6 Application of Biochar for Sustainable Development in Agriculture and Environmental Remediation

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6.1 Introduction

The early developments have largely focused on the use of biochar as a soil amendment in agriculture, but other applications in environmental remediation. Thus, this chapter offers comprehensive and updated information related to production of biochar, its use for agriculture sustainability as well as environmental remediation. The special structure and greater surface area, the high load density of the biochar help to absorb various soil contaminants. It also stabilises biomass and native soil organic matter (SOM) which enhances soil aeration, improves microbial activity and immobilises nitrogen which together reduces the emission of major greenhouse gases, i.e. CH4, CO2 and N2O. The role of biochar in developing sustainable development in the agriculture system is immense, and so is its potential to moderate climate change, which is far beyond its use in agriculture.

Biochar, a by-product of the pyrolysis process, is a biomass-derived black carbon intended for use as a soil modification. As a soil change, it is mainly used to improve soil nutrient status, C storage and/or filtration of percolating soil water. Biochar has an intrinsic energy value that can be used to increase the energy output of pyrolysis. Research has shown, however, that the use of biochar in soil can be more beneficial as it can increase soil organic carbon (SOC), boost the supply of nutrients to plants and thus enhance plant growth and soil physical, chemical and biological properties.

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Biochar is believed to support crop production through three primary mechanisms: direct alteration of soil chemistry through its intrinsic elemental and compositional structure (e.g. availability of nutrients and light organic molecules and decrease in soil acidity); provision of chemically active surfaces that modify soil nutrient dynamics or otherwise catalyse useful soil reactions (e.g. increasing the cation exchange capacity of the soil) and modifying physical character of the soil in a way that benefits root growth and/or nutrient and water retention and acquisition (e.g. reduction of soil bulk density, creation of stable macro-aggregates, improved tilth, provision of shelter for microorganisms).

Biochar has also been studied as a means of more sustainable catalytic converting (Kastner et al. 2012) activated carbon (Park et al. 2013), novel magnetic adsorbents (Chen et al. 2011), phosphate traps for soil remediation (Cao et al. 2009) and hydrogen storage (Sevilla and Mokaya 2014) using biorenewable materials. These green technological advances will increase the viability of pyrolysis-based bioenergy and foster economic growth in rural communities, while offering sustainable alternatives to meet consumer needs.

While increasingly recorded research has shown the beneficial effects of biochar on agricultural growth in recent years, the remedial aspect of biochar is missing. We, therefore, mentioned in this chapter the production of biochar and the use of biochar for sustainable development in agriculture and environmental rehabilitation.

6.2 Production of Biochar

Biochar processing from waste biomass is inexpensive and advantageous because this method offers renewable alternatives to fossil fuels, and the biochar commodity can also be used to combat climate change (Barrow 2012). Waste biomass has been commonly used to manufacture biochar from a number of sources (Cantrell et al. 2012), such as crop residues, forest waste, animal manure, food process (Li et al. 2013; Ahmad et al. 2014). Biochar processing can also produce oil and gas products that could be used as a source of renewable energy (Windeatt et al. 2014). Biomass thermal decomposition into biochar, oil and gaseous materials can be accomplished using a range of approaches including pyrolysis, gasification, hydrothermal carbonisation (HTC), torrefaction and conventional carbonisation methods (Stelt et al. 2011). Gasification is distinct from the general pyrolysis process (Ahmad et al. 2014). For gasification, biomass transforms into CO and H2 rich gases by reacting with biomass at high temperatures (N700 °C) in a regulated oxygen and/or steam system (Mohan et al. 2006). However, the yield of char from biomass gasification is very low, which is not suggested for the development of biochar. Hydrothermal carbonisation provided the final carbonaceous material (hydrochar) from a wet feedstock without an energy intensive pre-drying phase (Kumar et al. 2016), whereas extra thermal energy is usually needed for post-treatment of HTC streams, such as the separation of solid and liquid products (Kambo and Dutta 2015). Torrefaction is a pre-treatment process that has been extensively studied to transform biomass into carbon-rich solid fuel, such as biochar (Chen et al. 2015). It could also extract volatiles through different decomposition reactions in order to reduce the main limitations of biomass, improve the quality of biomass and adjust the combustion behaviour (Yu et al. 2017). However, the high inorganic metallic content of ash remains a significant challenge for the comprehensive use of biochar during the torrefaction process (Kambo and Dutta 2015). Biochar can be produced by thermochemical decomposition of biomass at 200–900 °C in the absence of oxygen, commonly known as pyrolysis (Ahmad et al. 2014; Demirbas and Arin 2002). Pyrolysis is generally divided into fast, intermediate and slow depending on the time of residence and temperature (Mohan et al. 2006). Fast pyrolysis with a very short retention time (<2 s) generates more liquid fuel, which is often used to produce bio-oil from biomass yielding around 75% (Mohan et al. 2006). Slow and intermediate pyrolysis processes with a residence time of a few minutes to several hours or even days are generally preferred for biochar production (25–35%) (Brown et al. 2009). The conventional way to synthesise biochar is through slow pyrolysis. Compared to HTC and torrefaction, it has higher carbon content (Wilk and Magdziarz 2017). In addition, slow pyrolysis results in lower liquid fuel yields and higher biochar yields compared to other thermal chemical processes (Windeatt et al. 2014; Yu et al. 2017). Biochar production is stated to be a complicated physicochemical process that affects the inherent inorganic substances and the pyrolysis mechanisms and interactions of major components such as cellulose, hemicellulose and lignin in biomass (Lian and Xing 2017). In general, the characteristics of biochar are determined by many variables, such as biomass feedstock, pyrolysis temperature, pyrolysis temperature residence and pyrolysis atmosphere (Windeatt et al. 2014). Preparation temperature and parent material (raw material, precursor, feedstock) are two major factors regulating the properties of biochars (Lian and Xing 2017; Tang et al. 2013). Lee et al. (2017) examined the ability of agricultural waste as a feedstock for slow pyrolysis biocharging (50 mL min − 1, N2 at 500 °C). The relationship between the thermochemical properties of the feedstocks and the biochar developed was calculated using various characterisation methods. In particular, several variables in the production of biochar, including pyrolysis conditions and feedstock types, can affect its exact function in environmental management (Ahmad et al. 2014; Safaei Khorram et al. 2016). The type of feedstock had a greater impact on the efficiency of biochars for metal removal than the pyrolysis temperature (Higashikawa et al. 2016). It has been presumed that the porous structure and sorption characteristics of the activated biochar are based on the physicochemical properties of the precursor biochar as well as the activation methods (Park et al. 2013). Actually, activated carbon, which is carbon dioxide treated with oxygen to increase microporosity and surface area, is the most widely used carbonaceous sorbent (Ahmad et al. 2014). In particular, the aromatic structures of the biochar can play an important role in the formation of porous networks during the activation process. In short, feedstock types and production processes may lead to biochars with different properties and therefore different effects, further studies on the effects of different types of biochars are required to systematically evaluate their effects on agriculture and environmental remediation (Saifullah et al. 2018).

6.3 Biochar and Microorganism

Bonanomi et al. (2015) reported that biochar is effective against both air-borne (e.g. *Botrytis cinerea* and different types of powdery mildew) and soil-borne pathogens (e.g. *Rhizoctonia solani* and species of *Fusarium* and *Phytophthora*). The use of biochar derived from citrus wood was capable of regulating air-borne grey mould, *Botrytis cinerea* on *Lycopersicon esculentum*, *Capsicum annuum* and *Fragaria ananassa.* While there is a lack of published data on the effects of biochar on soil-borne pathogens, evidence from Elmer et al. (2010) has shown that regulation of such pathogens may be possible. The addition of biochar in 0.32, 1.60 and 3.20% (w/w) of *Asparagus* soils infested with *Fusarium* increased the biomass of *Asparagus* plants and reduced *Fusarium* root rot disease (Elmer et al. 2010). In the same way, *Fusarium* root rot disease in *Asparagus* was also reduced by biochar inoculated with mycorrhizal fungi (Thies and Rillig 2009). A study of the suppression of bacterial wilt in tomatoes showed that biochar produced from municipal organic waste reduced the incidence of disease in *Ralstonia solanacearum* infested soil (Nerome et al. 2005). Ogawa (2006) promoted the use of modified biochars and biochars to manage soil diseases caused by bacteria and fungi. The mechanism of disease suppression has been due to the presence of calcium compounds, as well as changes in the physical, chemical and biological characteristics of the soil.

