P-ISSN: 2706-7483
E-ISSN: 2706-7491
IJGGE 2020; 2(1): 34-38
Received: 14-11-2019
Accepted: 16-12-2019

Introduction of biochar and its impacts on soil: An Overview

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Abstract

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) [22, 31]. 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) [41]. Biochar is differentiated from black carbon in that it is created with the intent to be used as a soil ameliorant (Barrow, 2012) [5]. 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) [3, 18]. 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) [18, 48] in addition to increased soil C sequestration (Lehmann, 2007a) [22].

Keywords: Biochar, doubly green revolution, Soil Chemical, Physical Properties

Introduction

This ability of biochar to amend soil quality issues, in conjunction with sequestering C, has contributed to a surge in biochar interest. Prior to 2000, a Google Scholar search of “biochar” returned 595 papers. Between 2000 and 2010 there were 4,340 papers, and within the past 6 years there were 15,400 papers published, an almost 2,500% increase from pre-2000 levels. Despite this spike in published papers, the concept of incorporating biochar into soil for agriculture is not new. Areas in the Amazon have soils rich in black carbon that date back to between 450 BC and AD 950 (Barrow, 2012) [5]. It is unclear whether the Amazonian dark earths, also known as Terra Preta, were anthropic (unintentionally formed by humans) or anthropogenic (intentionally formed by humans), but the source material it is most likely a mixture of ash from fires, midden waste, and slash and burn practices (Barrow, 2012; Spokas *et al.*, 2012) [5, 41]. Terra Preta soil is characterized by increased amounts of C, nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), compared to the surrounding soil (Glaser *et al.*, 2001; Pagano *et al.*, 2016) [12, 33]. Terra Preta sites are several times higher in soil C with large amounts of stable soil organic matter (Glaser *et al.*, 2001) [12] and harbor-specific soil biota that are thought to be responsible for the ability of the soil to maintain its higher quality (Barrow, 2012) [5].

Biochar is currently promoted as a way to initiate a “doubly green revolution” (Barrow, 2012) [5] 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) [17, 23, 30, 25]. 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) [12]. In addition, the lack of stabilizing minerals means that fertilizer application is only effective for a short-time postamendment (Glaser *et al.*, 2001) [12]. The stable nature of biochar (Kuzyakov *et al.*, 2014) [20] could make it a more effective long-term soil conditioner. In particular, one study found a single biochar application resulted in increased crop yields 4 years post amendment (Major *et al.*, 2010) [26].

Impacts of Biochar on Soil Chemical and Physical Properties

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) [11, 28, 48]. The chemical properties of soil are also impacted including an increase in soil carbon, pH, and CEC (Laghari *et al.*, 2016) [21]. 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) [3, 10, 5, 48]. The application of biochar can reduce ammonia volatilization and increase the immobilization of inorganic N (McHenry, 2011) [29]. 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) [3]. In addition, while biochar impacts on soil have been documented, less is known about how biochar changes in the soil environment (McHenry, 2011) [29]. Another important aspect of understanding how biochar impacts the soil is how it affects soil microbial communities and biogeochemical cycles (Xu *et al.*, 2012) [48].

Impacts of Biochar on soil biota

Biochar is considered recalcitrant due to its resistance to microbial decay (Lehmann *et al.*, 2011) [24]. However, the high porosity can provide additional niches for microorganisms (Barrow, 2012; Pietikainen *et al.*, 2000) [5, 35]. Depending on the biochar and soil type, biochar may also reduce changes within the microbial community structure and function (Anderson *et al.*, 2011) [2], have no effect on species richness or diversity (Rutigliano *et al.*, 2014) [37], or increase microbial abundance (Ding *et al.*, 2016) [11]. Biochar application has also been found to increase the amount of bacteria with decreased fungi abundance (Chen *et al.*, 2013) [9] or by increasing k-strategist microbial biomass and increasing species richness (Liang *et al.*, 2010; O’Neill *et al.*, 2009) [25, 32]. It may also increase plant root colonization by ectomycorrhizal fungi and arbuscular mycorrhizal fungi (Warnock *et al.*, 2007) [45] or shift the microbial community to one that prefers aromatic C (Bamminger *et al.*, 2014) [4]. Additionally, biochar can affect the activity of soil enzymes by inhibiting or increasing the contact with SOM (Thies *et al.*, 2015) [42]. 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.

Biochar and greenhouse gas emissions

The biochar-induced changes in soil microbial community structure and function may result in altered C and N cycling and a subsequent change in soil respiration and N2O flux. It can decrease emissions of GHG, including CO2 (Case *et al.*, 2014) [7], CH4 (Karhu *et al.*, 2011) [18], and N2O (Wang *et al.*, 2012; Zhang *et al.*, 2016) [44, 36]. However, some studies have also found a lack of significant differences for GHGs (Xiong *et al.*, 2007) [47] or increases in soil respiration (Deng *et al.*, 2016). Biochar can influence how C is stabilized within soils (Chen *et al.*, 2013) [9] and change the mineralization of native soil C (Liang *et al.*, 2010) [25]. Biochar may also alter the N cycle within soils by increasing the relative abundance of microbial communities involved in the reduction of N2O to N2 and the fixation of N2 to NH+4 (Anderson *et al.*, 2011) [2]. However, it is possible that microbial changes are short term due to the small amount of labile C in biochar (Ding *et al.*, 2016) [11]. It is important to consider these changes in GHG emissions from soils when considering biochar as a way to mitigate climate change.

