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▶ To cite this version:

Yang Ding, Yunguo Liu, Shaobo Liu, Zhongwu Li, Xiaofei Tan, et al.. Biochar to improve soil fertility. A review. Agronomy for Sustainable Development, 2016, 36 (2), pp.36. 10.1007/s13593-016-0372-z . hal-01532485

HAL Id: hal-01532485

https://hal.science/hal-01532485

Submitted on 2 Jun 2017

Agron. Sustain. Dev. (2016) 36: 36
DOI 10.1007/s13593-016-0372-z

REVIEW ARTICLE

Biochar to improve soil fertility. A review

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Accepted: 10 May 2016

Abstract Soil mineral depletion is a major issue due mainly to soil erosion and nutrient leaching. The addition of biochar is a solution because biochar has been shown to improve soil fertility, to promote plant growth, to increase crop yield, and to reduce contaminations. We review here biochar potential to improve soil fertility. The main properties of biochar are the following: high surface area with many functional groups, high nutrient content, and slow-release fertilizer. We discuss the influence of feedstock, pyrolysis temperature, pH, application rates, and soil types. We review the mechanisms ruling the adsorption of nutrients by biochar.

Keywords Biochar · Soil · Fertility · Nutrient · Mechanism

Contents

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1 Introduction

The needs to develop more sustainable agriculture systems and improve weak rural economies necessitate major changes in agriculture management. Soil degradation, including decreased fertility and increased erosion, is a major concern in global agriculture (Jianping 1999). Long-term cultivation of soils could result in degradation, containing soil acidification, soil organic matter depletion, and severe soil erosion (De Meyer et al. 2011). Furthermore, the decrease in soil organic matter decreases the aggregate stability of soil (Annabi et al. 2011). Therefore, it is crucial to remediate the degradation soils by simple and sustainable methods.

Manures and composts contain pathogens, heavy metals, and pharmaceuticals, which may cause long-term contamination of farmland. Moreover, manures and composts have the potential to lead to ammonia and methane releases, which can aggravate global warming and serious groundwater and stream nutrient pollution. Being a renewable resource and due to its economic and environmental benefits (Fig. 1), biochar is a promising resource for soil's fertility management. Furthermore, biochar loaded with ammonium, nitrate, and phosphate could be also proposed to be a slow-release fertilizer to enhance soil fertility (Spokas et al. 2012; Xu et al. 2014; Schmidt et al. 2015; Kammann et al. 2015).

Biochar is the by-product of biomass pyrolysis in an oxygen depleted atmosphere. It contains porous carbonaceous structure and an array of functional groups (Lehmann and Joseph 2009). Biochar's highly porous structure can contain amounts of extractable humic-like and fluvic-like substances (Lin et al. 2012). Moreover, its molecular structure shows a high degree of chemical and microbial stability (Cheng et al. 2008a). The physical and chemical properties of biochar are highly dependent on pyrolysis temperature and process parameters, such as residence time and furnace temperature, as well as on the feedstock type (Joseph et al. 2010; Bruun et al. 2011). A wide range of common raw materials are used as the feedstock, including wood chip, organic wastes, plant residues, and poultry manure (Sohi et al. 2010). The elemental composition of biochar generally include carbon, nitrogen, hydrogen, and some lower nutrient element, such as K, Ca, Na, and Mg (Zhang et al. 2015). Commonly, the carbon content increased with increasing pyrolysis temperature from 300 to 800 °C, while the contents of nitrogen and hydrogen decreased. Biochar has a high specific surface area and a number of polar or nonpolar substances, which has a strong affinity to inorganic ions such as heavy metal ions, phosphate, and nitrate (Schmidt et al. 2015; Kammann et al. 2015).

