Biochar for crop production: potential benefits and risks

Article *in* Journal of Soils and Sediments · February 2017

DOI: 10.1007/s11368-016-1360-2

Mubshar Hussain
Bahauddin Zakariya University

Muhammad Farooq
Sultan Qaboos University

Ahmad Nawaz
The Ohio State University

Abdullah M. Al-Sadi
Sultan Qaboos University

J Soils Sediments
DOI 10.1007/s11368-016-1360-2

BIOCHAR FOR A SUSTAINABLE ENVIRONMENT

Biochar for crop production: potential benefits and risks

Mubshar Hussain[1] · Muhammad Farooq[2,3,4] · Ahmad Nawaz[2,5] · Abdullah M. Al-Sadi[6] · Zakaria M. Solaiman[3] · Salem S. Alghamdi[4] · Ume Ammara[6] · Yong Sik Ok[7] · Kadambot H. M. Siddique[3]

Received: 19 September 2015 / Accepted: 11 January 2016

Abstract

Purpose Biochar, the by-product of thermal decomposition of organic materials in an oxygen-limited environment, is increasingly being investigated due to its potential benefits for soil health, crop yield, carbon (C) sequestration, and greenhouse gas (GHG) mitigation.

Materials and methods In this review, we discuss the potential role of biochar for improving crop yields and decreasing the emission of greenhouse gases, along with the potential risks involved with biochar application and strategies to avoid these risks.

Results and discussion Biochar soil amendment improves crop productivity mainly by increasing nutrient use efficiency and water holding capacity. However, improvements to crop production are often recorded in highly degraded and nutrient-poor soils, while its application to fertile and healthy soils does not always increase crop yield. Since biochars are produced from a variety of feedstocks, certain contaminants can be present. Heavy metals in biochar may affect plant growth as well as rhizosphere microbial and faunal communities and functions. Biochar manufacturers should get certification that their products meet International Biochar Initiative (IBI) quality standards (basic utility properties, toxicant assessment, advanced analysis, and soil enhancement properties).

Conclusions The long-term effects of biochar on soil functions and its fate in different soil types require immediate attention. Biochar may change the soil biological community composition and abundance and retain the pesticides applied. As a consequence, weed control in biochar-amended soils may be difficult as preemergence herbicides may become less effective.

Keywords Biochar · Crop productivity · Soil amendment · Soil fertility · Soil quality

Responsible editor: Jianming Xu

✉ Muhammad Farooq
mfarooq@uaf.edu.pk

[1] Department of Agronomy, Bahauddin Zakariya University, Multan, Pakistan

[2] Department of Agronomy, University of Agriculture, Faisalabad, Pakistan

[3] The UWA Institute of Agriculture, The University of Western Australia, Crawley, WA 6009, Australia

[4] College of Food and Agricultural Sciences, King Saud University, Riyadh 11451, Saudi Arabia

[5] Carbon Management and Sequestration Centre, School of Environment and Natural Resources, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210, USA

[6] College of Agricultural and Marine Sciences, Sultan Qaboos University, Al Khoud 123, Oman

[7] Korea Biochar Research Center, Kangwon National University, Chuncheon 200-701, South Korea

1 Introduction

The charred solid produced by thermal decomposition of organic materials in an oxygen-deficient environment, a process called pyrolysis, is known as biochar (Joseph et al. 2010). Biochar is not a pure carbon (C) as it includes ash, hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) (Duku et al. 2011; Lehmann and Joseph 2015). In the last decade, the use of biochar in arable lands has received great attention due to its agronomic and environmental benefits (Liu et al. 2013; Stavi and Lal 2013).

Published online: 29 January 2016

Biochar soil amendment has been considered to mitigate global warming, restore degraded lands, and offset water pollution by removing organic contaminants such as pesticides, dyes, pharmaceutical and personal care products, perfluorooctane sulfonate, humic acid, and *N*-nitrosomodimethylamine (Barrow 2012; Inyang and Dickenson 2015). Moreover, biochar can potentially inactivate *Escherichia coli* via disinfection, transform 95 % of 2-chlorobiphenyl via advanced oxidation processes, and thus help in water purification (Inyang and Dickenson 2015). Substantial reductions in greenhouse gas (GHG) emission, adsorption of contaminants, and improvement of soil fertility and crop productivity are among the benefits associated with biochar addition to agricultural soils (Lehmann et al. 2006; Sohi et al. 2010; Spokas 2010; Cayuela et al. 2013; Stavi and Lal 2013).

Agricultural land use acts as a source and/or sink of C depending on its effect on soil and plant processes (IPPC 2007; Stavi and Lal 2013). For instance, increased carbon dioxide (CO_2) emissions due to fertilizer addition may be partly offset by higher rates of photosynthesis, which are no longer restricted by the shortage of nutrients. Biochar application offers an attractive solution to correct this nutrient imbalance and is thus of particular interest to agronomists and farmers (Pratt and Moran 2010). Carbon sequestration in arable land is a potential option to alleviate climate change as most cropland soils are depleted of soil organic carbon (SOC) reserves. Biochar addition to cultivated land may be a potential tool for C sequestration by adding the bulk of recalcitrant C resistant to decomposition thus lessening GHG emissions (Lehmann et al. 2006; Spokas et al. 2009; McHenry 2010; Liu et al. 2014). Once added to soils, biochar is stable with the potential to store soil C for several hundred years and may provide other benefits such as improved water holding capacity (WHC) and nutrient supply (Lal 2008; Sohi et al. 2010).

Biochar application helps to increase crop productivity through increasing soil nutrient supply and microbial activity and decreasing nutrient leaching (Steiner et al. 2008; Graber et al. 2010; Major et al. 2010a; Liu et al. 2013; Ventura et al. 2013). Due to its liming effect (Van Zwieten et al. 2010), biochar helps to improve the supply of essential macro- and micronutrients for plant growth mainly in acidic soils (Chan and Xu 2009; Major et al. 2010a). Biochar soil amendment also improves soil structure by significantly increasing soil porosity and aeration (Glaser et al. 2002; Lehmann et al. 2003), enhances WHC, and improves nutrient retention in soil micropores (Lehmann and Joseph 2015). Biochar strongly influences the composition and abundance of the soil microbial community, depending on its taxa, and the source and production technology of specific biochar, and thus plays a critical role in nutrient cycling (Grossman et al. 2010; Liang et al. 2010; Khodadad et al. 2011; Lehmann et al. 2011).

Several open field and controlled environment studies identified that biochar has the potential to build up C sequestration and improve crop yields on many soil types, particularly nutrient-poor soils (Steiner et al. 2008; Graber et al. 2010; Major et al. 2010a; Van Zwieten et al. 2010; Zhang et al. 2010, 2012a, b; Jones et al. 2012). However, the technology and initial costs and the availability of feedstock to produce biochars are major barriers to its wider adoption (Duku et al. 2011). The economic feasibility of a new innovation is important for large-scale adoption, with most farmers, especially in developing countries in Africa and Asia, not expected to adopt this environmentally friendly technology without visible economic benefits.

Sorption of agrochemicals by biochars helps to reduce their leaching and uptake by crop plants (Yu et al. 2009, 2010). However, the application of biochar may reduce the efficacy of herbicides, preemergence herbicides in particular, which may make weed control difficult and accelerate the development of herbicide resistance in weeds due to “underdosing” of herbicides (Powles et al. 1996; Yang et al. 2006; Zheng et al. 2010). In this manuscript, the role of biochar application for improving crop productivity and soil health, along with its environmental benefits and the potential risks involved, has been presented.

2 Biochar properties

Biochars are produced from crop residues, forest residues, algae, sewage sludge, and manure (Duku et al. 2011; Lehmann and Joseph 2015). Pyrolysis methods have a significant impact on biochar properties such as biochar yield, pH, particle size, and surface area. Biochars generally improve soil WHC, cation exchange capacity (CEC), and C content in amended soils irrespective of their feedstock source or pyrolysis method (Lehmann et al. 2008). However, biochars from different feedstock sources or pyrolysis methods differ in pore size, pH, CEC, surface area and charge, etc. (Ahmad et al. 2012a; Rajapaksha et al. 2014) and, therefore, behave differently in contrasting soils owing to their varying adsorption behavior and biological activity (Brewer et al. 2009; Downie et al. 2009; Kolb et al. 2009; Kuzyakov et al. 2009; Fungo et al. 2014).

In a meta-analysis ($n = 94$), Enders et al. (2012) reported variation in ash content (0.4 to 88.2 %), volatile matter (13.2 to 70.0 %), and fixed C (0.0 to 77.4 %) in biochars synthesized from different sources and at varying temperatures. Therefore, both production technology and the original composition of the feedstock source strongly influence final biochar yield as well as physical and chemical properties. The effects of feedstock source and production technology on biochar properties are briefly discussed in the following sections.

2.1 Feedstock source

Agricultural residues logging and wood processing residues, algae, municipal solid waste, livestock/poultry waste, wastewater/sewage sludge, and biosolids are some of the feedstocks used for biochar synthesis (Duku et al. 2011; Ahmad et al. 2014a; Lehmann and Joseph 2015). The composition and quality characters of biochars such as particle size distribution, surface area, porosity, density, ash and moisture content, CEC, and pH are strongly influenced by the type, nature, and origin of the feedstock (Zhang et al. 2008; Downie et al. 2009; Enders et al. 2012; Rajapaksha et al. 2014). Increase in pH is a common feature of biochar (Rondon et al. 2007; Castaldi et al. 2011; Ahmad et al. 2014b; Rajapaksha et al. 2015; Table 2), and the pH value is highly dependent on the feedstock used. For instance, pH values ranged from 4 to 9 in biochars synthesized from different woody feedstocks (Enders et al. 2012). Likewise, the surface area of biochars derived from the woody material having abundance of lignocellulosic matter is significantly higher than that from the grassy material (Keiluweit et al. 2010). Bird et al. (2011) observed that biochars derived from macroalgae were relatively lower in C contents, surface area, and CEC. However, these biochars had high pH, ash, N, and other extractable inorganic nutrients like phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg) and therefore resembled biochars derived from poultry litter rather than those derived from lignocellulosic feedstocks. In another study, Lee et al. (2013) compared the sugarcane bagasse, paddy straw, cocopeat, palm kernel shell, and umbrella tree (stem and bark)-derived biochar for ash and moisture contents. They reported that the biochar derived from paddy straw had the highest ash contents, while cocopeat biochar had the maximum moisture contents. However, umbrella tree wood stem, sugarcane bagasse, and palm kernel shell had large microscopic surface area than cocopeat and paddy straw biochar (Lee et al. 2013). In another recent study, the highest pH, ash contents, and moisture contents were recorded in willow (*Salix viminalis* L.)-derived biochar (450 to 650 °C) than pine (*Pinus sylvestris* L.)-derived biochar (450 to 650 °C); however, CEC was the highest in pine-derived biochar (Nelissen et al. 2014). The above discussed characteristics of biochars have a profound effect on the soil ecosystem and indirectly on human health. For example, biochars with higher total porosity can favor the microbial colonization within the soil pores and can protect them from grazing by other organisms (Verheijen et al. 2010), thus favoring plant growth. Moreover, the addition of biochars helps soil to retain more water, thus improving water balance resulting in better nutrient availability. Biochar with higher sorption capacity can capture certain toxic compounds such as pesticides and herbicides, when added to soil (Cao and Harris 2010; Verheijen et al. 2010), thus restricting their entry into the food chain. The addition of biochars with alkaline pH may increase phytoavailability of various essential nutrients (Verheijen et al. 2010), such as sodium (Na), K, Ca, Mg, and molybdenum (Mo) to plants (Atkinson et al. 2010). In another study, Peng et al. (2011) reported that an increase in soil pH due to biochar addition in acidic soils can alleviate aluminum (Al) toxicity in ultisols and can improve the CEC which may enhance the bioavailability of P and base cations within the soil.

Biochars derived from various feedstocks vary in their sorption behaviors of soil minerals (Liang et al. 2006) and soil organic matter (SOM) (Kasozi et al. 2010), which strongly influence the pore space available to soil biota (Lehmann et al. 2011). For instance, biochars derived from the woody material are coarse and highly resistant in nature with C contents up to 80 % (Zhang et al. 2008; Duku et al. 2011). Thus, the C mineralization varies with the biochar feedstock source. For example, soils amended with grass-derived biochars, particularly during early incubation (first 90 days), had higher than probable (positive priming) C mineralization rates, while those amended with hardwood-derived biochars, particularly during later incubation (250–500 days), had less than probable (negative priming) C mineralization rates (Zimmerman et al. 2011). Moreover, total mineralized C typically increased from hardwood- to grass-derived biochars (Zimmerman et al. 2011).

Enders et al. (2012) indicated no enrichment of fixed C in soils amended with poultry biochar compared with a 10-fold rise of the fixed C in corn biochar (produced at 600 °C). However, with respect to C sequestration, macroalgal-derived biochars volumetrically had little potential compared with biochars produced from lignocellulosic feedstocks (Bird et al. 2011).

Interestingly, Kaal et al. (2009) noted minimal differences in the charcoal composition of biochars from different species (e.g., oak, birch, and legume) and concluded that the origin of biomass is not a deciding factor for the products of pyrolysis. Nonetheless, biochar properties do change with incubation period in soil, and the initial properties of biochar modulate these changes (Joseph et al. 2010). For example, Fungo et al. (2014) noted a 17 % lower emission of nitrous oxide (N_2O) from corn stover biochar compared with *Eucalyptus* wood biochar, and the release of methane (CH_4) was 21 % higher with steam-activated stover biochar than *Eucalyptus* wood biochar. Moreover, steam activation increased CH_4 emissions in corn stover biochar, while it decreased in *Eucalyptus* wood biochar by 14–70 %.

Thus, the choice of feedstock source depends on its nature, chemical composition, soil conditions where it will be used, and economic factors.

2.2 Production technology

Biochar can be produced as a co-product from several different processes viz. slow pyrolysis (SP), fast pyrolysis (FP), and gasification (Inyang and Dickenson 2015). In FP, feedstock biomass is combusted in the absence of oxygen at 425–550 °C, and the residence time is 2 s (Inyang and Dickenson 2015). In SP, feedstock biomass is combusted in the absence of oxygen at 350–800 °C, and the residence time varies from minutes to hours. During gasification, feedstock biomass is combusted in the presence of oxygen at ≥800 °C, and the residence time varies from seconds to hours. Sometimes, steam or CO_2 is also provided (Inyang and Dickenson 2015). Temperature, pressure, vapor residence time, and moisture content are some factors which affect the process of pyrolysis (Manyà 2012). More recently, a biochar called "hydrochar" has found its place in various scientific discussions. Hydrochar is produced by hydrothermal carbonization of biomass. Here, the biomass is treated with hot compressed water instead of drying (Kambo and Dutta 2015). Hydrochar is superior to biochar in many ways, e.g., it can reduce alkali and alkaline earth and heavy metal contents and had a higher heating value than that of biochar produced conventionally by SP (Kambo and Dutta 2015). However, hydrochar generally has low surface areas, poor microporosity (Hao et al. 2013), and less C stability compared to biochar.

The pyrolysis method significantly impacts biochar properties such as biochar yield, pH, particle size, and surface area (Ahmad et al. 2012a; Rajapaksha et al. 2014). In one study, FP drastically lowered pH and particle size and improved the surface area of biochar derived from wheat straw when compared with SP (Bruun et al. 2012). In this study, SP biochar completely pyrolyzed, while FP biochar left a labile unpyrolyzed biomass fraction (8.8 %). Moreover, 2.9 and 5.5 % of the SP and FP biochar-C was lost as CO_2 after 65 days of soil incubation, while 53 % of unpyrolyzed feedstock C was lost as CO_2. In addition, 43 % of N was immobilized with fresh FP biochar, while SP biochar had 7 % net N mineralization. The availability of the labile fraction of FP biochar probably supported a higher biochar-C loss and a larger soil microbial biomass (SMB) (Bruun et al. 2012). This indicates that the soil application of FP biochar materials has more potential to sequester C than SP biochar by providing a substrate for N retention (Bruun et al. 2012).

Biochars generated by SP and FP differ in their physicochemical characters and behave differently upon soil application (Brewer et al. 2009; Brown 2009). Biochars generated by FP at low temperatures produced partially pyrolyzed biomass and thus provided more C for microbial growth and had low potential for C sequestration in soil (Bruun et al. 2011). Consequently, application of partially pyrolyzed biomass enhances the immobilization of soil N because more N is required by developing soil biota as supplied by the substrate (Brewer et al. 2009). In contrast to FP, SP results in completely pyrolyzed biochars with less volatile C-substrate due to more char residence time in SP processes, and ultimately, the risks of N immobilization are reduced (Bruun et al. 2012).

Temperature during pyrolysis of biomass affects biochar properties. High pyrolysis temperature (600 °C) for low-ash biochars increased fixed C but decreased fixed C in those with more than 20 % ash (Enders et al. 2012). Particle size of biochar decreases with increasing pyrolysis temperature within 450–700 °C (Downie et al. 2009). In another study, increasing the pyrolysis temperature from 350 to 450 °C enhanced the pH and total C in miscanthus-derived biochar (Mimmo et al. 2014). In a recent study, Khanmohammadi et al. (2015) reported that pH and electrical conductivity (EC) of urban sewage sludge biochar were increased by 3.8 and 1.4 dS m^{-1}, proportionally to the increment of temperature from 300 to 700 °C, respectively. In this study, the biochar produced at low temperatures (300 °C) possessed higher total N and total organic carbon (OC) but low C/N ratio and total Na, K, and P contents. Increase in particle density and porosity was also noted upon pyrolysis with increment of temperature (Khanmohammadi et al. 2015).

Increasing pyrolysis temperature from 300 to 600 °C decreased poultry manure-derived biochar yield, total N, OC contents, and CEC and increased pH, ash content, OC stability, and total surface area. Likewise, maximum conversion of feed OC to biochar recalcitrant OC was recorded at 500 °C, although 81.2 % of the feed N was lost in volatiles at this temperature. Therefore, to generate agricultural use poultry litter biochar, pyrolysis at 300 °C is more suited, while for C sequestration and other environmental applications, pyrolysis at 500 °C is ideal (Song and Guo 2012). Fungo et al. (2014) reported 3 % less release of N_2O in biochars synthesized at 350 °C than at 550 °C, and the release of CH_4 was 10 % lower at 350 °C than at 550 °C. Novak et al. (2009a) introduced the concept of designer biochar. They opined that the process of biochar production can be tailored to form designer biochars that have specific characteristics to match selective chemical and/or physical issues of a degraded soil to which the biochar is to be applied. This can be achieved by altering the feedstock source and pyrolysis conditions. The benefits of biochar are only possible when organic waste management, biofuel production, and agronomic use of the biochar product are considered simultaneously. Biochar systems are likely to be successful where soils would benefit from biochar addition to improve water and nutrient retention, organic wastes are easily accessible (and not diverted to other forms of waste utilization), and economic conditions are favorable (Abiven et al. 2014).

In summary, the availability of feedstock source, pyrolysis conditions, pyrolysis temperature, target soil type, and social circumstances strongly influence the potential benefits of biochar application and should all be considered when selecting a biochar for a particular soil type at variable locations.

3 Impact on crop productivity

Biochar application may substantially improve soil fertility and crop productivity (Lehmann and Joseph 2015; Tables 1 and 2). For instance, biochar application (68 t ha^{-1}) increased biomass in rice (*Oryza sativa* L.) and cowpea (*Vigna unguiculata* (L.) Walp) by 20 and 50 %, respectively, and at 136.75 t ha^{-1} increased cowpea biomass by 100 % (Glaser et al. 2002). Biochar addition improved biomass and grain yields in durum wheat (*Triticum durum* L.) by up to 30 %, but there was no effect on grain N content (Vaccari et al. 2011). Oguntunde et al. (2004) recorded increases of 91 and 44 % in grain and biomass yield, respectively, in maize (*Zea mays* L.) on charcoal-amended soils when compared with adjacent field soils in Ghana. Likewise, in Kenya, maize yield in degraded soils doubled with the addition of *Eucalyptus*-derived biochar (Kimetu et al. 2008).

In Laos, biochar soil amendment improved the grain yield of upland rice at sites with low P availability. However, at sites with low native N supply, biochar reduced leaf chlorophyll contents suggesting that biochar may reduce grain yield in N-deficient soils if additional N is not applied (Asai et al. 2009; Nelson et al. 2011). Therefore, biochar application is likely to advance the productivity of upland rice in Laos, but the effects are reliant on soil fertility status and fertilizer management (Asai et al. 2009).

Several studies have indicated the strong potential of biochar application for improving crop yields, particularly on nutrient-poor soils (Van Zwieten et al. 2010; Zhang et al. 2012a; Table 1). The effect on crop yields particularly in nutrient-rich soils remains uncertain. Several other studies have revealed only small improvements or even reductions in grain yield with biochar application in nutrient-rich soils (Deenik et al. 2010; Gaskin et al. 2010; Van Zwieten et al. 2010; Table 1). For instance, Gaskin et al. (2010) noted a linear decrease in grain yield with increasing rates of biochar application.

