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Biochar: Its Impact on Soil and Environment

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A B S T R A C T

Biochar is the solid carbonaceous product obtained when plant and/or animal biomass is subjected to pyrolysis. It is a co-product of a controlled pyrolysis process, can be used as a tool for sequestering C in soil to offset greenhouse gas (GHG) emissions, and as a soil amendment. Whereas the impacts of biochar application on soil chemical properties are widely known, the research information on soil physical properties is scarce. Biochar is increasingly being recognized by scientists and policy makers for its potential role in carbon sequestration, reducing greenhouse gas emissions, renewable energy, waste mitigation, and as a soil amendment. The challenge of agricultural land depletion as a result of the pressure driven by the ever-growing population has brought about a renewed focus on the need for sustainable practices in agricultural production and environmental impacts of biochar. This chapter reviews the properties of biochar; its impacts on environment and in soil when incorporated into the soil. Relative to its original organic form, this chapter iterates the benefits of biochar as a more sustainable organic approach towards improving agricultural soil qualities and hence crop yield due to its stability and duration in soils for hundreds of years. The impacts of biochar on soil physical, chemical and biological properties through the enhancement of soil nutrient and water-holding capacity, pH, bulk density and stimulation of soil microbial activities are by improving aggregation, porosity, surface area and habitat for soil microbes in biochar-amended soils. It is therefore recommended that biochar be used as soil amendment, especially to a degraded soil for a large and long-term carbon sink restoration.

Introduction

Biochar is a type of black carbon produced from a carbonaceous material through the application of heat or chemicals (Lehmann, 2007b; Novak *et al.,* 2009). Biochar is defined as the carbonaceous product obtained when plant or animal biomass is subjected to heat treatment in an oxygen-limited environment and when applied to soil as an amendment (Lehmann and Joseph, 2009). Biochars made from diverse biomass species (feedstock) are characterized by different morphological and chemical properties but also characteristically differ based on specific pyrolysis conditions i.e., final pyrolysis temperature or peak temperature, rate of charring or ramp rate, and duration of charring time (Zimmerman, 2012).

Black carbon in soils can be a result of anthropogenic activities like fire pits or natural occurrences like volcanic activity or forest fires (Spokas *et al.,* 2012). Biochar is differentiated from black carbon in that it is created with the intent to be used as a soil ameliorant (Barrow, 2012). Specifically, biochar is a stable substrate created from organic material that has been combusted under low or no oxygen conditions through the process of pyrolysis (Atkinson *et al.,* 2010; Karhu *et al.,* 2011). Biochar may increase soil pH, nutrient retention, cation exchange capacity (CEC), crop biomass, and many other variables important to soil quality and agriculture (Schnell *et al.,* 2012; Xu *et al.,* 2012) in addition to increased soil C sequestration (Lehmann, 2007a). The carbon-rich by product that is produced when biomass (*e.g.,* agricultural crop residues, wood, waste, etc.) is heated through the process of pyrolysis in an oxygen-depleted environment is commonly referred to as biochar. However, biochar is a fairly loose term without any clear definition at the moment. According to Lehmann *et al.,* (2006), the term “biochar” is a relatively recent development and evolved in conjunction with issues such as soil management and carbon sequestration. Therefore, biochar is a term normally associated with plant biomass- or biowaste-derived materials contained within the black carbon (BC) continuum (Schmidt and Noack, 2000). This definition can include chars and charcoal, but excludes fossil fuel products or geogenic carbon (Lehmann *et al.,* 2006). Biochar differs from charcoal in regard to its purpose of use, which is not for fuel, but for atmospheric carbon capture and storage, and application to soil. Recently, the European Commission (Verheijen *et al.,* 2010) has defined biochar as charcoal (biomass that has been pyrolyzed in a zero or low oxygen environment) for which, owing to its inherent properties, scientific consensus exists that application to soil at a specific site is expected to sustainably sequester carbon and concurrently improve soil functions (under current and future management), while avoiding short- and long-term detrimental effects to the wider environment as well as human and animal health. This ability of biochar to amend soil quality issues, in conjunction with sequestering C, has contributed to a surge in biochar interest. The use of biochar as a soil additive has been proposed to simultaneously mitigate anthropogenic climate change while improving soil fertility and enhancing crop production (*e.g.,* Glaser *et al.,* 2002, 2009; Lehmann *et al.,* 2006; Ogawa *et al.,* 2006). However, the true potential of this practice in terms of both agronomic and environmental benefits has only been highlighted recently (*e.g.,* Glaser *et al.,* 2009;Lehmann and Joseph, 2009; Lehmann *et al.,* 2006; Sohi *et al.,* 2010). Biochar application to the nutrient-poor soils is increasingly being recognized as an attractive option, given the potential agronomical and environmental benefits. Biochar is currently promoted as a way to initiate a “doubly green revolution” (Barrow, 2012) by potentially addressing soil organic matter GHG emissions and food insecurity concurrently (Jones *et al.,* 2012; Lehmann *et al.,* 2006; Mukherjee and Lal, 2013; Sohi *et al.,* 2010). Specifically, biochar is being targeted in tropical soils. Sustainable agriculture in the tropics is difficult because of the rapid degradation of soil organic matter in some soils as a result of limited stabilizing minerals in a hot and rainy climate (Glaser *et al.,* 2001).

Biochar production

Biochars are heterogeneous in their properties due to the wide variety of feedstocks that can be used and pyrolysis technologies. Some common feedstocks include switchgrass, hardwoods, peanut hulls, corn hulls, pecan shells, bark, rice, sugarcane, leaves, paper sludge, cow manure, poultry manure, poultry litter, sewage sludge, and aquaculture waste (Atkinson *et al.*, 2010; Barrow, 2012; Spokas *et al.*, 2012; Xu *et al.*, 2012). Biochar can help eliminate the reluctance people may have to waste stream products by removing both the wetness and the odor through the process of pyrolysis (McHenry, 2011). Once the feedstock is established, there are many different types of pyrolysis, including slow pyrolysis, fast pyrolysis, flash pyrolysis, vacuum pyrolysis, hydropyrolysis, intermediate pyrolysis, and microwave-assisted pyrolysis (Manya`, 2012; Tripathi *et al.*, 2016). In addition to the solid biochar, bio-oil and bio-syngas are also products of pyrolysis (Tripathi *et al.*, 2016). Other methods to create biochar include torrefaction, flash carbonization, hydrothermal carbonization, and gasification (Cha *et al.*, 2016). The combination of many feedstocks and several pyrolysis technologies makes for a plethora of biochars all varying in hysicochemical properties. Once the biochar is created, other variables need to be documented. For instance, it is also important to maintain records of how the biochar was stored and if any chemical or thermal activation occurred as these factors can affect the surface chemistry of the biochar as well as how resistant it is to decay within soil (Spokas *et al.*, 2012).