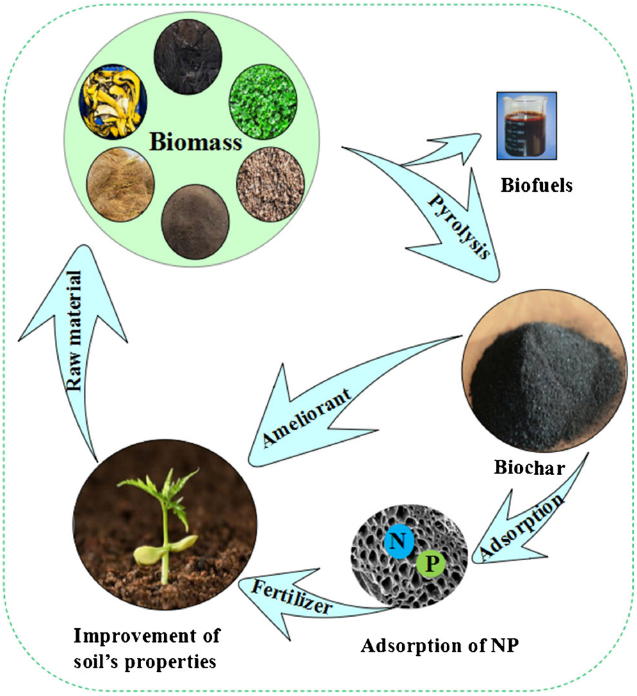


Fig. 1 The benefits of biochar applied as a tool for soil fertility management

Biochar was reported to improve not only soil chemical and physical properties but also soil microbial properties. Many studies indicated that the combination of biochar with soils could improve soil structure, increase porosity, decrease bulk density, and enhance aggregation and water retention (Baiamonte et al. 2015). In addition, biochar can increase soil electrical conductivity by 124.6 % (Oguntunde et al. 2004) and cation exchange capacity by 20 % (Laird et al. 2010), while reduce soil acidity by 31.9 % (Oguntunde et al. 2004). Moreover, biochar has also been tested to increase soil biological community composition (Grossman et al. 2010) and microbial biomass by 125 % (Liang et al. 2010). Steiner et al. (2008a) indicated that, after biochar application, basal respiration increased about by 30.1 % CO_2 in the following 35 h after substrate addition.

In recent years, an increasing interest in applying biochar is focused on the amendment of nutrient-poor soil for soil ecological restoration including sequestering carbon (Jiang et al. 2012; Liu et al. 2012). Various mechanisms have been suggested for the increase of plant nutrient availability in nutrient-limited agroecosystems such as (1) the initial addition of soluble nutrients contained in the biochar (Sohi et al. 2010) and the mineralization of the labile fraction of biochar containing organically bound nutrients (Lehmann et al. 2009); (2) reduction of nutrient leaching due to biochar's physicochemical properties (Liang et al. 2006); (3) lower escapable N losses by ammonia volatilization and N_2 and N_2O from denitrification (Cayuela et al. 2013); and (4) a retention of N, P, and S associated with the increase in biological activities or community shifts (Pietikäinen et al. 2000). In the field trials, many researchers reported that biochar application improved soil quality, increased crop production and promoted plant growth (Lehmann et al. 2006; Major et al. 2010; Zhang et al. 2010) (Table 1). Uzoma et al. (2011) found that, compared to the control, maize grain yield significantly increased by 150 and

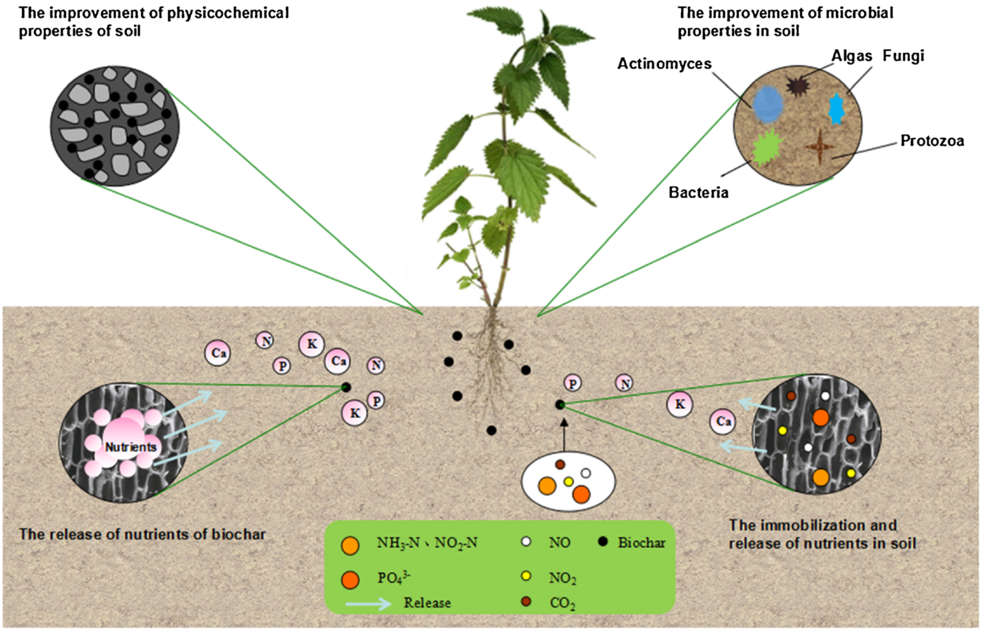
Table 1 Effects of biochar addition on crop yield

