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Review

A concise review of biochar application to agricultural soils to improve soil conditions and fight pollution

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A B S T R A C T

Application of biochar to soil can play a significant role in the alteration of nutrients dynamics, soil contaminants as well as microbial functions. Therefore, strategic biochar application to soil may provide agronomic, environmental and economic benefits. Key environmental outcomes may include reduced availability of toxic metals and organic pollutants, reduced soil N losses and longer-term storage of carbon in soil. The use of biochar can certainly address key soil agronomic constraints to crop production including Al toxicity, low soil pH and may improve nutrient use efficiency. Biochar application has also demerits to soil properties and attention should be paid when using a specific biochar for a specific soil property improvement. This review provides a concise assessment and addresses impacts of biochar on soil properties.

1. Introduction

Biochar is an organic material produced via thermal processing of biomass (in the absence of, or under reduced O_2 concentrations) (Gonzaga et al., 2017; Kalinke et al., 2017). Pyrolysis of biomass yields variable ratios of CO_2, combustible gases (H_2, CO, CH_4), volatile oils, tarry vapors, and a solid carbon-rich residue (biochar) (Suliman et al., 2016; Tripathi et al., 2016). A common characteristic of biochar is that it comprises mainly stable aromatic organic carbon that cannot readily be returned to the atmosphere (Sandhu et al., 2017; Sun et al., 2018).

Biochar provides opportunities to store carbon (C) in soil over much longer periods compared to unpyrolyzed biomass (Sheng and Zhu, 2018). Application of biochar affects several soil properties including electrical conductivity (EC), pH, cation exchange capacity (CEC), nutrient levels, porosity, bulk density, and microbial community structures (Blanco-Canqui, 2017; El-Naggar et al., 2018; Lamb et al., 2018; Liu et al., 2018; Sheng and Zhu, 2018; Shi et al., 2018). Changes in soil properties can alter soil fertility and crop productivity in various ways by improving nutrient levels and decreasing nitrogen (N) leaching (Liu et al., 2017d; Wang et al., 2017a). Biochar influences the microbial populations in soil by providing additional habitats, ultimately transforming nutrients to plant-available forms (Sheng and Zhu, 2018). Furthermore, biochar can reduce the risk of environmental pollutants (organic and inorganic) from soils by forming complexes or through sorption of organic compounds like herbicides (Ahmad et al., 2014; Bashir et al., 2017, 2018; Martin et al., 2012).

In light of the rapidly expanding knowledge on biochar application to soil, we have undertaken a concise review to highlight key benefits and risks. Although a number of reviews on biochar already available focused on specific soil properties, the present review describes the direct and indirect impacts of biochar on various soil properties and mechanisms of biogeochemical processes in soils and agricultural ecosystems that may encourage improvements in fighting pollution, overall soil function and ultimately crop productivity.

2. Structure, composition and characteristics of biochar

Biochar possesses many characteristics different from those of the feedstock material; furthermore, these characteristics are controlled by pyrolysis conditions such as maximum temperature, heating time and

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rate, oxygen, pressure, and other (Gonzaga et al., 2017; Kalinke et al., 2017). Biochar can contain crystalline sheets of graphene and amorphous aromatic compounds. Aromatic rings contain some incorporated elements as hetero-atoms mainly O, N, P and S (Suliman et al., 2016; Tripathi et al., 2016; Zhu et al., 2017). It is believed that the hetero-atoms present in aromatic rings of biochar play a great role in making the surface of biochar heterogeneous and reactive (Abdul et al., 2017; Li et al., 2016). Biochars are characterized typically by having a molar H/C ratio below that of the feedstock (Cayuela et al., 2015; Jacques et al., 2015; Liang et al., 2016). This indicates polymerization, and hence potential recalcitrance of the biochar product.

Biochar is highly heterogeneous, consisting of stable C, ash and labile components depending on the temperature of pyrolysis (Abdul et al., 2017; Li et al., 2016; Sun et al., 2018). Biochar produced from wood-based biomass is comparatively more resistant to biodegradation than biochar obtained from animal manures and crop residues (El-Naggar et al., 2018; Singh et al., 2014). However, manure based biochars are considered rich in nutrients (Meier et al., 2017; Zolfi-Bavariani et al., 2016; Zornoza et al., 2016). Previous studies have shown that the production temperature affects the yield of humic and fulvic acids in biochar (Jindo et al., 2016; Zhao et al., 2017). Biochars produced from the same biomass of chicken manure at different temperatures showed diverse properties of electrical conductivity (EC), pH, P and N concentrations (Chan et al., 2008), and similar results were also confirmed by Meier et al. (2017). Pyrolysis temperature of biochar production is mainly responsible for the determination of the amount of carbon lost during production and the physical and structural changes (Suliman et al., 2016; Zhao et al., 2017). Higher production temperature and residence times result in higher ash content, hence greater concentration of nutrients such as P, K and Ca. Volatile nutrients such as N tend to decrease at higher production temperatures (Li et al., 2016). Some main characteristics and elemental composition of biochar produced at various temperatures and from a variety of feedstock, and volatiles compounds found in biochars are given in Tables 1 and 2.

