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Biochar application to low fertility soils: A review of current status, and future prospects

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ABSTRACT

Rapid industrial development and human activities have caused a degradation of soil quality and fertility. There is increasing interest in rehabilitating low fertility soils to improve crop yield and sustainability. Biochar, a carbonaceous material intentionally produced from biomass, is widely used as an amendment to improve soil fertility by retaining nutrients and, potentially, enhancing nutrient bioavailability. But, biochar is not a simple carbon material with uniform properties, so appropriate biochar selection must consider soil type and target crop. In this respect, many recent studies have evaluated several modification methods to maximize the effectiveness of biochar such as optimizing the pyrolysis process, mixing with other soil amendments, composting with other additives, activating by physicochemical processes, and coating with other organic materials. However, the economic feasibility of biochar application cannot be neglected. Strategies for reducing biochar losses and its application costs, and increasing its use efficiency need to be developed. This review synthesized current understanding and introduces holistic and practical approaches for biochar application to low fertility soils, with consideration of economic aspects.

1. Introduction

1.1. Background of biochar research

Biochar (BC) is a carbon-rich by-product produced by thermal degradation of organic materials under an oxygen-depleted environment (i.e., pyrolysis), and is recently recognized as an emerging technology (Lehmann, 2007a, 2007b; Lehmann et al., 2011; Ok et al., 2015). Biochar has gained attention in the past few years because of its potential applications in waste management, renewable energy, carbon sequestration, greenhouse gas (GHG) emission reduction, and soil and water remediation, as well as its potential for enhancing soil quality and crop productivity (Kuppusamy et al., 2016; Lehmann and Joseph, 2015).

Due to the substantial benefits of BC, policy-makers in many developed and developing countries are interested in BC as a promising technology. Many studies and reviews have proven the potential benefits of specific BCs as conditioners of specific soils, examining such issues as soil fertility, nutrient availability, CO_2, N_2O, and CH_4 emissions, sorption of organic and inorganic contaminants, and more (Dai et al., 2017; Gul and Whalen, 2016; Jeffery et al., 2015a; Kuppusamy et al., 2016; Lin et al., 2017; Niazi et al., 2017; Randolph et al., 2017; Singh et al., 2015; Zheng et al., 2017). However, there has been

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relatively little focus on the economic feasibility of BC application when applied to low fertility soils.

This review aims to present the current status of BC application to improve fertility, particularly in low fertility soils, while highlighting its economic feasibility. It also discusses promising strategies of BC application methods for enhancing BC use efficacy and reducing application costs. Future opportunities and challenges in BC use for low fertility soils are also discussed.

1.2. Global issues of soil fertility and productivity

Soil fertility refers to the ability of a soil to sustain crop productivity. A fertile soil is a soil having sufficient ability to provide essential nutrients and water supply for plant growth without having any toxic elements that may inhibit plant development (Havlin et al., 2014; Voltr, 2012). Typically, soil fertility is controlled by the physical, chemical, and biological characteristics of soils (Igalavithana et al., 2015), and is critical to maintain and sustain agricultural homeostasis.

Low soil fertility is a common problem in many regions around the world (FAO, 2011). For example, the soils of arid and semi-arid regions often have low water retention capacity and inadequate nutrient supply levels for most agricultural plants (Khalifa and Yousef, 2015). Tropical regions also face difficulties in maintaining sustainable crop production. There, essential plant nutrients are readily leached from topsoil by heavy rainfall, and relatively high temperatures and an abundance of decomposers result in enhanced mineralization of soil organic matter (SOM) (Bruun et al., 2015; Nyssen et al., 2015). The decrease in SOM content negatively affects the soil fertility status mainly through decreasing the aggregate stability and soil capacity to retain water and nutrients (Annabi et al., 2011).

Anthropic activities, including intensive agricultural practices, rapid industrialization, may also magnify the soil degradation. Soil degradation leads to conditions that threaten soil function and productivity (Antoniadis et al., 2017; Lal, 2015; Rajkovich et al., 2012), including salinization, desertification, erosion, nutrient depletion, etc. (FAO, 2011; Smith et al., 2015). The United Nations Food and Agriculture Organization (FAO) classified 25% of global agricultural lands as ‘highly degraded’, 44% as ‘slightly-moderately degraded’, and approximately 10% as ‘recovered from degradation’ (Bindraban et al., 2012; FAO, 2011). Degradation commonly makes a soil low in fertility and thus constrains food production (Smith et al., 2015). Therefore, restoration and rehabilitation of low fertility or degraded soil are continuously emphasized as important to the food security of humanity.