Properties of biochar

Biochars are characterized by certain morphological and chemical properties which are borne from the physico-chemical alteration of the original feedstock as a result of pyrolytic process. Characteristically, these properties of biochar differ since they are controlled by factors such as type of organic material from which they are made, pyrolysis conditions (i.e. final pyrolysis temperature or peak temperature, rate of heat application – slow or fast pyrolysis), rate and duration of charring(Mukherjee 2011, Mukherjee *et al.*, 2011). The impact of biochar as an amendment depends on its properties. Key properties of biochar are the adsorptive properties that potentially alter soils surface area, pore size distribution, bulk density, water-holding capacity and penetration resistance. Some physical properties of biochar determined by variations in feedstock type and pyrolysis condition are discussed below.

Large surface area and presence of micropores

Large surface area amendment property of biochar contributes to the adsorptive properties of soil and potentially improves pore size distribution, bulk density and consequently leading to an increase in the soil available water needed for crop growth and development. In addition, a strong direct relationship exists between a biochar's surface area and the pore volume as measured using N_2 adsorption and Braunauer-Emmett-Teller (BET) modeling (Sweatman and Quirke, 2011; Jagiello and Thommes, 2004). It was reported that the surface area could also be measured by using other compounds such as CO_2 on carbonaceous materials at the micrometer scale (Jagiello and Thommes, 2004). It was stated that understanding and determination of the relative abundance and stability of pores of different sizes are keys to soil ecosystem functioning (Mukherjee and Lal, 2014). Important among these functions are aeration, hydrology and provision of habitat for microbes while the finer pores could be involved with molecular adsorption and transport (Atkinson *et al.,* 2010). Differences in production conditions, especially final combustion temperature, would result to variation in surface area of biochars even when they are produced from the same parent biomass. The relationship between the peak combustion temperature and surface morphological parameters (i.e. surface area, pore diameter and volume) of the resulting biochar is highly complex (Mukherjee and Lal, 2014). There may be either no simple relationship between surface area and peak temperature, or surface area may increase with increase in peak temperature up to a certain threshold and then decrease (Fernandes *et al.,* 2003). Due to variations in reports on surface area and peak temperature there are reports that the mechanisms responsible for increases in surface area with an increase in peak temperature or heating rate are not well understood (Mukherjee and Lal, 2014). However, the surface area increases with an increase in peak temperature of biochar production (Mukherjee, 2011).

Adsorptive property

The adsorptive nature of biochar is related to its surface area. The adsorptive capability of biochar is determined by its surface chemical properties and porous nature. It is an important physical property due to its influence in the uptake and binding effect of materials from their surroundings (Mukherjee and Lal, 2013). Biochar may adsorb poly aromatic compounds, polyaromatic and poly aliphatic hydrocarbons, other toxic chemicals, metals and elements or pollutants in soils, sediments, aerosols and water bodies (Schmidt and Noack, 2000).

Stability

This important physical property makes biochar a more sustainable soil amendment relative to its original fresh biomass for agricultural purpose However, degradation of at least some components (volatile matter or labile organic matter) of the biochar may occur (Hammes *et al.,* 2008). On the other hand, the difference in sub-soil characteristics due to variations in microbial activity and oxygen content may affect biochar oxidation and aging (Mukherjee and Lal, 2013). Biochar can move into sub-soil over time to enrich the zone. Hence, other factors associated with its physical stability in soil include its mobility into deeper soil profile (Mukherjee and Lal, 2013). The aggregate stability of biochar-amended soil may also determine the susceptibility of biochars to microbial processes in subsoil. These factors not only enhance the stability of soil organic matter in the deeper profile but also improve availability of water and nutrients to crops and decrease erosion risks.

Restoring/improving soil properties

Biochar has the potential capacity to restore a degraded soil when added to the soil. Biochar mineralizes gradually over a long period of time when applied to the soil. Nutrients from biochar are released gradually to improve the physical, chemical and biological conditions of the soil. The impact of biochar as an amendment is a function of its properties such as large surface area and presence of micropores (Mukherjee *et al.,* 2011). These are key properties because they contribute to the adsorptive properties of soils and potentially alter soil physical and hydrological properties.

Biochar and soil properties

Figure 1 illustrates the interaction between biochar and soil. The application of biochar to the soil will alter the physical and chemical properties of the soil. The net effect of biochar on the soil physical properties will depend on its interaction the physico-chemical characteristics of the soil, the weather conditions prevalent at the particular site and the management of its application (Verheijen *et al.,* 2010). Biochar application can reduce the bulk density of the different soils (Chen *et al.,* 2011). This could bring about improvement in soil structure or aggregation, and aeration enhancement, thus improving soil porosity. The higher the total porosity (micro and macropores) the higher is soil physical quality. This is because micropores are involved in molecular adsorption and transport of water and nutrients while macropores affect aeration and drainage (Atkinson *et al.,* 2010). Several studies have reported that as low as 0.5% (g g^{-1}) biochar application rate was sufficient to improve water-holding capacity and water retention(Jones *et al.,* 2010 and Uzoma *et al.,* 2011. Hence, this can be said to be good water-holding capacity amendment for sandy soils which are highly porous due to the preponderance of macropores.

Effect of biochar application on some soil physical properties

A key determinant of soil functions and processes is its physical properties, precisely and most importantly, its texture. Hence, the addition of biochar in soils with different textures should affect the soil hydraulic properties differently due to the fact that there is a correlation between soil texture and soil hydraulic properties. The impacts of biochar as a soil amendment on some soil physical and hydrological properties are briefly discussed below. Soil surface area is an intrinsic property of soil determined by the sizes of its particles. The surface area of soils is an important physical characteristic which plays a vital role in water- and nutrient-holding capacities, aeration and microbial activities (Van *et al.,* 2009); hence, it can be said to be partly controlling the essential functions of soil fertility. Biochar improves the physical aspects of soil, including the bulk density, particle size distribution, porosity, structure, and texture (Ding *et al.,* 2016; Manya`, 2012; Xu *et al.,* 2012). The large surface area of biochar and its porous nature partly explain increased retention of nutrients and water (Atkinson *et al.,* 2010; Barrow, 2012; Xu *et al.,* 2012). However, there are very few studies on soil properties in long-term field scale trials, so more research needs to be done to investigate these changes and elucidate the mechanisms (Atkinson *et al.,* 2010).The total porosity or pore size distribution of biochar is a factor that can play an important role in the alteration of the properties of biochar-amended soils. Biochars are usually characterized by the preponderance of micropores, which may alter the pore size distribution of coarse texture soil when added. There were significant increases in mesoporosity occurred at the expense of macropores in waste-derived biochar-amended soil compared to the control(Jones *et al.,* 2010). Bulk density, which is defined as the mass of soil per its unit volume, has been known to have a negative correlation with surface area. The well-structured soils (fine texture) are characterized by low bulk density values between 1.0 and 1.3 g cm^{-3} while poorly structured (coarse texture) soils are known to have high bulk density values between 1.6 and 1.8 g cm^{-3}(Oshunsanya, 2011). Though the data on aggregate stability and penetration resistance of biochar-amended soils are scarce, a few studies generally showed that low-temperature (220°C) hydrochar made from spent brewer's grains (a residue from beer brewing) responded positively to aggregation of Albic Luvisol by significantly increasing water-stable aggregates as compared to the control treatment (Mukherjee and Lal, 2013). Several authors have reported positive response of soil hydrological properties to biochar amendment. This may be due to the fact that soil hydrological properties such as infiltration rate, moisture content, hydraulic conductivity, water-holding capacity and water retention are invariably related to soil surface area, bulk density, porosity and aggregate stability (Mukherjee *et al.,* 2011). In other words, an alteration in these soil physical properties as caused by biochar application would lead to a change in soil hydrological properties.