According to Mackie et al. (2015), a mixture of compost and biochar-compost has increased microbial biomass, phospholipid fatty acids (PLFAs) and various enzyme activities, i.e. phosphatase, arylsulphatase, as well as an increase in bacterial taxon, i.e. *Actinobacteria,* 5–007-*Proteobacteria,* β-*Proteobacteria, Firmicutes* and *Gemmatimonadetes.*

Diazotrophs, a specialised group of bacteria (and Archaea), have a common function: they possess the enzyme nitrogenase and the ability to reduce atmospheric N2 to NH3, which can be nitrified ($NO3^{-}$) prior to plant uptake. These diazotrophs act as either free-living N-fixing soil bacteria (e.g. *Azospirillum* sp.; *Azotobacter* sp.) or mutualists inside plants (e.g. *Rhizobia* forming legume nodules or *Actinorhizal* associations of *Frankia* sp.) (DeLuca et al. 2006). Free-living bacteria are less successful at N2 fixation than symbiont rhizobia, i.e. 5 compared to 3–206 kg N2 ha − 1 y − 1, respectively. Despite the ubiquitous presence of these free-living N2 soil bacteria, few studies have shown that the use of activated carbon (Berglund et al. 2004) and biochar (Gundale and DeLuca 2006) will improve nitrification. Biochar micro-environment can also provide a favourable niche (fine structural pores) in which the concentration of oxygen decreases; low oxygen voltages with Fe and Mo ions are needed in order for nitrogenase to work effectively (Thies and Rillig 2009). Biochars are typically low in inorganic-N2 and this can give diazotrophs a competitive advantage for the colonisation of large surface biochars. This element, combined with the capacity of biochar for NH4+ exchange with soil solution, could alter the availability of soil-N2 to the plant and stimulate nodulation and fixation.

The role of biochar in the adsorption and protection of chemical signalling molecules derived from plants, such as node factors that enhance root nodulation through *Rhizobia*, has been suggested (Thies and Rillig 2009). Evidence exists to show that increasing rates of biochar application to soil can increase the proportion of N2 derived from *Phaseolus vulgaris* fixation and this increases in yield (Rondon et al. 2007). These beneficial effects were related to increased availability of Mo and B (source not determined) with an increase in soil pH. *Rhizobia* has increased role in neutral pH soils, whereas increasing alkalinity in acid soil improves nodulation and fixation.

The different functional groups within 'soil fungi,' i.e. saprophytes, pathogens and mycorrhizae, react differently to biochar applications (Thies and Rillig 2009). Saprophytes theoretically alter the persistence of biochar soil through decomposition. Their invasive hyphal growth and extracellular enzymatic ability enable them to colonise biochar pores. Soil pathogenic fungi are extensive and especially important in the management of plant diseases. However, the impact of biochar on soil pathogens (population structure and function) appears to be minimal. Matsubara et al. (2002) have shown that the resistance of asparagus seedlings to *Fusarium oxysporum* has been improved by the use of biochar.

While biochars themselves can contain only small amounts of plant nutrients to support mycorrhizal fungi (Lehmann et al. 2003a, 2003b; Gundale and DeLuca 2006), it is proposed that biochars increase the availability of soil nutrients by altering the physical-chemical properties of the soil. These changes in themselves alter the supply of nutrients and possibly mycorrhizal abundance, and modify the local nutritional balance, e.g. N/P ratios, thereby impacting root colonisation (Miller et al. 2002). The idea that the availability of nutrients or improved efficiency of use, due to the existence of biochar, needs a critical review to determine the function of soil microorganisms.

6.4 Application of Biochar

Biochar has a vast number of applications in agricultural and environment field, some of are described below:

6.4.1 Increased Soil Fertility

Biochar soil additions cause pH, electrical conductivity (EC), cation exchange capacity (CEC) and nutrient levels to change (Gundale and DeLuca 2006). The increase in soil pH induced by biochar application is not surprising given the well-known use of materials such as wood ash for pH modification and the availability of nutrients, especially P and K. Elevated CECs are caused by a rise in the load density per unit surface of organic matter, which is equivalent to a higher degree of oxidation, or an increase in the surface area for cation adsorption, or a combination of both.

Liang et al. (2006) reported an increase in organic matter adsorption and load density (CEC per unit surface area) in anthrosols due to black carbon particle surface oxidation. Ammonium leaching, although from greenhouse biochar experiments, has been reduced (by 60%) (Lehmann et al. 2003a, 2003b), although in some cases N2O emissions may be reduced (Spokas and Reicosky 2009). Other research using soils in Amazonian field studies have reported that biochar can act as an adsorber to minimise N leaching and increase N use quality (Steiner et al. 2008). A large area of research will appear to be needed to ensure that the pyrolysis process and the feedstock used have the potential to optimise soil N for plant availability while reducing leaching. Efficiency of N use will be an absolute requirement to sustain future population growth. In order to do this, much more needs to be considered with regard to the mechanistic effect of biochar (direct and indirect) on nitrification and Na-validity. Expectation of enhanced soil fertility benefits emerges from terra preta studies that involve high proportions of black carbon (Haumaier and Zech 1995; Glaser et al. 2002; Lehmann et al. 2003a, 2003b). The apparent fertility of the *Terra preta* is usually due to the high content of soil organic matter—organic matter contributes to the preservation of water, soil solution and cation and the retention ability of the aged biochar itself for nutrients and water. Black carbon present in terra preta is thought to come from partially-combusted biomass residues resulting from a variety of anthropogenic activities, including cooking and field fires. An especially striking aspect is the stronger relationship between soil carbon content and soil CEC in these soils compared to neighbouring soils, suggesting that biochar represents a higher proportion of soil carbon (Liang et al. 2006). Since CEC is representative of the ability to maintain key soil nutrient cations in a plant-available form and mitigate leaching losses, this is cited as a key factor where variations in crop productivity are observed. High levels of biocharging in the tropical environment have been correlated with increased plant uptake of P, K, Ca, Zn and Cu (Lehmann and Rondon 2006a, 2006b). In comparison to mainstream chemical fertilisers, biochar often contains bioavailable elements, such as selenium, which have the potential to help increase crop development.

Much speculation has been made about the possible effects of biochar on soil microbial activity, which Steiner has studied in depth in the sense of *Terra preta* (Steiner et al. 2003). Assuming that plant inputs and thus microbial substrate remain unchanged, enhanced microbial activity alone will minimise soil organic matter. This is, however, contrary to the finding in *Terra preta*, where soil organic matter is usually higher than in comparable surrounding soils (Liang et al. 2006). However, a shift in the balance of microbial activity between different functional groups could gain crop nutrition, specifically the enhancement of mycorrhizal fungi (Ishii and Kadoya 1994), which could lead to higher net primary productivity and carbon production. Relatively comprehensive literature records the stimulation of indigenous arbuscular mycorrhizal fungi by biochar, which has been expressed in plant growth Rondon et al. (2007), Nishio (1996). Warnock et al. (2007) analysed this literature in some detail, suggesting four mechanistic hypotheses, the most plausible of which were mixed nutrient, water and CEC effects.