Increased crop yield is a generally recognized benefit of biochar application; however, crop responses are highly variable and reliant on biochar type and application rates, soil properties, and climatic conditions (Table 1). For instance, Jeffery et al. (2011) conducted a meta-analysis for biochar application and crop productivity (either yield or aboveground biomass), found an overall small (~10 %) but significant improvement in grain yield by biochar application, and identified a liming effect and increase in soil WHC as principal reasons for biochar-induced yield gain (Jeffery et al. 2011). Among biochar feedstocks, poultry litter was the best (28 %), while biosolids had a negative effect (−28 %) on crop productivity (Jeffery et al. 2011).

In a recent study conducted for 3 years, Feng et al. (2014) reported that annual yield of either summer maize or winter wheat was not enhanced significantly due to biochar application; however, cumulative yield over the first 4 growing seasons were significantly higher with biochar application. Beside this study, most of the available studies are based on short-term experiments of 1 to 2 years' duration. So, more long-term experiments should be designed to monitor the effect of biochar application on crop productivity. In a review, Spokas et al. (2012) analyzed 44 published articles on biochar and found that about half of the biochars improved crop yield while the others had no or negative effect on crop yield.

Biochar-induced increases in specific surface area, CEC, soil porosity (Thies and Rillig 2009), WHC, nutrient retention (Glaser et al. 2002; Lehmann and Rondon 2006; Yamato et al. 2006), and liming effect (Rondon et al. 2007; Liu et al. 2013) are mainly responsible for improved crop productivity. For example, biochar obtained from crop biomass ashes can provide a P source similar to that of commercial P and K fertilizer (Schiemenz and Eichler-Loebermann 2010; Luo et al. 2014) or may improve the supply of Ca and Mg (Major et al. 2010a).

Biochar amendment has a synergistic effect with fertilizers in improving crop yield; for example, maize yield increased with biochar and fertilizer application more than fertilizer alone in acidic soil in Indonesia (Yamato et al. 2006). In another study, Steiner et al. (2007) harvested 4–12 times more yield of rice and sorghum (*Sorghum bicolor* L.) by charcoal application (11.25 t ha^{-1}) with compost and/or fertilizer than by using fertilizer alone. Biochar with NPK fertilizer application doubled the grain yields of rice and sorghum compared with NPK alone (Christoph et al. 2007). Mau and Utami (2014) also recorded increases in maize yield due to increased P availability and uptake under combined application of biochar and inoculation of arbuscular mycorrhiza (AM) fungal spores; however, biochar amendment alone did not improve maize growth or P uptake.

Biochar not only improves crop productivity under normal conditions (Table 1) but also improves crop yield under adverse conditions such as salinity and drought (Thomas et al. 2013; Haider et al. 2014). For example, biochar somewhat enhanced the permanent wilting point (Abel et al. 2013; Cornelissen et al. 2013), while the quantity of water retained at field capacity improved to a larger extent compared to the water held at permanent wilting point, i.e., increased plant available water. Therefore, the increase in WHC of biochar-amended soils can be used as an indicator of the overall rise in plant available water (Liu et al. 2014, 2015).

In a field study conducted on a boreal sandy clay loam, biochar soil amendment (10 t ha^{-1}) improved grain numbers in wheat in 2011 (dry year), probably by alleviating the water deficit (Tammeorg et al. 2014a). In another study, biochar addition to a fertile sandy clay loam in a boreal climate relieved the temporary water deficit thus improving harvestable yield (Tammeorg et al. 2014b). Recently, Haider et al. (2014) quoted that biochar application in poor sandy soils improved plant growth by improving soil-plant water relations (improved relative water content and leaf osmotic potential) and photosynthesis (reduced stomatal resistance and stimulated photosynthesis by increasing the electron transport rate of photosystem II) under well-watered and drought conditions.

Biochar application at high rates can mitigate adverse effects of salt stress for plant growth (Kim et al. 2016; Akhtar et al. 2015a). For instance, top dressing with biochar at 50 t ha^{-1} mitigated salt-induced mortality in *Abutilon theophrasti* and extended the survival rate of *Prunella vulgaris*. Plants of *A. theophrasti* receiving both biochar and salts had growth rates similar to plants devoid of salt addition (Thomas et al. 2013). Recently, Akhtar et al. (2015a) reported that biochar enhanced crop productivity in salt-affected soils; biochar application ameliorated salt stress by adsorbing Na^+ and increasing xylem K^+ content thereby increasing tuber yield in potato. The authors further observed positive residual effects of biochar application in reducing Na^+ uptake in the following wheat crop under salinity stress (Akhtar et al. 2015b). Therefore, biochar has the potential to mitigate salinity-induced reductions in mineral uptake, and may be a novel technique to alleviate the effects of salinization in arable and contaminated soils (Thomas et al. 2013; Kim et al. 2016).

In crux, biochar application has the potential to improve crop productivity on a variety of soils under normal and less than optimal environmental conditions if prepared and used wisely.

4 Impacts on soil quality

Biochar is known to improve physical, chemical, and biological properties in soil. The effect of biochar application on soil physicochemical properties, nutrient availability, and soil biota is discussed in the following sections.

4.1 Soil physical and chemical properties

Biochar application increases soil pH, porosity, and WHC and stabilizes SOM through increased soil aggregation and reduced soil bulk density (SBD) and tensile strength (Cao et al. 2009; Spokas et al. 2009; Zhang et al. 2010; Abel et al. 2013; Liu et al. 2015; Table 2). In general, biochar particles have low density with high porosity compared to that of soils which aids soil to hold more air and water, thus decreasing the SBD (Downie et al. 2009). Due to the lower SBD, biochar-amended soils had higher WHC which stimulate root growth and improve soil microbial activity (Major et al. 2010b; Zhang et al. 2010). For instance, Zhang et al. (2012a) reported that biochar lowered SBD and improved rice productivity in both cycles of rice growth. In another study, biochar addition to a highly productive Clarion loam decreased SBD (Laird et al. 2010a). In a recent study, Tammeorg et al. (2014b) reported more plant available water in the top 20 cm of soil during the first year, and reduced SBD in the second year of biochar application. The authors reported that biochar application might lower soil tensile strength leading to reduced tillage costs (Vaccari et al. 2011). Likewise, Chan et al. (2007) reported a reduction of −18 kPa in soil tensile strength with biochar application (100 t ha^{-1}) which is highly beneficial for root growth and mycorrhizal nutrient mining and facilitates seed germination.

Biochar improves the structure and function of SOM. For instance, Laird et al. (2010a) quoted up to 69 % increase in SOC after 500 days of biochar application on highly productive Clarion loam soil containing 2.0 % SOC. Although biochar behaves differently to SOC pools due to its very slow decomposition rate, it provides considerable benefits to soil by aggregation and retention of nutrients and water (Downie et al. 2009; Atkinson et al. 2010).

Several studies have reported the role of biochar in improving soil WHC (Lehmann et al. 2003; Thies and Rillig 2009; Anderson et al. 2011; Lee et al. 2015). For instance, WHC of agricultural soil in southern Finland increased by 11 % after the addition of 9 t ha^{-1} biochar (Karhu et al. 2011; Table 2) and increased by up to 15 % in a Clarion loam soil with the addition of biochar at 40 t ha^{-1} (Laird et al. 2010a; Table 2). However, according to Abel et al. (2013), biochar application improved water retention and available water contents (AWC) of soils with low SOM content (1–15 g kg^{-1}), while the effect was not significant for high SOM content (91 g kg^{-1}) soils. Further studies should be conducted to clarify whether this rise in WHC will improve water availability to plants with more recurrent droughts in the changing climate scenario. Biochar also improved saturated hydraulic conductivity (Glaser et al. 2002; Ayodele et al. 2009; Asai et al. 2009), infiltration rate (Glaser et al. 2002; Ayodele et al. 2009), and xylem sap flow (Asai et al. 2009).

Addition of biochar in soils improved soil stability (Piccolo et al. 1996) due to improved soil aggregation (Novotny et al. 2009). Biochar addition to clayey soils improved aggregate stability and reduced the detachment of colloidal materials. Biochar-induced changes in soil properties may also help to control soil erosion thus reducing the loss of particulate P from arable lands (Soinne et al. 2014; Lee et al. 2015).

Biochar-induced changes in soil pH have been observed in most of the studies (Rondon et al. 2007; Kimetu et al. 2008; Laird et al. 2010a; Zhang et al. 2010; Anderson et al. 2011). Biochar application (3 or 6 kg m^{-2}) increased soil pH from 5.2 to 6.7 in a field trial with wheat cultivation in two growing seasons (Castaldi et al. 2011). In a study on wheat, biochar application at 60 t ha^{-1} increased the soil pH from 5.1 to 6.39

Table 1 Influence of biochar application on productivity of different crops

Feedstock	Application rate	Production method	Type of experiment	Crops	Soil type	Response	Location	Reference
Bark of *Acacia mangium*	37 t ha^{-1}	Local made charcoal charred at 260–360 °C	Field	Maize	Acidic soil	+50 % (yield)	Indonesia	Yamato et al. (2006)
Eucalyptus deglupta Blume	25 g kg^{-1} soil	Charred for 1 h at 350 °C at 15 % O_2 level	Green house	Rice	Volcanic-ash inceptisol	+294 % (grain yield)	Colombia	Noguera et al. (2010)
Eucalyptus deglupta Blume	25 g kg^{-1} soil	Charred for 1 h at 350 °C at 15 % O_2 level	Green house	Rice	Volcanic-ash inceptisol	+166 % (biomass)	Colombia	Noguera et al. (2010)
Eucalyptus deglupta Blume	60 g kg^{-1} soil	Charred for 1 h at 350 °C at 15 % O_2 level	Pot	*Phaseolus vulgaris* L.	Clay-loam oxisol	+39 % (seed yield)	Colombia	Rondon et al. (2007)
Eucalyptus deglupta Blume	90 g kg^{-1} soil	Charred for 1 h at 350 °C at 15 % O_2 level	Pot	*Phaseolus vulgaris* L.	Clay-loam oxisol	+46 % (seed yield)	Colombia	Rondon et al. (2007)
Green waste	10 t ha^{-1}	Pyrolyzed at 450 °C	Pot	Radish	Alfisol	−30 % (biomass)	Australia	Chan et al. (2007)
Green waste	50 t ha^{-1}	Pyrolyzed at 450 °C	Pot	Radish	Alfisol	+91 % (biomass)	Australia	Chan et al. (2007)
Green waste	100 t ha^{-1}	Pyrolyzed at 450 °C	Pot	Radish	Alfisol	+130 % (biomass)	Australia	Chan et al. (2007)
Woodland of beech, hazel, oak, and birch	30 t ha^{-1}	Charred at 500 °C	Field	Durum wheat	Silty loam (pH 5.2)	+31 % (yield)	Italy	Vaccari et al. (2011)
Woodland of beech, hazel, oak, and birch	60 t ha^{-1}	Charred at 500 °C	Field	Durum wheat	Silty loam (pH 5.2)	+30.4 % (yield)	Italy	Vaccari et al. (2011)
Poultry litter	10 t ha^{-1} (without N)	Charred at 450 °C	Pot	Radish	Alfisol	+42 % (yield)	Australia	Chan et al. (2008)
Poultry litter	50 t ha^{-1} (without N)	Charred at 450 °C	Pot	Radish	Alfisol	+96 % (yield)	Australia	Chan et al. (2008)
Secondary forest wood	11 t ha^{-1}	Locally made charcoal	Field	Rice/ sorghum	Highly weathered xanthic ferralsol (pH 4.7)	+22 % (biomass)	Brazil	Steiner et al. (2007)
Secondary forest wood	11 t ha^{-1}	Locally made charcoal	Field	Rice/ sorghum	Highly weathered xanthic ferralsol (pH 4.7)	+17 % (grain yield)	Brazil	Steiner et al. (2007)
Teak and rosewood	4 t ha^{-1}	Earth mound method	Field	Rice	Acidic soil	No effect	Laos	Asai et al. (2009)
Teak and rosewood	8 t ha^{-1}	Earth mound method	Field	Rice	Acidic soil	−10 % (grain yield)	Laos	Asai et al. (2009)
Teak and rosewood	16 t ha^{-1}	Earth mound method	Field	Rice	Acidic soil	−26 % (grain yield)	Laos	Asai et al. (2009)
Eucalyptus or corn stover	10 t ha^{-1}	550 °C	Field	Corn	Fine sandy loam	No effect	New Zealand	Free et al. (2010)
Rice husk	4.13 kg m^{-2}	Charred in burning chamber having a chimney	Field	Rice	Anthraquic gleysols (pH 6.55)	Grain yield slightly decreased	IRRI Philippines	Haefele et al. (2011)
Rice husk	4.13 kg m^{-2}	As above	Field	Rice	Humic nitisols (pH 4.3)	+16–35 % (grain yield)	Sinilioan Philippines	Haefele et al. (2011)
Wheat straw	20 t ha^{-1} (without N)	Charred at 350–550 °C	Field	Corn	Calcareous loam soil (poor in OC)	+15.8 % (grain yield)	China	Zhang et al. (2012a)
Wheat straw	20 t ha^{-1} (with N)	Charred at 350–550 °C	Field	Corn	Calcareous loam soil (poor in OC)	+18.2 % (grain yield)	China	Zhang et al. (2012a)

Table 1 (continued)

Feedstock	Application rate	Production method	Type of experiment	Crops	Soil type	Response	Location	Reference
Wheat straw	40 t ha^{-1} (without N)	Charred at 350–550 °C	Field	Corn	Calcareous loam soil (poor in OC)	+7.3 % (grain yield)	China	Zhang et al. (2012a)
Wheat straw	40 t ha^{-1} (with N)	Charred at 350–550 °C	Field	Corn	Calcareous loam soil (poor in OC)	+12.1 % (grain yield)	China	Zhang et al. (2012a)
Wheat straw	10 t ha^{-1} (without N)	Charred at 350–550 °C	Field	Rice	Productive paddy soil (pH 6.5)	+11.6 % (grain yield)	China	Zhang et al. (2010)
Wheat straw	10 t ha^{-1} (with N)	Charred at 350–550 °C	Field	Rice	Productive paddy soil (pH 6.5)	+8.8 % (grain yield)	China	Zhang et al. (2010)
Wheat straw	40 t ha^{-1} (without N)	Charred at 350–550 °C	Field	Rice	Productive paddy soil (pH 6.5)	+14 % (grain yield)	China	Zhang et al. (2010)
Wheat straw	40 t ha^{-1} (with N)	Charred at 350–550 °C	Field	Rice	Productive paddy soil (pH 6.5)	+12.1 % (grain yield)	China	Zhang et al. (2010)
Maize straw	2.4 t ha^{-1}	Pyrolysis at 400 °C	Field	Rice	Sandy loam	+6 (grain yield)	China	Liu et al. (2015)
Wheat straw	20 t ha^{-1}	Pyrolysis at 350–550 °C	Field	Maize	Calcic Aqui-alluvic Primisol	+10.38 (grain yield)	China	Liu et al. (2014)
Rice straw	5 t ha^{-1}	Charred at 450 °C	Column	Rice	Sandy	−27.44 (grain yield)	Denmark	Ly et al. (2014)
Rice straw	5 t ha^{-1}	Charred at 450 °C	Column	Rice	Sandy	−35.76 (grain yield)	Denmark	Ly et al. (2014)
Pig manure compost	0.45 t ha^{-1}	Pyrolysis at 350–450 °C	Field	Rice	Entic Hydroagric Anthrosol	+13.49 (grain yield)	China	Qian et al. (2014)
Maize straw	0.45 t ha^{-1}	Pyrolysis at 350–450 °C	Field	Rice	Entic Hydroagric Anthrosol	+10.46 (grain yield)	China	Qian et al. (2014)
Peanut husk	0.45 t ha^{-1}	Pyrolysis at 350–450 °C	Field	Rice	Entic Hydroagric Anthrosol	+28.1 (grain yield)	China	Qian et al. (2014)
Municipal waste	0.45 t ha^{-1}	Pyrolysis at 350–450 °C	Field	Rice	Entic Hydroagric Anthrosol	+31.39 (grain yield)	China	Qian et al. (2014)
Wheat straw	10 t ha^{-1}	Pyrolysis at 350–550 °C	Field	Rice	Hydroagric Stagnic Anthrosol	+27.63 (grain yield)	China	Zhang et al. (2013)
Wheat straw	20 t ha^{-1}	Pyrolysis at 350–550 °C	Field	Rice	Hydroagric Stagnic Anthrosol	+9.2 (grain yield)	China	Zhang et al. (2013)
Wheat straw	40 t ha^{-1}	Pyrolysis at 350–550 °C	Field	Rice	Hydroagric Stagnic Anthrosol	+22.39 (grain yield)	China	Zhang A et al. (2013)
Rice straw	4.5 t ha^{-1}	Pyrolysis at 350–550 °C	Pot	Rice-wheat	Gleyi–Stagnic Anthrosol	+5.88 (grain yield)	China	Zhao et al. (2014)
Rice straw	9 t ha^{-1}	Pyrolysis at 350–550 °C	Pot	Rice-wheat	Gleyi–Stagnic Anthrosol	+5.88 (grain yield)	China	Zhao et al. (2014)
Rice straw	4.5 t ha^{-1}	Pyrolysis at 350–550 °C	Pot	Rice-wheat	Gleyi–Stagnic Anthrosol	+14.80 (grain yield)	China	Zhao et al. (2014)
Rice straw	9 t ha^{-1}	Pyrolysis at 350–550 °C	Pot	Rice-wheat	Gleyi–Stagnic Anthrosol	+21.35 (grain yield)	China	Zhao et al. (2014)
Wheat straw	40 t ha^{-1}	350–550 °C	Field	rice	Hydroagric Stagnic Anthrosol	+18.3 (grain yield)	China	Bian et al. (2014)

+ increase, − decrease, *OC* organic carbon

Table 2 Influence of biochar application on different soil properties

Factor	Feedstock	Application rate	Pyrolysis temperature	Soil type	Impact	Reference
Cation exchange capacity	Charcoal	300 g kg^{-1} soil	Unknown	Loam	+50 %	Tryon (1948)
	Mixed hardwood (*Querus* and *Carya* spp.)	20 g kg^{-1} soil	Slow pyrolysis (traditional kilns)	Clarion soil	+~20 %	Laird et al. (2010a)
Soil pH (H_2O)	Mixed hardwood (*Querus* and *Carya* spp.)	20 g kg^{-1} soil	Slow pyrolysis (traditional kilns)	Clarion soil	+1 unit	Laird et al. (2010a)
	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+7.99 %	Zhang et al. (2010)
	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+3.68 %	Zhang et al. (2010)
	Wheat straw	20 t ha^{-1} (with and without N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	+1.15	Zhang et al. (2012b)
	Wheat straw	40 t ha^{-1} (with and without N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	+1.10	Zhang et al. (2012b)
	Municipal biowaste	40 t ha^{-1}	450–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+13.56	Bian et al. (2013)
	Municipal biowaste	40 t ha^{-1}	450–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+12.28	Bian et al. (2013)
	Sewage sludge	5 g kg^{-1} soil	–	–	+3.47	Khan et al. (2014)
	Sewage sludge	10 g kg^{-1} soil	–	–	+6.58	Khan et al. 2014)
	Sewage sludge	50 g kg^{-1} soil	550 °C for 6 h	Acidic soil	+20.9	Khan et al. (2013)
	Sewage sludge	100 g kg^{-1} soil	550 °C for 6 h	Acidic soil	+34.1	Khan et al. (2013)
	Wheat straw	10 t ha^{-1}	350–550 °C	Ferric-accumulic Stagnic Anthrosols	+3.27	Cui et al. (2011)
	Wheat straw	20 t ha^{-1}	350–550 °C	Ferric-accumulic Stagnic Anthrosols	+4.78	Cui et al. (2011)
	Wheat straw	40 t ha^{-1}	350–550 °C	Ferric-accumulic Stagnic Anthrosols	+5.94	Cui et al. (2011)
	Wheat straw	10 metric t ha^{-1}	450 °C	Ferric-accumulic Stagnic Anthrosols	+1.78	Cui et al. (2013)
	Wheat straw	20 metric t ha^{-1}	450 °C	Ferric-accumulic Stagnic Anthrosols	+4.37	Cui et al. (2013)
	Wheat straw	40 metric t ha^{-1}	450 °C	Ferric-accumulic Stagnic Anthrosols	+4.69	Cui et al. (2013)
	Wheat straw	40 t ha^{-1}	350–550 °C	Calcic Aqui-alluvic Primisol	No effect	Liu et al. 2014)
	Pig manure compost	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	+1.76	Qian et al. (2014)
Soil water holding capacity	Charcoal	450 g kg^{-1} soil	Unknown	Sand	+18 %	Tryon (1948)
	By-product of birch charcoal	9 t ha^{-1}	400 °C	Silt-loam slightly acidic	+11 %	Karhu et al. (2011)
	Mixed hardwood (*Querus* and *Carya* spp.)	20 g kg^{-1} soil	Slow pyrolysis (traditional kilns)	Clarion soil	+15 %	Laird et al. (2010a)
Soil bulk density	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	−11.88 %	Zhang et al. (2010)
	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	−10.10 %	Zhang et al. (2010)