Biochar and soil chemical properties

Most studies of biochar as a soil amendment have focused majorly on soil nutrient status, taking into consideration cation exchange capacity, nutrient content, pH, the carbon sequestration potential of the amended soil, and vegetative growth and yield of crops. Biochar has the potential to improve soil CEC due to the fact that it is often characterized by high CEC values, due to its negative surface charges and its high specific surface area as was reported for biochar produced from crop residues (Yuan, 2011). Furthermore, the immediate beneficial effect of biochar application on crop productivity in tropical soils may result from increase in availability of nitrogen, phosphorus, potassium, calcium, copper and zinc as reported for soils amended with secondary forest biochar (Lehmann *et al.,* 2003). The chemical properties of soil are also impacted including an increase in soil carbon, pH, and CEC (Laghari *et al.,* 2016). Biochar application can directly or indirectly affect SOC dynamics. Indirectly, biochar could affect net primary production and, thus, the amount of biomass that may remain in agroecosystems. This would result to alteration in soil carbon inputs. The higher belowground net primary production and increased root-derived carbon inputs after biochar application may particularly result in an increase in SOC (Sohi *et al.,* 2010). Directly, biochar can inhibit degradation process, and as a result increase the mean residence time (MRT) of SOC (i.e. the mean time that a SOC-carbon atom spends in soil). As a direct consequence, biochar application would enhance SOC stabilization processes and contribute to SOC sequestration.

Effect of biochar on soil microbiology

Biochar is considered recalcitrant due to its resistance to microbial decay (Lehmann *et al.,* 2011). However, the high porosity can provide additional niches for microorganisms (Barrow, 2012; Pietika¨inen *et al.,* 2000). Depending on the biochar and soil type, biochar may also reduce changes within the microbial community structure and function (Anderson *et al.,* 2011), have no effect on species richness or diversity (Rutigliano *et al.,* 2014), or increase microbial abundance (Ding *et al.,* 2016). Biochar application has also been found to increase the amount of bacteria with decreased fungi abundance (Chen *et al.,* 2013) or by increasing k-strategist microbial biomass and increasing species richness (Liang *et al.,* 2010; O'Neill *et al.,* 2009). It may also increase plant root colonization by ectomycorrhizal fungi and arbuscular mycorrhizal fungi (Warnock *et al.,* 2007) or shift the microbial community to one that prefers aromatic C (Bamminger *et al.,* 2014). Additionally, biochar can affect the activity of soil enzymes by inhibiting or increasing the contact with SOM (Thies *et al.,* 2015). The variety of different biochars, with varying chemical and physical properties, in conjunction with varying soil environments likely causes the wide range of microbial responses to biochar amended soils. Studies have shown higher microbial biomass but yet lower microbial activity in biochar amended soil than the neighbouring soils (Thies and Rillig M, 2009). However, most studies have focused on biochar interaction with mycorrhizal fungi (Thies and Rillig M, 2009). Specifically, biochar has been reported to have symbiotic relationship with the mycorrhizal system. According to Warnock *et al.*, 2007 the four mechanisms by which biochar could improve mycorrhizal abundance (40%) and functioning are listed as follows:

Alteration of soil physico-chemical properties,

Indirect effects on mycorrhizae through effects on other soil microbes,

Plant-fungus signalling interference, and

Detoxification of allelochemicals on biochar.

Nutrient immobilization and release

The potential benefits of biochar to improving soil fertility through nutrient addition and improvements in fertilizer-use efficiency are well recognized, as stated above. However, unintentional consequences such as nutrient sorption, increased leaching of some nutrients, and increased EC need consideration prior to biochar application to soil. The changes in N dynamics following biochar application are not fully understood (Clough *et al.,* 2010; Lehmann, 2007a; Singh *et al.*, 2010a).However, it has been suggested that weathering of biochar in soil can lead to immobilization of N (Singh *et al.,* 2010a; Yao *et al.,* 2009). It has been noted that biochar at high application rates (10% or 20%, w/w) can effectively reduce NH_4 leaching in contrasting soils (Lehmann *et al.,* 2003). But this effect depends on biochar type and soil and their contact time (aging). Singh *et al.,* (2010a) demonstrated that while freshly added biochars had little effect on NH4 leaching, upon aging in soil (around 5 months), the wood- and poultry litter-based biochars produced at 550 (Singh and Heffernan, 2002). Biochar applications may result in increased initial leaching of nutrients (*e.g.*, nitrate) from soil, especially when the biochars have high N content (Singh *et al.,* 2010a). As biochar alters N dynamics in soil, it can be expected to influence gaseous losses of N. Loss of N as N_2O provides a small, but environmentally significant route for N loss from soil to the atmosphere. Nitrous oxide is produced through a range of mechanisms in soil including nitrification, nitrifier denitrification, and denitrification (Baggs, 2008), and it has been suggested that biochar can play a significant role in altering these processes (Singh *et al.*, 2010a; Van Zwieten *et al.*, 2009, 2010b). Incorporation of biochar into soil has been reported to either stimulate or suppress depending on initial soil moisture content (Rondon *et al.,* 2007; Singh *et al.*, 2010a;Yanai *et al.*, 2007) or make no change in N2O emissions (Clough *et al.,* 2010). Different biochar–soil combinations may show varying results. Further studies on biochar application on N dynamics in soils are warranted (Clough *et al.,* 2010; Lehmann, 2007a). While the artificial aging of biochar in the presence of humic substances resulted in immobilization of N (Yao *et al.,* 2009), the availability of other nutrients, particularly P, Ca, Mg, K increased. Sinclair *et al.,* (2010) noted increases in plant available P following amendment with animal manure biochar in a field studies on a ferrosol, a result not observed with greenwaste biochar. Conversely, high rates of biochar application (4.4% and 11%, w/w) to a sandy Yellow Earth resulted in a small but statistically significant reduction in plant available P (Van Zwieten *et al.,* 2010c). It has been suggested that biochar may increase the EC of leachate, attributed to loss of Na and K from the biochar–soil matrix

(Lehmann *et al.,* 2003; Novak *et al.,* 2009). It is clear that impacts on nutrients are dependent upon the properties of both soil and biochar. The wide range of effects on nutrient dynamics from biochar application to soil is still poorly understood, as effects can be highly soil and biochar specific. Given the ability of biochar to immobilize a wide range of organic and inorganic chemicals, it is conceivable that by applying biochar to soil could influence the plant uptake of a range of organic compounds or micronutrients and their unbalanced uptake may affect even the quality of the produce. This aspect has not received any attention in the literature so far. C were able to reduce leaching of NH_4 by 55–65% in an Alfisol.

