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Review

Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions

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ABSTRACT

Soil microbial communities are responsive to biochar amendments. As the residence time of biochar in soil is expected to be hundreds to thousands of years, the changes in microbial community structure and functions could persist for a long period of time. Given that biochar is being applied as a soil amendment in many parts of the world, the long-term consequences for soil microbial communities need to be considered. The objective of this review is to document how biochar creates new habitats and changes the soil environment for microorganisms, which may lead to changes in microbial abundance, community structure and activities. Our meta-analysis revealed that slow pyrolyzed biochars produced from various feedstocks at temperatures from 300 °C to 600 °C consistently increased some physico-chemical properties (i.e., pH, cation exchange capacity and aggregation) and microbial parameters (i.e., abundance and community structure of microorganisms) in a vast number of soils during short ($\leq$90 days) laboratory incubations and longer (1–3 years) field studies. The biochar-mediated changes in soil physico-chemical and biological properties appeared to be a function of soil texture and biochar type based on its feedstock and production temperature, which determines key biochar characteristics such as surface area, porosity and pH. Biochars derived from manure or crop residue feedstocks tend to promote microbial abundance more than wood-derived biochars. Biochars derived from wood and other lignocellulosic-rich feedstocks tend to exhibit beneficial effects on soil microbial abundance later ($\geq$60 days) than biochars from manure or crop residue feedstocks. Coarse textured soils tend to have less aggregation, lower microbial biomass and lower enzyme activities when amended with slow pyrolyzed biochars produced at high temperatures (>600 °C), but these biochars did not affect the physico-chemical and biological properties of clayey soils. Further research is needed to evaluate the magnitude of biochar influence on soil microbial abundance and activities considering (1) the biochar particle size, surface area, porosity, nutrient content and pH, and (2) the soil organic matter (SOM) content and microbial abundance of the soil matrix. Once the microbial activities in the biochar–soil system are understood, they can be manipulated through organic and inorganic fertilizer applications to sustain or improve agricultural crop production.

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1. Introduction

Biochar is a solid carbonaceous residue made by burning biomass under oxygen-free to oxygen-deficient conditions. Wood chips, crop residues, nut shells, seed mill screenings, algae, animal manure and sewage sludge are some of the many feedstocks used in biochar production. Biochar is highly resistant to decomposition when applied to soil, its residence time ranges from tens of years to millennia (Preston and Schmidt, 2006; Verheijen et al., 2010). The persistent nature of biochar-C in soil indicates that it will contribute to soil C sequestration (Ennis et al., 2012; Lai et al., 2013; Malghani et al., 2013) and reduce greenhouse gas emissions (Stewart et al., 2013), resulting in a negative carbon balance for bioenergy generation systems that produce biochar (Lehmann, 2007).

Historically, biochar was used as a soil amendment for at least 2000 years in the Amazon basin. The "Terra Preta" soils that were regularly amended with biochar and other organic materials (e.g., fish and animal bones, plant tissues, animal feces) have higher pH, are richer in nutrients and have larger microbial populations and more diverse microbial community structure than unamended Oxisols, which are generally acidic and infertile (Liang et al., 2008; Germano et al., 2012; Taketani et al., 2013; Table 1). The higher productivity of Terra Preta soils than their unamended Oxisol counterparts led to world-wide interest in applying biochar to agricultural soils and is creating new markets for the biochar produced as a co-product from the thermochemical conversion of biomass via pyrolysis. Soil microbial communities are responsive to biochar amendment because it increases microbial abundance and activities (Lehmann et al., 2011; Chan et al., 2008; Ameloot et al., 2013a) by providing an environment with ample aeration, water and nutrients (Ameloot et al., 2013b; McCormack et al., 2013). A diverse microbial community structure is implicated in efficient nutrient transfer to crops and greater nutrient retention in soil (e.g., Gul et al., 2014a,b), which is beneficial in reducing nutrient loss from agricultural soil to the environment.

Table 1
Characteristics of Tera Preta soils of various land use types (i.e., secondary forest, grassland and agricultural land, compared to nearby unamended Oxisols (compiled from Liang et al., 2008; Germano et al., 2012; Taketani et al., 2013).

Soil chemical characteristics	Terra Preta	Unamended Oxisol
pH	4.1–5.5*	2.6–3.8
Organic C content (g kg^{-1})	15.7–31.5*	10.2–21.8
Total nitrogen (mg kg^{-1})	10–18	4–16
Total phosphorus (mg kg^{-1})	5026–9064*	139–273
Total calcium (mg kg^{-1})	40–17545*	50–165
Soil biological characteristics: microbial diversity indices		
Shannon–Weiner	6.08–6.38	5.59–5.66
Simpson	0.004	0.006–0.007
ACE (abundance-based coverage estimators)	1834.0–3523.3	1559.6–1684.5
S_{obs}	941–1696	820–852
Chao1	1551.1–2736.4	1214.4–1379.9
Singletons	10–17	11–13

Values with an asterisk (*) were significantly different ($P < 0.05$) the referenced papers.

The thermochemical conversion processes generating renewable fuels such as combustible gas (syngas) and bio-oil, leaving biochar as a byproduct, include slow and fast pyrolysis, gasification and hydrothermal carbonization. Due to the cost and scale of production that is commercially feasible, the slow and fast pyrolysis pathways are most commonly employed in making biochar to be used as a soil amendment for agriculture. Slow pyrolysis biochar is a product of traditional heating of feedstocks under oxygen-limiting conditions, for cooking and house-warming purposes and it is achieved by heating the feedstocks at temperatures from 300 to 800 °C at atmospheric pressure for hours to days (Brewer and Brown, 2012). Fast pyrolysis aims to maximize the production of bio-oil by rapid quenching of vapor produced from burning biomass at higher temperatures (400–1000 °C) with a fast heating rates i.e., >300 °C s^{-1}, for few hours (i.e., 1–2 h; Brewer and Brown, 2012; Mohanty et al., 2013).

The physico-chemical characteristics of slow and fast pyrolysis biochars depend on the feedstocks and production temperature used. Higher production temperatures yield biochars with greater surface area and porosity (Mukherjee et al., 2011; Brewer and Brown, 2012; Mohanty et al., 2013), more alkaline pH, higher carbon:nitrogen (C:N) ratio (Singh and Cowie, 2010; Cantrell et al., 2012; Novak et al., 2013; Ronsse et al., 2013) and lower dissolved organic carbon (DOC) concentrations (Uchimiya et al., 2013; Budai et al., 2014; Rajapaksha et al., 2014). These variations in biochar characteristics have implications when biochar is applied as a soil amendment. Depending on the native soil properties (e.g., texture and SOM content), biochar inputs can cause negligible to significant alteration of soil physico-chemical and biological properties.

The objective of this review is to document how biochar produced from slow and fast pyrolysis creates new habitats and changes the soil physico-chemical environment for microorganisms, which may lead to changes in microbial abundance, community structure and activities. Specifically, this review seeks to answer the following questions: (1) how does biochar type, based on its feedstock, production temperature and characteristics such as surface area, porosity and pH, affect soil physico-chemical and biological properties? and (2) will soil attributes (e.g., texture) buffer or resist biochar-induced changes in physico-chemical properties and microbial processes?

2. Biochar properties as function of feedstock and production temperature

Each biochar has distinct physico-chemical properties such as surface area, pH, concentration of various elements/nutrients