 7 to 400, with a numerical average of 67. However, the low decomposition rate of biochars despite their high C:N ratios make nitrogen immobilization insignificant, which is an additional advantage over the application of organic amendments such as manure (Lehmann, 2007).

Soil pH: Biochar plays a role in enriching the labile nutrient pool by altering the soil pH, leading to increased bioavailability of nutrients, facilitating microbial activity and also root access to water and nutrients. Upon its application to soil, biochar can elevate the bioavailability of nutrients by the liming effect and by trapping trivalent species (Nigussie et al., 2012).

Weathered soils abundant in iron and aluminum tend to be acidic due to the liberation of hydronium ions upon hydroxide formation (Sato et al., 2009; Novak et al., 2009). Insoluble iron and aluminum phosphates reduce the phosphorous bioavailability in such soils (Novak et al., 2009). The liming effect arises as a result of the calcium oxides present in the biochar that react with the soil phosphorous in order to form calcium phosphates.

The solubility of these complexes make the inorganic P bioavailable to the plant while reducing the soil acidity (Novak et al., 2009). The exchangeable sites of biochar show high affinity for trivalent aluminum and iron reducing their availability to form insoluble complexes with P (Nigussie et al., 2012). The high cost associated with liming makes biochar a more economically viable technique (Masulili et al., 2010).

Furthermore, the presence of elements such as Al, Cu, and Mn in the soil that can cause toxic effects to the plant at acidic pH are also negated by biochar application (Atkinson et al., 2010).

Water-holding capacity: WHC is an integral aspect of agriculture that is dependent on the texture of soil and precipitation rate. Soil OM is a key factor determining its WHC, which influences nutrient movement and leaching, prominently in the rooting zone (Atkinson et al., 2010). Reduced WHC results in poor crop productivity and soil degradation (Amezketa, 1999). Soil WHC can be influenced by biochar application due to humic substances, porous nature, and interactions with roots (Ding et al., 2016).

The pore structure of biochars have different effects on the soil quality (Yuan et al., 2015). Micropores and mesopores are important for the retention of available water content whereas macropores are involved in hydraulic conductivity (Herath et al., 2013). Biochar is reported to influence WHC more significantly in sandy soils than in soils with a high clay fraction (Atkinson et al., 2010).

In addition to water retention, the macroporous structure of biochar assists in improving soil aeration and water infiltration (Yuan et al., 2015). Soil aggregation is a term used to describe the process of soil particles adhering to each other, creating pore spaces for holding water and air. Biochar enhances this aggregation by interacting with soil OM, minerals, and microorganisms (MOs) (Kelly et al., 2017).

Soil bulk density: Bulk density, defined as the weight of soil in a given volume, serves as an indicator of soil compaction and soil health. Bulk density has a noteworthy effect on key soil processes as it affects infiltration, rooting depth, available water capacity, soil porosity, and MO activity. For example, a soil with a bulk density greater than 1.6 g cm^{-3} would restrict root growth. Soil OM, texture, and the packing arrangement are factors governing bulk density (Jury and Stolzy, 2018).

The organic amendments used dictate the value that the soil bulk density will assume. Biochar application, however, has shown to result in a significant reduction in bulk density as compared to manure application. This is attributed to the porous structure of the biochar. Biochar particles are highly porous and thereby have low densities that when applied to soil can lead to a decrease in the overall soil bulk density (Laird et al., 2010b; Herath et al., 2013).

11.4 INFLUENCE OF BIOCHAR ON SOIL ENZYMES

Changes in biological properties must also be considered for prudent evaluation of soil fertility (Sherene, 2017). The enzymatic activity that takes place in the rhizosphere poses a significant impact on the nutrient bioavailability to the plant, which in turn affects plant health and productivity (Abubakar and Attanda, 2013). Soil enzymes are an effective means of appraising soil quality due to their high sensitivity and the rapid responses elicited to changes in the soil environment (Sherene, 2017).

MOs, fauna, and plant roots in the soil are sources from which these enzymes originate and are usually stabilized in the soil matrix by forming complexes with OM, humic colloids, or clay particles (Bandick and Dick, 1999; Laird et al., 2010b). Soil enzymes perform their inherent role of catalysis, taking part in metabolic processes such as degradation of OM, mineralization, and nutrient transformation whose efficiencies are dependent on temperature and pH (Burns et al., 2013).