Biochar type	Biochar rate (t ha^{-1})	Crops	Soil type	Yield/biomass increase over control (%)	Reference
Secondary forest wood	68	Cowpea	Xanthic Ferralsol	20	Glaser et al. (2002)
	136.75	Cowpea	Xanthic Ferralsol	100	
	68	Rice	Xanthic Ferralsol	50	
Poultry litter	10	Radish	Alfisol	42	Chan et al. (2008a, b)
	50.5	Radish	Alfisol	96	
Orchard pruning	22	Grape	Sandy clay loam	20	Genesio et al. (2015)
Charcoal	0.5	Moong	Dehli soil	22	Glaser et al. (2002)
Greenwaste	100	Radish	Alfisol	266	Chan et al. (2008a, b)
Cow manure	15	Maize	Sandy soil	150	Uzoma et al. (2011)
Logs of *Eucalyptus deglupta*	30	Rice	Inceptisol	294	Noguera et al. (2010)
Wheat straw	40	Rice	Paddy soil	14	Zhang et al. (2010)
Hardwood	19	Maize	Midwestern mollisols	10	Rogovska et al. (2014)
	38	Maize	Midwestern mollisols	17	
	58	Maize	Midwestern mollisols	48	
Wheat straw	40	Rapeseed	Upland red soil	36.02	Liu et al. (2014)
	40	Sweet potato	Upland red soil	53.77	
Black carbon	20	Maize	Oxisol	28 (the second year)	Major et al. (2010)
	20	Maize	Oxisol	30 (the third year)	
	20	Maize	Oxisol	140 (the fourth year)	

98 % after the application of biochar at 15 and 20 t ha^{-1}, respectively. However, grain yield decreased by 23.3, 10, and 26.7 % while the application rate of biochar was 4, 8, and 16 t ha^{-1}, respectively (Asai et al. 2009). The decreased crop yield may be attributed to the high volatile matter, as well as toxic and harmful substance in biochar, which can reduce nutrient uptake and inhibit plant growth. Thereby, the improvements of crop production and plant growth may be dependent on the properties of biochar and soil. It is significant to understand the mechanisms which may induce changes on soil fertilizer after biochar application into soil.

In this review, we critically discussed the influence of biochar on soil properties, including soil physicochemical and biological properties. Moreover, the mechanisms of biochar in the improvement of soil fertility were also reviewed. In order to better understand the connections between biochar and soil, four following aspects are included in this paper (Fig. 2): (i) biochar as a source of nutrients; (ii) adsorption and desorption of nutrients on biochar; (iii) the influence of biochar on properties of soils; and (iv) the effects of biochar on biota in soil. The purpose of this review is to lay the foundation for future researches.

Fig. 2 The possible mechanisms for improving soil fertility



2 Biochar as a source of nutrients

2.1 The potential of biochar as fertilizer

Organic matter and inorganic salt, such as humic-like and fluvic-like substances and available N, P, and K, can serve as fertilizer and be assimilated by plants and microorganisms. Lin et al. (2012) indicated that biochars produced from *Acacia saligna* at 380 °C and sawdust at 450 °C contained humics (humic-like and fluvic-like materials) of 17.7 and 16.2 %, respectively. Biochar made from *Lantana camara* at 300 °C contained available P (0.64 mg kg^{-1}), available K (711 mg kg^{-1}), available Na (1145 mg kg^{-1}), available Ca (5880 mg kg^{-1}), and available Mg (1010 mg kg^{-1}) (Masto et al. 2013). Similarly, fresh biochar had potential of nutrient availability and could release large amounts of N (23–635 mg kg^{-1}) and P (46–1664 mg kg^{-1}) (Mukherjee and Zimmerman 2013; Zheng et al. 2013). Therefore, these data may indicate that biochar has great potential as available nutrients.