Biochar is unique in its characteristics compared with other organic materials. These characteristics include porosity (including various pore sizes), large surface area, ash, pH, EC, CEC, and nutrient level (Gonzaga et al., 2017; Kalinke et al., 2017; Sandhu et al., 2017; Sun et al., 2018). The pore size of biochar differs depending on the material used for biochar production and usually ranges from nano (< 0.9 nm), micro (< 2 nm) to macropores (> 50 nm) (Figueiredo et al., 2017;

Table 2
Volatiles, organic solvents, and water extracts from biochars.

Class	Compound	Class	Compound
Volatiles			
Alkene	Ethylene	Benzene	Toluene
	Acetylene	Alkyl	Methane
	Propylene		Ethane
Alcohol	Methanol		Propane
	Ethanol		Butane
Acetate	Methyl acetate	Ketone	Methyl ethyl ketone
Organic solvent			
Alkanoic acid	3-methyl-butyric acid	Hydroxy and acetoxy acids	3-acetoxy-butyric acid
	n-alkanoic acid		2-hydroxy-propionic acid
Diols and triols	Ethane-1,2-diol		3-hydroxy-butyric acid
	Propane-1.2-diol	Phenols	phenol
Benzoic acids	Benzoic acid		hydroxyquinone
	2-methyl-benzoic acid		resorcinol
Water extracts			
Hydroxy acids	lactic acid	Dicarboxylic acids	Succinic acid
	hydroxy-acetic acid		2-Methyl butanedioic acid
	Glyceric acid	n-Alkanoic acid	Hexanoic acid
Aromatic organic acid	Benzenepropanoic acid		Hexadecanoic acid
Polyol	Glycerol		Octadecanoic acid
	Myo-inositol	Sugar alcohol	Mannitol

Note: Data presented in the above table is derived from earlier studies (Graber et al., 2010, 2014; Zhu et al., 2017).

Table 1
Effect of pyrolysis temperatures on the elemental composition of biochar from various feedstocks.

Feedstock	Pyrolysis temperature (°C)	C ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C/N	P ($g\ kg^{-1}$)	K ($g\ kg^{-1}$)	Reference
Wheat straw	450	468	6	78	8	3	(Liu et al., 2018)
Peanut shell	350	555	15	37	1	Nd	(Zheng et al., 2018)
Wheat straw	700–750	320	Nd	Nd	4	50	(Hansen et al., 2017)
Wood of willow (*Salix alba*)	400	652	22	30	Nd	Nd	(Rechberger et al., 2017)
Wood of willow (*Salix alba*)	525	760	24	32	Nd	Nd	(Rechberger et al., 2017)
Wheat husk	525	575	32	18	Nd	Nd	(Rechberger et al., 2017)
Wood mixture [Norway spruce (*Picea abies* + European Beech (*Fagus sylvatica*)]	550–600	744	5.6	133	2	6	(Haider et al., 2017)
Rice straw	300	496	17	29	Nd	Nd	(Feng and Zhu, 2017)
Rice straw	500	584	14	42	Nd	Nd	(Feng and Zhu, 2017)
Rice straw	700	565	11	51	Nd	Nd	(Feng and Zhu, 2017)
Maize straw	400	503	17	30	Nd	Nd	(Luo et al., 2017)
Walnut shell	900	517	Nd	Nd	Nd	Nd	(Wang et al., 2017)
Mixture of conifers species + algal digestate	600–700	660	Nd	Nd	Nd	Nd	(Wang et al., 2017)
Acacia wood	550	893	4	223	23	11	(Abujabhah et al., 2016)
Bamboo	600	869	7	124	1	6	(Liu et al., 2011)
Rice straw	550	427	8	53	2	1	(Liu et al., 2011)
Maize straw	500	580	23	25	Nd	Nd	(Xu et al., 2016)
Willow wood	550	475	4	119	8	7	(Agegnehu et al., 2015)
Hay grass	400	590	19	31	Nd	Nd	(Jeffery et al., 2015)
Hay grass	600	495	17	29	Nd	Nd	(Jeffery et al., 2015)
Wheat straw	300	517	14	37	3	30	(Naeem et al., 2014)
Wheat straw	400	620	9	69	3	32	(Naeem et al., 2014)
Wheat straw	500	662	9	74	3	36	(Naeem et al., 2014)
Rice straw	300	452	12	38	1	36	(Naeem et al., 2014)
Rice straw	400	555	10	56	1	41	(Naeem et al., 2014)
Rice straw	500	630	9	70	1	48	(Naeem et al., 2014)

Note: For the ease of readers, values ≥ 0.5 were rounded to 1, and values < 0.5 were rounded to 0. Nd: not detected.