6.4.2 Water Retention in Soil

Both the mineral and organic components of the soil contribute to the soil water holding capacity, but only the latter can be actively controlled. Water is kept tighter in small pores, so clay soils hold more water. Lower soil bulk density commonly correlated with higher soil organic matter is a partial indicator of how organic matter changes soil structure and pore size distribution. Many researches, in which the impact of biochar on crop yield was assessed, cited moisture retention as a key factor in the results. Given that the pore size of the biochar is relatively constant, while that of the mineral soil is determined primarily by its texture, it can be predicted that the available moisture in sandy soil will increase, will have a neutral effect on medium textured soils and will decrease the available moisture in clay soils. Any impact of the size of the biochar particle could be short-lived, as it appears to be relatively rapidly disintegrating into fine fractions. Experimentally, the usual technique for determining pore size characteristics is the moisture-release curve, which shows how easily soil moisture is drawn from soil under increasing stress.

The method is well adapted for distinguishing differences between soils of contrasting texture, but its sensitivity may be less adequate for discriminating against the effect of contrasting management at a particular location: high levels of replication may be required to demonstrate a significant impact of a management intervention of a realistic magnitude. In a more recent study (Gaskin et al. 2007), moisture-release curves were determined using samples of loamy sand soil from field experiments where biochar was applied at rates of up to 88 t ha-1. In soils where biochar was applied at concentrations of up to 22 t ha-1, there was no difference from non-modified soil, although at the maximum rate the difference was substantial at water potentials in the range of 0.01–0.20 MPa. The mean volumetric effect of the water content was doubled by the addition of biochar at the maximum potential. Soil temperature, soil cover, evaporation and evapotranspiration influence the available soil water. The comparison of the actual volumetric water content between biochar-modified and control soils in field experiments can, therefore, be confounded by any indirect impact of biochar on plant growth and soil thermal properties. Soil organic matter increases soil water holding capacity and in the biochar-enriched terra preta with their associated higher levels of soil organic matter, Glaser (2002) reported a water retention capacity that was 18% higher than in adjacent soils in which charcoal was low or absent. This was likely a combined effect of the char itself and the higher levels of organic matter that this promotes.

The effect of biochar (BC) and hydrochar (HTC) on water retention characteristics (WRC) as well as on the wettability of sandy soils has been documented using lab and field studies. Sandy soils with varying quantities of organic matter were mixed with BCz (feedstock maize) and HTC. The total added was 1, 2,5 and 5 wt percent, respectively. The mixtures were packed in 100 cm3 of soil columns. In the field campaign, the same quantities of BCf (feedstock beech wood) were applied to the soil. Samples of undisturbed soil were taken 6 months after incorporation. Accessible water capacity (AWC) was calculated for these field samples. The WRC was measured in the pressure head range from saturation to wilting point (15,848 cm) for the packed soil columns. The amount of water repellency was calculated for all samples using the water drop penetration time test.

6.4.3 Increased Crop Yield

Glaser et al. (2002) analysed a number of early studies performed in the 1980s and 1990s, which appeared to demonstrate major impacts of low-carbon additions (0.5 t ha-1) on different plant species. Higher rates appeared to inhibit plant growth. In later studies, the combination of higher biochar application rates together with NPK fertiliser increased crop yields on tropical Amazonian soils (Steiner et al. 2008) and semi-arid soils in Australia (Ogawa 2006). Due to year-on-year variance in climate and its effect on short-term dynamics, the results of a number of recent field experiments have not yet been reported though generating data. The essence and mechanistic basis for interactions between crops, soil type, biochar feed stock and production method and application rate will have to be understood in order to increase the predictive potential for soil biochar output and to open up the possibility for large-scale deployment.

6.4.4 Restoring the Soil Properties

6.4.4.1 Effects of Biochar on Soil Physical Properties

Biochar is a long-term adaptation technique that enhances soil physical and chemical properties that contribute to soil fertility. Possible mechanism for improving yield by increasing porosity and water storage space, as well as reducing bulk density (Jeffery et al. 2011; Lu et al. 2014; Nelissen et al. 2015). For e.g., ash content in biochars ranged from 0.35 to 59.05%, which was rich in available nutrients, in particular cationic elements such as K (0–560 mmol kg − 1), Ca (3–1,210 mmol kg − 1), Mg (0–325 mmol kg − 1) and Na (0–413 mmol kg − 1) (Rajkovich et al. 2012).

Soil Structure

Biochar incorporation into soil can alter physical properties such as structure, pore size, bulk density, soil aeration, water holding ability, plant growth and soil fertility. The introduction of biochar into soil will alter the physical properties of soils such as structure, pore size distribution and density with logical consequences for soil aeration, water holding capability, plant growth and soil workability. Sohi et al. (2009) suggested an analogy between the effect of the incorporation of biochar and the observed increase in soil water repellency due to burning. The re-arrangement of amphiphilic molecules by fire heat, as suggested by Doerr et al. (2000), does not affect the soil, but may have an effect on the biochar itself during pyrolysis. In addition, soil hydrology can be influenced by the partial or complete blockage of soil pores by the smallest fraction of the particle size of the biochar, thus reducing the rate of water infiltration. Liu et al. (2014) stated that when 40 t ha-1 biochar was applied, the soil water stable aggregate (>0.25 mm) in the 0–15 cm soil layer increased considerably compared to other treatments.

6.4.4.2 Porosity, Aggregate Stability, Soil Surface, Bulk Density, Penetration Resistance Porosity

The application of biochar may boost the physical properties of the soil, in particular its high porosity and wide inner surface area. Porosity depends on the carbon temperature and pyrolysis activation of up to 750 °C and the parent feed stock forms. Pore sizes in biochar have been reported to range from <2 nm to >50 nm, with an increase in the small diameter pore fraction as the pyrolysis temperature increases. However, the high porosity of carbon dioxide particles does not inherently increase the amount of plant-available water in the soil, since pore sizes <200 nm tend to retain water at a higher water potential than those produced by plants (Lal and Shukla 2004). Herath et al. 2013 concluded that biochar increased macroporosity in the soil of Tokomaru and mesoporosity in the soil of Egmont.

Soil Density

Biochar has a much lower mass density than mineral soils; therefore, the application of biochar will reduce the overall mass density of the soil. Tensile strength of hard soil under investigation also decreased with a rising rate of biochar application. Jein and Wang (2013) stated that the application of 5% biochar decreased the bulk density (1.08 mg m-3) from 1.42 mg m-3.

Surface Area

The specific surface area of biochar, which is typically higher than sand and equal to/or higher than clay, would result in a net increase in the total soil-specific surface when applied as an amendment. Evidence suggests that biochar application to soil can increase the overall net surface area of the soil and, as a result, improve soil water retention and soil aeration. The direct effect is related to the broad inner surface of the biochar. Increased soil-specific surface area and physical conditions can also support native microbial communities.

Soil Water

Influence of biochar on soil physical properties will affect soil response to water, aggregation and workability, shrinking dynamics, permeability and soil water retention. This change may be attributable to physical changes in soil where small carbohydrate particles block soil pores and reduce water penetration rates. Glaser et al. (2002) found that Amazonian char rich anthrosols had a field water retention potential of 18%, which is higher than the non-charcoal surrounding soil. The hydrophobic polyaromatic backbone reduces the flow of water into the aggregate pores, resulting in improved aggregate stability and availability of water. The results of this study also suggest that the application of cow manure biochar to sandy soil is not only beneficial for crop growth, but also significantly improved the physico-chemical properties of the coarse soil. Uzoma et al. (2011) reported that the lower bulk density and porous nature of added biochar increased water use efficiency consequent to improvement in field capacity and hydraulic conductivity. Granatstein et al. (2009) also reported an improvement in water holding ability of both sandy and silt loam soil due to the use of biochar.