Table 2 (continued)

Factor	Feedstock	Application rate	Pyrolysis temperature	Soil type	Impact	Reference
	By-product of birch charcoal	9 t ha^{-1}	400 °C	Silt-loam slightly acidic	−3.85 %	Karhu et al. (2011)
	Wheat straw	20 t ha^{-1} (without N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	−10.22 %	Zhang et al. (2012b)
	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	−20.44 %	Zhang et al. (2012b)
	Wheat straw	20 t ha^{-1} (with N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	−9.56 %	Zhang et al. (2012b)
	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	−12.5 %	Zhang et al. (2012b)
	Sewage sludge	50 g kg^{-1} soil	550 °C for 6 h	Acidic soil	−4.46	Khan et al. (2013)
	Sewage sludge	100 g kg^{-1} soil	550 °C for 6 h	Acidic soil	−9.82	Khan et al. (2013)
	Wheat straw	40 t ha^{-1}	350–550 °C	Calcic Aqui-alluvic Primisol	−5.33	Liu et al. (2014)
Total carbon	Sewage sludge	5 g kg^{-1} soil	–	–	+38	Khan et al. (2014)
	Sewage sludge	10 g kg^{-1} soil	–	–	+133	Khan et al. (2014)
	Sewage sludge	5 g kg^{-1} soil	550 °C	Acidic soil	+554.5	Khan et al. (2013)
	Sewage sludge	10 g kg^{-1} soil	550 °C	Acidic soil	+818.2	Khan et al. (2013)
Total nitrogen	Sewage sludge	5 g kg^{-1} soil	–	–	+48.48	Khan et al. (2014)
	Sewage sludge	10 g kg^{-1} soil	–	–	+66.67	Khan et al. (2014)
	Sewage sludge	5 g kg^{-1} soil	550 °C	Acidic soil	+350	Khan et al. (2013)
	Sewage sludge	10 g kg^{-1} soil	550 °C	Acidic soil	+550	Khan et al. (2013)
	Pig manure compost	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−0.85	Qian et al. (2014)
	Rice straw	4.5 t ha^{-1}	350–550 °C	Gleyi–Stagnic Anthrosol	+9.77	Zhao et al. (2014)
	Rice straw	9 t ha^{-1}	350–550 °C	Gleyi–Stagnic Anthrosol	+13.35	Zhao et al. (2014)
Soil organic carbon	Wheat straw	20 t ha^{-1} (without N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	+44 %	Zhang et al. (2012b)
	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	+57.8 %	Zhang et al. (2012b)
	Wheat straw	20 t ha^{-1} (with N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	+25 %	Zhang et al. (2012b)
	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loam)	+42.2 %	Zhang et al. (2012b)
	Mixed hardwood (*Querus* and *Carya* spp.)	20 g kg^{-1} soil	Slow pyrolysis (traditional kilns)	Clarion soil	+69 %	Laird et al. (2010a)
	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+57.2 %	Zhang et al. (2010)
	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+55.17 %	Zhang et al. (2010)
	Municipal biowaste	40 t ha^{-1}	450–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+20.15	Bian et al. (2013)
	Municipal biowaste	40 t ha^{-1}	450–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+18.65	Bian et al. (2013)
	Wheat straw	10 t ha^{-1}	350–550 °C		+10.13	

Table 2 (continued)

Factor	Feedstock	Application rate	Pyrolysis temperature	Soil type	Impact	Reference
				Ferric-accumulic Stagnic Anthrosols		Cui et al. (2011)
	Wheat straw	20 t ha^{-1}	350–550 °C	Ferric-accumulic Stagnic Anthrosols	+35.13	Cui et al. (2011)
	Wheat straw	40 t ha^{-1}	350–550 °C	Ferric-accumulic Stagnic Anthrosols	+57.31	Cui et al. (2011)
	Wheat straw	10 metric t ha^{-1}	450 °C	Ferric-accumulic Stagnic Anthrosols	+16.18	Cui et al. (2013)
	Wheat straw	20 metric t ha^{-1}	450 °C	Ferric-accumulic Stagnic Anthrosols	+33.15	Cui et al. (2013)
	Wheat straw	40 metric t ha^{-1}	450 °C	Ferric-accumulic Stagnic Anthrosols	+50.97	Cui et al. (2013)
	Wheat straw	40 t ha^{-1}	350–550 °C	Calcic Aqui-alluvic Primisol	+24.21	Liu et al. (2014)
	Pig manure compost	0.45 t ha^{-1}	350-450 °C	Entic Hydroagric Anthrosol	+29.85	Qian et al. (2014)
	Rice straw	4.5 t ha^{-1}	350–550 °C	Gleyi–Stagnic Anthrosol	+50	Zhao et al. (2014)
	Rice straw	9 t ha^{-1}	350–550 °C	Gleyi–Stagnic Anthrosol	+101	Zhao et al. (2014)

+ increase, − decrease

(Vaccari et al. 2011). In another study, Zhang et al. (2012a) reported that biochar improved rice productivity and soil pH in both cycles of rice growth. Various other studies have also reported an increase in soil pH due to biochar application (Table 2).

Biochar application also helps to improve ion exchange capacity (Lehmann et al. 2003; Liang et al. 2006; Laird et al. 2010a). For instance, *Eucalyptus* biochar significantly increased soil CEC in degraded soils in Kenya (Kimetu et al. 2008). Likewise, soil CEC increased by about 20 % due to increases in soil-specific surface area after 500 days of biochar addition (Laird et al. 2010a).

In conclusion, biochar amendment improves SOC, soil pH, CEC, porosity, WHC, nutrient retention, and soil aggregation and lowers SBD and tensile strength to facilitate plant growth due to improved root growth and higher nutrient uptake.

4.2 Nutrient availability and leaching

Increased C storage, improved soil fertility, and reduced nutrient leaching are among the most pronounced effects of biochar soil amendment (Novak et al. 2009b; Laird et al. 2010a; Van Zwieten et al. 2010; Liu et al. 2013; El-Naggar et al. 2015).

Cation adsorption and increased pH, particularly in acid soils, are the major factors responsible for increased nutrient retention in biochar-amended soils (Lehmann et al. 2003; Liang et al. 2006; Van Zwieten et al. 2010; Ventura et al. 2013). The higher surface charge density of biochars helps to maintain cations for ion exchange, while the higher surface area, porosity, and existence of both polar and nonpolar surface sites assist biochars to retain organic molecules and nutrients (Liang et al. 2006; Ahmad et al. 2014a), thus boosting up the soil fertility (Ding et al. 2010; Laird et al. 2010b; Prendergast-Miller et al. 2011). Therefore, biochar application in soils may be an efficient practice for improving soil nutrient content, availability, and crop production (Lehmann and Rondon 2006; Novak et al. 2009b; Graber et al. 2010; Major et al. 2010a).

Oguntunde et al. (2004) reported substantial increases in exchangeable cations and P, soil pH, and EC on biochar-amended soils compared with adjacent fields in Ghana. Biochar improved Ca and Mg availability due to its liming effect, thus increasing maize yield (Liu et al. 2013). In paddy fields, N contents increased by 5.43 and 18.77 % in biochar-amended soils with 20 and 40 t ha^{-1}, respectively (Zhang et al. 2012a). In another study, biochar application not only enhanced biological N fixation in bean crops but also improved plant available micronutrient such as B and Mo (Rondon et al. 2007). Sometimes, the effects of biochar remain consistent for several years without further addition. For instance, biochar consistently increased K availability over five seasons with a single amendment of 40 t ha^{-1} (Liu et al. 2013).

Likewise, significant improvement in soil fertility in acidic sandy soils in southwestern USA has also been reported (Novak et al. 2009b) due to biochar application. In a study, biochar application increased total N contents and improved rice ecosystem functioning by reducing N_2O-N emissions in paddy fields (Liu et al. 2012). In a recent study, biochar application enhanced soluble K and SOC contents in the upper 20 cm of soil but had no effect on other nutrients. However, soil nitrate (NO_3)-N contents decreased in the biochar-amended soil more than the untreated soil in the first year but increased in the second year; there was no significant effect on N uptake possibly due to its low nutrient availability and high SOM (Tammeorg et al. 2014b). In two recent studies on acidic soil, biochar application improved total N (Khan et al. 2013, 2014; Zhao et al. 2014) and total C (Khan et al. 2013, 2014; Table 2). Hu et al. (2014) found that biochar application enhanced soil C sequestration by enhancing total SOC concentrations and NO_3-N in soil. Güereńa et al. (2013) also reported that N retention in soil can be enhanced by the addition of biochar.

Biochar application regulates nutrient cycling primarily by modulating the supply of substrates. Biochar with low specific surface area, which maintains an active and protected enzyme pool, may enhance the degradation of highly soluble substrates, while biochars with high specific surface area and porosity slow down degradation by making substrates unavailable (Lammirato et al. 2011). Loss of nitrogenous fertilizers through NO_3 leaching is common in agricultural soils, but this could be significantly reduced by biochar application (Ding et al. 2010). Prendergast-Miller et al. (2011) used a wheat seedling rhizobox approach to differentiate between the rhizosphere and nonrhizosphere (bulk) soil amended with biochar to monitor NO_3 leaching. Biochar application restricted NO_3 within the rhizosphere, reduced leaching, and improved N use efficiency (Mandal et al. 2016). In another study, de la Rosa and Knicker (2011) mixed ^{15}N-enriched pyrogenic organic material (PyOM) obtained from *Lolium perenne* charred for 4 min at 350 °C in a typical Mediterranean agricultural soil and incubated for 72 days. Mixing ^{15}N-PyOM enhanced N retention and increased total SOC and N contents of the soils by 5–10 % after 72 days of incubation. Fairly low recalcitrance of N-rich PyOM and N was slowly transferred to an available form much like a slow release N-fertilizer. Biochar application also helps to reduce N losses by suppressing N_2O emissions (Fungo et al. 2014; Pandey et al. 2014).

Laird et al. (2010a) reported that biochar application reduced leaching of N, P, Mg, and silicon (Si) from manure-amended columns filled with typical Midwestern USA agricultural soils; in particular, the columns with 20 g kg^{-1} applied biochar reduced N and P leaching by 11 and 69 %, respectively. Therefore, biochar soil amendment could be an efficient technique to reduce nutrient leaching in production agriculture (Laird et al. 2010a, b). In biochar-amended acidic soils, P availability increased due to increased soil pH while Al availability to plants decreased (Hammes and Schmidt 2009). Field application of mango wood biochar at 23.2 and 116.1 t ha^{-1} improved P availability by 163 and 208 %, respectively (Warnock et al. 2010). Application of biochar in combination with inoculation of Arbuscular mycorrhizal (AM) fungal spores improved the availability and uptake of soil P by maize plants, which in turn enhanced plant yield. However, application of biochar alone did not improve maize growth or P uptake by maize plants (Mau and Utami 2014).

In conclusion, biochar-mediated changes in soil physical, chemical, and biological properties contribute to reduced nutrient leaching and improved soil fertility.

4.3 Soil biota

In general, most of the C in biochar is not available to soil microbes (Theis and Rillig 2009); however, there is evidence for biochar's role in promoting soil microbial biomass, growth, and activity (Rondon et al. 2007; O'Neill et al. 2009; Liang et al. 2010; Smith et al. 2010; Joseph et al. 2015). For example, addition of black C in soils by anthropogenic or natural fires reportedly enhances microbial growth and activity (Kolb et al. 2009). Sorption and subsequent inactivation of growth-inhibiting materials by biochar modulates the abundance of soil biota in biochar-amended soils (Lehmann et al. 2011). Biochar amendment strongly influences soil microbial community composition and abundance as observed in biochar-rich terra preta soils in the Amazon (Yin et al. 2000; Kim et al. 2007; O'Neill et al. 2009; Grossman et al. 2010; Liang et al. 2010). Changes in microbial community composition or activity in response to biochar application influence the nutrient cycles, crop growth, and SOM decomposition (Kuzyakov et al. 2009; Liang et al. 2010). Biochars may stimulate activity of soil AM fungi (Ishii and Kadoya 1994) and thus play a critical role in nutrient cycling (Lambers et al. 2008).

Biochar addition to soil promotes the growth of soil biota involved in N cycling, in particular those which reduce flux of N_2O to either promote denitrification of N_2O to di-nitrogen (N_2) or produce ammonium (NH_4^+) that can be adsorbed on the biochar surface and thus modulate soil N dynamics (Anderson et al. 2011).

Biochars behave differently in soils with respect to soil biological activities depending on feedstock (Kuzyakov et al. 2009) and soil types (Kolb et al. 2009) due to variable pH, surface area, charge properties, and pore size (Brewer et al. 2009). For instance, less acidic soil conditions favor microbial activity and in particular increase the activity of autotrophic nitrifying bacteria (De Luca et al. 2009). The effects of biochar on soil enzyme activities also vary and depend on soil type and a particular enzyme (Bailey et al. 2011). Moreover, biochar reacts with a range of substrates rendering them unavailable to enzyme action. Similarly, biochar has a strong influence on the soil microbial community owing to modulation in soil water dynamics, CEC, and principal C forms (Bailey et al. 2011).

Biochar improved the abundance of bacterial families [Bradyrhizobiaceae (8 %), Hyphomicrobiaceae (14 %), Streptosporangineae (6 %), and Thermomonosporaceae (8 %)], either by advancing their abundance or reducing the scale of loss, but suppressed the abundance of Streptomycetaceae (−11 %) and Micromonosporaceae (−7 %) (Anderson et al. 2011). Of these, Bradyrhizobiaceae and Hyphomicrobiaceae are involved in N cycling, with 454 genera/species involved in NO_3 denitrification to N_2. Thus, organisms involved in nitrification of NH_4^+ to nitrite (NO_2^-) were less abundant. Biochar also enhanced the growth of microbes capable of reducing N_2O flux (Anderson et al. 2011). Moreover, biochar application promoted phosphate-solubilizing bacteria and modified C fluxes by encouraging the abundance of bacterial families capable of degrading highly recalcitrant C (Anderson et al. 2011).

Contrasting reports are available about the effects of biochar on ecto- and AM fungal biomass and root colonization of plants. For instance, according to Ishii and Kadoya (1994) and Matsubara et al. (2002), biochar addition improved plant health by increasing nutrient supply and pathogen resistance, while others reported significant reductions in both root colonization, hyphal length, and P availability (Warnock et al. 2010). According to Warnock et al. (2007), biochar influences soil AM fungi by altering nutrient availability, other soil microbial communities like phosphate-solubilizing bacteria, plant-fungi signaling, and habitat creation and shelter from hyphal grazers; however, all these mechanisms are innately interconnected. The physicochemical properties of biochars such as CEC, WHC, and pH affect nutrient availability and manipulate the microbial community. Warnock et al. (2010) conducted three trials, each with a different soil type, using five biochars and ten application rates; two of the trials used *Plantago lanceolata* as an AM fungal host plant, while the third trial was conducted under field conditions. AM fungi abundance either declined or remained constant in all biochar treatments, with the decline related to major changes in soil properties, principally soil P availability. Lodge pole pine biochar application at 2 and 4 % (*w*/*w*) decreased AM fungi abundance in roots by 58 and 73 % and soil P availability by 28 and 34 %, respectively, but AM fungi abundance was not significantly affected in soil. Peanut shell biochar addition increased P supply by 101 % but decreased AM fungal root colonization and extraradical hyphal lengths by 74 and 95 %, respectively. Likewise, field-applied mango wood biochar at 23.2 and 116.1 t C ha^{-1} enhanced P accessibility by 163 and 208 % and reduced soil AM fungi abundance by 43 and 77 %, respectively. These findings may have implications for soil management where the goal is to increase the services provided by AM fungi (Warnock et al. 2010). Warnock et al. (2007) showed that biochar amendment had positive effects on two of the most common mycorrhizal fungi, being AM fungi and ectomycorrhizal (EM). Biochar application improved the formation rate and tip number of EM infection in larch seedling roots by 19–157 % (Makoto et al. 2010). Similarly, application of *Eucalyptus* wood biochar at 0.6–6.0 t ha^{-1} enhanced AM fungi colonization of wheat roots by 20–40 % after 2 years compared with a rate of only 5–20 % without biochar addition (Solaiman et al. 2010). In contrast, Gaur and Adholeya (2000) and Warnock et al. (2010) reported less AM fungi abundance with biochar addition. These rarely observed reductions in AM fungi abundance are probably caused by related increases in nutrient availability thus reducing the need for symbionts (Lehmann et al. 2011). Moreover, in some cases, the release of certain organic molecules from fresh biochars may enhance or depress the abundance and activity of soil biota for short periods of time (Lehmann et al. 2011).

Biochar humic substance products (B-HSP) cause change in plant P nutrition (Graber et al. 2015), possibly by improving mycorrhizal colonization (Blackwell et al. 2010). In a recent study, Vanek and Lehmann (2015) reported that biochar applied with iron (Fe)-P and enriched (>2×) with AM hyphae enhanced AM colonization by 6 % and improved AM-related Fe-P uptake by 12 % ($p < 0.05$). Soluble P located on biochar enhanced total plant and microbial P, and biochar application reversed reductions in specific root length induced by AM. Indeed, biochar application enhanced AM's access to sparingly soluble P and root/microbial access to soluble P (Vanek and Lehmann 2015). In another study, Elmer and Pignatello (2011) reported that biochar application enhanced AM colonization by sorbing allelopathic chemicals, which otherwise depress AM colonization.

Other than bacteria and fungi, earthworms are an important component of soil biota performing several vital and useful functions in soil ecosystems including SOM decomposition and nutrient cycling and improving soil structure. In agricultural fields, earthworms boost nutrient mineralization and biochar elevates nutrient retention; both processes could direct the buildup of nutrient stock for plant growth (Barot et al. 2007; Boudsocq et al. 2009). The ability of earthworms to execute these functions can be disturbed by the addition of harmful substances. According to Li et al. (2011), earthworms avoided soil amended with 100 and 200 g kg^{-1} dry biochar (apple wood) and lost weight after 28 days of exposure due to desiccation, but biochar had no effect on earthworm reproduction. Nonetheless, polycyclic aromatic hydrocarbons (PAHs) were found in the tested biochar (25.9, 3290, and 102 mg kg^{-1} of fluorene, naphthalene, and phenanthrene, respectively), but there was no evidence of lipid peroxidation or increased superoxide dismutase activity in biochar-exposed earthworms which suggests that the occurrence of toxic substances was not the avoidance motive. However, wetting the biochar to field capacity before application to soil alleviated the earthworm's avoidance to biochar even at a rate of 100 g kg^{-1} (90 t ha^{-1}). Therefore, wetting biochar before or immediately after soil application is desired to avoid desiccation of earthworms (Li et al. 2011). In a recent study, spruce chip biochar (30 t ha^{-1}) did not affect the habitat choice of earthworms within 2 days, but by 2 weeks, the earthworms tended to avoid biochar owing to a decline in soil water potential (Tammeorg et al. 2014c), which might have caused desiccation.

In conclusion, biochar application strongly influences soil microbial community composition and abundance. Biochar stimulates soil microbial activity which helps to modulate nutrient cycling.

5 Environmental benefits

Carbon sequestration, rehabilitation of degraded lands, reduced GHG emissions, adsorption of contaminants to offset streams, and groundwater pollution are among the environment-related benefits linked with biochar (Lehmann et al. 2006; Lehman and Joseph 2009; Beesley et al. 2010; Mohan et al. 2014). In the following sections, biochar-induced environmental benefits are discussed.

5.1 Carbon sequestration

Carbon sequestration is the long-term storage of CO_2 or other forms of carbon to mitigate or defer global warming. Increased soil C stock is the most pronounced effect of biochar soil application (Lehmann et al. 2006; Spokas et al. 2009; McHenry 2010; Sohi et al. 2010; Stavi and Lal 2013; Zhang and Ok 2014). Merging bioenergy production with the application of pyrolysis by-product biochar in soil removes CO_2 from the atmosphere, as more C is sequestered than emitted (Roberts et al. 2010). According to Lehmann (2007), 20 % more CO_2 is captured from the atmosphere and sequestered by biochar soil amendment.

