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Review

Benefits and limitations of biochar amendment in agricultural soils: A review

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ABSTRACT

Current agriculture faces multiple challenges due to rapid increases in food demand and environmental concerns. Recently, biochar application in agricultural soils has attracted a good deal of attention. According to literature findings, biochar has proven to play various beneficial roles with respect to the enhancement of crop yield as a fertilizer and soil quality as a soil conditioner. It can further be used to remediate soil pollution as an adsorbent, while supporting the mitigation of greenhouse gases (GHGs) through the expansion of the soil carbon pool. The efficacy of biochar application on agricultural environments is found to be controlled by various factors such as pyrolysis temperature, feed stock, soil type, and biotic interactions. The combined effects of these factors may thus exert a decisive control on the overall outcome. Furthermore, the biochar application can also be proven to be detrimental in some scenarios. This review evaluates both the potential benefits and limitations of biochar application in agriculture soils.

1. Introduction

Food security is a major issue (Richards et al., 2016). Although there have been noticeable advances in agricultural practices after World War II, the global food supply is yet inadequate to meet the actual demands. Further, a list of emerging issues (e.g., climate change, desertification, and soil pollution) still remain to be resolved for the agriculture sector (Lobell and Field, 2007; Pullagurala et al., 2018). In particular, industrialization since the 1850s has generated a variety of industrial wastes which deteriorated soil quality and agricultural productivity (Keller et al., 2014; Reddy and Kim, 2015; Reddy et al., 2016a,b; Li et al., 2016b). Likewise, soil contamination has been accelerated by increasing quantities of pollutants such as heavy metals, engineered nanomaterials, polycyclic aromatic hydrocarbons (PAHs), and persistent organic and inorganic chemicals (Kim et al., 2011, 2012; Wang et al., 2014; Reddy et al., 2016a,b; Reddy et al., 2017, 2018). These anthropogenic sources have constantly affected plant environments, thereby causing harm to the terrestrial food chain (Gardea-Torresdey et al., 2014). Many studies have witnessed the negative impacts of contaminants on soil composition and biodiversity (Saha et al., 2015).

Biochar has recently received increased attention due to its wide range of agricultural benefits. Biochar is a carbon-based solid obtained by biomass pyrolysis. Its elemental composition comprises carbon, nitrogen, hydrogen, potassium, and magnesium all of which can serve as major nutrients in plant growth. The addition of biochar increases the amount of organic matter in the soil (e.g, organic carbon), thereby improving soil physicochemical and biological properties. Biochar can positively or negatively affect the soil microbial growth to alter the agricultural environment. This review provides a brief overview of the potential benefits of biochar based on its properties and performance along with limitations involved in its application.

2. Physiochemical properties of biochar

Biochar is a very stable, carbon-based material obtained from the pyrolysis of biomass under anaerobic conditions, and is highly recalcitrant in soils (Fig. 1). The parent material or biomass can be obtained from agricultural, municipal, animal, or industrial sources

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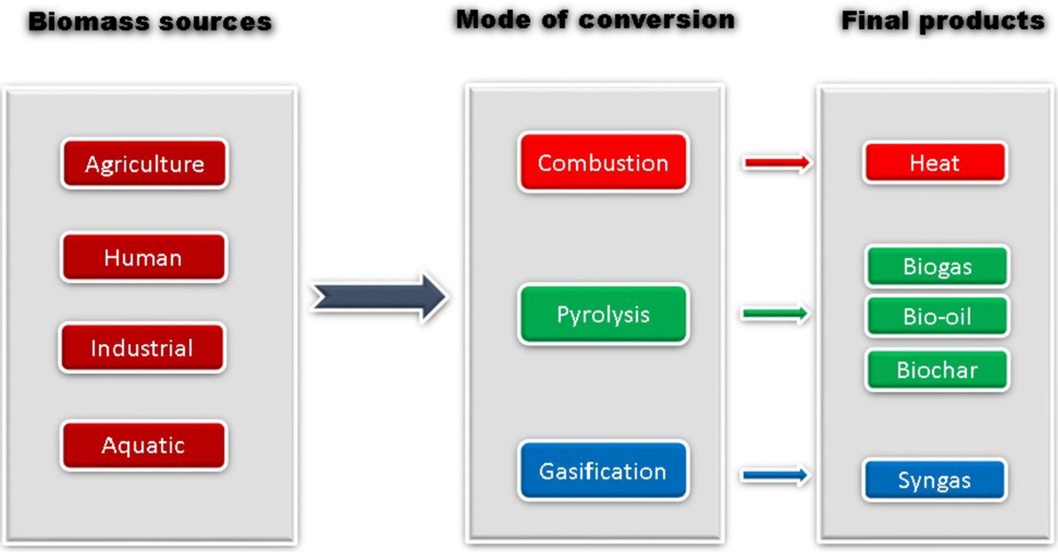

Fig. 1. Biomass sources and methods of conversion to final products.