6.4.4.3 Liming Effect in Soil/Reduced Toxicity and pH

Biochar can act as a liming agent, resulting in increased pH and availability of nutrients for a variety of soil types (Glaser et al. 2002; Lehmann and Rondon 2006a, 2006b). Biochar carbonate concentration promotes liming in soils and can increase the pH of neutral or acidic soils (Van Zwieten et al. 2009). Mbagwu and Piccolo (1997) reported increases in pH of different soils and textures by up to 1.2 pH units from pH 5.4 to 6.6. Tryon (1948) recorded a higher increase in pH in sandy and loamy soils than in clay soils. The pH of the various soils increased more after the use of hardwood charcoals (pH 6.15) than coniferous charcoals (pH 5.15), possibly due to different ash contents of 6.38% and 1.48% respectively (Glaser et al. 2002).

The biochar-associated liming effect may not be suitable for all soil types and plant communities. Increased soil pHs associated with biocharging have resulted in micronutrient deficiencies in agricultural crops (Kishimoto and Sugiura 1985) and forest vegetation (Mikan and Abrams 1995); thus, prior to application, it is necessary to recognise the existence of calcifuge vegetation. In addition, many forest plants, fungi and bacteria thrive in lower pH soils (Meurisse 1976, 1985); thus, altering the pH of the forest soil by adding biochar can result in unfavourable shifts in the upper and lower soil flora. Understanding the interactions between biochar production and application conditions and soil texture, organic matter and pH will be crucial in evaluating the long-term effects of biochar application on forest soils.

Soil pH is an essential factor influencing the supply of biochar nutrients (Silber et al. 2010). The release of PO4− and NH4+ was pH-dependent while the release of K+ and NO3− was not pH-dependent (Zheng et al. 2013). In addition, at pH 2–7, the content of PO4− and NH4+ released from biochars would have decreased with an increase in pH values, whereas that of K+ remained relatively constant (Zheng et al. 2013). Similarly, the initial release of Ca and Mg from corn straw biochar was also pH-dependent, with a rise in releases as the pH decreased from 8.9 to 4.5 (Silber et al. 2010). As a result, pH and lower temperature pyrolysis can increase the availability of N and P, whereas higher temperature pyrolysis can increase the availability of K.

6.4.5 Improve Soil Organic Carbon (SOC)

The soil carbon reservoir, composed of organic and inorganic carbon, is the largest carbon pool in the terrestrial ecosystem and has a gross reserve of approximately 3.3 times that of the atmospheric carbon pool (Wang et al. 1999). Soil organic carbon content (SOC) is also used as an important index for determining potential soil fertility (Spaccini et al. 2001; Dalal et al. 2003) and its complex balance has a direct effect on soil fertility and crop yields.

Human activities, such as high fertilisation rates and intensive crop rotation systems, have resulted in decreases in soil organic matter and carbon/nitrogen ratios and global imbalances in soil carbon pools (Lemenih et al. 2005; Collard and Zammit 2006). Overall decreases in soil microbial communities and microbial imbalances (Bell et al. 1998; Oldeman et al. 2017) have severely reduced the supply of nutrients and soil transformation capability. These changes have resulted in major nutrient imbalances in the soil environment (Parton et al. 1987), which have influenced crop production.

Biochar usually refers to the highly aromatic organic matter derived from the pyrolysis of any solid biomass. It can persist in the environment and plays an important role in global biogeochemical cycling, climate change and environmental systems as a part of the SOC pool (Marin-Spiotta et al. 2014; Brodowski et al. 2006). Biochar is generally referred to as highly aromatic organic matter derived from the pyrolysis of any solid biomass. It can stay in the ecosystem and plays an important role in global biogeochemical cycles, climate change and environmental processes as part of the SOC pool (Marin-Spiotta et al. 2014; Brodowski et al. 2006). Biochar is also known to be a significant source of atmospheric CO2 (Forbes et al. 2006). Furthermore, as a potential source of the highly aromatic portion of soil humus, biochar plays a key role in sustaining and growing the SOC pool and maintaining soil nutrients, improving soil fertility and maintaining the balance of the soil ecosystem (Hart and Luckai 2013; Chan et al. 2008). Microbial soil populations are considered to be acutely sensitive to changes in soil environment (Zhang et al. 2005).

Biochar is alkaline and porous, has a high specific surface area and multiple negative surface loads, and contains high-charge dense materials (Steiner et al. 2008). Increased soil biochar content can alter the soil ecosystem and microbial habitat, altering the biogeochemical cycle of soil carbon. As a material with a high carbon content, the addition of biochar to the soil would directly complement the organic carbon sources required for soil carbon cycling (Yin et al. 2014; Wu et al. 2012). The high stability of the biochar is due to its complex aromatic structure and its physical and chemical defensive effects. As the biochar enters the soil, its stable group significantly enriches the SOC pool and is retained in the soil for a long time, thereby enriching the total amount of organic matter in the soil (Woolf and Lehmann 2012). Labile components of biochar, such as aliphatic carbon speciation, can complement the soil carbon pool in the form of soluble organic matter (Brewer et al. 2009; Schmidt and Noack 2000). Biochar can boost soil water holding capacity (Laird et al. 2010), reduce soil bulk density, promote soil ECE (Cation Exchange Capacity) and pH (Van Zwieten et al. 2009), alter soil biochemical reactions and stimulate soil enzyme activity (Acosta-Martinez and Tabatabai 2000) and promote soil microbial reproduction.

6.4.6 Role of Biochar in Climate Change

6.4.6.1 N_2O and CH_4 Emissions

The main greenhouse gases associated with agriculture are nitrous oxide (N2O) and methane (CH4). Cropland and grassland are an important agricultural source of N2O emissions, whereas paddy fields, livestock waste and enteric fermentation are the major sources of CH4 emissions. When added to soil, biochar will minimise greenhouse gas emissions by dramatically reducing N2O emissions. Emissions of N2O, a greenhouse gas that is nearly 300 times higher than CO2 in terms of global warming potential, have been decreased by 40%. Laboratory studies show that the reduction of N2O emissions from biochar-treated soil depends on soil moisture and soil aeration (Yanai et al. 2007). Greenhouse gas emission reductions could be 12% to 84% higher if biochar is used instead of combusted for energy purposes (Lehman et al. 2006).

The retention of nutrients by biochar can depend on the temperature of the biochar pyrolysis, soil types, fertiliser doses and soil water content. Some studies have shown that the inclusion of biochar in soil effectively decreases N2Oemission from different soils. For example, Rondon et al. (2005) stated that 50% reductions in N2Oemissions were found in soybean systems, while 80% reductions in N2Oemissions were found in grass systems. Similarly, treatment with biochars could minimise N2Oemissions from 1768 to 45–699 μgN2O-N m − 2 h − 1 (Wang et al. 2013) and suppress N2Oemissions between 21.3% and 91.6% (Stewart et al. 2012). However, several studies have confirmed that there is no impact (Cheng et al. 2012) or even increase (Clough et al. 2010) was detected on N_2Oemissions after the application of biochar.

The global warming potential (GWP) of the gas represents two aspects: the efficiency of the molecule in the absorption of incoming solar radiation and its rate of chemical breakdown in the atmosphere. By definition, the global warming potential (GWP) of CO2 is1.0; by contrast, the nitrous oxide GWP is 310. Under anaerobic conditions, N2O is released from soil by means of denitrification, a method in which specialised microbes that obtain energy from nitrate reduction (NO3-) or intermediate gases are dinitrogen-based. However, it appears that nitrifying bacteria, which are generally involved in the conversion of N2 to ammonium (NH4+), i.e. nitrification, can simultaneously denitrify (Bateman and Baggs 2005).