Although total N, P, and K in biochars may not necessarily reflect the actual availability of these nutrients to plants (Spokas et al. 2012), the available N, P, and K (e.g., ammonia (NH_4^+), nitrate (NO_3^-), phosphate (PO_4^{3-}) and K^+) may be associated with the amounts of total N, P, and K. For example, the loss of total N was contributed to the decrease of available N in higher temperatures biochars (Koutcheiko et al. 2007). Besides, the available K content significantly increased with the increase of total K amount (Zheng et al. 2013). Many current studies evaluated nutrients availability in biochars by conducting short-term column leaching experiments or using kinetic models. For instance, Wu et al. (2011) reported that 15–20 % of Ca, 10–60 % of P, and about 2 % of N in *mallee* wood biochar was readily leachable with distilled water after 24 h. However, it is not sufficient to calculate the long-term nutrients availability of biochars. In the practical application, total N, P, and K in biochar could be used as an indirect indicator for choosing appropriate biochar.

2.2 Factors affecting nutrient content and availability in biochars

Nutrient contents in biochars were determined greatly by feedstock source and pyrolytic temperature (Table 2). For example, N losses began at about 400 °C, then half of the N was lost as volatiles at about 750 °C in three woody and four herbaceous biochars (Lang et al. 2005). Moreover, the contents of available N (water-soluble) in biochars decreased from 39 to 8 mg kg^{-1} with the increase of pyrolysis temperatures from 350 to 600 °C, which could be attributed to the loss of total N and the heterocyclization of N during pyrolysis (Zheng et al. 2013). Contrasted to total N content in biochars, total P content significantly increased from 0.12 to 0.17 % with the increase of temperature from 300 to 600 °C (Zheng et al. 2013), which was attributed to the loss of carbon and relatively stable P in plant biomass in response to heating (Page et al. 1982). However, the available P in the biochars produced at lower temperature was much higher than the high-temperature biochars. Actually, the reasons could be explained that biochar contained less crystallized P-associated minerals in lower temperature biochars. Additionally, the total K content increased from 3.7 % at 300 °C to 5.02 % at 600 °C, while the available K (water-soluble) content increased with the increase of pyrolysis temperature (37 % at 300 °C and 47 % at 600 °C) (Zheng et al. 2013).

Additionally, biochars produced from different feedstocks present various nutrient elements composition. For instance, swine manure biochar produced at 400 °C contained large amounts of N (3.2 %) and P (6.1 %) (Tsai et al. 2012), while *Arundo donax* biochar produced at 400 °C had little N (0.69 %) and P (0.13 %) constituents (Zheng et al. 2013). Moreover, the ash content in the biochars made at 350 °C of poultry litter (30.7 %) (Cantrell et al. 2012) was much higher than that produced from pine wood chip at 350 °C (1.5 %) (Spokas et al. 2011).

The pH of the soil is an important factor affecting nutrient availability of biochar (Silber et al. 2010). The release of PO_4^{3-} and NH_4^+ were pH-dependent while the release of K^+ and NO_3^- was not (Zheng et al. 2013). Furthermore, at pH 2–7, the content of PO_4^{3-} and NH_4^+ released from the biochars would be decreased with the increase of pH values, whereas that of K^+ remained relatively stable (Zheng et al. 2013). Similarly, the initial Ca and Mg release from corn straw biochar was also pH-dependent, exhibiting an increase in released quantities as pH decreased from 8.9 to 4.5 (Silber et al. 2010).

The influence of application time on nutrient release from biochars should be considered. Zheng et al. (2013) set a series of time gradient to explore the relationship between time and water-soluble nutrients release by determining the concentration of NH_4^+, PO_4^{3-}, and K^+. They found that the NH_4^+ release from biochars produced from *A. donax* (giant reed) at 300 to 600 °C mainly occurred within 120 h, indicating that these biochars contain slow-release NH_4^+, whereas the PO_4^{3-} and K^+ release mainly occurred within 24 h, indicating that these biochars contained fast-release PO_4^{3-} and K^+. Besides, high C mineralization and N immobilization of volatile matter in biochar by microorganisms could decrease the release of nutrients (Zimmerman 2010; Deenik et al. 2010). In practice, these influencing factors could be co-existence when biochar application into soil. Relatively, lower pyrolysis temperature and pH may increase the availability of N and P, while higher pyrolysis temperature may increase the availability of K.