Potential drawbacks of Biochar

Despite the ability of biochar to improve a number of soil problems, it is not a straight forward process. An issue with the creation of biochar is choosing a feedstock with low moisture content. While there are some methods that work well with wetter feedstocks, the biochar they create has a high oxygen-to-carbon ratio, which results in a lower aromatic structure that is easier to degrade in soil (Spokas *et al.,* 2012). Due to the difference in structure, these types of biochar are less suited to carbon sequestration compared to a more recalcitrant biochar. While it is possible to dry out wetter feedstock, this can add onto the cost and time of production. Another important initial feedstock characteristic is the concentration of its elemental makeup, as the concentration of these elements is often magnified in the final product (Spokas *et al.,* 2012). Therefore, a feedstock high in elements known to cause plant toxicity would not make a biochar that is ideal for crop production. The process of pyrolysis may also produce harmful byproducts such as polycyclic aromatic hydrocarbons (Laghari *et al.,* 2016). Another variable to the complex issue of biochar as a soil amendment is the wide variety of agriculture management practices that impact how soils function. This includes what tillage practices are used, the type of fertilizer, the rate of fertilizer, the type of crop rotation, and the agricultural history of the land under cultivation (Karhu *et al.,* 2011; Major *et al.,* 2010). Even when biochar and fertilizer are applied, crop yields do not always increase; therefore it is not just increasing nutrient availability that is responsible for increased crop yields, and other variables are also responsible (Spokas *et al.,* 2012). It is important to establish what biochar does within the soil because it is very stable and nearly impossible to remove from the soil (Barrow, 2012; Jones *et al.,* 2012). Therefore, if adverse effects were to occur, little could be done to quickly remedy the situation.

Biochar and environmental remediation

The properties of biochar make it an ideal candidate for environmental remediation of organic and inorganic pollutants for both contaminated water and soils due to the high surface area, microporosity, and the negatively and positively charged surface functional groups (Ahmad *et al.,* 2014). Biochar can be used to sorb organic compounds like pesticides and herbicides; however it reduces the ability of microbes to break down these substances and thereby increasing the longevity of these contaminants in the environment (Xie *et al.,* 2015). For inorganic ions, metals can be physically entrapped or chemically sorbed onto the biochar (Inyang *et al.,* 2016). Unlike with organic compounds, biochar is not inhibiting microbial breakdown of inorganic pollutants while trapped within the micropores (Beesley *et al.,* 2011). Additionally, biochar is alkaline and therefore the increase of soil pH stabilizes metals, with the exception of arsenic (Ahmad *et al.,* 2014; Beesley *et al.,* 2011). The alkalinity may also cause some metals to precipitate out of solution and onto the surface of the biochar (Inyang *et al.,* 2016). This can reduce the availability of these metals to plants (Zhang *et al.,* 2013). There are unknowns associated with the use of biochar as a remediation tool, including the saturation point of biochar and the longevity of metal immobilization (Beesley *et al.,* 2011). Additionally, different biochars created at different temperatures had varying responses to metals although high pyrolysis temperature and an animal-derived biochar tend to be the most effective (Higashikawa *et al.,* 2016).Optimizing feedstock and pyrolysis factors and matching them to specific environmental contaminants require further testing. The success of field trials (Zhang *et al.,* 2013) and the economic feasibility of large-scale applications alsoneed to be considered (Higashikawa *et al.,* 2016). Lastly, the combination of biochar with phytoremediation or the growth of abioenergy crop also needs to be further explored (Paz-Ferreiro *et al.,* 2014.

Greenhouse gas emissions from soil affected by biochar amendment

The GHGs: CO2, methane (CH4), and nitrous oxide (N_2O) are the main contributors to radiative forcing in the atmosphere (Van Zwieten *et al.,* (2009); Lal, 2004 and 2008). Besides various anthropogenic activities (fossil fuel combustion, cement production, industrial procedures), agronomic practices (drainage of wetlands, plowing, land use conversion), rice (*Oryza sativa*) paddy fields, fertilizers, livestock and wetlands are important sources of GHGs such as CH_4 and N_2O (Lal, 2004). Emission of GHGs from biochar-amended soils depends on biomass types, pyrolysis conditions (temperature, duration), soil type, climatic conditions, and soil physical properties (Rondon, 2007). Yet, the application of biochar amendments may either have no effect or even increase emissions of GHGs (Zimmerman, 2010). In some cases, application of biochar may initially enhance emission of CO_2. Jones *et al.,* 2012 argued that the initial C loss during a short-term CO_2 emission is comparatively negligible compared to the amount of C stored within the biochar itself and thus should not overshadow the C sequestration potential of biochar on a long-term basis. Nonetheless, 17%–23% of biochar-C can be mineralized leading to CO_2 emission [72]. Such contradictory results of GHG emissions from lab incubation (Rondon, 2007) *versus* field observations (Scheer *et al.,* 2011) indicate that care should be taken in interpretation and extrapolation of lab incubation data to large field scale. In addition, some of the proposed mechanisms of GHG emissions from soils are also debatable (Lehmann, 2008).

N_2O emissions from biochar-amended soils

Some field and incubation studies have demonstrateda reduction in N_2O emissions from biochar-amended soils (Rogovska *et al.,* 2011). For example, a field trial withpaddy soil (hydroagric Stagnic Anthrosol) amended with biochar from wheat straw (*Triticum sativum*)produced at 350–550 °C indicated that CH_4 emission increased by 31 and 49% while N_2O emission decreased by 50 and 70%, at application rates of 10 and 40 Mg ha−1, respectively(Zhang *et al.,* 2012). Another study, conducted on a fine loamy Clarion soil amended with biochars produced from oak (*Quercus spp.*) and hickory (*Carya spp.*) at 450–500 °C, demonstrated reduction of N_2O but enhancement of CO_2 emission in a long-term column incubation experiment. In this study, soil BD was weakly correlated with N*2*O flux indicating that an increase in soil aeration reduced N_2O emission (Rogovska *et al.,* 2011). However, another soil incubation study with hardwood biochar demonstrated that N_2O emission from amended sandy loam was suppressed up to 98% compared to that of the control, but enhancement of soil aeration by biochar amendment did not contribute to this effect (Case *et al.*, 2012). Although most studies document N_2O reduction from biochar-amended soils, there are also examples where biochar-amended soils stimulated N_2O emissions. For example, an initial N_2O enhancement due to higher labile N content of biochar and microbial activity was observed by Singh *et al.*, 2010; however, such a spike eventually decreased over time. Yanai *et al.*, 2010 observed that addition of 10% (w/w) municipal waste biochar produced at 700 °C to a clay loam soil suppressed N_2O emission by 89% when soil was wetted up to 78% water-filled pore space (WFPS). However, N_2O emission was significantly enhanced by up to 51% when the same soil was re-wetted at 83% WFPS. This phenomenon was attributed to aeration improvements of soil that stimulates N_2O-producing microbial activity.