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, micro porosity, and the negatively and positively charged surface functional groups (Ahmad *et al.*, 2014) [1]. 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) [46]. For inorganic ions, metals can be physically entrapped or chemically sorbed onto the bio char (Inyang *et al.*, 2016) [14]. Unlike with organic compounds, biochar is not inhibiting microbial breakdown of inorganic pollutants while trapped within the micropores (Beesley *et al.*, 2011) [6]. 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) [1, 6]. The alkalinity may also cause some metals to precipitate out of solution and onto the surface of the biochar (Inyang *et al.*, 2016) [14]. This can reduce the availability of these metals to plants (Zhang *et al.*, 2013) [9].

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) [6]. Additionally, different bio chars 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) [13]. Optimizing feedstock and pyrolysis factors and matching them to specific environmental contaminants require further testing. The success of field trials (Zhang *et al.*, 2013) [9] and the economic feasibility of large-scale applications also need to be considered (Higashikawa *et al.*, 2016) [13]. Lastly, the combination of biochar with phytoremediation or the growth of a bioenergy crop also needs to be further explored (Paz-Ferreiro *et al.*, 2014) [34].

Biochar production

Biochars are heterogeneous in their properties due to the wide variety of feedstock that can be used and pyrolysis technologies. Some common feedstock include switch grass, 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; Manya, 2012; Spokas *et al.*, 2012; Xu *et al.*, 2012) [3, 10, 5, 28, 41, 48]. 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) [29]. Once the feedstock is established, there are many different types of pyrolysis, including slow pyrolysis, fast pyrolysis, flash pyrolysis, vacuum pyrolysis, hydro pyrolysis, intermediate pyrolysis, and microwave-assisted pyrolysis (Manya`, 2012; Tripathi *et al.*, 2016) [43]. In addition to the solid biochar, bio-oil and bio-syngas are also products of pyrolysis (Tripathi *et al.*, 2016) [43]. Other methods to create biochar include Torre faction, flash carbonization, hydrothermal carbonization, and gasification (Cha *et al.*, 2016). The combination of many feedstock and several pyrolysis technologies makes for a plethora of biochars all varying in physicochemical 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) [41].

Importance of characterization

However, it is this versatility that also makes it difficult to establish experimental repeatability. The starting stock properties of biochar greatly influence the characteristics of the final product (Atkinson *et al.*, 2010; Barrow, 2012; Ippolito *et al.*, 2012) [3, 5, 16]. Biochar properties can be influenced by the pyrolysis process and the different variables within the process. These variables include how quickly the organic matter is heated, to what temperature it is heated to, how long it remains at that temperature, what the pressure is during this process, and what happens to the biochar post pyrolysis (Ippolito *et al.*, 2012; Manya, 2012) [15, 28]. Manipulating these variables can lead to a biochar with specific characteristics, which would be useful to amending soil in a precise manner.

It is important to have a well-characterized biochar for studies in order to begin making meaningful comparisons between studies. This will help provide more insight into how the different properties of biochar translate to changes in agriculture and carbon sequestration. The growth of this body of knowledge as well as advances in pyrolysis technology and other ways to modify biochar will allow the deliberate control of the biochar production variables which allows for the creation of a biochar with specific properties (Rajapaksha *et al.*, 2016; Spokas *et al.*, 2012) [36, 41]. While it is still a poorly understood process, some relationships between conditions and properties have been established; these relationships include increasing temperatures which result in lower yield, greater surface area, lower oxygen content, and higher fixed carbon (Manya`, 2012) [28]. The temperature can also affect Ca, Mg, and NO3 leaching, with lower temperatures resulting in less leaching (Ippolito *et al.*, 2012) [15]. High pyrolysis temperatures usually result in higher pH biochars, lower ash contents, and higher CaCO3 equivalence (Singh *et al.*, 2010) [39]. Higher temperature biochar also usually has lower CEC (Ippolito *et al.*, 2015) [16]. It also increases electrical conductivity (Kloss *et al.*, 2012) [19]. These high temperatures increase the aromatic structure of the biochar, which can allow it to better resist microbial mineralization and therefore improve C sequestration (Kloss *et al.*, 2012; Spokas *et al.*, 2012) [19, 41]. Given the wide range of biochar starting materials and the multitude of variables that can be manipulated during the process of pyrolysis, it is clear why there are inconsistent results in agricultural field and greenhouse trials with biochar. However, the ability to tailor biochar, either through feedstock or through pyrolysis manipulation, offers considerable opportunity for the use of biochar as a soil ameliorant or crop enhancer. As more characterization studies, field trials, and greenhouse trials are undertaken, trends on how different biochars and their specific properties impact soils and crop growth can be ascertained. With this information, a soil with a deficiency or problem can be matched with a biochar that was created from a specific feedstock and under certain pyrolysis conditions to amend that precise problem (Ippolito *et al.*, 2015) [16].

Potential drawbacks of Biochar

Despite the ability of biochar to improve a number of soil problems, it is not a straightforward 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) [41]. 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) [41]. 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) [21].

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) [18, 26]. 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) [41]. 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) [5, 17]. Therefore, if adverse effects were to occur, little could be done to quickly remedy the situation.

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) [11, 42]. 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) [27]. 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) [9]. Lastly, increased understanding in the creation of designer biochars to target specific soil deficiencies using tailored biochar feed stocks and pyrolysis processes (Ding *et al.*, 2016) [11]. 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.

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