Soils subjected to organic amendments, crop rotations, and cover crops have shown enhanced enzymatic activity that elevates nutrient cycling processes in the soil (Du et al., 2014). Application of biochar serves to alter physiochemical properties of the soil and the microbial community composition, which affects soil fertility as a consequence (Warnock et al., 2007). The expanding scope of biochar-based soil amendments as a plausible means of managing soil biota provides evidence for the growing interest in the field (Ding et al., 2016).

11.4.1 Influence of Biochar on Microorganism-Derived Soil Enzymes

There have been various reports of variations in MO populations upon biochar application (Anderson et al., 2011). The reported rise in numbers of anaerobic and cellulose hydrolyzing bacteria, for example, has been shown to result from biochar amendments (Lehmann et al., 2011). Three mechanisms can be used to portray this alteration, which results from the influence that biochar has on (Warnock et al., 2007) (1) nutrient availability and soil physiochemical parameters, (2) the activity of MO and the ability to serve as a refuge for colonizing MO, and (3) its effect on the signaling dynamics between plants and MO, discussed as follows.

Influence on nutrient availability and alterations in soil physiochemical properties: MO and their enzymes contribute substantially to the regulation of processes such as nutrient cycling. Some examples of enzymes involved in nutrient cycling are β-glycosidase, β-ᴅ-cellobiosidase, and β-xylosidase involved in the carbon cycle; *N*-acetyl-β-glucosaminidase, urease, and leucine aminopeptidase involved in the nitrogen cycle; and phosphomonoesterase involved in the phosphorous cycle (Sherene, 2017; Song et al., 2018). Biochar can have an effect on these enzymatic activities. The genus *Pseudomonas* is an MO involved in the cycling of phosphorous, releasing phosphatase enzymes that catalyze the hydrolysis of ester phosphate bonds. This leads to the inorganic phosphorous becoming solubilized and made bioavailable (Beheshti et al., 2017; Khan et al., 2007).

Application of biochar leads to a change in physiochemical properties of soil that causes MO composition and their functions to be altered significantly by the additional complexity to the extracellular enzyme activities. Biochar is comprised of macropores, mesopores, and micropores of varying sizes that can become a habitat for MO. Saprophytic fungi can form colonies inside these pores leading to the decomposition of the biochar. This makes the nutrients available for the plant, increasing the crop growth. Fungi such as *Trichoderma* and *Penicillium* spp., for example, produce enzymes such as manganese peroxidase and phenol oxidase to depolymerize the biochar (Rillig and Thies, 2012). The intricate porous structure of biochar leads to an enhancement in oxygen diffusion, increasing the respiratory activities of certain aerobic organisms that carry out ammonia oxidation and methane oxidation.

The adverse influence of biochar amendments on microbial enzyme activities have also been reported in the literature. The ability of acidophilic *Thiobacillus* to oxidize sulfur is an example of a mechanism that is diminished due to this practice. As sulfur is not bioavailable in its usual organic form, it has to be oxidized to sulfate by enzymes. However, the ability of the bacterium to carry out this process is hindered by the addition of biochar since it creates an unfavorable environment for sulfur oxidation (DeLuca et al., 2015). Another example would be the reported decrease in maximum velocity of enzymes such as cellobiosidase and glucosidase with higher rates of biochar application (12 t of biochar per hectare or greater) (Akça and Namli, 2015). Furthermore, an inhibition of the enzyme function can occur due to the sorption of organic and inorganic substrates onto biochar (Lehmann et al., 2011).

Influence on the activity of MO and its role in acting as a refuge for MO colonization: Colonization of MO can have an indirect effect on soil enzyme dynamics that is favored by the carbonaceous and nutrient-rich nature of biochar. Examples of these colonizing MO include mycorrhiza helper bacteria (MHB) and phosphorous solubilizing bacteria (PSB) (Riedlinger et al., 2006). Specific conditions induce bacteria to secrete metabolites such as flavonoids and furans that assist the growth of fungal hyphae and subsequent colonization of Ectomycorrhiza (ECM) and Arbuscularmycorrhiza (AMF) in plant roots (Warnock et al., 2007). Raffinose produced by strains of *Paenibacillus* (Hildebrandt et al., 2006) and flavonoids produced by *Rhizobium* and *Bradyrhizobium* (Cohn et al., 1998) species can also contribute to extraradical mycelium growth and to an increase in root colonization of AM fungi.

Influence on the signaling dynamics between plants and MO: Biochar application can modify signaling pathways between microbes and plant roots. These variations can result due to changes in pH and the temperature at which the biochar was produced. Flavonoid signaling compounds are dependent on pH and can elicit excitatory or inhibitory responses in soil biota (Warnock et al., 2007). If excitatory in nature, these responses would yield high fungal populations in the soil. Biochar produced at high temperatures can capture signaling molecules that are not immediately detected by AMF hyphae or spores, thereby promoting signal transduction. Changes in signal dynamics due to these factors can indirectly contribute to soil enzyme dynamics by causing changes in microbial populations.