The mean residence time of biochar in soils is estimated to be more than 1000 years (Lehmann et al. 2008; Liang et al. 2008; Nguyen and Lehmann 2009; Zimmerman 2010; Ahmad et al. 2014a). The long-lasting stability of biochar is the basic foundation when considering it as a C sequestration technique. Even when subjected to severe weathering conditions in a tropical climate, biochar was highly resistant to chemical degradation with no obvious decline in stocks (Schneider et al. 2011).

Abiven et al. (2011) reported that soluble and colloidal fractions of freshly pyrolyzed char were very small (<2.7 g kg^{-1}) but likely to rise with residence time in soil. Novak et al. (2009b) reported that biochar application to acidic sandy soils in southwestern USA enhanced SOC, as SOM is gradually sorbed onto biochar surfaces and within pores where it is protected from degradation (Vasilyeva et al. 2011). Luo et al. (2011) added biochar to a clay-loam soil at pH 3.7 and 7.6. After 87 days of incubation, 0.14 and 0.18 % of biochar700 (biochar produced at 700 °C) and 0.61 and 0.84 % of biochar350 (biochar produced at 350 °C) were mineralized in low and high pH soils, respectively. The priming effect possibly occurred due to the water-soluble component of the biochars. Moreover, the higher decline in the priming effect of biochar with rising pyrolysis temperatures provides an option to control priming effects of biochar application in soil. If biochar is used for C sequestration, a priming effect may occur with increased CO_2 emission from soil leading to reduced SOC; however, this will be compensated for by the additional C added from incorporating biochar (Luo et al. 2011). Smith et al. (2010) found that more CO_2 was released from soils with biochar amendment, which increased further at higher application rates. However, this CO_2 evolution diminished 6 days after incubation suggesting that most of the carbon in the biochar slowly decays. Recently, El-Naggar et al. (2015) reported that incorporating biochar into calcareous soils benefits carbon sequestration and soil fertility.

Carbon mineralization is usually higher in biochar-amended soils due to faster utilization of a small labile portion of biochar, but the applied biochar did not compensate for the loss of native SOM. In some cases, negative priming has been observed in biochar-amended soil possibly due to stabilization of labile soil C (Cross and Sohi 2011). However, the unaltered CO_2 emission from soil along with the constant rise in SOC over time (five crop seasons) with single biochar (40 t ha^{-1}) amendment verified strong microbial stability of biochar-derived C in soil devoid of a priming effect for native SOM (Liu et al. 2014). Van Zwieten et al. (2013) reported no net raise in CO_2 release in poultry biochar-amended ferrosol. Biochar is therefore extremely resistant to microbial degradation, noticeably expanding the recalcitrant portion of SOC and lessening the release of CO_2 from soil (Glaser et al. 2002; Lehmann 2007).

The key mechanisms, which stabilize biochar added to soil, are known as the intrinsic recalcitrant nature of biochar, spatial separation of substrate and decomposers, and the creation of interactions among mineral surfaces (Sollins et al. 1996). Purakayastha et al. (2015) reported that maize biochar had a lower C mineralization rate than rice biochar (2.34 vs. 4.49 %) suggesting its higher capability for long-term C sequestration. The treatment with added biochar had the most soil C under a wheat-pearl millet cropping system. However, after 34 days of incubation, sandy and sandy loam soils with maize-derived biochar had the highest decay rate when compared with unamended soils (Awad et al. 2012). Moreover, the highest activities of cellobiohydrolase, β-glucosidase, and chitinase were noted in the biochar-amended soils. Due to the readily available C in tested biochar, biochar addition was recommended especially in areas where rapid decomposition of plant residue is needed between crop seasons.

In a modeling study, Woolf et al. (2010) described the C sequestration potential of biochar addition to soil. Biochar soil amendment has the potential to annually sequester C equal to 12 % of the present anthropogenic CO_2 release. They also reported that the most sustainable potential for C sequestration from biochar is 1–1.8 Gt C annually by 2050. Hence, biomass pyrolysis and soil storage can sequester C up to several hundred gigatons of C release and may be offset by 2100, which is a major portion of the total C sequestration needed to alleviate global climate change.

Plant and their residues have impact on the stability of biochar in soil. In a study, sugarcane residues at a rate of 0, 1, 2, and 4 % (*w/w*) were applied to the soil in combination with two wood biochars (450 and 550 °C) at a rate of 2 % (*w/w*) (Keith et al. 2011). As a small fraction (0.4–1.1 %) of the applied wood biochar-C was mineralized, there was a simultaneous increase in biochar-C mineralization with increasing application rates of sugarcane residues. On the other hand, biochar application minimized the rate of C mineralization in sugarcane residues, and this was enhanced with increasing rate of residue addition. Over time, the interactive priming of biochar-C and sugarcane residue-C mineralization was stabilized (Keith et al. 2011). In a recent study, Wu et al. (2015) reported that rice plants enhanced the surface oxidation of biochar particles with no significant effects on other biochar characteristics and its decomposition rate. Using ^{13}C labeling, they found that rice plants can significantly enhance the incorporation of C from biochar into SMB. Almost 0.047 % of the biochar-C was incorporated into the rice plants during the whole rice-growing cycle, which indicated that root exudates and transportation of biochar-C into rice plants might lower biochar stability in paddy soil (Wu et al. 2015). Indeed, rice exudates can adsorb directly on the surfaces of biochar surfaces (Joseph et al. 2010), which provide more available C for soil microbes to enhance co-metabolic decomposition of the biochar (Wu et al. 2015). Joseph et al. (2010) reported that roots/root hairs interact with biochars, initiating many reactions, through nutrient uptake and root exudate release, which increases the complexation reactions, and the activity of the microbes in rhizosphere, thus affecting biochar stability. However, studies on the impacts of living plants and rhizodeposition on decomposition of biochar are limited (Whitman et al. 2014). As the decomposition of biochar is mediated by continuous release of rhizodeposits, further studies are required on the mechanisms of biochar priming in soil-plant systems.

5.2 Impacts on GHG balance

Greenhouse gases absorb thermal infrared radiation, emitted by the atmosphere, earth's surface, and clouds. The heat-trapping process by GHGs within the surface-troposphere system is called the greenhouse gas effect. Atmospheric CO_2, CH_4, and N_2O are the key long-lived GHGs forcing global warming; therefore, their mitigation from the environment is urgent (Forster et al. 2007; Zhang and Ok 2014).

Despite agriculture being the largest sink of CO_2 during photosynthesis, agricultural activities impact global warming due to the significant release of GHGs such as CO_2, N_2O, and CH_4 (Verhoeven et al. 2006; Forster et al. 2007; IPPC 2007). Biochar as soil amendments has the potential to mitigate these emissions in dryland (Yamato et al. 2006; Rondon et al. 2007; Steiner et al. 2007; Van Zwieten et al. 2009; Fungo et al. 2014), irrigated (Yanai et al. 2007; Singh et al. 2010), and submerged ecosystems (Zhang et al. 2010) (Table 3). The impact of biochar application on GHG emissions is discussed below.

5.2.1 Carbon dioxide emission

Carbon dioxide is the principal GHG and the consistent rise in its release is the main cause of global warming. There are some controversies regarding the role of biochar on CO_2 release (Van Zwieten et al. 2013; Cayuela et al. 2013; Liu et al. 2014). For instance, after 3 years of biochar addition, 77–100 % and 31–54 % of untreated rice husk was mineralized aerobically and anaerobically, respectively, into CO_2, while the corresponding values for carbonized rice husk (CRH) were only 4.4 and 8.5 % (Knoblauch et al. 2011). Biochar application (40 t ha^{-1}), without N fertilization, caused substantial release of CO_2 in maize (Zhang et al. 2012b). Moreover, Haefele et al. (2011) suggested that CRH is stable in different rice soils and systems, perhaps for thousands of years. However, adding 9 t ha^{-1} biochar to arable soil in southern Finland had no effect on CO_2 release when compared with control plots (Karhu et al. 2011). In contrast, Aguilar-Chávez et al. (2012) reported that biochar addition reduced CO_2 emission during 45 days of incubation without affecting wheat yield possibly due to the fixing of SOM with biochar making it unavailable for microbial degradation. Spokas and Reicosky (2009) reported a reduced rate of CO_2 fluxes with incubation of 16 different biochars in three dissimilar soils in laboratory conditions. Hence, CO_2 release in biochar-amended soils was either abridged by the adsorption of dissolved organic C on biochar surfaces (Thies and Rillig, 2009) or due to enhanced formation of biochar-induced soil aggregates, inside of which SOM could be sheltered from decay (Liang et al. 2010; Awad et al. 2013).

Pyrolysis temperature during biochar preparation also affects the emission of CO_2 from soil. According to Yoo and

Table 3 Influence of biochar application on emission of greenhouse gases (GHGs)

GHGs	Feedstock	Application rate	Pyrolysis temperature	Soil type	Impact	Reference
Methane (CH_4)	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+34 %	Zhang et al. (2010)
	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	+41 %	Zhang et al. (2010)
	Wheat straw	10 t ha^{-1}	350–550 °C	Hydroagric Stagnic Anthrosol	−3.2	Zhang et al. (2013)
	Wheat straw	24 t ha^{-1}	500 °C	Stagnic Anthrosols	−33.9	Liu J et al. (2014)
	Wheat straw	48 t ha^{-1}	500 °C	Stagnic Anthrosols	−40.2	Liu J et al. (2014)
	Maize straw	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−25	Qian et al. (2014)
	Maize straw	2.4 t ha^{-1}	400 °C	Inceptisol	−25.06	Liu Q et al. (2015)
	Peanut husk	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−50.6	Qian et al. (2014)
	Endocarp of the babassu palm nut	30 Mg ha^{-1}	Unknown	Vertisols Aquerts	−47.3	de Sousa et al. (2014)
	Endocarp of the babassu palm nut	30 Mg ha^{-1}	Unknown	Vertisols Aquerts	−26	de Sousa et al. (2014)
	By-product of birch charcoal	9 t ha^{-1}	400 °C	Silt-loam slightly acidic	−96 %	Karhu et al. (2011)
	Sewage sludge	50 g kg^{-1} soil	550 °C for 6 h	Acidic soil	−78.4	Khan et al. 2013
	Sewage sludge	100 g kg^{-1} soil	550 °C for 6 h	Acidic soil	−61.8	Khan et al. 2013
	Municipal waste	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−45.7	Qian et al. (2014)
Nitrous oxide (N_2O)	Maize stover	15 t ha^{-1} (steam activated)	350 °C	Humic Acrisol	−15	Fungo et al. (2014)
	Maize stover	15 t ha^{-1} (nonactivated)	350 °C	Humic Acrisol	No effect	Fungo et al. (2014)
	Maize stover	15 t ha^{-1} (steam activated)	550 °C	Humic Acrisol	−22 %	Fungo et al. (2014)
	Maize stover	15 t ha^{-1} (nonactivated)	550 °C	Humic Acrisol	−13 %	Fungo et al. (2014)
	Corn straw	2.4 t ha^{-1}	400 °C	Inceptisol	−10.64	Liu Q et al. (2015)
	Maize straw	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−33.8	Qian et al. (2014)
	Eucalyptus wood	15 t ha^{-1} (steam activated)	350 °C	Humic Acrisol	−6 %	Fungo et al. (2014)
	Eucalyptus wood	15 t ha^{-1} (nonactivated)	350 °C	Humic Acrisol	−8 %	Fungo et al. (2014)
	Eucalyptus wood	15 t ha^{-1} (steam activated)	550 °C	Humic Acrisol	No effect	Fungo et al. (2014)
	Eucalyptus wood	15 t ha^{-1} (nonactivated)	550 °C	Humic Acrisol	No effect	Fungo et al. (2014)
	Municipal biowaste	10 % on wt basis	700 °C for 4 h	Loam to clay loam (Typic Hapludand)	−89 %	Yanai et al. (2007)
	Wheat straw	20 t ha^{-1} (with N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loamy)	−10.7	Zhang et al. (2012b)
	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loamy)	−41.8	Zhang et al. (2012b)
	Wheat straw	24 t ha^{-1}	500 °C	Stagnic Anthrosols	+150	Liu J et al. (2014)
	Wheat straw	48 t ha^{-1}	500 °C	Stagnic Anthrosols	+190	

Table 3 (continued)

GHGs	Feedstock	Application rate	Pyrolysis temperature	Soil type	Impact	Reference
						Liu J et al. (2014)
	Wheat straw	20 t ha^{-1}	450–550 °C	Acidic to neutral soils	−40 %	Liu et al. (2012)
	Wheat straw	40 t ha^{-1} (with N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	−40 to 51 %	Zhang et al. (2010)
	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Hydroagric Stagnic Anthrosol, anentic Halpudept	−21 to 28 %	Zhang et al. (2010)
	Wheat straw	40 t ha^{-1}	450–550 °C	Acidic to neutral soils	−60 %	Liu et al. (2012)
	Wheat straw	10 t ha^{-1}	350–550 °C	Hydroagric Stagnic Anthrosol	−22.6	Zhang A et al. (2013)
	Wheat straw	20 t ha^{-1}	350–550 °C	Hydroagric Stagnic Anthrosol	−45.1	Zhang A et al. (2013)
	Wheat straw	40 t ha^{-1}	350–550 °C	Hydroagric Stagnic Anthrosol	−39.5	Zhang A et al. (2013)
	Rice straw	6.67 t ha^{-1}	500 °C	Acidic (pH = 5.7)	−9.46	Pandey et al. (2014)
	Rice straw	6.67 t ha^{-1}	500 °C	Acidic (pH = 5.7)	−12.9	Pandey et al. (2014)
	Peanut husk	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−31	Qian et al. (2014)
	Canola stalk	10 t ha^{-1}	350–400 °C for 4 h	Hydroagric Stagnic Anthrosol	−24.3	Sun et al. (2015)
	Bamboo	15‾20 t ha^{-1}	700–800 °C for 25 h	Dystric Cambisols	−15	Watanabe et al. 2014
	By-product of birch charcoal	9 t ha^{-1}	400 °C	Silt-loam slightly acidic	No effect	Karhu et al. (2011)
	Waste wood chips	20 g kg^{-1} soil	290 °C	Clay	−10.99	Lai et al. (2013)
	Waste wood chips	50 g kg^{-1} soil	290 °C	Clay	−28.55	Lai et al. (2013)
	Waste wood chips	20 g kg^{-1} soil	700 °C	Clay	−21.18	Lai et al. (2013)
	Waste wood chips	50 g kg^{-1} soil	700 °C	Clay	−34.58	Lai et al. (2013)
	Waste wood chips	20 g kg^{-1} soil	290 °C	Sandy loam	−13.86	Lai et al. (2013)
	Waste wood chips	50 g kg^{-1} soil	290 °C	Sandy loam	−17.96	Lai et al. (2013)
	Waste wood chips	20 g kg^{-1} soil	700 °C	Sandy loam	−12.16	Lai et al. (2013)
	Waste wood chips	50 g kg^{-1} soil	700 °C	Sandy loam	−37.20	Lai et al. (2013)
	Bagasse (by-product of sugarcane industry)	1 t ha^{-1}	400–500 °C for 2 h	Silt-loam	−40	Ali et al. (2013)
	Bagasse (by-product of sugarcane industry)	1 t ha^{-1}	400–500 °C for 2 h	Silt-loam	−26	Ali et al. (2013)
	Municipal biowaste	40 t ha^{-1}	450–550 °C	Hydroagric Stagnic Anthrosol	−50	Bian et al. (2013)
	Municipal biowaste	40 t ha^{-1}	450–550 °C	Hydroagric Stagnic Anthrosol	−55.2	Bian et al. (2013)
	Municipal waste	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−39.4	Qian et al. (2014)
	Sewage sludge	50 g kg^{-1} soil	550 °C for 6 h	Acidic soil	−92.8	Khan et al. 2013

Table 3 (continued)

GHGs	Feedstock	Application rate	Pyrolysis temperature	Soil type	Impact	Reference
	Sewage sludge	100 g kg^{-1} soil	550 °C for 6 h	Acidic soil	−96	Khan et al. 2013
Carbon dioxide (CO_2)	Wheat straw	40 t ha^{-1} (without N)	350–550 °C	Aquic Fluvent (calcareous, fluvo-aquic loamy)	+12 %	Zhang et al. (2012b)
	By-product of birch charcoal	9 t ha^{-1}	400 °C	Silt-loam slightly acidic	No effect	Karhu et al. (2011)
	Maize stover	15 t ha^{-1}	350 °C	Humic Acrisol	No effect	Fungo et al. (2014)
	Maize stover	15 t ha^{-1}	550 °C	Humic Acrisol	No effect	Fungo et al. (2014)
	Peanut husk	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−4.4	Qian et al. (2014)
	Eucalyptus wood	15 t ha^{-1}	350 °C	Humic Acrisol	No effect	Fungo et al. (2014)
	Municipal waste	0.45 t ha^{-1}	350–450 °C	Entic Hydroagric Anthrosol	−6.6	Qian et al. (2014)

+ increase, − decrease

Kang (2012) and Kammann et al. (2012), biochars produced at higher pyrolysis temperatures release less CO_2 than biochars produced at lower temperatures. Based on the results of a 365-day in vitro incubation study, Qayyum et al. (2012) concluded that total CO_2 emissions occur in the following order: wheat straw > hydrochar (200 °C) > low-temperature biochar (sewage sludge, 400 °C) > charcoal (550 °C) > no biochar. They further stated that biochars should match the aims of their use: high-temperature biochars are good for soil C sequestration and low-temperature biochars are preferred for upgrading soil fertility. Various studies have also reported reduction in CO_2 emission due to biochar application (Table 3).

5.2.2 Nitrous oxide emission

Nitrous oxide is the most important GHG due to its maximum per molecule global warming potential (IPCC 2007). Therefore, advances to lessen its emission from agriculture, paddy fields in particular, are needed to mitigate global climate change. Due to alternative wetting and drying conditions, rice paddies are the major source of N_2O emissions (Verhoeven et al. 2006). Biochar application significantly lowered N_2O emissions in rice paddy (Zhang et al. 2010)and other crop ecosystems (Steiner 2010; Stavi and Lal 2013). For example, biochar-amended acidic soils in soybean plots in eastern Colombian Plains reduced N_2O emissions by up to 50 % (Rondon et al. 2005). In another study, Yanai et al. (2007) reported reductions in N_2O emission of about 85 % in rewetted soils with 10 % biochar compared with soils devoid of biochar. Biochars generated from municipal biowastes also reduced N_2O emissions in laboratory studies (Yanai et al. 2007). Spokas et al. (2009) noted a considerable drop (by 63 %) in N_2O emissions in arable soils in Minnesota, while Case et al. (2015) reported a 91 % reduction in soil N_2O production in near-saturated, fertilized sandy loam soil. In a recent study, Mandal et al. (2016) reported that poultry litter biochar and macadamia nut shell biochar mitigated NH_3 volatilization in soils by up to 70.56 %.

In a study on three different paddy sites, Liu et al. (2012) reported that total N_2O emissions ranged from 1.5 to 1.9 kg N_2O ha^{-1} without biochar and from 0.8 to 1.3 kg and 0.7 to 0.9 kg N_2O ha^{-1} with biochar applications of 20 and 40 t ha^{-1}, respectively. Therefore, crop residue biochar seems to be an exclusive ecological engineering technique to cut back N_2O emissions tied with enhancing soil fertility and sustaining rice productivity (Liu et al. 2012; Zhang and Ok 2014). Likewise, Castaldi et al. (2011) reported 26–79 % lower N_2O fluxes in char-treated plots than control plots. Several other researchers also reported reduced N_2O emissions in biochar-amended soils (Zhang et al. 2012b; Van Zwieten et al. 2013; Cayuela et al. 2013; Liu et al. 2013; Ali et al. 2015; Thu et al. 2015; Zhang et al. 2016; Table 3).

Reduced mineralization rates by biochar application lead to less mineral N in the soil for conversion into N_2O and that reduced denitrification due to biochar-induced improvement in soil aeration reduced N_2O

emissions (Aguilar-Chávez et al. 2012). Biochar-induced alterations in soil aeration and WHC are associated with reduced N_2O as the occurrence of anaerobic pockets potentially decreased where bacterial-mediated denitrification processes are likely to occur (Yanai et al. 2007). Increased soil pH with biochar addition may increase the activity of N_2O reductase of denitrifier microbes leading to a reduced ratio of N_2O/N_2 (Yanai et al. 2007; Wang et al. 2013). According to Bagreev et al. (2001), adsorption of N_2O on the highly porous surface of biochars may explain the reduction in N_2O emissions. Few reports highlighted that NH_4^+ is adsorbed on free biochar particles, and consequently, soil NH_4^+ availability is reduced, which finally limits NO_3^- synthesis, and as a consequence, N_2O emissions from both nitrification and denitrification decline (Berglund et al. 2004; Lehmann et al. 2006). Different studies have reported reduction in N_2O emission due to biochar application (Table 3).