Table 2 Effect of feedstock and pyrolytic temperature on biochar's properties

Feedstock	Pyrolytic temperature (°C)	Total C (%)	Total N (%)	Total C (mg g^{-1})	Total N (mg g^{-1})	C:N	Total P (%)	Total K (%)	Total P (mg g^{-1})	Total K (mg g^{-1})	pH	Reference
Wood	200	48.8	0.2			242.5			0.3	1.3	4.6	Zhang et al. (2015)
	400	42.7	0.3			129.5			0.6	3.8	6.9	
	600	45.5	0.4			111			0.6	4.4	9.5	
Orchard pruning	500	77.81	0.91			63.53			23.3	13.9	9.8	Baronti et al. (2014)
Achillea millefolium	400	55.8	2.22			25.1			2.78	17.62	9.65	Van de Voorde et al. (2014)
Festuca rubra	400	59.9	2.39			25.0			2.15	10.31	8.92	Van de Voorde et al. (2014)
Soybean straw	300			576	12.7	45			2.7	–	7.66	Yuan et al. (2011)
	500			626	3.7	171			4.4	–	10.92	
	700			579	1.0	574			5.8	–	11.10	
Arundo donax	300	65.26	0.65			117	0.12	3.70			8.42	Zheng et al. (2013)
	350	66.97	0.64			121	0.12	3.80			8.09	
	400	72.25	0.69			121	0.13	4.18			8.06	
	500	73.12	0.63			136	0.16	4.77			9.73	
	600	78.61	0.55			165	0.17	5.02			10.67	
Hypochaeris radicata	400	53.2	1.72		17.32	30.9			2.71	16.99	9.89	Van de Voorde et al. (2014)
Jacobaea vulgaris	400	59.7	2.04		18.88	29.3			2.64	14.53	9.67	
Peanut straw	300			537	26.0	21			6.3	–	8.60	Yuan et al. (2011)
	500			485	15.1	32			9.5	–	10.86	
	700			470	15.1	31			11.6	–	11.15	
Swine manure	400	41.8	3.2			–	6.1	3.1			7.50	Tsai et al. (2012)
	500	41.8	2.6			–	6.9	2.7			10.21	
	600	41.1	2.5			–	6.9	2.9			10.74	
	700	43.9	2.0			–	7.5	2.7			11.84	
	800	42.1	1.6			–	7.7	2.7			11.44	
Bagasse	500	85.59	1.11			–	0.005	0.026			9.3	Lee et al. (2013)
Cocopeat	500	84.44	1.02			–	0.003	0.230			10.3	
Paddy straw	500	86.28	3.25			–	0.034	0.213			10.5	
Palm kernel shell	500	87.85	1.11			–	0.003	0.012			6.9	
Leucanthemum vulgare	400	58.4	1.96		19.62	29.7			2.80	15.68	9.30	Van de Voorde et al. (2014)
Lotus corniculatus	400	59.9	3.22		31.05	18.6			2.47	10.43	9.06	
Plantago lanceolata	400	57.5	2.54		22.67	22.7			2.88	16.04	9.40	
Canola straw	300			616	1.9	325			1.6	–	6.48	Yuan et al. (2011)
	500			634	0.4	1610			2.7	–	9.39	
	700			549	0.4	1584			4.8	–	10.76	
Wood stem	500	89.31	0.78			–	0.001	0.020			9.5	Lee et al. (2013)
Wood bark	500	84.84	1.83			–	0.005	0.065			9.6	
Corn straw	300			536	14.4	37			2.5	–	9.37	Yuan et al. (2011)

Table 2 (continued)

Feedstock	Pyrolytic temperature (°C)	Total C (%)	Total N (%)	Total C (mg g^{-1})	Total N (mg g^{-1})	C:N	Total P (%)	Total K (%)	Total P (mg g^{-1})	Total K (mg g^{-1})	pH	Reference
	500			419	9.0	46			4.0	–	10.77	
	700			245	7.8	31			6.8	–	11.32	
Bamboo shoot shell	300	64.0	3.02			24.73	–	0.31			8.5	Ye et al. (2015)
	350	64.6	3.08			24.48	0.35	0.59			9.6	
	400	67.2	3.10			25.28	0.41	1.07			10.2	
	450	67.3	2.99			26.25	0.46	1.20			10.0	
	500	69.3	2.80			28.92	0.56	1.71			9.8	