Since the start of the Green Revolution in the 1960s, the use of inorganic fertilizers has been a major means of increasing agricultural productivity (Vanlauwe et al., 2010). However, sole dependence on inorganic fertilizer is not a sustainable option for maintaining soil fertility and crop yields long-term (Usman et al., 2015a; Srinivasarao et al., 2014). Intensive agricultural practices that rely on inorganic fertilizers can threaten soil quality and sustainability (Carlson et al., 2015). Therefore, there is an increasing demand for sustainable, environmental-friendly, and economical soil amendments that can maintain or enhance soil quality and crop productivity without negative side effects (Ahmad et al., 2014; Ok et al., 2015; Shaheen and Rinklebe, 2015). Those soil amendments should be abundant and biodegradable, and should originate from non-GHG-producing renewable sources if possible (Inyang et al., 2015; Kuppusamy et al., 2016; Rinklebe et al., 2016).

1.3. Biochar properties

The physicochemical properties of BC (e.g., composition, surface area, water holding capacity, pH, electrical conductivity, particle, pore size distribution, etc.) generally depend on pyrolysis conditions and feedstock characteristics (Ahmad et al., 2012; Lehmann and Joseph, 2015; Rajapaksha et al., 2014; Solaiman and Anawar, 2015; Shaheen et al., 2018), and can thus range widely (Lehmann and Joseph, 2015). The large influence of pyrolysis temperature on the properties of three types of feedstocks (wood, manure, and grass) is clearly shown using a publicly available database (University of California - Davis Biochar Database, 2015, UC, 2015), summarizing 147–616 studies, depending upon the parameter (Fig. 1). Biochar typically contains volatile and condensed aromatic organic substances (Brewer et al., 2011) and inorganic elements (Cantrell et al., 2012; Spokas et al., 2012). Biochar made at higher temperatures, typically has a large inner surface area with high porosity, organic C, and adsorption capacity, commonly along with high pH (Park et al., 2015; Rajapaksha et al., 2015) and cation exchange capacity (CEC) (Singh et al., 2010; Spokas, 2010). Biochar ageing in a soil can also alter its properties (Joseph et al., 2010; Mukherjee et al., 2014). Hence, the potential benefits of BC application to soils vary depending on the BC and soil types (Butnan et al., 2015).

Due to its properties, BC is widely applicable for addressing environmental issues, including waste management, energy production, and climate change mitigation (El-Naggar et al., 2018a, 2018b, 2018c). For instance, BC amendment to soil may enhance the soil's physicochemical properties (i.e., CEC, pore size distribution, soil structure, bulk density, hydraulic conductivity, soil water retention, etc.) (Lei and Zhang, 2013; Lu et al., 2014; Omondi et al., 2016) and increase soil nutrient bioavailability (Dai et al., 2017; Gul and Whalen, 2016; Kuppusamy et al., 2016; Raboin et al., 2016). Due to its high chemical stability, BC has great potential to increase soil C sequestration, thereby reducing atmosphere GHG concentration. Moreover, BC is an excellent immobilizer of toxic elements in contaminated soils (Beiyuan et al., 2017; Igalavithana et al., 2017; Ok et al., 2015; Shaheen et al., 2015a).

2. Biochar for low fertility soils

Application of BC might improve degraded, and low fertility soils, and thereby increase crop productivity (Biederman and Harpole, 2013; Glaser et al., 2002; Kuppusamy et al., 2016; Randolph et al., 2017). However, some studies have reported that BC application was not effective enough to rehabilitate the degraded soils and to recover their optimum crop productivity (e.g., Schmidt et al., 2015). The positive, negative, or neutral impact BC may have on soils is summarized in Table 1. In this section, the potential enhancements and limitations of BC application to low fertility soils are discussed.

2.1. Enhancement of soil fertility and productivity

The role of BC application in the enhancement of soil fertility and productivity can be categorized into aspects relating to nutrient cycling, crop productivity, soil pH, CEC, nitrogen (N), microbial communities, water retention, and C sequestration.

2.1.1. Nutrient supply and retention

Biochar is a substance having the capacity to retain macronutrients directly, such as N (Gul and Whalen, 2016; Lin et al., 2017; Randolph et al., 2017; Yue et al., 2017; Zhang et al., 2017). This can be attributed to the nutrient content of BC itself (Glaser et al., 2002; Shepherd et al., 2017). Biochar can act as an organic fertilizer by providing soil nutrients that were present in the precursor biomass (Gul and Whalen, 2016; Lehmann et al., 2003). But the application of BC has many additional benefits for plant nutrient cycling, such as increasing retention and use efficiency, and reducing leaching, thereby improving soil fertility (Laird et al., 2010; Randolph et al., 2017). Laghari et al. (2015) reported that BC application to low fertility sandy soils increased total C by 7–11%, K by 37–42%, P by 68–70%, and Ca by 69–75% as compared to no application. In this study, those impacts were estimated via X-ray fluorescence analysis which consider the total concentration of element oxides on surfaces of particles and doesn't reflect their availability in soils. However, the other fertility parameters such as soil physical properties and crop growth showed significant improvements in BC-