The potential of biochars to mitigate especially N_2O emission varies with feedstock source and pyrolysis temperature. For instance, N_2O emissions were 17 % less for maize stover biochar than *Eucalyptus* wood biochar and 3 % lower for biochar pyrolyzed at 350 °C compared with that at 550 °C (Fungo et al. 2014).

5.2.3 Methane emission

Methane is an important GHG with 25 times more global warming potential than CO_2; paddy fields are among the principal anthropogenic sources of its global release (Forster et al. 2007; Zhang et al. 2010). Biochar has the potential to overcome CH_4 emissions especially from paddy fields (Knoblauch et al. 2011; Feng et al. 2012). Liu et al. (2011) quoted a 51–91 % reduction in paddy CH_4 emissions with biochar application, while Karhu et al. (2011) reported that the 96 % reduction in CH_4 emissions with 9 t ha^{-1} biochar on agricultural soil in southern Finland was due to improved soil aeration. Improved soil aeration may reduce CH_4 production and/or boost CH_4 oxidation (Van Zwieten et al. 2009). Depending on the estimated C budget of various rice crop residue treatments, Knoblauch et al. (2011) found that charring rice residues and the addition of the obtained black C to paddy fields diminished field CH_4 emissions by as much as 80 % compared with the incorporation of untreated rice residues at harvest. According to Feng et al. (2012), reduced CH_4 emissions under biochar amendment do not result from inhibition of methanogenic archaeal growth but rather from the methanotrophic proteobacterial abundances leading to reduced ratios of methanogenic to methanotrophic densities deep in paddy fields. Biochar-amended acidic soils in eastern Colombian Plains almost repressed CH_4 release in soybean plots (Rondon et al. 2005).

The potential of biochars to mitigate especially CH_4 emission is also linked with several other biochar and soil-related factors. For instance, steam activation increased CH_4 emissions in maize stover biochar but reduced it by 14–70 % for *Eucalyptus* wood biochar. Release of CH_4 was 21 % higher for activated maize stover biochar than *Eucalyptus* wood biochar and 10 % less for biochar at 350 °C compared with biochar at 550 °C (Fungo et al. 2014). Different studies have reported reduction in CH_4 emission due to biochar application (Table 3).

5.3 Sorption of agrochemicals

Biochar has the potential to reduce soil and water contamination through sorption of agrochemicals, thus offering a cost-effective and environmentally friendly tool to manage polluted environments (Ahmad et al. 2014a; Mohan et al. 2014). For instance, biochar generated by burning wheat and rice residues was 400–2500 times more effective than soil in sorbing (Yang and Sheng 2003a). Likewise, red gum (*Eucalyptus* spp.) chip biochar amendment substantially increased diuron sorption in soil (Yu et al. 2006). Other evidence suggests that biochar soil application can immobilize pollutants in soil (Smernik 2009) and thus minimize phytotoxicity (Beesley et al. 2010; Kim et al. 2015).

According to Yao et al. (2011), anaerobically digested sugar beet tailings had the highest phosphate exclusion ability (73 %) suggesting their usefulness as adsorbents to reclaim phosphate. If biochar is used as a sorbent to reclaim nutrients such as phosphate from water, then the same biochar can be directly applied to agricultural fields as a slow release fertilizer to improve soil fertility (Yao et al. 2011; Karunanithi et al. 2015; Park et al. 2015a, b).

Biochar soil amendment due to enhanced sorption has a strong influence on the fate and behavior of organic contaminants in the environment. Adding a small quantity of char to soils inhibited biodegradation of benzonitrile (Zhang et al. 2005) and may therefore be an efficient technique to reduce nutrient leaching in production agriculture (Laird et al. 2010a). This enhanced nutrient retention in the soil profile may help to increase nutrient availability to plant roots, and minimize the risk of leaching and polluting surface or groundwater resources (Laird et al. 2010a; Kim et al. 2015).

5.4 Immobilization of heavy metals in contaminated soils

Subsistence of heavy metals at higher levels in contaminated soils often poses long-term risks to ecosystems and humans. Biochars can adsorb anthropogenic chemicals such as steroid hormones and heavy metals when added to soil or water (Cao et al. 2009; Spokas et al. 2009; Atkinson et al. 2010; Sohi et al. 2010; Tong et al. 2011; Paz-Ferreiro et al. 2014). Biochar application has been proposed as a soil amendment as it increases soil CEC and pH, and may also sequester toxic heavy metals (Steiner et al. 2007; Ahmad et al. 2012b; Moon et al. 2013; Rajapaksha et al. 2015). Due to their large specific surface area, microporous structure, active functional groups, and high pH (Chen and Lin 2001), biochars act as an adsorbent and have the potential to sequester heavy metals in soil (Ahmad et al. 2014b). Equilibrium and kinetic adsorption data elucidated that black C derived from wheat residues had a strong affinity for heavy metals (Wang et al. 2011). Soil amended with biochar adsorbed more heavy metals such as copper (Cu) through cation exchange mechanisms and by forming complexes with surface functional groups in the added biochar (Uchimiya et al. 2011a; Puga et al. 2015; Park et al. 2015a, b; Jiang et al. 2016). According to Uchimiya et al. (2011b), Cu and lead (Pb) stabilization ability in highly weathered acidic soils is directly linked to the amount of oxygen-containing surface functional groups in the biochars. Addition of biochar derived from poultry manure decreased the amount of exchangeable Al in acidic chromosol soil (Chan et al. 2008).

Biochar immobilized heavy metals in acidic ultisol by forming mineral precipitates and increasing specific adsorption of the heavy metals by lessening zeta potential and increasing soil CEC and pH, thereby increasing the surface charge (Jiang et al. 2012a). The increasing soil pH with added biochar amplified the hydrolysis of heavy metal cations and formed precipitates of metal (oxy) hydroxides (Ahmad et al. 2014b; Kim et al. 2015; Rajapaksha et al. 2015). Acid soluble Cu, Pb, and cadmium (Cd) concentrations decreased by 19.7–100, 18.8–77.0, and 5.6–14.1 %, respectively, as the amount of added biochar increased. However, enduring heavy metal contents were low and changed little with the addition of biochar (Jiang et al. 2012a). Jiang et al. (2012b) reported a linear rise in the adsorption of Pb after 30 days of incubation with varying levels of biochar addition in three soils (two ultisols and one oxisol).

Both electrostatic and nonelectrostatic mechanisms were involved in the adsorption of Pb; the nonelectrostatic mechanism was more common, forming surface complexes amid Pb and functional groups on biochar. Consequently, biochar application reduced the activity and supply of Pb to plants by elevating its nonelectrostatic adsorption in acidic variable-charge soils (Jiang et al. 2012b). According to Cao et al. (2009), phosphate in biochars also formed precipitates of Cu and Pb to enhance their fixation in soil. Broiler litter biochar at low pyrolysis temperature (350 °C) enhanced heavy metal immobilization in alkaline soil (Uchimiya et al. 2010). In an incubation study, sewage sludge biochar-amended soil reduced Cu, Ni, and Zn leaching more than sludge incorporation (Méndez et al. 2012). Biochar amendment has the potential to adsorb heavy metals such as Cu, Pb, and Cd from aqueous media and cab be used to remove these metals from water (Mohan et al. 2007; Cao et al. 2009; Tong et al. 2011; Paz-Ferreiro et al. 2014; Park et al. 2015a, b). According to Mohan et al. (2012), biochar has the potential to remove anions of chromium and fluoride from water at very low pH. In a pot trial study, addition of hardwood-derived biochar on contaminated soil decreased the concentrations of zinc (Zn), Cd, and PAHs in soil pore water (Beesley et al. 2010).

6 Resistance against diseases

The potential of biochar soil amendment for managing diseases such as potato rot or damping off was reported long ago (Allen 1847; Retan 1915). Several recent studies have reported the potential of biochar amendment to induce resistance in plants against different diseases caused by bacteria, fungi, and nematodes (Matsubara et al. 2002; Elmer and Pignatello 2011; Jaiswal et al. 2014).

The addition of biochar from coconut, coffee residues, and wood significantly decreased *Fusarium* infection in asparagus (Matsubara et al. 2002; Elmer and Pignatello 2011). Similarly, biochar addition to organic potting mix and sandy soil reduced the disease severity of powdery mildew (*Leveillula taurica*) (Elad et al. 2010). Biochar prepared from citrus wood was effective against gray mold (caused by *Botrytis cinerea*) in pepper and tomato and powdery mildew in tomato by developing systemic resistance (Elad et al. 2010). In other studies, soil-borne diseases such as *Fusarium* root rot in asparagus (Elmer and Pignatello 2011) and *Phytophthora* canker in oaks and maples (Zwart and Kim 2012) were suppressed by the application of biochar.

Plant defense mechanisms are usually tailored according to the biological strategy of the invading pathogen. For example, biochar soil amendment for *Rhizoctonia solani* suppression in cucumber is feedstock and rate dependent (Jaiswal et al. 2014). The most effective rate for suppressing this disease was 1 % for *Eucalyptus* biochar and 0.5 % for greenhouse waste biochar. The biochar amendments induced resistance in plants against diseases by inducing systemic resistance. This resistance is either derived from large microbial populations like *Trichoderma* spp. or from phytotoxic compounds (e.g., ethylene and propylene glycol) in biochar-treated soils (Graber et al. 2010). The addition of two biochars (greenhouse waste and wood biochar) effectively reduced the disease severity of fungus-induced foliar diseases produced with several infection strategies: necrotrophic (*Botrytis cinerea*), hemibiotrophic (*Colletotrichum acutatum*), and biotrophic (*Podosphaera apahanis*) (Harel et al. 2012). Elmer and

Pignatello (2011) suggested that the decline in *Fusarium* infection of asparagus after the addition of biochar may be due to adsorbed allelopathic compounds in biochar (e.g., caffeic and ferulic acids). Root exudates may act as chemoattractants for a range of pathogens such as *Pythium* (Jones et al. 1991) which stimulate spores to germinate by producing linoleic and oleic acids (Windstam and Nelson 2008). Activated C in biochar can adsorb allelopathic compounds (Callaway and Aschehoug 2000; Kulmatiski and Beard 2011). After 3 years of soil residency, there was no significant difference in nutrients, mycorrhizal colonization, microbial growth, or weed emergence in biochar-treated or untreated soil. However, reapplication of biochar on previously biochar-treated soil substantially reduced saprophytic fungal growth and mycorrhizal root colonization (Quilliam et al. 2012).

The addition of biochar from wood and municipal biowaste reduced bacterial wilt in tomato (*Ralstonia solanacearum*) (Nerome et al. 2005). Biochar application (up to 40 % *v*/*v*) significantly improved disease suppression for up to 90 days after planting. Gram-negative bacteria primarily use glucose-derived biochar, while yeast-derived biochar promotes fungi (Khavazi et al. 2007). Charcoal produced from coconut fiber substantially reduced the incidence of *Fusarium* crown and root rot with a simultaneous increase in AM colonization in asparagus seedlings (Matsubara et al. 2002). Biochar from ground hardwood also reduced root lesions caused by *Fusarium oxysporum* f. sp. *asparagi* and *Fusarium proliferatum* in asparagus (Elmer and Pignatello 2011).

Soil amendments with biochar increased the ratio of total (nonplant-parasitic) free-living nematodes (TFLN)/total plant-parasitic nematode (TPPN) by decreasing TPPN and increasing TFLN populations. Poultry litter biochar had the greatest reductions in TPPN (8.5- and 12.9-fold for diseased and asymptomatic grapevines, respectively) (Rahman et al. 2014). In wheat, biochar application increased the abundance of fungivores but significantly decreased the abundance of plant parasites particularly nematode trophic groups (Zhang et al. 2013).

The overall effect of biochars in soil pathogen suppression may come from several mechanisms: (i) better growth and resistance to pathogens due to improved nutrient solubilization and uptake; (ii) increased population of beneficial microbes, which produce antibiosis, competition, or parasitism and provide direct protection against soil pathogens; (iii) organic compounds derived from biochar-amended soils may suppress sensitive components of the soil microbiota increasing resistant microbial communities; and (iv) biochar may induce systemic plant defense mechanisms, with elicitors being biochar-borne chemicals and/or biochar-induced microorganisms (Elad et al. 2010; Elad et al. 2012).

Chemical compounds in residual tars, which are added to soil with biochar, may have direct toxic effects on soil pathogens. For instance, Graber et al. (2010) identified biochar compounds (glycol, hydroxy-propionic and butyric acids, benzoic acid and o-cresol, recorsinol, hydroquinone, and 2-phenoxyethanol) which suppress microbial growth and survival. These toxic compounds even at low levels may suppress sensitive components of soil microbiota, which in turn produce resistant microbial communities (Graber et al. 2010).

Increased induced resistance is elicited by specific stimuli to protect plants against a wide range of pathogens such as bacteria, viruses, fungi, and nematodes (Vallad et al. 2004). Systemic acquired resistance can be activated by numerous chemical compounds besides microorganisms. Biochar contains residual tars—a complex mixture of organic compounds including medium and long chain n-alkanoic acids, hydroxy and acetoxy acids, benzoic acids, short and medium chain diols and triols, phenols and polyphenols, amines, amides, and aliphatic hydrocarbons (Graber et al. 2010)—which are present at relatively low levels.

7 Potential risks

Biochar amendment in arable soils is gaining interest due to several agronomic and environment-related benefits including allaying global warming, restoring degraded lands, enhancing agricultural productivity, and offsetting stream and groundwater pollution (Lehmann et al. 2006; Spokas 2010; Barrow 2012; Stavi and Lal 2013; Cayuela et al. 2013; Liu et al. 2014). However, certain risks such as the potential source of toxicants, retention of heavy metals, and the suppression of the efficacy of applied pesticides due to retention and ecotoxicology effects on soil microbes are linked with biochar addition to arable land (Chagger et al. 1998; Beesley et al. 2010; Liesch et al. 2010; Yang et al. 2010).

7.1 Potential source of toxicants

Biochar may be the carrier of various dangerous compounds like heavy metals (Cd, Cu, Cr, Ni, Zn) (Hospido et al. 2005), PAHs, polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) (Sonja and Glaser 2012), and other toxins such as volatile organic compounds, xylenols, cresols, acrolein, and formaldehyde (Chagger et al. 1998; McClellan et al. 2007; Thies and Rillig 2009; Kim et al. 2015). Especially, the PAHs are very harmful to many plant and microbial communities (Ogawa 1994; Zackrisson et al. 1996).

These toxic materials are produced by the catalytic meeting of dioxin structures from O_2, C, and chloride (Cl) at 300–325 °C and other multistep reactions in the postcombustion zone (Chagger et al. 1998), frequently catalyzed by Fe and Cu.

For example, Brown et al. (2006) found different PAHs in several biochars generated from small chunks of pitch pine wood.

Toxic PAHs formed during biochar synthesis by incomplete combustion are somewhat recalcitrant; however, the increasing pyrolysis temperature may affect PAH contents in biochar. According to Kloss et al. (2012), PAH contents increased with high pyrolysis temperatures in straw-based biochar but decreased in wood-based biochar. Busch et al. (2012) quoted a reduction in shoot and radical length in maize with the addition of biochar generated at high pyrolysis temperature but not that at low temperature. They assumed that the decline in radical and shoot length was due to identified PAHs, mainly naphthalene, in the biochar extract of high-temperature biochars. However, high pyrolysis temperature improved the specific surface area of biochar; higher specific area is helpful in sandy soils to enhance the withholding of nonpolar pollutants in soils (Kloss et al. 2012).

According to Rogovska et al. (2012a), germination and plant growth decreased with biochar application due to the presence of some phytotoxic compounds. Other biochar features such as sorptive ability for allelochemicals (Rogovska et al. 2012a) often help to improve the germination process. However, little information is available about the role of biochars in germination, which also depends on soil type and pyrolysis conditions related to the biochars tested (Solaiman et al. 2012; Ahmad et al. 2012b). For instance, biochars derived from papermill waste at 10 t ha^{-1} (~1 % weight basis) enhanced germination of wheat in a ferrosol but had no effect on the other tested crops including radish and soybean in both a ferrosol and a calcarosol (Van Zwieten et al. 2010). Rogovska et al. (2012b) used aqueous biochar extracts to conduct standard germination tests with measurements of early seedling growth to identify biochars that contain phytotoxic compounds. Solaiman et al. (2012) noted that different biochars and their application rate influenced wheat seed germination and seedling growth and the responses of mung bean and subterranean clover differed from that of wheat.

7.2 Retention of heavy metals and contaminants

Subsistence of heavy metals in contaminated soils at high concentrations often poses long-term risks to ecosystems and humans. According to Beesley et al. (2010), applied biochar enhanced Cu and arsenic (As) contents by more than 30-fold with a simultaneous increase in soil-dissolved organic carbon and pH. Likewise, Uchimiya et al. (2010) reported that organic fractions of biochars with high carboxyl contents can mobilize Cu retained by alkaline soil. In another study, biochar application increased As and Cu mobility in the field profile and Pb in the mesocosms, while the effect on Cd was not significant (Beesley and Dickinson 2011). The addition of small amounts of char in soils inhibited biodegradation of benzonitrile (Zhang et al. 2005). Several other reports highlighted diminished biodegradation of pesticides by selected microbes in biochar-amended soils (Zhang et al. 2005; Yang et al. 2006; Loganathan et al. 2009).

7.3 Efficacy of pesticides

Biochar application tends to reduce the efficacy of soil-applied pesticides due to reduced bioavailability in soils, increased residual life, and reduced plant uptake (Yu et al. 2011). Biochar application can control pesticide behavior; for instance, biochar-induced sorption of soil-applied pesticides may reduce their efficacy by controlling their bioavailability to organisms and vulnerability to leaching (Yang and Sheng 2003b; Loganathan et al. 2009). According to Yang et al. (2006), wheat char soil amendment increased the sorption of diuron reducing its bioavailability, microbial degradation, and efficacy against barnyard grass. The addition of small amounts of char to soils also inhibited the biodegradation of benzonitrile (Zhang et al. 2005), reduced herbicidal efficacy of diuron against barnyard grass (Yang et al. 2006), and restrained plant uptake of pesticides from soil (Yu et al. 2009; Yang et al. 2010).

Acetamiprid belongs to the neonicotinoid group of insecticides largely used for controlling sucking insect pests like aphids, leafhoppers, and whiteflies. Soil amendment (0.5 % (*w*/*w*)) with biochar derived from red gum wood (*Eucalyptus* spp.) increased sorption of acetamiprid and ultimately decreased its dissipation relative to unamended soil (Yu et al. 2011). However, the biochar-induced sorption rate of acetamiprid varied with soil type, being 52.3, 27.4, and 11.6 % in red, paddy, and black soil, respectively. The degree of increase in sorption and decrease in dissipation rate of acetamiprid was more evident in low SOM soils, which highlighted that SOM may be correlated with biochar by either blocking its pores and/or competing for sorption sites (Yu et al. 2011). A significant increase in sorption and decrease in desorption of acetamiprid from the biochar surface are key mechanisms for its reduced dissipation in biochar-amended soils leading to less bioavailability to soil organisms (Yu et al. 2006).

According to Yang and Sheng (2003b), char generated by open field burning of rice and wheat residues sorbed 2500 times more diuron than soil. Likewise, Sheng et al. (2005) reported increased sorption of 80–86 % of diuron and bromoxynil and 70 % of ametryn in 1 % (*w*/*w*) wheat char-amended soils. Kookana (2010) and Mesa and Spokas (2011) concluded in their reviews that soil-applied chars (generated by open burning of biomass) and biochars (generated through pyrolysis) strongly manipulate the bioavailability and efficacy of soil-applied pesticides.

Jones et al. (2011) conducted a study to evaluate the effect of biochar type, time after inclusion into soil, dose rate and particle size on the sorption, biodegradation, and leaching of the herbicide simazine. The results indicated that application of both fresh and aged biochars at 10–100 t ha^{-1} altered the behavior of the pesticide in soil by changing its solubility, availability, transport, and spatial distribution with overall suppressed simazine biodegradation and leaching. Moreover, simazine mineralization, sorption, and leaching rate were inversely linked to biochar particle size. The major drawback related to biochar application is its potential negative effect on the efficacy of soil-applied pesticides (e.g., preemergent herbicides), but this could decrease by using large particle size biochars (Jones et al. 2011).

Nag et al. (2011) conducted an inclusive study to evaluate the effect of biochar application on the efficacy of two herbicides (atrazine and trifluralin) with different modes of action (photosynthesis vs. root tip mitosis inhibitor) applied at nil, half, full, two, and four times the recommended rate in two contrasting soils sown to annual ryegrass (*Lolium rigidum*) and incorporated with wheat straw biochar [0, 0.5, and 1.0 % (*w*/*w*)] produced at 450 °C for 1 month. Based on the results, it was concluded that biochar amendment enhanced the persistence of herbicides in soil, and weed control was insufficient even at the higher than recommended doses, particularly in the case of atrazine. Moreover, herbicide application at recommended levels in biochar-amended soils is unlikely to provide effective weed control and may even assist in the development of weed resistance (Nag et al. 2011). Likewise, different herbicide chemistry and modes of action will affect the selection of the appropriate application rate in biochar-amended soils for weed control (Nag et al. 2011).