11.4.2 Faunal Population Response to Biochar in Soil

The involvement of soil fauna in the events of enzymatic action has not been extensively studied. Soil fauna is an essential part of fungal and bacterial energy channels (Cragg and Bardgett, 2001). However, its involvement is significant as fauna is positioned at the top of the food chain and thereby understanding of the effects of biochar application on its characteristics and biology can widen scientific understanding of the various microbial responses produced with biochar amendment to soil. For instance, the N-cycling MO in the guts of earthworms have more pronounced action with biochar amendment (Lehmann et al., 2011).

11.4.3 Plant Root Response to Biochar in Soil

Plant roots secrete many exudates that pose beneficial and harmful effects to rhizosphere microbial populations. Such compounds include inorganic ions and substances, amino acids, volatile aromatic compounds, proteins, and enzymes (Dundek et al., 2014). These exudates can vary according to the different plant species and conditions. Pruned tea bushes, for example, secrete more root exudates that influence microbiological and biochemical properties in the rhizosphere than unpruned tea plants (Pramanik et al., 2017). MO abundance of species such as *Bacillus*, *Pseudomonas*, and *Trichoderma* can alter in response to the induced systemic resistance produced by exudates of plants of tomato, pepper, and bean, respectively (Kolton et al., 2011). Therefore, these diverse plant root exudes including enzymes enable the communication with rhizosphere MO to cope with plant pathogens. However, information on this in regard to biochar amendment is minimal (Akhter et al., 2015).

11.5 EFFECT OF BIOCHAR ON CROP GROWTH

Increased crop yields, seed germination, and crop growth is evident after biochar application to soils. The interface between the plant root and the soil (the rhizosphere) and the root system of the plant are vital components in crop growth since they are involved in water and nutrient uptake, storage, and regulation. The rhizosphere tends to be larger in soils containing biochar (Zheng et al., 2013a).

Since it is a proven fact that the plant roots are attracted to biochar, we know it is involved in the direct uptake of plant nutrients. Rhizosheath size can help determine the efficiency of phosphorous uptake to the plant under phosphorous-deficient conditions (Prendergast-Miller et al., 2014). Biochar addition leads to decreased accumulation of rhizosheath, indicating increased supply of phosphorous to the plant (Brown et al., 2012). Considerable enhancements of root volume, length, and surface area have been reported after biochar amendment (Zheng et al., 2013a).

The amount of sunlight reflected by the earth surface is known as the albedo. The black surfaces of biochar increase the albedo of farmlands leading to enhanced crop growth due to improved rates of photosynthesis (Usowicz et al., 2016).

The contributions of enhanced nutrient cycling and enzyme activity on crop growth have been comprehensively discussed in the previous subsections. Multiple studies have reported high crop yields after biochar application (Irfan et al., 2017; Zheng et al., 2013a,b; Lehmann et al., 2003; Graber et al., 2010; Herath et al., 2015). However, a decrease in plant yield and MO community has been observed by some as a result of high biochar application rates (Herath et al., 2015). This could be as a consequence of the toxic elements and the high percentage of volatile content in the soil, leading to an abatement in nutrient uptake by the plant (Asai et al., 2009).

11.6 CONCLUSIONS

Biochar contributes to soil fertility by either acting as a direct nutrient source or by altering the physiochemical properties in the soil. The nutrient content that constitutes biochar is dependent on the type of feedstock used. Optimum pyrolysis conditions should be employed to ensure minimal volatilization of essential nutrients. A high percentage of the nutrients present in biochar should be in their bioavailable forms. This makes biochar an effective slow-release nutrient source when applied to soil. It, however, is not a long-term contributor to soil fertility.

Significant enhancement in crop productivity can be seen with biochar application to acidic soils as it leads to an increase in the soil pH. Biochar can act as a stable carbon source in the soil and can elevate the soil CEC resulting in the retention of many micro- and macronutrients. The WHC of soil, water infiltration, and soil aeration are governed by macropores of biochar particles. The overall soil enzyme activity that originates from MO, plants, and animals is enhanced by biochar application, which heightens the decomposition of OM and nutrient cycling.

The simplicity, cost effectiveness, and physical and chemical characteristics associated with biochar has attracted research interest worldwide. It has the potentially to expand the success SA practices.

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