The availability of NH4+ is usually regulated by the climate-driven mineralisation of organic matter, but its concentration is greatly enhanced by the use of nitrogen fertiliser or by the use of dung or slurry in livestock and grassland systems. Regardless of the environment or source, the majority of soil nitrogen is in organic form and N2O emanates through the use of a relatively small and dynamic nitrogen reservoir. Life cycle evaluations quantifying the benefits of biochar-based energy strategies are very heavily dependent on a decrease in N2O emissions that often accompanies the addition of mineral nitrogen fertilisers. Accounting for this effect makes a great difference to the overall analysis of how a biochar to soil strategy impacts on net greenhouse gas balance (Gaunt and Lehmann 2008).

Yanai et al. (2007) showed that 'bio-waste' carbon dioxide was used during the re-wetting of a former grassland soil, high in organic matter, in laboratory incubation (25 °C). Nine-tenths of N2O was suppressed in five-day soil-wetting emission episodes to 73% and 78% water-filled pore space. At a marginally higher pore-filled water region (83%), carbon dioxide had the opposite effect, increasing N2O emissions. The rate of biochar applied used in the study was equivalent to a relatively high application rate of 180 t ha-1 in topsoil.

In arable soil with a much lower C content (2.2% C), Sohi et al. (2009) studied the impact of willow charcoal at a much lower rate of 10 t C ha-1, which was assessed during 20 °C incubation of wet (70% water holding capacity) and re-wetted (20% water holding capacity) soils, with and without simultaneous addition of small amounts of inorganic N (equivalent 75 kg N ha-1). More moderate suppression of 15% was proportionally equivalent for all interventions where there was some response at all (the already-wet soil did not emit significant N2O). After 6 months, the available soil N would have been mostly consumed and the soil would have been well balanced. A second inorganic N addition (without new charcoal) at this time showed no difference in N_2O emissions between amended and control soils.

It is currently estimated that 1325% of N in N of corn fertiliser is converted to N2O emissions (Wang 2008). Biochar reportedly decreases N2O soil emissions resulting from the use of N fertilisers (Yanai et al. 2007; Rondon et al. 2006; Van Zwieten et al. 2009). A laboratory research in Japan (Yanai et al. 2007) showed that soils changed with 10 wt percent of soil as biochar suppressed 89% of N2O emissions. In the meantime, laboratory incubation studies (Van Zwieten et al. 2009) have shown that soils modified with biochar from poultry litter emit approximately 40%–80% less N2O than control. However, the same study found that yard waste biochar generated at lower temperatures increased N_2O emissions by 100%. These findings show that not all biochars can minimise N2O emissions equally (Van Zwieten et al. 2009). For this study, the baseline scenario assumes that biochar processing takes place under conditions such that soil N2O emissions from N fertiliser applications are reduced by 50%. Therefore, 0.394 kg of N2O emissions to the air would be avoided with each tonne of biochar added. Sensitivity analysis also looks at the effects of varying soil N2O emissions.

Despite some claims that good management of compost piles results in minimal or zero CH4 or N2O emissions, numerous studies have found that even well maintained compost piles (turning, aeration, proper moisture content) emit quantifiable quantities of CH4 and N2O. The CH4 is produced by microorganisms when the biomass is processed under anaerobic conditions. N2O is produced during the decomposition of biomass by denitrification and nitrification processes. Studies of yard waste compost (grass clippings, green leaves and brush) have reported that 0.030 kg and 2.79 kg of N2O and CH4 are released, respectively, per tonne of dry organic material (Lehmann et al. 2006) assuming moisture content.

6.4.6.2 Carbon Sequestering

Carbon sequestration is the capture and preservation of carbon to prevent its release into the atmosphere. Studies indicate that biochar sequestration of approximately

50% of the available carbon in the biomass feedstock is pyrolysed, depending on the feedstock type (Lehmann et al. 2006). Carbon sequestration in agricultural soils is also promoted as a realistic solution to slow down the rate of CO2 rise in the atmosphere (Mekuria and Noble 2013). Over the last two to three decades, a variety of land and crop management activities have been promoted to recover organic soil carbon and reduce the net CO2 emissions from agricultural systems in the tropics (Smith et al. 2008; Sohi and Shackley 2009; Woodfine 2009). Practices for restoring organic soil carbon and minimising net CO2 emissions include, but are not limited to, crop rotation, avoiding the use of bare fallow, conservation of tillage, management of organic inputs such as manure and crop residues, restoration of degraded agricultural land, water management and agroforestry (Banger et al. 2010; Batlle-Bayer et al. 2010; Shafi et al. 2010; Wang et al. 2010; Bangroo et al. 2011; Fallahzade and Hajabbasi et al. 2012).

Studies have shown that smallholder farmers can minimise greenhouse gas emissions and preserve carbon stocks in soil and vegetation at relatively low cost by adopting crop and land management practices (Nair et al. 2007). However, the study by Giller et al. (2009) and Sanchez (2000) established a number of constraints, including a low degree of mechanisation within the smallholder system, a lack of suitable implements, an issue of weed control under the no-till system and a lack of adequate technical knowledge that hinders the large-scale adoption of practices by smallholder farmers. Woodfine (2009) added that the availability of funds to catalyse the initial transition is a crucial obstacle for realising the implementation of several mitigation activities. Operational improved crop and land management practices can require more manual labour than traditional agricultural practices (Suprayogo et al. 2010a, 2010b). Optimising these advantages and disadvantages can be a difficult job, which in itself is a drawback as there is a lack of skilled staff and extension workers to provide information and advice to farmers. In addition, the time pattern of influence to reduce the rise in CO2 varies between practices and, in most situations, the decrease in CO2 emissions as a result of the recommended practices is temporary (Smith et al. 2008). For example, a study in Kenya showed that the residual effect of manure applied for 4 years only lasted another 7 or 8 years when assessed by yield, SOC and OlsenP (Suprayogo et al. 2010a, 2010b). The consequences of no-till practices are often quickly reversed and contribute to the release of CO2 into the environment as soon as the system has begun to be interrupted.

6.4.7 Bioenergy from Agricultural and Forestry Residues

Ogawa (2006) proposed a scheme for carbon sequestration by forestation and carbonisation. The scheme concerned fast-growing plantation tree species fixing atmospheric CO2, with items consisting not only of traditional wood, wood chips and pulp, but also of the transfer of waste and residues to the carbonisation process and the re-application of this stabilised carbon back to the plantation soil. This method has been formally suggested under the Clean Development Framework in Sumatra, Indonesia. In Minas Gerais, Brazil, a current commercial project says, under CDM, a carbon credit for the replacement of coal-derived coke for the smelting of iron by pyrolysed eucalyptus plantation. The project produces 300,000 t-1 of charcoal. The 'fines' of carbon dioxide, which account for about 5% of the substance, are used for the manufacture of briquettes rather than for use in soils. In Australia, the potential for integration of oil production from mallee trees with the processing of wood waste for the production of biochar for use in crop production has been investigated examined (McHenry 2009).

Seifritz (1993) measured the size and expense of the carbon gain that could be realised by converting plantation forest biomass directly to biochar. The scenario included no energy capture in the conversion, demonstrating instead the net primary efficiency that is retained by the cultivation process and the long life of charcoal relative to the nature and fate of conventional timber products. In the tropical sense, 'slash and char' scenarios have been addressed, where one-off biochar inputs are made during the conversion of land from forest to agriculture (Steiner 2006) or maybe 'crop and char' with a positive feedback loop between one-off, periodic or rotational biochar inputs and an increase in the productivity of biomass and feedstock. However, as examples of viable, village-scale bioenergy based on gasification technology are growing in developing countries, it is conceivable that technological progress in tandem with increased income from 'crop and charcoal' practices may eventually lead to combined biochar production and energy capture on the same scale.