Sorption of all insecticides and herbicides by biochars is enhanced by biochar application (Zheng et al. 2010) but reduces their efficacy (Yang et al. 2006) and improves environmental health and food safety as crop uptake and leaching of these substances may be reduced (Yu et al. 2009, 2010). Moreover, biochar addition reduces the potential of surface and groundwater pollution and curtails human exposure via transfer in the food chain in the case of foliar-applied pesticides, thus contributing to the development of sustainable agricultural systems (Jones et al. 2011).

In conclusion, the direct input cost to growers to control weeds in biochar-amended soil will increase as higher rates of certain herbicides are needed to achieve the preferred level of weed control. The reduced efficacy of soil-applied herbicides in biochar-amended soils will lead to faster development of weed resistance due to “underdosing” (less than the required rate of application) of herbicides, except where application rates are adjusted based on biochar content of soils (Powles et al. 1996). This should be considered when managing plant diseases and weeds with biochars. It is, therefore, important to consider these agronomic, economic, and environment-related effects of biochar application to soil (Kookana et al. 2011).

7.4 Ecotoxicological effect on soil organisms

Some compounds found in biochars, such as PAHs, formaldehyde, cresols, xylenols, acrolein, and other toxic carbonyl compounds (depending on pyrolysis conditions), may have bactericidal or fungicidal actions when applied to soil (Painter 2001). Earthworms are the most valuable markers of soil health (Paoletti et al. 1998) as they are highly responsive to soil contamination (Yeardley et al. 1996). Some studies have tested the effect of biochar soil amendment on earthworm population dynamics by monitoring their mortality or avoidance behavior. For instance, Wen et al. (2009) tested three soils spiked with pentachlorophenol (PCP) in the laboratory and one field-contaminated soil with 2 % biochar amendment, humic acid, and peat aged for either 7 or 250 days. The results confirmed a reduction in bioavailability and bioaccumulation factor of PCP for earthworms with biochar amendment in all studied soils. However, in a recent study, Tammeorg et al. (2014c) reported that spruce chip biochar (30 t ha^{-1}) amendment did not affect the habitat choice of earthworms within 2 days, but after 2 weeks, the earthworms tended to avoid biochar mainly due to the slight decline in soil water potential rather than to the presence of toxic substances such as PAHs. Likewise, alkaline biochars added at higher rates can create a negative soil environment (e.g., pH and EC) for earthworm activity (Liesch et al. 2010).

7.5 Negative impacts of biochar on crop productivity and soil quality

Improper biochar application may decrease the crop productivity and can deteriorate the soil quality. For example, many years back, Kishimoto and Sugiura (1985) noted a 51 % increase in soybean (*Glycine max* L.) yield with 0.5 t ha^{-1} biochar application, while higher applications of 5 and 15.25 t ha^{-1} reduced yield by 37 and 71 %, respectively, mainly due to biochar-induced micronutrient deficiency owing to increased soil pH in loam textured volcanic ash soil in Japan. In another study, ryegrass (*L. perenne* L.) production was reduced by 8 and 30 % when biochar was applied at 100 and 120 t ha^{-1}, respectively (Baronti et al. 2010). Kammann et al. (2011) also reported that the growth of quinoa (*Chenopodium quinoa*) was retarded when biochar was applied at higher rates (100–200 t ha^{-1}). In another field study, application of teak and rosewood biochar at 8 and 16 t ha^{-1} reduced the grain yield of rice by 10 and 26 %, respectively, on an acidic soil (Asai et al. 2009). This yield reduction due to biochar application might be due to immobilization of N due to high C/N ratios (Rondon et al. 2007), hydrophobic biochar properties (McClellan et al. 2007), and liming of alkaline-intolerant species (Mikan and Abrams 1995).

Moreover, the addition of biochar may reduce the relative proportion of easily minerizable (active) SOC pool, thus lowering the soil quality. Sometimes, biochar application to soil can cause waterlogging in heavy clay soils, may injure acid-loving plants and earthworms, and can reduce the efficacy of soil-applied pesticides (Chalker-Scott 2014). The levels of Na can increase due to biochar application depending on biochar source. Biochar application is less useful in the soil having high SOM, and the addition of biochar in such soils can reduce growth of plants (Chalker-Scott 2014). Hottle (2013) reported that application of improper biochar types to particular soils (e.g., alkaline soil amended with high pH biochar) may negatively impact soil quality. Some biochars may also possess a high amount of ash which may contain salts which may cause soil salinity.

7.6 GHG emission

It is well documented that biochar application into soil can reduce the emission of CO_2, CH_4, and N_2O. However, few studies have also reported that biochar application enhances GHGs emission. In a study, application of wheat straw biochar (pyrolyzed at 350–550 °C) at 40 t ha^{-1} with or without N enhanced the CH_4 emission by 34 and 41 %, respectively, on a Hydroagric Stagnic Anthrosol soil (Zhang et al. 2010; Table 3). Liu et al. (2014) also reported 150 and 190 % increase in N_2O emission due to wheat straw biochar (pyrolyzed at 500 °C) application at 24 and 48 t ha^{-1} respectively, on a Stagnic Anthrosols soil (Table 3). On a calcareous, fluvo-aquic loamy soil, application of wheat straw biochar (pyrolyzed at 350–550 °C) at 40 t ha^{-1} enhanced the CO_2 emission by 12 % (Table 3; Zhang et al. 2012b). In another study, the cumulative CO_2 flux was enhanced by 6 and 10 % with the application of biochar at 5 and 25 t ha^{-1}, respectively, under a maize-soybean rotation on an Alfisol in Central Ohio (Hottle 2013). Likewise, the CH_4 emission was enhanced by 44.9 % by municipal biowaste biochar (40 t ha^{-1}) in rice (Bian et al. 2013).

7.7 Hazardous impact on human health during biochar application

As the biochars are in the dust form, they may be dangerous to humans during their application to agricultural soils. For example, rice husk biochar pyrolyzed at higher temperatures may possess toxic crystalline materials, e.g., silica which are very harmful to human health (Paul 2011) and they can affect the respiratory system if they enter during the biochar application process in soil. There is a dire need for future studies to evaluate the impact of the dust created during biochar application on human health.

8 Conclusions

The impact of agriculture on GHG emissions is substantial; intensively managed croplands emit considerable CO_2, CH_4, and N_2O, which has increased their atmospheric concentrations. Furthermore, some intensive farming practices have increased soil erosion as well as contaminated off-site water sources. At the same time, conservation agriculture practices may reduce GHG emissions, mitigating climate change. However, as emphasized in this review, the agronomic efficiency of conservation practices is site dependent and not relevant to all geographic zones and climatic conditions. Nevertheless, specific conservation practices—agroforestry systems and application of biochar in soil—can boost sequestration of SOC as well as increase fertilizer efficiency, enhance productive capacity, and advance global food security. At the same time, these practices support a range of ecosystem services such as reduced soil erosion and contamination of off-site water sources, and increased species diversity and ecosystem health, and can therefore be used in reclaiming degraded lands. Future regulations should facilitate national and international schemes of payments for these agricultural practices, encouraging wider implementation throughout the world.

References

Abel S, Peters A, Trinks S, Schonsky H, Facklam M, Wessolek G (2013) Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma 202:183–191

Abiven S, Hengartner P, Schneider MPW, Singh N, Schmidt MWI (2011) Pyrogenic carbon soluble fraction is larger and more aromatic in aged charcoal than in fresh charcoal. Soil Biol Biochem 43:1615–1617

Abiven S, Schmidt MWI, Lehmann J (2014) Biochar by design. Nat Geosci 7:326–327

Aguilar-Chávez Á, Díaz-Rojas M, del Rosario M, Cárdenas-Aquino DL, Luna-Guido M (2012) Greenhouse gas emissions from a wastewater sludge-amended soil cultivated with wheat (*Triticum* spp. L.) as affected by different application rates of charcoal. Soil Biol Biochem 52:90–95

Ahmad M, Lee SS, Dou X, Mohan D, Sung JK, Yang JE, Ok YS (2012a) Effects of pyrolysis temperature on soybean stover- and peanut shell-derived biochar properties and TCE adsorption in water. Bioresour Technol 118:536–544

Ahmad M, Lee SS, Yang JE, Ro HM, Lee YH, Ok YS (2012b) Effects of soil dilution and amendments (mussel shell, cow bone, and biochar) on Pb availability and phytotoxicity in military shooting range soil. Ecotox Environ Safe 79:225–231

Ahmad M, Lee SS, Lim JE, Lee SE, Cho JS, Moon DH, Hashimoto Y, Ok YS (2014a) Speciation and phytoavailability of lead and antimony in a small arms range soil amended with mussel shell, cow bone and biochar: EXAFS spectroscopy and chemical extractions. Chemosphere 95:433–441

Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M, Lee SS, Ok YS (2014b) Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:19–23

Akhtar SS, Andersen MN, Liu F (2015a) Biochar mitigates salinity stress in potato. J Agron Crop Sci. doi:10.1111/jac.12132

Akhtar SS, Andersen MN, Liu F (2015b) Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. Agric Water Manage 158:61–68

Ali MA, Hoque MA, Kim PJ (2013) Mitigating global warming potentials of methane and nitrous oxide gases from rice paddies under different irrigation regimes. AMBIO 42:357–368

Ali MA, Kim PJ, Inubushi K (2015) Mitigating yield-scaled greenhouse gas emissions through combined application of soil amendments: a comparative study between temperate and subtropical rice paddy soils. Sci Total Environ 529:140–148

Allen RL (1847) A brief compend of American agriculture. CM Saxton, New York

Anderson CR, Condron LM, Clough TJ, Fiers M, Stewart A, Hill RA, Sherlock RR (2011) Biochar induced soil microbial community change: implications for biogeochemical cycling of carbon, nitrogen and phosphorus. Pedobiologia 54:309–320

Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, Inoue Y, Shiraiwa T, Horie T (2009) Biochar amendment techniques for upland rice production in northern Laos 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Res 111:81–84

Atkinson CJ, Fitzgerald JD, Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337:1–18

Awad YM, Blagodatskaya E, Ok YS, Kuzyakov Y (2012) Effects of polyacrylamide, biopolymer, and biochar on decomposition of soil organic matter and plant residues as determined by ^{14}C and enzyme activities. Eur J Soil Biol 48:1–10

Awad YM, Blagodatskaya E, Ok YS, Kuzyakov Y (2013) Effects of polyacrylamide, biopolymer and biochar on the decomposition of ^{14}C-labelled maize residues and on their stabilization in soil aggregates. Eur J Soil Sci 64:488–499

Ayodele A, Oguntunde P, Joseph A, Dias DDS Jr (2009) Numerical analysis of the impact of charcoal production on soil hydrological behavior, runoff response and erosion susceptibility. Rev Bras Cienc Solo 33:137–145

Bagreev A, Bashkova S, Locke DC, Bandosz TJ (2001) Sewage sludge derived materials as efficient adsorbent for removal of hydrogen sulfide. Environ Sci Technol 35:1537–1543

Bailey VL, Fansler SJ, Smith JL, Bolton H Jr (2011) Reconciling apparent variability in effects of biochar amendment on soil enzyme activities by assay optimization. Soil Biol Biochem 43:296–301

Baronti S, Alberti G, DelleVedove G, Di Gennaro F, Fellet G, Genesio L, Miglietta F, Peressotti A, Vaccari FP (2010) The biochar option to improve plant yields: first results from some field and pot experiments in Italy. Italian J Agron 5:3–12

Barot S, Ugolini A, Brikci FB (2007) Nutrient cycling efficiency explains the long term effect of ecosystem engineers on primary production. Funct Ecol 21:1–10

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

Beesley L, Dickinson N (2011) Carbon and trace element fluxes in the pore water of an urban soil following green waste compost, woody and biochar amendments, inoculated with the earthworm *Lumbricus terrestris*. Soil Biol Biochem 43:188–196

Beesley L, Moreno-Jimenez E, Gomez-Eyles JL (2010) Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environ Pollut 158:2282–2287

Berglund LM, De Luca TH, Zackrisson O (2004) Activated carbon amendment of soil alters nitrification rates in Scots pine forests. Soil Biol Biochem 36:2067–2073

Bian R, Zhang Z, Zhang A, Zheng J, Li L, Joseph S, Pan G, Chang A, Zheng J (2013) Effect of municipal biowaste biochar on greenhouse gas emissions and metal bioaccumulation in a slightly acidic clay rice paddy. BioResources 9:685–703

Bian R, Joseph S, Cui L, Pan G, Li L, Liu X, Zhang A, Rutlidge H, Marjo C, Wong S, Chia C, Gong B, Munroe P, Donne S (2014) A three-year experiment confirms continuous immobilization of cadmium and lead in contaminated paddy field with biochar amendment. J Hazard Mater 272:121–128

Bird MI, Wurster CM, de Paula Silva PH, Bass AM, de Nys R (2011) Algal biochar—production and properties. Bioresource Technol 102:1886–1891

Blackwell P, Krull E, Butler G, Herbert A, Solaiman ZM (2010) Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. Soil Res 48:531–545

Boudsocq S, Lata JC, Mathieu J, Abbadie L, Barot S (2009) Modelling approach to analyse the effects of nitrification inhibition on primary production. Funct Ecol 23:220–230

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

Brown R (2009) Biochar production technology. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 127–146

Brown RA, Kercher AK, Nguyen TH, Nagle DC, Ball WP (2006) Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. Org Geochem 37:321–333

Bruun EW, Hauggaard-Nielsen H, Norazana I, Egsgaard H, Ambus P, Jensen PA, Johansen KD (2011) Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. Biomass Bioenerg 35: 1182–1189

Bruun EW, Ambus P, Egsgaard H, Hauggaard-Nielsen H (2012) Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. Soil Biol Biochem 46:73–79

Busch D, Kammann C, Grünhage L, Müller C (2012) Simple biotoxicity tests for evaluation of carbonaceous soil additives: establishment and reproducibility of four test procedures. J Environ Qual 41: 1023–1032

Callaway RM, Aschehoug ET (2000) Invasive plants versus their new and old neighbors: a mechanism for exotic invasion. Science 290: 521–523

Cao X, Harris W (2010) Properties of dairy-manure-derived biochar pertinent to its potential use in remediation. Bioresour Technol 101: 5222–5228

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

Case SDC, McNamara NP, Reay DS, Stott AW, Grant HK, Whitakera J (2015) Biochar suppresses N_2O emissions while maintaining N availability in a sandy loam soil. Soil Biol Biochem 81:178–185

Castaldi S, Riondino M, Baronti S, Esposito FR, Marzaioli R, Rutigliano FA, Vaccari FP, Miglietta F (2011) Impact of biochar application to a Mediterranean wheat crop on soil microbial activity and greenhouse gas fluxes. Chemosphere 85:1464–1471

Cayuela ML, Sánchez-Monedero MA, Roig A, Hanley K, Enders A, Lehmann J (2013) Biochar and denitrification in soils: when, how much and why does biochar reduce N_2O emissions? Sci Rep 3:17–32

Chagger HK, Kendall A, McDonald A, Pourkashanian M, Williams A (1998) Formation of dioxins and other semi-volatile compounds in biomass combustion. Appl Energ 60:101–114

Chalker-Scott L (2014) Biochar: a home gardener's primer. Washington State University Puyallup Research and Extension Center. Washington State University Extension and the U.S. Department of Agriculture

Chan KY, Xu Z (2009) Biochar: nutrient properties and their enhancement. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 67–84

Chan KY, Van Zwieten L, Meszaros I, Downie A, Joseph S (2007) Agronomic values of greenwaste biochar as a soil amendment. Aust J Soil Res 45:629–634

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

Chen JP, Lin M (2001) Equilibrium and kinetics of metal ion adsorption onto a commercial H-type granular activated carbon: experimental and modeling studies. Water Res 35:2385–2394

Christoph GT, Wenceslau L, Johannes N, Thomas M, deVasconcelos JL, Winfried EHB, Zech W (2007) Long-term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered central Amazonian upland soil. Plant Soil 291: 275–290

Cornelissen G, Martinsen V, Shitumbanuma V, Alling V, Breedveld GD, Rutherford DW, Sparrevik M, Hale SE, Obia A, Mulder J (2013) Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. Agron J 3:256–274

Cross A, Sohi SP (2011) The priming potential of biochar products in relation to labile carbon contents and soil organic matter status. Soil Biol Biochem 43:2127–2134

Cui L, Li L, Zhang A, Pan G, Bao D, Chang A (2011) Biochar amendment greatly reduces rice cd uptake in a contaminated paddy soil: a two-year field experiment. BioResources 6:2605–2618

Cui L, Chen T, Yan J, Fu Q, Yang Y, Chang A, Li L, Quan G, Ding C (2013) Influence of biochar on microbial activities of heavy metals contaminated paddy fields. BioResources 8: 5536–5548

de la Rosa JM, Knicker H (2011) Bioavailability of N released from N-rich pyrogenic organic matter: an incubation study. Soil Biol Biochem 43:2368–2373

De Luca TH, MacKenzie MD, Gundale MJ (2009) Biochar effects on soil nutrient transformations. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 251–270

de Sousa AMB, Santos RRS, Gehring C (2014) Charcoal in Amazonian paddy soil—nutrient availability, rice growth and methane emissions. J Plant Nutr Soil Sci 177:39–47

Deenik JL, McClellan T, Uehara G, Antal MJ, Campbell S (2010) Charcoal volatile matter content influences plant growth and soil nitrogen transformations. Soil Sci Soc Am J 74:1259–1270

Ding Y, Liu YX, Wu WX, Shi DZ, Yang M, Zhong ZK (2010) Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water Air Soil Pollut 213:47–55

Downie A, Crosky A, Munroe P (2009) Physical properties of biochar. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 13–32

Duku MH, Gu S, Hagan EB (2011) Biochar production potential in Ghana—a review. Renew Sust Energ Rev 15:3539–3551

Elad Y, David DR, Harel YM, Borenshtein M, Kalifa HB, Silber A, Graber ER (2010) Induction of systemic resistance in plants by biochar, a soil-applied C sequestering agent. Phytopathology 100: 913–921

Elad Y, Cytryn E, Harel YM, Lew B, Graber ER (2012) The biochar effect: plant resistance to biotic stresses. Phytopathol Mediterr 50: 335–349

Elmer WH, Pignatello JJ (2011) Effect of biochar amendments on mycorrhizal associations and Fusarium crown and root rot of asparagus in replant soils. Plant Dis 95:960–966

El-Naggar AH, Usman ARA, Al-Omran A, Ok YS, Ahmad M, Al-Wabel MI (2015) Carbon mineralization and nutrient availability in calcareous sandy soils amended with woody waste biochar. Chemosphere 138:67–73

Enders A, Hanley K, Whitman T, Joseph S, Lehmann J (2012) Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresource Technol 114:644–653

Feng Y, Xu Y, Yu Y, Xie Z, Lin X (2012) Mechanisms of biochar decreasing methane emission from Chinese paddy soils. Soil Biol Biochem 46:80–88

Feng L, Gui-tong L, Qi-mei L, Xiao-rong Z (2014) Crop yield and soil properties in the first 3 years after biochar application to a calcareous soil. J Integ Agric 13:525–532

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey D, Haywood J, Lean J, Lowe D, Myhre G, Nganga J, Prinn R, Raga G, Schultz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge, United Kingdom, pp 129–234

Free HF, McGill CR, Rowarth JS, Hedley MJ (2010) The effect of biochars on maize (*Zea mays*) germination. New Zealand J Agric Res 53:1–4

Fungo B, Guerena D, Thiongo M, Lehmann J, Neufeldt H, Kalbitz K (2014) N_2O and CH_4 emission from soil amended with steam-activated biochar. J Plant Nutr Soil Sci 177:34–38

Gaskin JW, Speir RA, Harris K, Das KC, Lee RD, Morris LA, Fisher DS (2010) Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agron J 102:623–633

Gaur A, Adholeya A (2000) Effects of the particle size of soil-less substrates upon AM fungus inoculum production. Mycorrhiza 10:43–48

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

Graber ER, Harel YM, Kolton M, Cytryn E, Silber A, Davi DR, Tsechansky L, Borenshtein M, Elad Y (2010) Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. Plant Soil 337:481–496

Graber ER, Tsechansky L, Mayzlish-Gati E, Shema R, Koltai H (2015) A humic substances product extracted from biochar reduces Arabidopsis root hair density and length under P-sufficient and P-starvation conditions. Plant Soil 395:21–30