(Kwapinski et al., 2010). The pyrolysis temperatures generally employed range from 300 to 1000 °C. Biomass is largely composed of organic compounds such as cellulose, hemicellulose, and lignin (Fahmi et al., 2008). Lignin is the most stable of these compounds, and is resistant to degradation at even higher temperatures. In contrast, temperatures above 300 °C can decrease the cellulose and hemicellulose contents. The temperature and duration of pyrolysis are determined based on the target purpose. In some cases, catalytic additives such as K_3PO_4 and clinoptilolite are used to reduce the pyrolysis temperature (Mohamed et al., 2016). During pyrolysis, water and volatile organics from the biomass may evaporate, thereby increasing the aromatic content. The parent biomass source and pyrolysis temperature affect the physiochemical properties of the biochar obtained. For instance, pyrolysis temperature is the main control on atomic ratio and structural composition (Liu et al., 2010). Although raw biomass is slightly acidic, pyrolysis at high temperatures increases its alkalinity (Al-Wabel et al., 2017). This is due to the partial detachment of the functional groups leading to the formation of unpaired negative charges such as carboxyl (COO^-) and hydroxyl groups (OH^-) that have the ability to attract positive charges (Singh et al., 2010). High-temperature pyrolysis also causes release of hydrogen- and oxygen-containing groups, contributing to increased carbon content. The tendency of the surface functional groups to attract positive charges enhances the cation exchange capacity, which is an important property of biochars for remediation of metal-contaminated soils. Furthermore, the porosity, pore size, and surface area of biochars depend on pyrolysis temperature as the high temperature of pyrolysis leads to formation of pores via the release of volatile organics (Brewer et al., 2014). Thus biochar's properties can be targeted to a range of different purposes by adjusting the pyrolysis temperature. The advantages of biochars with various physiochemical properties are shown in Fig. 2.

3. Fate and impact of biochar in agricultural soils

Understanding the fate and impacts of biochar in agricultural soil is important. Previous research has found that biochar can be an excellent soil conditioner in agricultural soils. In terms of soil physical properties, the application of biochar increases the soil aggregate stability and water holding capacity by enhancing soil pore characteristics and water retention. Soil texture and type also have a pivotal role. For instance, the benefits of biochar amendment are more pronounced in a coarse-textured than a fine-textured soil, and sandy soils are more responsive than clay-rich soils (Blanco-Canqui, 2017). Biochar particle size and application depth also affect the overall water holding capacity. According to Ibrahim et al. (2017), the water holding capacity of biochar-amended sandy soil was maximized with biochar particle sizes in the range of 0.5–1.0 mm. The preferred depth of biochar application is 4–6 cm. Biochar concentration also affects the soil's water retention capacity. An experimental study carried out by Kameyama et al. (2016) showed that concentrations of biochar greater than 3% were able to increase the water holding capacity of clay soils by 60%. However, the optimal biochar concentration must be determined on a case-by-case basis. In the case of sandy loam soil, pore size is decreased at higher biochar contents ($> 5\%$), which affects the hydraulic conductivity of the soil (Devereux et al., 2012).

The biomass feedstock is also crucial. This was experimentally proven in the study carried out by Lei and Zhang (2013), wherein the hydraulic properties of biochar were more enhanced in a wood chip-derived biochar than in a dairy manure-derived biochar. This is due to the higher porosity and surface area of the wood chip biochar. The aforementioned qualities help enhance water adsorption onto the surface of the biochar particles. The biochar amendment also improves the soil fertility as it facilitates the biochemical cycling of nitrogen and phosphorous (Gul and Whalen, 2016). Furthermore, the organic matter and inorganic ions (e.g., N, P, and K) of the biochar provide nutrients to the plant. The mean residence time of biochar is estimated to be over 3000 years. This indicates that biochars are quite stable, with very low rates of decomposition in soil. However, it must be noted that the phospholipid and glycolipid contents of the biochar are easily decomposed (Kuzyakov et al., 2014). In addition to the benefits described above, biochars also affect various other physical properties of a soil, such as swelling/shrinkage, tensile strength, surface area, and density of cracking (Zong et al., 2014).

3.1. Plant growth and stress management

Application of biochar has been shown to yield a wide range of benefits to plant growth and stress management. Studies have documented the role of biochar in improving agronomical parameters and environments for various plant species. Addition of less than 5% biochar enhanced the germination, yield, and root development of the halophytes such as *sesbania* and seashore mallow (Zheng et al., 2017). Alvarez-Campos et al. (2018) also showed that rice hull-based biochar applied at a rate of 2% to a sandy soil increased the biomass yield and sucrose content of sugarcane plants. Coconut husk biochar added at a rate of 30 t ha^{-1} was associated with a 90% increase of *Zea mays*