In the absence of sufficient technological growth, charcoal processing and production could not deliver the same benefits to human health as, for example, replacing current biomass burning practices with basic yet cleaner and more efficient combustion technology. Submicron soot particles formed by condensation reactions in combustion gas streams are the most recalcitrant types of black carbon but, despite the relatively small amount of carbon involved, can have a major effect on the albedo of both the global atmosphere and the ice caps, alter the radiative balance and intensify climate change (Ramanathan and Carmichael 2008). At present, global emissions of soot are expected to decline as rural biomass consumers in developing countries turn to clean fossil fuel combustion (Streets et al. 2004). Charcoal processing produces less soot than open burning, but despite the potential size of future biochar production, its future contributions to the global soot inventory have not been formally evaluated.

6.5 Conclusion

In the light of the available literature relating to each and every phase of biochar development and its application, we have concluded that there is an urgent need for low-cost biochar-based waste material for the sustainability of agriculture and environmental remediation, as well as for the daily erosion and infertility of agricultural land.

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References

Acosta-Martinez V, Tabatabai M (2000) Enzyme activities in a limed agricultural soil. Biol Fertil Soils 31:85–91

Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D et al (2014) Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:19–33

Banger K, Toor GS, Biswas A, Sidhu SS, Sudhir K (2010) Soil organic carbon fractions after 16-years of applications of fertilizers and organic manure in a Typic Rhodalfs in semiarid tropics. Nutr Cycl Agroecosyst 86(3):391–399

Bangroo SA, Kirmani NK, Ali T, Wani MA, Bhat MA, Bhat MI (2011) Adapting agriculture for enhancing ecoefficiency through soil carbon sequestration in agroecosystem. Res J Agric Sci 2:164–169

Barrow CJ (2012) Biochar: potential for countering land degradation and for improving agriculture. Appl Geogr 34:21–28

Bateman EJ, Baggs EM (2005) Contributions of nitrification and denitrification to N2O emissions from soils at different water-filled pore space. Biol Fert Soils 41:379–388

Batlle-Bayer L, Batjes NH, Bindraban PS (2010) Changes in organic carbon stocks upon land use conversion in the Brazilian Cerrado: a review. Agric Ecosyst Environ 137(1–2):47–58

Bell M, Moody P, Connolly R, Bridge B (1998) The role of active fractions of soil organic matter in physical and chemical fertility of Ferrosols. Soil Res 36:809–820

Berglund LM, DeLuca TH, Zackrisson TH (2004) Activated carbon amendments of soil alters nitrification rates in scots pine forests. Soil Biol Biochem 36:2067–2073

Bonanomi G, Ippolito F, Scala F (2015) A" black" future for plant pathology? Biochar as a new soil amendment for controlling plant diseases. J Plant Pathol 1:97(2)

Brewer CE, Schmidt-Rohr K, Satrio JA, Brown RC (2009) Characterization of biochar from fast pyrolysis and gasification systems. Environ Progr Sustain Energy 28:386–396

Brodowski S, John B, Flessa H, Amelung W (2006) Aggregate-occluded black carbon in soil. Eur J Soil Sci 57:539–546

Brown D, Gassner M, Fuchino T, Maréchal F (2009) Thermo-economic analysis for the optimal conceptual design of biomass gasification energy conversion systems. Appl Therm Eng 29:2137–2152

Cantrell KB, Hunt PG, Uchimiya M, Novak JM, Ro KS (2012) Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresour Technol 107:419–428

Cao X, Ma L, Gao B, Harris W (2009) Dairy-manure derived biochar effectively sorbs lead and atrazine. Environ Sci Technol 43:3285–3291

Chan K, Van Zwieten L, Meszaros I, Downie A, Joseph S (2008) Using poultry litter biochars as soil amendments. Soil Res 46:437–444

Chen B, Chen Z, Lv S (2011) A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. Bioresour Technol 102:716–723

Chen WH, Peng JH, Bi XTT (2015) A state-of-the-art review of biomass torrefaction, densification and applications. Renew Sust Energ Rev 44:847–866

Cheng Y, Cai Z, Chang SX, Wang J, Zhang J (2012) Wheat straw and its biochar have contrasting effects on inorganic N retention and N2O production in a cultivated black Chernozem. Biol Fertil Soils 48:941–946

Clough TJ, Bertram JE, Ray JL, Condron LM, O'Callaghan M, Sherlock RR, Wells NS (2010) Unweathered wood biochar impact on nitrous oxide emissions from a bovine-urine-amended pasture soil. Soil Sci Soc Am J 74:852–860

Collard S, Zammit C (2006) Effects of land-use intensification on soil carbon and ecosystem services in Brigalow (Acacia harpophylla) landscapes of Southeast Queensland, Australia. Agric Ecosyst Environ 117:185–194

Dalal R, Eberhard R, Grantham T, Mayer D (2003) Application of sustainability indicators, soil organic matter and electrical conductivity, to resource management in the northern grains region. Aust J Exp Agric 43:253–259

DeLuca TH, MacKenzie MD, Gundale MJ, Holben WE (2006) Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests. Soil Sci Soc Am J 70:448–453

Demirbas A, Arin G (2002) An overview of biomass pyrolysis. Energy Sources 24:471–482

Doerr SH, Shakesby RA, Walsh RPD (2000) Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Sci Rev 51:33–65

Elmer W, White JC, Pignatello JJ (2010) Impact of biochar addition to soil on the bioavailability of chemicals important in agriculture. Report, University of Connecticut, New Haven

Fallahzade J, Hajabbasi MA (2012) The effects of irrigation and cultivation on the quality of desert soil in central Iran. Land Degrad Dev 23(1):53–61

Forbes M, Raison R, Skjemstad J (2006) Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems. Sci Total Environ 370:190–206

Gaskin JW, Speir A, Morris LM, Ogden L, Harris K, Lee D, Das KC (2007) Potential for pyrolysis char to affect soil moisture and nutrient status of a loamy sand soil. Georgia Institute of Technology

Gaunt JL, Lehmann J (2008) Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environ Sci Technol 42:4152–4158

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics view. Field Crops Res 114:23–34

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. Biol Fertil Soils 35(4):219–230

Granatstein D, Kruger C, Collins H, Garcia-Perez M, Yoder J (2009) Use of biochar from the pyrolysis of waste organic material as a soil amendment. Center for Sustaining Agric. Nat. Res. Washington State University, Wenatchee, WA. WSDA Interagency Agreement. C.;800248

Gundale MJ, DeLuca TH (2006) Temperature and source material influence ecological attributes of ponderosa pine and Douglas-fir charcoal. For Ecol Manag 231:86–93

Hart S, Luckai N (2013) Review: charcoal function and management in boreal ecosystems. J Appl R Soc Ecol 6:181499. 50:1197–1206

Haumaier L, Zech W (1995) Black carbon—possible source of highly aromatic components of soil humic acids. Org Geochem 23(3):191–196

Herath HMSK, Camps-Arbestain M, Hedley M (2013) Effect of biochar on soil physical properties in two contrasting soils: an Alfisol and an Andisol. Geoderma 209–210:188–197

Higashikawa FS, Conz RF, Colzato M, Cerri CEP, Alleoni LRF (2016) Effects of feedstock type and slow pyrolysis temperature in the production of biochars on the removal of cadmium and nickel from water. J Clean Prod 137:965–972

Ishii T, Kadoya K (1994) Effect of charcoal as a soil conditioner on citrus growth and vesicular-arbuscular mycorrhizal development. J Jpn Soc Hort Sci 65:529–535

Jeffery S, Verheijen FGA, Van Der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ 144:175–187

Jein SH, Wang CS (2013) Effects of biochar on soil properties and erosion potential in a highly weathered soil. Catena 110:225–233

Kambo HS, Dutta A (2015) Comparative evaluation of torrefaction and hydrothermal carbonization of lignocellulosic biomass for the production of solid biofuel. Energy Convers Manag 105:746–755