Grossman JM, O'Neill BE, Tsai SM, Liang B, Neves E, Lehmann J, Thies JE (2010) Amazonian anthrosols support similar microbial communities that differ distinctly from those extant in adjacent, unmodified soils of the same mineralogy. Microb Ecol 60:192–205

Güereña D, Lehmann J, Hanley K, Enders A, Hyland C, Riha S (2013) Nitrogen dynamics following field application of biochar in a temperate North American maize-based production system. Plant Soil 365:239–254

Haefele SM, Konboon Y, Wongboon W, Amarante S, Maarifat AA, Pfeiffer EM, Knoblauch C (2011) Effects and fate of biochar from rice residues in rice-based systems. Field Crops Res 121:430–440

Haider G, Koyro HW, Azam F, Steffens D, Müller C, Kammann C (2014) Biochar but not humic acid product amendment affected maize yields via improving plant-soil moisture relations. Plant Soil 395: 141–157

Hammes K, Schmidt MWI (2009) Changes of biochar in soil. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 169–178

Hao W, Björkman E, Lilliestråle M, Hedin N (2013) Activated carbons prepared from hydrothermally carbonized waste biomass used as adsorbents for CO_2. Appl Ener 112:526–532

Harel YM, Elad Y, Rav-David D, Borenstein M, Shulchani R, Lew B, Graber ER (2012) Biochar mediates systemic response of strawberry to foliar fungal pathogens. Plant Soil 357:245–257

Hospido A, Moreira T, Martín M, Rigola M, Feijoo G (2005) Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: anaerobic digestion versus thermal processes (10 pp). Int J Life Cycle Assess 10:336–345

Hottle RD (2013) Impact of biochar on plant productivity and soil properties under a maize soybean rotation on an Alfisol in Central Ohio. PhD dissertation, Graduate Program in Environmental Science, The Ohio State University, USA

Hu Y-L, Wu F-P, Zeng D-H, Chang S-X (2014) Wheat straw and its biochar had contrasting effects on soil C and N cycling two growing seasons after addition to a Black Chernozemic soil planted to barley. Biol Fert Soils 50:1291–1299

Intergovernmental Panel on Climate Change (IPCC) (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis, Contribution of Working Group into the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 498–540

Inyang M, Dickenson E (2015) The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: a review. Chemosphere 134:232–240

Ishii T, Kadoya K (1994) Effects of charcoal as a soil conditioner on citrus growth and vesicular arbuscular mycorrhizal development. J Jap Soc Hort Sci 63:529–535

Jaiswal AK, Elad Y, Graber ER, Frenkel O (2014) *Rhizoctonia solani* suppression and plant growth promotion in cucumber as affected by biochar pyrolysis temperature, feedstock and concentration. Soil Biol Biochem 69:110–118

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

Jiang J, Xu RK, Jiang TY, Li Z (2012a) Immobilization of Cu(II), Pb(II) and Cd(II) by the addition of rice straw derived biochar to a simulated polluted Ultisol. J Hazard Mater 229(230):145–150

Jiang TY, Jiang J, Xu RK, Li Z (2012b) Adsorption of Pb(II) on variable charge soils amended with rice-straw derived biochar. Chemosphere 89:249–256

Jiang S, Huang L, Nguyen TAH, Ok YS, Rudolph V, Yang H, Zhang D (2016) Copper and zinc adsorption by softwood and hardwood biochars under elevated sulphate-induced salinity and acidic pH conditions. Chemosphere 142:64–71

Jones S, Donaldson S, Deacon J (1991) Behaviour of zoospores and zoospore cysts in relation to root infection by *Pythium aphanidermatum*. New Phytol 117:289–301

Jones DL, Edwards-Jones G, Murphy DV (2011) Biochar mediated alterations in herbicide breakdown and leaching in soil. Soil Biol Biochem 43:804–813

Jones DL, Rousk J, Edwards-Jones G, DeLuca TH, Murphy DV (2012) Biochar mediated changes in soil quality and plant growth in a three year field trial. Soil Biol Biochem 45:113–124

Joseph SD, Camps-Arbestain M, Lin Y, Munroe P, Chia CH, Hook J, Van Zwieten L, Kimber S, Cowie A, Singh BP, Lehmann J, Foidl N, Smernik RJ, Amonette JE (2010) An investigation into the reactions of biochar in soil. Aust J Soil Res 48:501–515

Joseph S, Anawar HM, Storer P, Blackwell P, Chia C, Lin Y, Munroe P, Donne S, Hovart J, Wang J, Solaiman ZM (2015) Effect of enriched biochars containing nanophase magnetic iron particles on mycorrhizal colonisation, plant growth, nutrient uptake and soil quality improvement. Pedosphere 25:749–760

Kaal J, Cortizas AM, Nierop KGJ (2009) Characterisation of aged charcoal using a coil probe pyrolysis–GC/MS method optimized for black carbon. J Anal Appl Pyrol 85:408–416

Kambo HS, Dutta A (2015) Comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renew Sust Ener Rev 45:359–378

Kammann CI, Linsel S, Gößling JW, Koyro HW (2011) Influence of biochar on drought tolerance of *Chenopodium quinoa* Willd and on soil-plant relations. Plant Soil 345:195–210

Kammann C, Ratering S, Eckhard C, Müller C (2012) Biochar and hydrochar effects on greenhouse gas (carbon dioxide, nitrous oxide, methane) fluxes from soils. J Environ Qual 41:1052–1066

Karhu K, Mattilab T, Bergströma I, Regina K (2011) Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity—results from a short-term pilot field study. Agric Ecosyst Environ 140:309–313

Karunanithi R, Szogi A, Bolan N, Naidu R, Loganathan P, Hunt PG, Vanotti MB, Saint CP, Ok YS, Krishnamoorthy S (2015) Phosphorus recovery and reuse from waste streams. Adv Agron 131:173–250

Kasozi GN, Zimmerman AR, Nkedi-Kizza P, Gao B (2010) Catechol and humic acid sorption onto a range of laboratory-produced black carbons (biochars). Environ Sci Technol 44:6189–6195

Keiluweit M, Nico PS, Johnson MG, Kleber M (2010) Dynamic molecular structure of plant biomass-derived black carbon (biochar). Environ Sci Technol 44:1247–1253

Keith A, Singh B, Singh BP (2011) Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil. Environ Sci Technol 45:9611–9618

Khan S, Chao C, Waqas M, Peter H, Arp H, Zhu YG (2013) Sewage sludge biochar influence upon rice (*Oryza sativa* L.) yield, metal bioaccumulation and greenhouse gas emissions from acidic paddy soil. Environ Sci Technol 47:8624–8632

Khan S, Reid BJ, Li G, Zhu YG (2014) Application of biochar to soil reduces cancer risk via rice consumption: a case study in Miaoqian village, Longyan, China. Environ Inter 68:154–161

Khanmohammadi Z, Afyuni M, Mosaddeghi MR (2015) Effect of pyrolysis temperature on chemical and physical properties of sewage sludge biochar. Waste Manage Res. doi:10.1177/0734242X14565210

Khavazi K, Rejali F, Seguin P, Miransari M (2007) Effects of carrier, sterilisation method, and incubation on survival of *Bradyrhizobium japonicum* in soybean (*Glycine max* L.) inoculants. Enzyme Microb Technol 41:780–784

Khodadad CLM, Zimmerman AR, Green SJ, Uthandi S, Foster JS (2011) Taxa-specific changes in soil microbial community composition induced by pyrogenic carbon amendments. Soil Biol Biochem 43:385–392

Kim JS, Sparovek S, Longo RM, De Melo WJ, Crowley D (2007) Bacterial diversity of terra preta and pristine forest soil from the Western Amazon. Soil Biol Biochem 39:648–690

Kim HS, Kim KR, Kim HJ, Yoon JH, Yang J, Ok Y, Owens G, Kim KH (2015) Effect of biochar on heavy metal immobilization and uptake by lettuce (*Lactuca sativa* L.) in agricultural soil. Environ Earth Sci 74:1249–1259

Kim HS, Kim KR, Yang JE, Ok YS, Owens G, Nehls T, Wessolek G, Kim KH (2016) Effect of biochar on reclaimed tidal land soil properties and maize (*Zea mays* L.) response. Chemosphere 142:153–159

Kimetu JM, Lehmann J, Ngoze SO, Mugendi DN, Kinyangi JM, Riha S, Verchot L, Recha JW, Pell AN (2008) Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. Ecosystems 11:726–739

Kishimoto S, Sugiura G (1985) Charcoal as a soil conditioner. In: Proceedings of a Symposium on Forest Products Research International: achievements and the future. 22–26 April 1985, CSIR Conference Center, Pretoria, South Africa, 5, pp 1–15

Kloss S, Zehetner F, Dellantonio A, Hamid R, Ottner F, Liedtke V, Schwanninger M, Gerzabek MH, Soja G (2012) Characterization of slow pyrolysis biochars: effects of feedstocks and pyrolysis temperature on biochar properties. J Environ Qual 41:990–1000

Knoblauch C, Maarifat AA, Pfeiffer EM, Haefele SM (2011) Degradability of black carbon and its impact on trace gas fluxes and carbon turnover in paddy soils. Soil Biol Biochem 43:1768–1778

Kolb SE, Fermanich KJ, Dornbush ME (2009) Effect of charcoal quantity on microbial biomass and activity in temperate soils. Soil Sci Soc Am J 73:1173–1181

Kookana RS (2010) The role of biochar in modifying the environmental fate, bioavailability, and efficacy of pesticides in soils: a review. Aust J Soil Res 48:627–637

Kookana RS, Sarmah AK, Van Zwieten L, Krull E, Singh B (2011) Biochar application to soil: agronomic and environmental benefits and unintended consequences. Adv Agron 112:104–144

Kulmatiski A, Beard KH (2011) Long-term plant growth legacies overwhelm short-term plant growth effects on soil microbial community structure. Soil Biol Biochem 43:823–830

Kuzyakov Y, Subbotina I, Chen HQ, Bogomolova I, Xu XL (2009) Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biol Biochem 41:210–219

Lai WY, Cheng CH, Lai CM, Pai CW, Ke GR, Chen SY, Chung RS, Chen CC, Chen CT (2013) The effects of woodchip biochar application on crop yield, carbon sequestration and greenhouse gas emissions from soils planted with rice or leaf beet. J Taiwan Inst Chem Eng 44: 1039–1044

Laird D, Fleming P, Wang B, Horton R, Karlen D (2010a) Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158:436–442

Laird DA, Fleming P, Davis DD, Horton R, Wang B, Karlen DL (2010b) Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158:443–449

Lal R (2008) Black and buried carbons' impacts on soil quality and ecosystem services. Soil Tillage Res 99:1–3

Lambers H, Raven JA, Shaver GR, Smith SE (2008) Plant nutrient-acquisition strategies change with soil age. Trends Ecol Evol 23: 95–103

Lammirato C, Miltner A, Kaestner M (2011) Effects of wood char and activated carbon on the hydrolysis of cellobiose by β-glucosidase from *Aspergillus niger*. Soil Biol Biochem 43:1936–1942

Lee Y, Park J, Ryu C, Gang KS, Yang W, Park YK, Jung J, Huyn S (2013) Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500 °C. Bioresour Technol 148:196–201

Lee SS, Shah HS, Awad YM, Kumar S, Ok YS (2015) Synergy effects of biochar and polyacrylamide on plants growth and soil erosion control. Environ Earth Sci 74:2463–2473

Lehmann J (2007) A handful of carbon. Nature 447:143–144

Lehmann J, Joseph S (2009) Biochar for environmental management: an introduction. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology, 1st edn. Earthscan, London, pp 1–12

Lehmann J, Joseph S (2015) Biochar for environmental management: an introduction. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science, technology and implementation, 2nd edn. Earthscan from Routledge, London, pp 1–1214

Lehmann J, Rondon M (2006) Bio-char soil management on highly weathered soils in the humid tropics. In: Uphoff N, Ball AS, Herren H, Husson O, Laing M, Palm C, Pretty J, Sanchez P, Sanginga N, Thies J (eds) Biological approaches to sustainable soil systems. Taylor & Francis, Boca Raton, pp 517–530

Lehmann J, da Silva JP, Steiner C, Nehls T, Zech W, Glaser B (2003) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249:343–357

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems—a review. Mitig Adapt Strateg Glob Change 11: 403–427

Lehmann J, Skjemstad J, Sohi S, Carter J, Barson M, Falloon P, Coleman K, Woodbury P, Krull E (2008) Australian climate-carbon cycle feedback reduced by soil black carbon. Nat Geosci 1:832–835

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota—a review. Soil Biol Biochem 43:1812–1836

Li D, Hockaday WC, Masiello CA, Alvarez PJJ (2011) Earthworm avoidance of biochar can be mitigated by wetting. Soil Biol Biochem 43: 1732–1737

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

Liang B, Lehmann J, Solomon D, Sohi S, Thies JE, Skjemstad JO, Luizão FL, Engelhard MH, Neves EG, Wirick S (2008) Stability of biomass-derived black carbon in soils. Geochim Cosmochim Acta 72:6078–6096

Liang B, Lehmann J, Sohi SP, Theis JE, O'Neill B, Trujillo L, Gaunt J, Solomon D, Grossman J, Neves EG, Luizão FJ (2010) Black carbon affects the cycling of non black carbon in soil. Org Geochem 41: 206–213

Liesch AM, Weyers SL, Gaskin JW, Das KC (2010) Impact of two different biochars on earthworm growth and survival. Ann Environ Sci 4:1–9

Liu YX, Yang M, Wu YM, Wang HL, Chen YX, Wu WX (2011) Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar. J Soils Sediments 11:930–939

Liu X, Qu J, Li LQ, Zhang A, Jufeng Z, Zheng J, Pan G (2012) Can biochar amendment be an ecological engineering technology to depress N_2O emission in rice paddies?—a cross site field experiment from South China. Ecol Eng 42:168–173

Liu XY, Zhang AF, Ji CY, Joseph S, Bian RJ, Li LQ, Pan GX, Paz-Ferreiro J (2013) Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data. Plant Soil 373:583–594

Liu J, Wu J, Li Y, Su Y, Ge T, Jones DL (2014a) Effects of biochar amendment on the net greenhouse gas emission and greenhouse gas intensity in a Chinese double rice cropping system. Eur J Soil Biol 65:30–39

Liu X, Ye Y, Liu Y, Zhang A, Zhang X, Li L, Pan G, Kibue GW, Zheng J, Zheng J (2014b) Sustainable biochar effects for low carbon crop production: a 5-crop season field experiment on a low fertility soil from Central China. Agric Syst 129:22–29

Liu C, Wang H, Tang X, Guan Z, Reid BJ, Rajapaksha AU, Ok YS, Sun H (2015a) Biochar increased water holding capacity but accelerated organic carbon leaching from a sloping farmland soil in China. Environ Sci Pollut Res. doi:10.1007/s11356-015-4885-9

Liu Q, Liu B, Ambus P, Zhang Y, Hansen V, Lin Z, Shen D, Liu G, Bei Q, Zhu J, Wang X, Ma J, Lin X, Yu Y, Zhu C, Xie Z (2015b) Carbon footprint of rice production under biochar amendment—a case study in a Chinese rice cropping system. GCB Bioener. doi:10.1111/gcbb.12248

Loganathan VA, Feng Y, Sheng GD, Clement TP (2009) Crop-residue-derived char influences sorption, desorption and bioavailability of atrazine in soils. Soil Sci Soc Am J 73:967–974

Luo Y, Durenkamp M, Nobili MD, Lin Q, Brookes PC (2011) Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biol Biochem 43:2304–2314

Luo Y, Jiao Y, Zhao X, Li G, Zhao L, Meng H (2014) Improvement to maize growth caused by biochars derived from six feedstock's prepared at three different temperatures. J Integ Agric 13:533–540

Ly P, Vu QD, Jensen LS, Pandey A, de Neergaard A (2014) Effects of rice straw, biochar and mineral fertiliser on methane (CH_4) and nitrous oxide (N_2O) emissions from rice (*Oryza sativa* L.) grown in a rainfed lowland rice soil of Cambodia: a pot experiment. Paddy Water Environ 13:465–475

Major J, Lehmann J, Rondon M, Goodale C (2010a) Fate of soil-applied black carbon: downward migration, leaching and soil respiration. Glob Change Biol 16:1366–1379

Major J, Rondon M, Molina D, Riha SJ, Lehmann J (2010b) Maize yield and nutrition during 4 years biochar application to a Colombian savanna oxisol. Plant Soil 333:117–128

Makoto K, Tamai Y, Kim YS, Koike T (2010) Buried charcoal layer and ectomycorrhizae cooperatively promote the growth of *Larix gmelinii* seedlings. Plant Soil 327:143–152

Mandal S, Thangarajan R, Bolan NS, Sarkar B, Khan N, Ok YS, Naidu R (2016) Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat. Chemosphere 142:120–127

Manyà JJ (2012) Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. Environ Sci Technol 46:7939–7954

Matsubara YI, 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 Jap Soc Hort Sci 71: 370–374

Mau AE, Utami SR (2014) Effects of biochar amendment and arbuscular mycorrhizal fungi inoculation on availability of soil phosphorus and growth of maize. J Degr Min Lands Manage 1:69–74

McClellan AT, Deenik J, Uehara G, Antal M (2007) Effects of flash carbonized macadamia nutshell charcoal on plant growth and soil chemical properties. American Society of Agronomy (Abstracts, 3–7 November, New Orleans, LA)

McHenry MP (2010) Carbon-based stock feed additives: a research methodology that explores ecologically delivered C biosequestration, alongside live weights, feed use efficiency, soil nutrient retention, and perennial fodder plantations. J Sci Food Agric 90:183–187

Méndez A, Gómez A, Paz-Ferreiro J, Gascó G (2012) Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil. Chemosphere 89:1354–1359

Mesa AC, Spokas K (2011) Impacts of biochar (black carbon) additions on the sorption and efficacy of herbicides. In: Kortenkamp A (ed) Herbicides and environment. InTech, Vienna, pp 315–340

Mikan CJ, Abrams MD (1995) Altered forest composition and soil properties of historic charcoal hearths in southeastern Pennsylvania. Can J Forest Res 25:687–696

Mimmo T, Panzacchib P, Baratieria M, Daviesb CA, Tonona G (2014) Effect of pyrolysis temperature on *miscanthus* (*Miscanthus* × *giganteus*) biochar physical, chemical and functional properties. Biom Bioener 62:149–157

Mohan D, Pittman CU Jr, Bricka M, Smith F, Yancey B, Mohammad J, Steele PH, Alexandre-Franco MF, Gómez-Serrano V, Gong H (2007) Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production. J Colloid Interf Sci 310:57–73

Mohan D, Sharma R, Singh VK, Steele P, Pittman CU Jr (2012) Fluoride removal from water using bio-char, a green waste, low-cost adsorbent: equilibrium uptake and sorption dynamics modeling. Ind Eng Chem Res 51:900–914

Mohan D, Sarswat A, Ok YS, Pittman CU (2014) Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent—a critical review. Bioresour Tech 160:191–202

Moon DH, Park JW, Chang YY, Ok YS, Lee SS, Ahmad M, Koutsospyros A, Park JH, Baek K (2013) Immobilization of lead in contaminated firing range soil using biochar. Environ Sci Pollut Res 20:8464–8471

Nag SK, Kookana R, Smith L, Krull E, Macdonald LM, Gill G (2011) Poor efficacy of herbicides in biochar-amended soils as affected by their chemistry and mode of action. Chemosphere 84:1572–1577

Nelissen V, Ruysschaert G, Müller-Stöver D, Bodé S, Cook J, Ronsse F, Shackley S, Boeckx P, Hauggaard-Nielsen H (2014) Short-term effect of feedstock and pyrolysis temperature on biochar characteristics, soil and crop response in temperate soils. Agronomy 4:52–73

Nelson NO, Agudelo SC, Yuan W, Gan J (2011) Nitrogen and phosphorus availability in biochar-amended soils. Soil Sci 176:218–226

Nerome M, Toyota K, Islam T, Nishijima T, Matsuoka T, Sato K, Yamaguchi Y (2005) Suppression of bacterial wilt of tomato by incorporation of municipal biowaste charcoal into soil. Soil Microorg (Japan) 59:98–114

Nguyen BT, Lehmann J (2009) Black carbon decomposition under varying water regimes. Org Geochem 40:846–853

Noguera D, Rondón M, Laossi KR, Hoyos V, Lavelle P, de Carvalho MHC, Barot S (2010) Contrasted effect of biochar and earthworms on rice growth and resource allocation in different soils. Soil Biol Biochem 42:1017–1027

Novak JM, Busscher WJ, Laird DL, Ahmedna M, Watts DW, Niandou MAS (2009a) Impact of biochar amendment on fertility of a Southeastern Coastal Plain soil. Soil Sci 174:105–112

Novak JM, Lima I, Xing B, Gaskin JW, Steiner C, Das KC, Ahmedn M, Rehrah D, Watts DW, Busscher WJ, Schomberg H (2009b) Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Ann Environ Sci 3:195–206