CO_2 and CH_4 emissions from biochar-amended soils

In contrast to decreases in N_2O emission in most cases, biochar-amended soils may enhance CO_2 and CH_4 emissions (Rondon *et al.*, 2005). Initial spikes in CO_2 release from biochar-amended soils are caused both by biotic and abiotic processes (Zimmerman, 2010). Liu *et al.*, (2011) reported that CH_4 and CO_2 emissions were reduced by 51 and 91%, respectively, when a paddy soil was amended with bamboo (*Bambuseae spp.*) and rice straw biochar pyrolyzed at 600 °C (Liu, *et al.*, 2012).

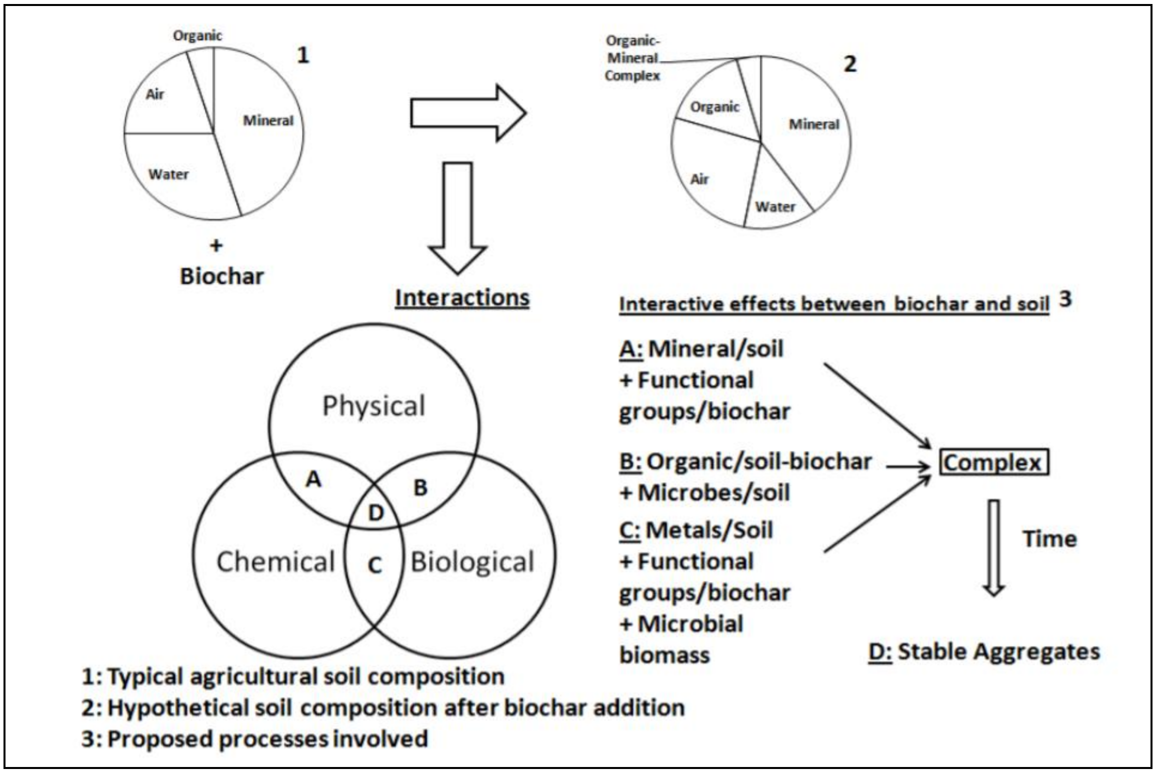
Acidic soil amended with biochar suppressed CH_4 by 100% and N_2O by 80% in a greenhouse experiment. In a long-term field study, CH_4 emission was reduced from a tropical acid savanna soil in the eastern Colombian Plains amended with biochar derived from mango tree(*Mangifera indica*) (Rondon *et al.*, 2005). Spokas *et al.*, 2009 observed reduced emission of CO_2 from a silt loam soil amended with wood chip biochar compared to un-amended control, at a rate of >20% (w/w). A 100-day incubation study conducted by Spokas and Reicosky, 2009 demonstrated reductions in emissions of all three GHGs when three different soil types were amended with 16 types of biochars. However, no consistent trends were observed in response to types of soil and amendment.

No change in CO_2 or CH_4 emissions

Some studies have documented minimal impacts or no significant differences in the net GHG fluxes under field trials or laboratory incubation studies with biochars. While soil N_2O fluxes decreased by up to 79% in different biochar-treated compared to control plots but no significant differences occurred in CH_4 and CO_2 fluxes. A field study in Australia carried out by Scheer *et al.*, indicated no significant difference in GHG fluxes from control *versus* treated red Ferrosol-amended with cattle waste biochar produced at 550 °C.

Spokas and Reicosky observed that among the 16 biochars used, eight of the biochars had no significant change in CO_2 concentrations in biochar-amended soils compared to controls. Similarly, Singh *et al.*, 2010a observed that emission of N_2O from wood and poultry manure biochars-amended Alfisols and Vertisols was suppressed by 73% compared to control, while overall CO_2 emission was not significant by addition of biochar. In addition, Hilscher *et al.*, 2009 observed that a loam soil amended with biochar derived from pine (*Pinus sylvestris*) wood had no changes in respired CO_2 compared to control but enhanced emission with biochar derived from rye grass (*Lolium perenne*)indicating feedstock dependency on gaseous flux.

Fig.1 Schematic representation of interactions between biochar and soil (Mukherjee and Lal, 2013)



Mechanisms affecting GHG fluxes with biochar amendment

The effects on GHG fluxes following application of biochar are often contradictory. Specific mechanisms governing such effects are not clearly understood (Case *et al.,* 2012). Specific responses may be related to soil chemical, physical (abiotic) or microbiological (biotic) properties and associated processes (Van *et al.,* 2019).

N_2O flux

The N_2O gaseous flux is complex because both aerobic and anaerobic processes are involved. The mechanisms of N_2O production from unamended soils are governed by three biotic pathways (Khalil *et al.,* 2004):

Nitrification, Nitrifier denitrification and Denitrification

These pathways are related to soil physical properties such as moisture content, and aeration. The mechanisms of N_2O reduction from biochar-amended soils are attributed to increased soil aeration (Yanai *et al.*, 2007) sorption of NH_4^+ or NO_3^- or presence of microbial inhibitor compounds such as ethylene.

In contrast, a range of pH and higher soil aeration may have no impact on N_2O emission from biochar-amended soils, and reduction in N_2O emission is explained by physical or biological immobilization of NO_3^- (Case *et al.,* 2012). In addition, some studies have documented enhanced N_2O emission with biochar amendment. For example, Yanai *et al.*, 2007 observed N_2O suppression by 89% from clay loam soil amended with 10% (w/w) municipal waste biochar derived at 700 °C under 78% WFPS but re-wetting soils at 83% WFPS significantly enhanced N_2O emission by up to 51%. This phenomenon was attributed to aeration improvement of soil and stimulation of N_2O -producing activity of microbes or nitrifiers (Dobbie and Smith, 2001) however, intermittent wetting is identified as one of the causes enhancing N_2O production from various types of soils.