Kastner JR, Miller J, Geller DP, Locklin J, Keith LH, Johnson T (2012) Catalytic esterification of fatty acids using solid acid catalysts generated from biochar and activated carbon. Catal Today 190:122–132

Kishimoto S, Sugiura G (1985) Charcoal as soil conditioner. Int Arch Future 5:12–23
Kumar G, Shobana S, Chen WH, Bach QV, Sang HK, Atabani AE et al (2016) A review of thermo chemical conversion of microalgal biomass for biofuels: chemistry and processes. Green Chem 19:44–67
Laird DA, Fleming P, Davis DD, Horton R, Wang B, Karlen DL (2010) Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158:443–449
Lal R, Shukla MR (2004) Principles of soil physics. Marcel Dekker, New York
Lee XJ, Lee LY, Gan S, Thangalazhy-Gopakumar S, Ng HK (2017) Biochar potential evaluation of palm oil wastes through slow pyrolysis: thermo chemical characterization and pyrolytic kinetic studies. Bioresour Technol 236:155–163
Lehmann J, Rondon M (2006a) Bio-char soil management on highly weathered soils in the humid tropics. Biol Approaches Sustain Soil Syst 113(517):530
Lehmann J, Rondon M (2006b) Bio-char soil management on highly weathered soils in the humid tropics. In: Uphoff N (ed) Biological approaches to sustainable soil systems. CRC Press, Boca Raton, pp 517–530
Lehmann J, Kern D, German L, McCann J, Martins GC, Moreira L (2003a) Soil fertility and production potential. Chapter 6. In: Lehmann J, Kern DC, Glaser B, Woods WI (eds) Amazonian dark earths: origin, properties, management. Kluwer Academic, Dordrecht, pp 105–124
Lehmann J, Kern DC, Glaser B, Woods WI (2003b) Amazonian dark earths: origin, properties and management. Kluwer Academic Publishers, Dordrecht
Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems—a review. Mitigat Adaptat Strateg Glob Chan 11:403–427
Lemenih M, Karltun E, Olsson M (2005) Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia. Agric Ecosyst Environ 105:373–386
Li J, Li Y, Wu M, Zhang Z, Lü J (2013) Effectiveness of low-temperature biochar in controlling the release and leaching of herbicides in soil. Plant Soil 370:333–344
Lian F, Xing B (2017) Black carbon (biochar) in water/soil environments: molecular structure, sorption, stability, and potential risk. Environ Sci Technol 51:13517–13532
Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizão FJ, Petersen J, Neves EG (2006) Black carbon increases cation exchange capacity in soils. Soil Sci Soc Am J 70:1719–1730
Liu Z, Chen X, Jing Y, Li Q, Zhang J, Huang Q (2014) Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil. Catena 123:45–51
Lu SG, Sun FF, Zong YT (2014) Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (Vertisol). Catena 114:37–44. https://doi.org/10.1016/j.catena.2013.10.014
Mackie KA, Marhan S, Ditterich F, Schmidt HP, Kandeler E (2015) The effects of biochar and compost amendments on copper immobilization and soil microorganisms in a temperate vineyard. Agric Ecosyst Environ 201:58–69
Marin-Spiotta E, Chaopricha NT, Plante AF, Diefendorf AF, Mueller CW, Grandy AS, Mason JA (2014) Long-term stabilization of deep soil carbon by fire and burial during early Holocene climate change. Nat Geosci 7:428–432
Matsubara Y-I, Hasegawa N, Fukui H (2002) Incidence of Fusarium root rot in asparagus seedlings infected with arbuscular mycorrhizal fungus as affected by several soil amendments. J Jpn Soc Hortic Sci 71:371–374
Mbagwu JSC, Piccolo A (1997) Effects of humic substances from oxidized coal on soil chemical properties and maize yield. In: Drozd J, Gonet SS, Senesi N, Weber J (eds.) The role of humic substances in the ecosystems and in environmental protection. IHSS, Polish Society of Humic Substances, Wroclaw, pp 921–925
McHenry MP (2009) Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: certainty, uncertainty and risk. Agric Ecosyst Environ 129(1-3):1–7

Mekuria W, Noble A (2013) The role of biochar in ameliorating disturbed soils and sequestering soil carbon in tropical agricultural production systems. Appl Environ Soil Sci:354965
Meurisse RT (1976) Soil chemical and other properties of western hemlock soils in Oregon—their relationship to productivity. In: Atkinson WA, Zazoski RT (eds.) Western hemlock management: proceedings of a conference; May 1976; Alderbrook, WA. Contrib. No. 34. University of Washington, College of Forest Resources, Institute of Forest Products: Seattle, WA. 317 p
Meurisse RT (1985) Properties of Andisols important to forestry. In: Beinroth FH, Lusio WL, Maldonado FP, Eswaran H (eds.) Proceedings of the sixth international soil classification workshop, Chile and Ecuador. Part 1: papers. U.S. Department of Agriculture, Soil Management Support Services, Washington, pp 53–67
Mikan CJ, Abrams MD (1995) Altered forest composition and soil properties of historic charcoal hearths in southeastern Pennsylvania. Can J For Res 25:687–696
Miller RM, Miller SP, Jastrow JD, Rivetta CB (2002) Mycorrhizal mediated feedbacks influence net carbon gain and nutrient uptake in Andropogon gerardii. New Phytol 155:149–162
Mohan D, Pittman CU, Steele PH (2006) Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuel 20:848–889
Nair PKR (2007) The coming of age of agroforestry. J Sci Food Agric 87(9):1613–1619
Nelissen V, Ruysschaert G, Manka'Abusi D, D'Hose T, De Beuf K, Al-Barri B, Cornelis W, Boeckx P (2015) Impact of a woody biochar on properties of a sandy loam soil and spring barley during a two-year field experiment. Eur J Agron 62:65–78. https://doi.org/10.1016/j.eja.2014.09.006
Nerome M, Toyota K, Islam TM, Nishimima T, Matsuoka T, Sato K et al (2005) Suppression of bacterial wilt of tomato by incorporation of municipal biowaste charcoal into soil. Soil Micro 59:9–14
Nishio M (1996) Microbial fertilizers in Japan. National Institute of agro-environmental sciences, Ibaraki, Japan
Ogawa M (2006) Charcoal use in agriculture in Japan. In: Keynote address, 1st Asia Pacific biochar conference, May 17–20, Gold Coast, Australia
Oldeman L, Hakkeling R, Sombroek WG (2017) World map of the status of human-induced soil degradation: an explanatory note. In: International soil reference and information centre
Park J, Hung I, Gan Z, Rojas OJ, Lim KH, Park S (2013) Activated carbon from biochar: influence of its physicochemical properties on the sorption characteristics of phenanthrene. Bioresour Technol 149:383–389
Parton W, Schimel DS, Cole C, Ojima D (1987) Analysis of factors controlling soil organic matter levels in Great Plains Grasslands1. Soil Sci Soc Am J 51:1173–1179. https://doi.org/10.2136/sssaj1987.03615995005100050015x
Rajkovich S, Enders A, Hanley K, Hyland C, Zimmerman AR, Lehmann J (2012) Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol Fertil Soils 48:271–284. https://doi.org/10.1007/s00374-011-0624-7
Ramanathan V, Carmichael G (2008) Global and regional climate changes due to black carbon. Nat Geosci 1(4):221
Rondon M, Ramirez J, Lehmann J (2005) Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. In: Proceedings of the 3rd USDA symposium on greenhouse gases and carbon sequestration in agriculture and forestry. Baltimore, MD, p 208
Rondon MA, Molina D, Hurtado M, Ramirez J, Lehmann J, Major J, Amezquita E (2006) In Enhancing the productivity of crops and grasses while reducing greenhouse gas emissions through bio-char amendments to unfertile tropical soils, 18th world congress of soil science, 9–15, Philadelphia, PA
Rondon MA, Lehmann J, Ramirez J, Hurtado M (2007) Biological nitrogen fixation by common beans (Phaseolus vulgaris L) increases with bio-char additions. Biol Fertil Soils 43:699–708
Safaei Khorram M, Zhang Q, Lin D, Zheng Y, Fang H, Yu Y (2016) Biochar: a review of its impact on pesticide behavior in soil environments and its potential applications. J Environ Sci 44:269–279