Novotny EH, Hayes MHB, Madari BE, Bonagamba TJ, de Azevedo ER, de Souza AA, Song GX, Nogueira CM, Mangrich AS (2009) Lessons from the Terra Preta de Indios of the Amazon region for the utilisation of charcoal for soil amendment. J Brazilian Chem Soc 20:10038–10100

O'Neill B, Grossman J, Tsai MT, Gomes JE, Lehmann J, Peterson J, Neves E, Thies JE (2009) Bacterial community composition in Brazilian Anthrosols and adjacent soils characterized using culturing and molecular identification. Microb Ecol 58:23–35

Ogawa M (1994) Symbiosis of people and nature in the tropics. Farming Japan 28:10–34

Oguntunde PG, Fosu M, Ajayi AE, van de Giesen N (2004) Effects of charcoal production on maize yield, chemical properties and texture of soil. Biol Fert Soils 39:295–299

Painter TJ (2001) Carbohydrate polymers in food preservation: an integrated view of the Maillard reaction with special reference to discoveries of preserved foods in Sphagnum dominated peat bogs. Carbohyd Polym 36:335–347

Pandey A, Mai TLA, Mai VT, Jensen LS, Vu DQ, Bui TPL, de Neergaard A (2014) Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. Agric Ecosyst Environ 196:137–146

Paoletti MG, Sommaggio D, Favretto MR, Petruzzelli G, Pezzarossa B, Barbafieri M (1998) Earthworms as useful bioindicators of agroecosystem sustainability in orchards and vineyards with different inputs. Appl Soil Ecol 10:137–150

Park JH, Cho JS, Ok YS, Kim SH, Kang SW, Choi IW, Heo JS, DeLaunee RD, Seo DC (2015a) Competitive adsorption and selectivity sequence of heavy metals by chicken bone-derived biochar: batch and column experiment. J Environ Sci Health. doi:http://dx.doi.org/10.1080/10934529.2015.1047680

Park JH, Ok YS, Kim SH, Cho JS, Heo JS, Delaune RD, Seo DC (2015b) Evaluation of phosphorus adsorption capacity of sesame straw biochar on aqueous solution: influence of activation methods and pyrolysis temperatures. Environ Geochem Health doi: 10.1007/s10653-015-9709

Paul H (2011) Biochar knowledge gaps. Available: http://www.econexus.info/publication/biochar-knowledge-gaps. Accessed 20 Nov 2015

Paz-Ferreiro J, Lu H, Fu S, Méndez A, Gascó G (2014) Use of phytoremediation and biochar to remediate heavy metal polluted soils: a review. Solid Earth 5:65–75

Peng X, Ye L, Wang C, Zhou H, Sun B (2011) Temperature and duration-dependent rice straw-derived biochar: characteristics and its effects on soil properties of an Ultisol in Southern China. Soil Tillage Res 112:159–166

Piccolo A, Pietramellara G, Mbagwu JSC (1996) Effects of coal derived humic substances on water retention and structural stability of Mediterranean soils. Soil Use Manage 12:209–213

Powles SB, Preston C, Bryan IB, Jutsum AR (1996) Herbicide resistance: impact and management. Adv Agron 58:57–93

Pratt K, Moran D (2010) Evaluating the cost-effectiveness of global biochar mitigation potential. Biomass Bioener 34:1149–1158

Prendergast-Miller MT, Duvall M, Sohi SP (2011) Localisation of nitrate in the rhizosphere of biochar-amended soils. Soil Biol Biochem 43:2243–2246

Puga AP, Abreu CA, Melo LCA, Paz-Ferreiro J, Beesley L (2015) Cadmium, lead, and zinc mobility and plant uptake in a mine soil amended with sugarcane straw biochar. Environ Sci Pollut Res 22:17606–17614

Purakayastha TJ, Kumari S, Pathak H (2015) Characterisation, stability, and microbial effects of four biochars produced from crop residues. Geoderma 239(240):293–303

Qayyum MF, Steffens D, Reisenauer HP, Schubert S (2012) Kinetics of carbon mineralization of biochars compared with wheat straw in three soils. J Environ Qual 41:1210–1220

Qian L, Chen L, Joseph S, Pan G, Li L, Zheng J, Zhang X, Zheng J, Yu X, Jiafang W (2014) Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. Carbon Manage 5:145–154

Quilliam RS, Marsden KA, Gertler C, Rousk J, DeLuca TH, Jones DL (2012) Nutrient dynamics, microbial growth and weed emergence in biochar amended soil are influenced by time since application and reapplication rate. Agric Ecosyst Environ 158:192–199

Rahman L, Whitelaw-Weckert M, Orchard B (2014) Impact of organic soil amendments, including poultry litter biochar, on nematodes in a Riverina, NSW vineyard. Soil Res 52:604–619

Rajapaksha AU, Vithanage M, Zhang M, Ahmad M, Mohan D, Chang SX, Ok YS (2014) Pyrolysis condition affected sulfamethazine sorption by tea waste biochars. Bioresour Technol 166:303–308

Rajapaksha A, Ahmad M, Vithanage M, Kim KR, Chang J, Lee S, Ok YS (2015) The role of biochar, natural iron oxides, and nanomaterials as soil amendments for immobilizing metals in shooting range soil. Environ Geochem Health 37:931–942

Retan GA (1915) Charcoal as a means of solving some nursery problems. J Forest 13:25–30

Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J (2010) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ Sci Technol 44:827–833

Rogovska N, Laird D, Cruse R, Trabue S, Heaton E (2012a) Evaluation of biochar quality utilizing standard germination test. J Environ Qual 41:1–9

Rogovska NP, Laird D, Cruse RM, Trabue S, Heaton E (2012b) Germination tests for assessing biochar quality. J Environ Qual 41:1014–1022

Rondon M, Ramirez JA, 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, Baltimore, USA, March 21–24, 2005

Rondon M, Lehmann J, Ramirez J, Hurtado M (2007a) Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. Biol Fert Soils 43:699–708

Rondon MA, Lehmann J, Ramírez J, Hurtado M (2007b) Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. Biol Ferti Soils 43:699–708

Schiemenz K, Eichler-Loebermann B (2010) Biomass ashes and their phosphorus fertilizing effect on different crops. Nutr Cycl Agroecosyst 87:471–482

Schneider MPW, Lehmann J, Schmidt MWI (2011) Charcoal quality does not change over a century in a tropical agro-ecosystem. Soil Biol Biochem 43:1992–1994

Sheng GY, Yang MN, Huang MS, Yang K (2005) Influence of pH on pesticide sorption by soil containing wheat residue-derived char. Environ Pollut 134:457–463

Singh PB, Hatton JB, Singh B, Cowie LA, Kathuria A (2010) Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. J Environ Qual 39:1224–1235

Smernik RJ (2009) Biochar and sorption of organic compounds. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London

Smith JL, Collins HP, Bailey VL (2010) The effect of young biochar on soil respiration. Soil Biol Biochem 42:2345–2347

Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. Adv Agron 105:47–82

Soinne H, Hovi J, Tammeorg P, Turtola E (2014) Effect of biochar on phosphorus sorption and clay soil aggregate stability. Geoderma 219(220):162–167

Solaiman ZM, Blackwell P, Abbott LK, Storer P (2010) Direct and residual effect of biochar application on mycorrhizal colonization, growth and nutrition of wheat. Aust J Soil Res 48:546–554

Solaiman ZM, Murphy DV, Abbott LK (2012) Biochars influence seed germination and early growth of seedlings. Plant Soil 353:273–287

Sollins P, Homann P, Caldwell BA (1996) Stabilization and destabilization of soils organic matter: mechanisms and controls. Geoderma 74:65–105

Song W, Guo M (2012) Quality variations of poultry litter biochar generated at different pyrolysis temperatures. J Anal Appl Pyrol 94:138–145

Sonja S, Glaser B (2012) One step forward toward characterization: some important material properties to distinguish biochars. J Environ Qual 41:1001–1013

Spokas KA (2010) Review of the stability of biochar in soils: predictability of O:C molar ratios. Carbon Manage 1:289–303

Spokas KA, Reicosky DC (2009) Impacts of sixteen different biochars on soil greenhouse gas production. Ann Environ Sci 3:179–193

Spokas KA, Koskinen WC, Baker JM, Reicosky DC (2009) Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. Chemosphere 77:574–581

Spokas KA, Cantrell KB, Novak JM, Archer DA, Ippolito JA, Collins HP, Boateng AA, Lima IM, Lamb MC, McAloon AJ, Lentz RD, Nichols KA (2012) Biochar: a synthesis of its agronomic impact beyond carbon sequestration. J Environ Qual 41:973–989

Stavi I, Lal R (2013) Agroforestry and biochar to offset climate change: a review. Agron Sustain Dev 33:81–96

Steiner C (2010) Biochar in agricultural and forestry applications. In: Biochar from agricultural and forestry residues—a complimentary use of waste biomass, U.S.-focused biochar report: assessment of biochar's benefits for the United States of America

Steiner C, Teixeira WG, Lehmann J, Nehls T, Macedo J, Blum WH, Zech W (2007) Long term effect of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291:275–290

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

Sun H, Zhang H, Min J, Feng Y, Shi W (2015) Controlled-release fertilizer, floating duckweed, and biochar affect ammonia volatilization and nitrous oxide emission from rice paddy fields irrigated with nitrogen-rich wastewater. Paddy Water Environ. doi:10.1007/s10333-015-0482-2

Tammeorg P, Parviainen T, Nuutinen V, Simojoki A, Vaara E, Helenius J (2014a) Effects of biochar on earthworms in arable soil: avoidance test and field trial in boreal loamy sand. Agric Ecosyst Environ 191:150–157

Tammeorg P, Simojoki A, Mäkelä P, Stoddard F, Alakukku L, Heleniu J (2014b) Biochar application to a fertile sandy clay loam in boreal conditions: effects on soil properties and yield formation of wheat, turnip rape and faba bean. Plant Soil 374:89–107

Tammeorg P, Simojoki A, Mäkelä P, Stoddard FL, Alakukku L, Helenius J (2014c) Short-term effects of biochar on soil properties and wheat yield formation with meat bone meal and inorganic fertiliser on a boreal loamy sand. Agric Ecosys Environ 191:108–116

Thies J, Rillig MC (2009a) Characteristics of biochar: biological properties. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 85–105

Thies JE, Rillig MC (2009b) Characteristics of biochar: biochar properties. In: Lehmann J, Joseph S (eds) Biochar for environmental management—science and technology. Earthscan, London, pp 85–105

Thomas SC, Frye S, Gale N, Garmon M, Launchbury R, Machado N, Melamed S, Murray J, Petroff A, Winsborough C (2013) Biochar mitigates negative effects of salt additions on two herbaceous plant species. J Environ Manage 129:62–68

Thu TN, Phuong LBT, Van TM, Hong SN (2015) Effect of water regimes and organic matter strategies on mitigating green house gas emission from rice cultivation and co-benefits in agriculture in Vietnam. Int J Environ Sci Develop 7:85–90

Tong XJ, Li JY, Yuan JH, Xu RK (2011) Adsorption of Cu(II) by biochars generated from crop straws. Chem Eng J 172:828–834

Tryon EH (1948) Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecol Monograp 18:81–115

Uchimiya M, Lima IM, Klasson KT, Wartelle LH (2010) Contaminant immobilization and nutrient release by biochar soil amendment: roles of natural organic matter. Chemosphere 80:935–940

Uchimiya M, Chang S, Klasson KT (2011a) Screening biochars for heavy metal retention in soil: role of oxygen functional group. J Hazard Mater 190:432–441

Uchimiya M, Klasson KT, Wartelle LH, Lima IM (2011b) Influence of soil properties on heavy metal sequestration by biochar amendment: 1. Copper sorption isotherms and the release of cations. Chemosphere 82:1431–1437

Vaccari FP, Baronti S, Lugato E, Genesio L, Castaldi S, Fornasier F, Miglietta F (2011) Biochar as a strategy to sequester carbon and increase yield in durum wheat. Eur J Agron 34:231–238

Vallad GE, Goodman RM (2004) Systemic acquired resistance and induced systemic resistance in conventional agriculture. Crop Sci 44:1920–1934

Van Zwieten L, Singh B, Joseph S, Kimber S, Cowie A, Chan KY (2009) Biochar and emissions of non-CO_2 greenhouse gases from soil. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 227–249

Van Zwieten L, Kimber S, Morris S, Chan KY, Downie A, Rust J, Joseph S, Cowie A (2010) Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant Soil 327:235–246

Van Zwieten L, Kimber SWL, Morris SG, Singh BP, Grace PR, Scheer C, Rust J, Downie AE, Cowie AL (2013) Pyrolysing poultry litter reduces N_2O and CO_2 fluxes. Sci Total Environ 465:279–287

Vanek SJ, Lehmann J (2015) Phosphorus availability to beans via interactions between mycorrhizas and biochar. Plant Soil 395:105–123

Vasilyeva NA, Abiven S, Milanovskiy EY, Hilf M, Rizhkov OV, Schmidt MWI (2011) Pyrogenic carbon quantity and quality unchanged after 55 years of organic matter depletion in a Chernozem. Soil Biol Biochem 43:1985–1988

Ventura M, Sorrenti G, Panzacchi P, George E, Tonon G (2013) Biochar reduces short-term nitrate leaching from a horizon in an apple orchard. J Environ Qual 42:76–82

Verheijen F, Jeffery S, Bastos AC, van der Velde M, Diafas I (2010) Biochar application to soils. A critical scientific review of effects on soil properties, processes, and functions. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg

Verhoeven JTA, Arheimer B, Yin CQ, Hefting MM (2006) Regional and global concerns over wetlands and water quality. Trends Ecol Evol 21:96–103

Wang XS, Miao HH, He W, Shen HL (2011) Competitive adsorption of Pb(II), Cu(II), and Cd(II) ions on wheat-residue derived black carbon. J Chem Eng Data 56:444–449

Wang C, Lu H, Dong D, Deng H, Strong PJ, Wang H, Wu W (2013) Insight into the effects of biochar on manure composting: evidence supporting the relationship between N_2O emission and denitrifying community. Environ Sci Technol 47:7341–7349

Warnock DD, Lehmann J, Kuyper TW, Rillig MC (2007) Mycorrhizal responses to biochar in soil—concepts and mechanisms. Plant Soil 300:9–20

Warnock DD, Mummey DL, McBride B, Major J, Lehmann J, Rillig MC (2010) Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: results from growth-chamber and field experiments. Appl Soil Ecol 46:450–456

Watanabe A, Ikeya K, Kanazaki N, Makabe S, Sugiura Y, Shibat A (2014) Five crop seasons' records of greenhouse gas fluxes from upland fields with repetitive applications of biochar and cattle manure. J Environ Manage 144:168–175

Wen B, Li RJ, Zhang S, Shan XQ, Fang J, Xiao K, Khan SU (2009) Immobilization of pentachlorophenol in soil using carbonaceous material amendments. Environ Pollut 157:968–974

Whitman T, Enders A, Lehmann J (2014) Pyrogenic carbon additions to soil counteracts positive priming of soil carbon mineralization by plants. Soil Biol Biochem 73:33–41

Windstam S, Nelso EB (2008) Temporal release of fatty acids and sugars in the spermosphere: impacts on Enterobacter cloacae-induced biological control. Appl Environ Microbiol 74:4292–4299

Woolf D, James E, Amonette F, Street-Perrott A, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1:1–9

Wu M, Feng Q, Sun X, Wang H, Gielen G, Wua W (2015) Rice (*Oryza sativa* L.) plantation affects the stability of biochar in paddy soil. Sci Rep. doi:10.1038/srep10001

Yamato M, Okimori Y, Wibowo IF, Anshori S, Ogawa M (2006) Effects of the application of charred bark of Acacia mangium on the yield of maize, cowpea and peanut and soil chemical properties in south Sumatra, Indonesia. Soil Sci Plant Nutr 52:489–495

Yan YN, Sheng GY (2003) Pesticide adsorptivity of aged particulate matter arising from crop residue burns. J Agric Food Chem 51:5047–5051

Yanai Y, Toyota K, Okazaki M (2007) Effect of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. Soil Sci Plant Nutr 53:181–188

Yang YN, Sheng GY (2003) Enhanced pesticide sorption by soils containing particulate matter from crop residue burns. Environ Sci Technol 37:3635–3639

Yang YN, Sheng GY, Huang MS (2006) Bioavailability of diuron in soil containing wheat-straw-derived char. Sci Total Environ 354:170–178

Yang XB, Ying GG, Peng PA, Wang L, Zhao JL, Zhang LJ, Yuan P, He HP (2010) Influence of biochars on plant uptake and dissipation of two pesticides in an agricultural soil. J Agric Food Chem 58:7915–7921

Yao Y, Gao B, Inyang M, Zimmerman AR, Cao X, Pullammanappallil P, Yang L (2011) Biochar derived from anaerobically digested sugar

beet tailings: characterization and phosphate removal potential. Bioresource Technol 102:6273–6278
Yeardley RB, Lazorchak JM, Gast LC (1996) The potential of an earthworm avoidance test for evaluation of hazardous waste sites. Environ Toxicol Chem 15:1532–1537
Yin B, Crowle D, Sparovek G, De Melo WJ, Borneman J (2000) Bacterial functional redundancy along a soil reclamation gradient. Appl Environ Microbiol 66:4361–4365
Yoo G, Kang H (2012) Effects of biochar addition on greenhouse gas emissions and microbial responses in a short-term laboratory experiment. J Environ Qual 41:1193–1202
Yu XY, Ying GG, Kookana RS (2006) Sorption and desorption behavior of diuron in soil amended with charcoal. J Agric Food Chem 54: 8545–8550
Yu XY, Ying GG, Kookana RS (2009) Reduced plant uptake of pesticides with biochar addition to soil. Chemosphere 76:665–671
Yu X, Pan L, Ying GG, Kookana RS (2010) Enhanced and irreversible sorption of pesticide pyrimethanil by soil amended with biochars. J Environ Sci 22:615–620
Yu XY, Mu CL, Gu C, Liu C, Liu XJ (2011) Impact of woodchip biochar amendment on the sorption and dissipation of pesticide acetamiprid in agricultural soils. Chemosphere 85:1284–1289
Zackrisson O, Nilsson MC, Wardle DA (1996) Key ecological function of charcoal from wildfire in the boreal forest. Oikos 77:10–19
Zhang M, Ok YS (2014) Biochar soil amendment for sustainable agriculture with carbon and contaminant sequestration. Carbon Manage 5:255–257
Zhang P, Sheng GY, Feng YC, Miller DM (2005) Role of wheat-residue-derived char in the biodegradation of benzonitrile in soil: nutritional stimulation versus adsorptive inhibition. Environ Sci Technol 39: 5442–5448
Zhang Q, Yang Z, Wu W (2008) Role of crop residue management in sustainable agricultural development in the North China Plain. J Sust Agric 32:137–148
Zhang AF, Cui LQ, Pan GX, Li LQ, Hussain Q, Zhang XH, Zheng JW, Crowley D (2010) Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. Agric Ecosyst Environ 139:469–475
Zhang A, Bian R, Pan G, Cui L, Hussain Q, Li L, Zheng J, Zheng J, Zhang X, Han X, Yu X (2012a) Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles. Field Crops Res 127:153–160
Zhang A, Liu Y, Pan G, Hussain Q, Li L, Zheng J, Zhang X (2012b) Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. Plant Soil 351:263–275
Zhang A, Bian R, Hussain Q, Li l, Pan G, Zheng J, Zhang X, Zheng J (2013a) Change in net global warming potential of a rice–wheat cropping system with biochar soil amendment in a rice paddy from China. Agric Ecosyst Environ 173:37–45
Zhang XK, Li Q, Liang WJ, Zhang M, Bao XL, Xie ZB (2013b) Soil nematode response to biochar addition in a Chinese wheat field. Pedosphere 23:98–103
Zhang D, Pan G, Wu G, Kibue GW, Li L, Zhang X, Zheng J, Zheng J, Cheng K, Joseph S, Liu X (2016) Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rainfed low fertility inceptisol. Chemosphere 142: 106–113
Zhao X, Wang J, Wang S, Xing G (2014) Successive straw biochar application as a strategy to sequester carbon and improve fertility: a pot experiment with two rice/wheat rotations in paddy soil. Plant Soil 378:279–294
Zheng W, Guo M, Chow T, Bennett DN, Rajagopalan N (2010) Sorption properties of greenwaste biochar for two triazine pesticides. J Hazard Mater 181:121–126
Zimmerman AR (2010) Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). Environ Sci Technol 44:1295–1301
Zimmerman AR, Gao B, Ahn MY (2011) Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol Biochem 43:1169–1179
Zwart DC, Kim SH (2012) Biochar amendment increases resistance to stem lesions caused by *Phytophthora* spp. in tree seedlings. Hort Sci 47:1736–1740