Thus, the mechanisms behind the biochar role in N_2O flux in soil are still unclear, and apparently dependent on properties of both biochar and soil and antecedent conditions (Van, 2009).

CO_2 flux

Application of biochar can initially increase CO_2 efflux (Smith *et al.,* 2010) because of:

Microbial decomposition of 'young' or more labile components of biochar,

Abiotic release of inorganic C and

The 'priming effect' by enhanced decomposition of existing OM or soil humus by biochar addition.

Thus, initial CO_2 release by biochar addition is due both to (i) mineralization of labile-C added through biochar and (ii) stimulation of microbial activity and thereby higher initial decomposition of SOM by biochar addition is expected.

Release of labile soluble C from biochar by the first mechanism is due to increased availability of the medium as microbial substrate. In one study, initial CO_2 released from biochar-amended soils was estimated to be coming equally from microbial breakdown of soluble or labile C as well as from the abiotic release of mineral or carbonate C (Jones *et al.,* 2012). This change in CO_2 flux is reported to be affected not by soil physical properties (*i.e.*, BD, porosity, and moisture content) upon biochar addition into the soil, but mostly by soil temperature regime and land management (Scheer *et al.*, 2011).

CH_4 flux

Increase in soil aeration and porosity by biochar amendment may decrease production of CH_4 from soil as anoxic conditions created may increase oxidation of CH_4 (Van *et al.*, 2011).

The latter depends on both diffusion and methanotrophs activity in soil (Liu *et al.*, 2011). Furthermore, the aerobic, well drained soils can be a sink for CH_4 due to the high rate of CH_4 diffusion and subsequent oxidation by methanotrophs (Dalal and Allen, 2008).

Clearly, two mechanisms: (i) decrease in CH_4 production, and (ii) increase in CH_4 oxidation by methanotrophs may be operational in the soil/biochar system depending on specific conditions (Karhu *et al.,* 2011).

In summary, the emissions of CO_2, CH_4 and N_2O from biochar-amended soil are controlled by soil physical properties such as moisture content, aeration, porosity, OM content and they could both be biotic (microbial response) or abiotic (mineralization or decomposition of SOM).

However, the responses are soil/biochar specific, complex and mechanisms are not clear yet.

Future research

While biochar has been the topic of much research, there are still large knowledge gaps that need to be addressed. The longevity of biochar in field conditions and the long-term impacts of biochar are two unknowns. The mechanisms behind how biochar impacts the soil environment, including changes in soil physical and chemical properties as well as the impact of biochar on the soil microbial communities, need to be further explored especially in regards to changes in biogeochemical cycles (Ding *et al.*, 2016; Thies *et al.*, 2015). More research is needed to find ways to alter biochar to further reduce GHG emission when amended into soils, especially in field experiments (Mandal *et al.*, 2016). Additionally full-scale outdoor trials of biochar as a way to restore contaminated soils and assess how long biochar retains the metals as it ages in the field (Zhang *et al.*, 2013). Lastly, increased understanding in the creation of designer biochars to target specific soil deficiencies using tailored biochar feedstocks and pyrolysis processes (Ding *et al.*, 2016). As biochar continues to be utilized as a soil conditioner, these unknowns need to be addressed given the difficulty of removing biochar from the environment.

References

Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M, Lee SS, and Ok YS. (2014) Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere* 99: 19–33.

Anderson CR, Condron LM, Clough TJ, Fiers M, Stewart A, Hill RA, and Sherlock RR. (2011) Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. Pedobiologia 54(5–6): 309–320. http://dx.doi.org/10.1016/j.pedobi.2011.07.005.

Atkinson CJ, Fitzgerald JD, and Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. Plant and Soil 337 (1–2): 1–18. http://dx.doi.org/10.1007/s11104-010-0464-5.

Baggs, E. M. (2008). A review of stable isotope techniques for N_2O source partitioning in soils: Recent progress, remaining challenges and future considerations. *Rapid Commun. Mass Spectrom.* 22, 1664–1672.

Bamminger C, Zaiser N, Zinsser P, Lamers M, Kammann C, and Marhan S. (2014). Effects of biochar, earthworms, and litter addition on soil microbial activity and abundance in a temperate agricultural soil. *Biology and Fertility of Soils* 50(8): 1189–1200. http://dx.doi.org/10.1007/s00374-014-0968-x.

Barrow CJ. (2012) Biochar: Potential for countering land degradation and for improving agriculture. Applied Geography 34: 21–28.

Beesley L, Moreno-Jime´nez E, Gomez-Eyles JL, Harris E, Robinson B, and Sizmur T. (2011). A review of Biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution* 159(12): 3269–3282. http://dx.doi.org/10.1016/j.envpol.2011.07.023.

Case, S.D.C.; McNamara, N.P.; Reay, D.S.; Whitaker, J.(2012)**.** The effect of biochar addition on N_2O and CO_2 emissions from a sandy loam soil—The role of soil aeration. *Soil Biol. Biochem.*, 51, 125–134.

Cha JS, Park SH, Jung S-C, Ryu C, Jeon J-K, Shin M-C, and Park Y-K. (2016) Production and utilization of biochar: A review. Journal of Industrial and Engineering Chemistry 40: 1–15.
http://dx.doi.org/10.1016/j.jiec.2016.06.002.

Chen H-X, Du Z-L, Guo W, Zhang Q-Z. (2011). Effects of biochar amendment on cropland soil bulk density, cation exchange capacity, and particulate organic matter content in the North China plain. *Yingyong Shengtai Xuebao*.; 22: 2930–4.

Chen J, Liu X, Zheng J, Zhang B, Lu H, Chi Z, Pan G, *et al.*, (2013) Biochar soil amendment increased bacterial but decreased fungal gene abundance with shifts in community structure in a slightly acid rice paddy from southwest china. Applied Soil Ecology 71: 33–44. http://dx.doi.org/10.1016/j.apsoil.2013.05.003.

Clough, T. J., Bertram, J. E., Ray, J. L., Condron, L. M., O'Callaghan, M., Sherlock, R. R., and Wells, N. S. (2010). Unweathered wood biochar impact on nitrous oxide emissions from a bovine-urine amended pasture soil. *Soil Sci. Soc. Am. J.* 74, 852–860.

Dalal, R.C.; Allen, D.E. (2008). Turner review No. 18. Greenhouse gas fluxes from natural ecosystems. *Aust. J. Bot.*, 56, 369–407.

Ding Y, Liu Y, Liu S, Li Z, Tan X, Huang X, Zeng G, Zhou L, and Zheng B (2016) Biochar to improve soil fertility. A review. Agronomy for Sustainable Development 36(2): 36.

http://dx.doi.org/10.1007/s13593-016-0372-z.

Dobbie, K.E.; Smith, K.A. (2001). The effects of temperature, water-filled pore space and land use on N_2O emissions from an imperfectly drained gleysol. *Eur. J. Soil Sci*., 52, 667–673.

Fernandes MB, Skjemstad JO, Johnson BB, Wells JD, Brooks P. (2003). Characterization of carbonaceous combustion residues. In: Morphological, elemental and spectroscopic features. *Chemosphere*; 51: 785–95.