Saifullah DS, Naeem A, Rengel Z, Naidu R (2018) Biochar application for the remediation of salt-affected soils: challenges and opportunities. Sci Total Environ 625:320–335

Sanchez PA (2000) Linking climate change research with food security and poverty reduction in the tropics. Agric Ecosyst Environ 82(1–3):371–383

Schmidt MW, Noack AG (2000) Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. Global Biogeochem Cycles 14:777–793

Seifritz W (1993) Should we store carbon in charcoal? Int J Hydrog Energy 18:405–407

Sevilla M, Mokaya R (2014) Energy storage applications of activated carbons: supercapacitors and hydrogen storage. Energy Environ Sci 7:1250–1280

Shafi M, Bakht J, Attaullah A, Khan MA (2010) Effect of crop sequence and crop residues on soil C, soil N and yield of maize. Pak J Bot 42(3):1651–1664

Silber A, Levkovitch I, Graber ER (2010) PH-dependent mineral release and surface properties of corn straw biochar: agronomic implications. Environ Sci Technol 44:9318–9323. https://doi.org/10.1021/es101283d

Smith P, Martino D, Cai Z et al (2008) Greenhouse gas mitigation in agriculture. Philos Trans R Soc B 363:789–813

Sohi SP, Shackley S (2009) Biochar: carbon sequestration potential. Copenhagen, Denmark

Sohi S, Lopez-Capel E, Krull E, Bol R (2009) Biochar, climate change and soil: a review to guide future research. In: CSIRO land and water science report

Spaccini R, Zena A, Igwe C, Mbagwu J, Piccolo A (2001) Carbohydrates in water-stable aggregates and particle size fractions of forested and cultivated soils in two contrasting tropical ecosystems. Biogeochem 53:1–22. https://doi.org/10.1023/A:1010714919306

Spokas KA, Reicosky DC (2009) Impacts of sixteen different biochars on soil greenhouse gas production. Ann Environ Sci

Steiner C (2006) Slash and char as alternative to slash and burn: soil charcoal amendments maintain soil fertility soil charcoal amendments maintain soil fertility and establish a carbon sink. Doctoral dissertation, Dissertation Faculty of Biology, Chemistry and Geosciences University of Bayreuth, Germany

Steiner C, Teixeira W, Lehmann J, Zech W (2003) Microbial response to charcoal amendments of highly weathered soils and Amazonian dark earths in Central Amazonia—preliminary results. In: Lehmann J, Kern DC, Glaser B, Woods WI (eds) Amazonian dark earths: origin, properties, management. Kluwer Academic Publishers, Dordrecht

Steiner C, Das KC, Garcia M, Förster B, Zech W (2008) Charcoal and smoke extract stimulate the soil microbial community in a highly weathered xanthic Ferralsol. Pedobiologia 51:359–366. https://doi.org/10.1016/j.pedobi.2007.08.002

Stelt MJCVD, Gerhauser H, Kiel JHA, Ptasinski KJ (2011) Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass Bioenergy 35:3748–3762

Stewart CE, Zheng J, Botte J, Cotrufo MF (2012) Co-generated fast pyrolysis biochar mitigates greenhouse gas emissions and increases carbon sequestration in temperate soils. GCB Bioenergy 5:153–164. https://doi.org/10.1111/gcbb.12001

Streets DG, Bond TC, Lee T, Jang C (2004) On the future of carbonaceous aerosol emissions. J Geophys Res Atmosph 27(D24):109

Suprayogo D, Hairiah K, Noordwijk MV, Cadisch G (2010a) Agroforestry interactions in rainfed agriculture: can hedgerow intercropping systems sustain crop yield on an ultisol in Lampung (Indonesia)? Agri 32:3

Suprayogo D, Hairiah K, Van Noordwijk M, Cadisch G (2010b) Agroforestry interactions in rainfed agriculture: can hedgerow intercropping systems sustain crop yield on an ultisol in Lampung (Indonesia)?AGRIVITA. J Agric Sci 32(3):205–215

Tang J, Zhu W, Kookana R, Katayama A (2013) Characteristics of biochar and its application in remediation of contaminated soil. J Biosci Bioeng 116:653–659

Thies JE, Rillig MC (2009) Characteristics of biochar: biological properties. Chapter 6. In: Lehmann J, Joseph S (eds) Biochar for environmental management science and technology. Earthscan, London, pp 85–105
Tryon EH (1948) Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecol Monogr 18:82–115
Uzoma KC, Inoue M, Andry H, Fujimaki H, Zahoor A, Nishihara E (2011) Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manag 27:205–212
Van Zwieten L, Singh B, Joseph S, Kimber S, Cowie A, Chan KY (2009) Biochar and emissions of non-CO2 greenhouse gases from soil. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology 1. Earthscan, London, pp 227–250
Wang M (2008) Greenhouse gases, regulated emissions, and energy use in transportation (GREET) model, 1.8b; U Chicago Argonne, LLC
Wang Y, Zhao S, Niu D (1999) Research state of soil carbon cycling in terrestrial ecosystem. Chin J Ecol 18:29–35
Wang Q, Li Y, Alva A (2010) Cropping systems to improve carbon sequestration for mitigation of climate change. J Environ Protec 1:207–215
Wang Z, Zheng H, Luo Y, Deng X, Herbert S, Xing B (2013) Characterization and influence of biochars on nitrous oxide emission from agricultural soil. Environ Pollut 174:289–296. https://doi.org/10.1016/j.envpol.2012.12.003
Warnock DD, Lehmann J, Kuyper TW, Rillig MC (2007) Mycorrhizal responses to biochar in soil—concepts and mechanisms. Plant Soil 300:9–20
Wilk M, Magdziarz A (2017) Hydrothermal carbonization, torrefaction and slow pyrolysis of Miscanthus giganteus. Energy 140:1292–1304
Windeatt JH, Ross AB, Williams PT, Forster PM, Nahil MA, Singh (2014) Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. J Environ Manag 146:189–197
Woodfine A (2009) Using sustainable land management practices to adapt to and mitigate climate change in sub-Saharan Africa, resource guide version 1.0. TERR AFRICA. http://www.terrafrica.org/
Woolf D, Lehmann J (2012) Modelling the long term response to positive and negative priming of soil organic carbon by black carbon. Biogeochemistry 111:83–95
Wu W, Yang M, Feng Q, McGrouther K, Wang H, Lu H, Chen Y (2012) Chemical characterization of rice straw-derived biochar for soil amendment. Biomass Bioenergy 47:268–276
Yanai Y, Toyota K, Okazaki M (2007) Effects of charcoal addition on N2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. Soil Sci Plant Nutr 53:181–188
Yin Y-F, He X-H, Ren G, Yang YS (2014) Effects of rice straw and its biochar addition on soil labile carbon and soil organic carbon. J Integr Agr 13:491–498
Yu KL, Lau BF, Show PL, Ong HC, Ling TC, Chen WH et al (2017) Recent developments on algal biochar production and characterization. Bioresour Technol 246:2–11
Zhang W, Wei H, Gao H, Hu Y (2005) Advances of studies on soil microbial diversity and environmental impact factors. Chin J Ecol 24:48–52
Zheng H, Wang Z, Deng X, Zhao J, Luo Y, Novak J, Herbert S, Xing B (2013) Characteristics and nutrient values of biochars produced from giant reed at different temperatures. Bioresour Technol 130:463–471