Fernandes MB, Skjemstad JO, Johnson BB, Wells JD, Brooks P. (2003). Characterization of carbonaceous combustion residues. In: Morphological, elemental and spectroscopic features. *Chemosphere*; 51: 785–95.

Glaser, B., Lehmann, J., and Zech, W. (2002). Ameliorating physical and chemical properties

Glaser, B., Parr, M., Braun, C., and Kopolo, G. (2009). Biochar is carbon negative. *Nat.Geosci*. 2(1), 2.

Hammes K, Torn MS, Lapenas AG, Schmidt MWI. (2008). Centennial black carbon turnover observed in a Russian steppe soil. *Biogeosciences;* 5: 1339–50.

Higashikawa FS, Conz RF, Colzato M, Cerri CEP, and Alleoni LRF. (2016) Effects of feedstock type and slow pyrolysis temperature in the production of biochars on the removal of cadmium and nickel from water. *Journal of Cleaner Production* 137: 965–972. http://dx.doi.org/10.1016/j.jclepro.2016.07.205.

Hilscher, A.; Heister, K.; Siewert, C.; Knicker, H. (2009). Mineralisation and structural changes during the initial phase of microbial degradation of pyrogenic plant residues in soil. *Org. Geochem*., 40, 332–342.

Inyang MI, Gao B, Yao Y, Xue Y, Zimmerman A, Mosa A, Pullammanappallil P, Ok YS, and Cao, X. (2016) A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. *Critical Reviews in Environmental Science and Technology* 46(4): 406–433. http://dx.doi.org/10.1080/10643389.2015.1096880

Jagiello J, Thommes M. (2004). Comparison of DFT characterization methods based on N_2,Ar, CO_2, and H_2 adsorption applied to carbons with various pore size distributions. *Carbon*; 42: 1227–32.

Jagiello, J.; Thommes, M. (2004). Comparison of DFT characterization methods based on N_2, Ar, CO_2,and H_2 adsorption applied to carbons with various pore size distributions. *Carbon*, 42, 1227–1232.

Jones BEH, Haynes RJ, Phillips IR. (2010). Effect of amendment of bauxite processing sand with organic materials on its chemical, physical and microbial properties. *J Environ Manag,* 91: 2281–8.

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

Jones, D.L.; Murphy, D.V.; Khalid, M.; Ahmad, W.; Edwards-Jones, G.; DeLuca, T.H. (2011).Short-term biochar-induced increase in soil CO2 release is both biotically and abiotically mediated. *Soil Biol. Biochem*., 43, 1723–1731.

Karhu K, Mattila T, Bergstro¨m I, and Regina K. (2011) Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity—Results from a short-term pilot field study. *Agriculture, Ecosystems & Environment* 140(1–2): 309–313.

Khalil, K.; Mary, B.; Renault, P. (2004). Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration. *Soil Biol. Biochem*., 36, 687–699.

Laghari M, Naidu R, Xiao B, Hu Z, Mirjat MS, Hu M, Kandhro MN, *et al.,* (2016) Recent developments in biochar as an effective tool for agricultural soil management: A review. *Journal of the Science of Food and Agriculture* 96(15): 4840–4849. http://dx.doi.org/10.1002/jsfa.7753.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. Geoderma, 123, 1–22.

Lal, R. (2008). Carbon sequestration. Philos. Trans. R. *Soc. B Biol. Sci*, 363, 815–830.

Lehmann J. (2007a) A handful of carbon. *Nature* 447(7141): 143–144.

Lehmann J. (2007b) Bio-energy in the black. *Frontiers in Ecology and the Environment* 5(7): 381–387.

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: 343–57.

Lehmann J, Gaunt J, and Rondon M (2006) Bio-char sequestration in terrestrial ecosystems—A review. *Mitigation and Adaptation Strategies for Global Change* 11(2): 395–419.

Lehmann, J., and Joseph, S. (2009). Biochar for environmental management: An introduction. In "Biochar for Environmental Management: Science and Technology" (J. Lehmann and S. Joseph, Eds.), Earthscan, London.

Liang B, Lehmann J, Sohi SP, Thies JE, O'Neill B, Trujillo L, Gaunt J, *et al.*, (2010) Black carbon affects the cycling of non-black carbon in soil. Organic Geochemistry 41(2): 206–213.http://dx.doi.org/10.1016/j.orggeochem.2009.09.007. 2008 Australian Organic Geochemistry Conference: A national conference held in association with the International Humic Substances Society and the Natural Organic Matter Interest Group.

Liu, Y.X.; Yang, M.; Wu, Y.M.; Wang, H.L.; Chen, Y.X.; Wu, W.X. (2011). Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar. *J. Soils Sediments*, 11, 930–939.

Major J, Rondon M, Molina D, Riha SJ, and Lehmann J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna *Oxisol. Plant and Soil 333* (1–2): 117–128. http://dx.doi.org/10.1007/s11104-010-0327-0.

Manya` JJ. (2012) Pyrolysis for biochar purposes: A review to establish current knowledge gaps and research needs. *Environmental Science & Technology* 46(15): 7939–7954. http://dx.doi.org/10.1021/es301029g.

McHenry MP. (2011) Soil organic carbon, biochar, and applicable research results for increasing farm productivity under Australian agricultural conditions. *Communications in Soil Science and Plant Analysis* 42(10): 1187–1199. http://dx.doi.org/10.1080/00103624.2011.566963.

Mukherjee A and Lal R. (2013) Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy* 3(2): 313–339.

Mukherjee A, Zimmerman AR, Harris WG. (2011). Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma*; 163: 247–55.

Mukherjee A. (2011). Physical and Chemical Properties of a Range of Laboratory-produced Fresh and Aged Biochars [thesis]. Gainesville, FL, USA: University of Florida;.

Novak JM, Lima I, Xing B, Gaskin JW, Christoph S, Das KC, Ahmedna M, Rehrah D, Watts DW, and Busscher WJ (2009) Characterization of designer biochar produced at different distribution, implications and current challenges. *Glob. Biogeochem. Cycle* 14, 777–793. Earthscan: London, UK, 2009.

O'Neill B, Grossman J, Tsai MT, Gomes JE, Lehmann J, Peterson J, Neves E, and Thies JE (2009) Bacterial community composition in Brazilian anthrosols and adjacent soils characterized using culturing and molecular identification. *Microbial Ecology 58(1):* 23–35. http://dx.doi.org/10.1007/s00248-009-9515-y. of highly weathered soils in the tropics with charcoal: A review. *Biol. Fertil. Soils* 35,219–230.

Ogawa, M., Okimori, Y., and Takahashi, F. (2006). Carbon sequestration by carbonization of biomass and forestation: Three case studies. Mitig. Adapt. Strateg. Glob. Change 11, 429–444.

Oshunsanya SO 2011. Soil Physics. 1st ed. Nigeria: Dabank Publishers;. 166 p.

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

Pietika¨inen J, Kiikkila¨ O, and Fritze H (2000) Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. *Oikos 89(2*): 231–242. http://dx.doi.org/10.1034/j.1600-0706.2000.890203.x.

Rogovska, N.; Laird, D.; Cruse, R.; Fleming, P.; Parkin, T.; Meek, D. (2011). Impact of biochar onmanure carbon stabilization and greenhouse gas emissions. *Soil Sci. Soc. Am. J.,* 75,871–879.

Rondon, M. A., Lehmann, J., Ramı´rez, J., and Hurtado, M. (2007). Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. *Biol. Fertil. Soils* 43, 699–708.

Rondon, M.; Ramirez, J.; Lehmann, J. (2005). Charcoal Additions Reduce Net Emissions of Greenhouse Gases to the Atmosphere. In Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, MD, USA, 21–24 March; p. 208.

Rutigliano FA, Romano M, Marzaioli R, Baglivo I, Baronti S, Miglietta F, and Castaldi S (2014) Effect of biochar addition on soil microbial community in a wheat crop. *European Journal of Soil Biology* 60: 9–15.

Scheer, C.; Grace, P.R.; Rowlings, D.W.; Kimber, S.; Van Zwieten, L. (2011). Effect of biochar amendment on the soil-atmosphere exchange of greenhouse gases from an intensive subtropical pasture in northern New South Wales, Australia. *Plant Soil* : 345, 47–58.

Schmidt MWI, Noack AG. (2000). Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. *Glob Biogeochem Cycles*. ;14:777–93.

Schmidt, M. W. I., and Noack, A. G. (2000). Black carbon in soils and sediments: Analysis,

Schnell RW, Vietor DM, Provin TL, Munster CL, and Capareda S. (2012). Capacity of biochar application to maintain energy crop productivity: Soil chemistry, sorghum growth, and runoff water quality effects. *Journal of Environmental Quality* 41(4): 1044. http://dx.doi.org/10.2134/jeq2011.0077

Sinclair, K., Slavich, P., Morris, S., Kimber, S., Downie, A., and Van Zwieten, L. (2010). Influence of biochar on soil fertility, carbon storage and biomass in subtropical pasture: Results from a 3 year field study. In "Proceedings of the 3rd International Biochar Conference, Rio de Janeiro, Brazil, 12–15 September 2010," pp. 169–170.

Singh, B. P., Hatton, B. J., Singh, B., Cowie, A. L., and Kathuria, A. (2010a). Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *J. Environ. Qual*. 39(4), 1224–1235.

Singh, B., and Heffernan, S. (2002). Layer charge characteristics of smectites from *Vertosols (Vertisols)* of New South Wales. *Aust. J. Soil Res.* 40, 1159–1170.

Smith, J.L.; Collins, H.P.; Bailey, V.L. (2010). The effect of young biochar on soil respiration. *Soil Biol.Biochem.*, 42, 2345–2347.

Sohi SP, Krull E, Lopez-Capel E, and Bol, R. (2010) A review of biochar and its use and function in soil. In: Donald LS (ed.). *Advances in Agronomy*, 105: pp. 47–82, San Diego, CA: Academic Press Chapter 2,

Spokas KA, Cantrell KB, Novak JM, Archer DW, Ippolito JA, Collins HP, Boateng AA, *et al.*, (2012) Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *Journal of Environmental Quality* 41(4): 973. http://dx.doi.org/10.2134/jeq2011.0069

Spokas, K.A.; Reicosky, D.C. (2010). Impacts of sixteen different biochars on soil greenhouse gas production. *Ann. Environ. Sci*. 2009, 3, 179–193.

Sweatman MB, Quirke N. (2001). Characterization of porous materials by gas adsorption: Comparison of nitrogen at 77 k and carbon dioxide at 298 k for activated carbon. Langmuir; 17: 5011–20.

Sweatman, M.B.; Quirke, N. (2001).Characterization of porous materials by gas adsorption: Comparison of nitrogen at 77 k and carbon dioxide at 298 k for activated carbon. Langmuir, 17, 5011–5020.

Thies JE, Rillig M. (2009).Characteristics of biochar: biological properties. In: Lehmann J, Joseph S. (eds.) Biochar for Environmental Management: Science and Technology. London: Earthscan;. pp. 85–105.

Thies JE, Rillig MC, and Graber ER. (2015) Biochar effects on the abundance, activity, and diversity of soil biota. In: Biochar for environmental management: Science, technology and implementation, London: Earthscan, Routledge.

Tripathi M, Sahu JN, and Ganesan P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renewable and Sustainable Energy Reviews 55: 467–481.

Uzoma KC, Inoue M, Andry H, Zahoor A, Nishihara E. (2011). Influence of biochar application on sandy soil hydraulic properties and nutrient retention. *J Food Agric Environ;*9:1137–43.

Van Zwieten L, Singh B, Joseph S, Kimber S, Cowie A, Yin Chan K. (2009). Biochar and emissions of non-CO2 greenhouse gases from soil. In: Lehmann J, Joseph S. (eds.) *Biochar for Environmental Management*. VA, USA: Earthscan: London Sterling.

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

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.JRC Scient. Technical reports.; 1-166.

Warnock DD, Lehmann J, Kuyper TW, and Rillig MC. (2007) Mycorrhizal responses to biochar in soil—Concepts and mechanisms. *Plant and Soil* 300(1–2): 9–20. http://dx.doi.org/10.1007/s11104-007-9391-5.

Xie T, Reddy KR, Wang C, Yargicoglu E, and Spokas K. (2015) Characteristics and applications of biochar for environmental remediation: A review. *Critical Reviews in Environmental Science and Technology* 45(9): 939–969.

Xu G, Lv Y, Sun J, Shao H, and Wei L.(2012) Recent advances in biochar applications in agricultural soils: Benefits and environmental implications. Clean: Soil, Air, Water 40(10): 1093–1098. http://dx.doi.org/10.1002/clen.201100738.

Yanai, Y., Toyota, K., and Okazaki, M. (2007). Effects 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.

Yao, F. X., Arbestain, M. C., Virgel, S., Blanco, F., Arostegui, J., Macia-Agullo, J. A., and Macias, F. (2009). Simulated geochemical weathering of a mineral ash-rich biochar in a modified Soxhlet reactor. *Chemosphere* 80, 724–732.

Yuan JH, Xu RK, Zhang H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures. *Biores Technol*;102:3488–97.

Zhang X, Wang H, He L, Lu K, Sarmah A, Li J, Bolan NS, Pei J, and Huang H. (2013) Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environmental Science and Pollution Research* 20(12): 8472–8483. http://dx.doi.org/10.1007/s11356-013-1659-0.

Zhang, A.F.; Bian, R.J.; Pan, G.X.; Cui, L.Q.; Hussain, Q.; Li, L.Q.; Zheng, J.W.; Zheng, J.F.; Zhang, X.H.; Han, X.J.; *et al.*, (2012). 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.

Zimmerman AR. (2010). Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environ Sci Technol*; 44: 1295–301.

Zimmerman, A.R. Environmental stability of biochar. In *Biochar and Soil Biota*; Ladygina, N.,Rineau, F., Eds.; CRC Press: Boca Raton.

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