3 The influence of biochar on properties of soils

Currently, some studies have focused on the amendment of biochar on physical and chemical properties of various soils (Table 3). Biochar could possibly be part of a long-term adaptation strategy, as it could improve soil physical properties including the increase of porosity and water storage capacity, as well as the decrease of bulk density (Lu et al. 2014; Nelissen et al. 2015). Biochar may also be used as a sustainable amendment to enhance soil chemical properties (Lehmann et al. 2011; Glaser et al. 2002). For example, the content of ash in biochars ranged from 0.35 to 59.05 %, which were rich in available nutrients, especially cationic elements, such as K (0–560 mmol kg^{-1}), Ca (3–1210 mmol kg^{-1}), Mg (0–325 mmol kg^{-1}), and Na (0–413 mmol kg^{-1}) (Rajkovich et al. 2012). Similarly, Yuan et al. (2011) reported that the content of soluble base cations (K^+, Ca^{2+}, Mg^{2+}, and Na^+) ranged from 48 to 330 cmol kg^{-1}. Moreover, ash content could increase soil pH which may determine cation exchange capacity of various charged soils (Sollins et al. 1988) and nutrient availability (Mengel and Kirkby 2001). Actually, besides the direct amendment of biochar on soil's properties, biochar can also alter microbial and nutritional status of the soil within the plant rooting zone through changing soil physical properties (e.g., bulk density, porosity, and particle size distribution). Overall, the improvement of soil properties is highly contributed to the increased of both nutrient and water use efficiency and crop productivity.

3.1 The effect of biochar on physical and chemical properties of soils

The physical and chemical properties of biochar are keys to understand performances and mechanisms of biochar in the improvement of soil's fertility. A possible main mechanism for yield improvement may be the increase of soil water holding capacity after biochar treatment (Jeffery et al. 2011). Biochar has high total porosity, and it could both retain water in small pores and thus increase water holding capacity and assist water to infiltrate from the ground surface to the topsoil through the larger pores after heavy rain (Asai et al. 2009). Peake et al. (2014) indicated that biochar application could increase available water capacity by over 22 %. Nelissen et al. (2015) demonstrated that biochar application could increase available water capacity from 0.12 to 0.13 m^3 m^{-3}. Moreover, the formation and stability of soil aggregates could increase the crop production and the prevention of soil degradation (Amezketa 1999). The capacity of soil aggregation increased ranging from 8 to 36 % after the application of rice husk biochar (Lu et al. 2014). They also reported that the application of rice husk biochar application could increase soil pore structure parameters by 20 % and shear strength, as well as decrease soil swelling by 11.1 % (Lu et al. 2014). In

Table 3 The influence of biochar on soil's physical and chemical properties

Biochar rate	Soil type	Incubation	Bulk density (g cm^{-3})	pH	Cation exchange capacity (cmol kg^{-1})	Available K (mg kg^{-1})	Available P (mg kg^{-1})	Reference
Wood—450, 0 t ha^{-1}	Sandy clay loam	Year 2	–	6.86	–	–	–	Jones et al. (2012)
Wood—450, 0 t ha^{-1}		Year 3	1.04	6.44	–	–	16	
Wood—450, 50 t ha^{-1}		Year 2	–	7.18	–	–	–	
Wood—450, 50 t ha^{-1}		Year 3	1.08	6.6	–	–	16	
Control	Sandy soil	Day 0	1.37	5.6	2.2	37	28	Novak and Busscher (2013)
Control		Day 120	1.62	5.2	1.8	14	29	
Peanut hull—400, 2 %		Day 0	1.49	7.3	2.7	319	47	
Peanut hull—400, 2 %		Day 120	1.57	7.1	2.4	111	39	
Peanut hull—500, 2 %		Day 0	1.57	7.4	2.4	304	38	
Peanut hull—500, 2 %		Day 120	1.59	7.4	2.1	145	33	
Control	Red soil	Day 100	–	4.67	–	211	34	Dai et al. (2013)
Reed—500, 1 %		Day 100	–	4.7	–	156	38	
Reed—500, 3 %		Day 100	–	4.77	–	228	52	
Sow manure—500, 1 %		Day 100	–	5.95	–	310	129	
Sow manure—500, 3 %		Day 100	–	6.76	–	687	175	
Pineapple peel—500, 1 %		Day 100	–	5.58	–	745	62	
Pineapple peel—500, 3 %		Day 100	–	6.83	–	1790	116	
White lead trees—700, 0 %	Acidic soil	Day 105	1.42	3.95	7.41	–	–	Jien and Wang (2013)
White lead trees—700, 2.5 %		Day 105	1.15	4.65	9.26	–	–	
White lead trees—700, 5 %		Day 105	1.08	5.07	10.8	–	–	
Original soil	Fe-leaching-stagnic anthrosol	Day 60	–	6.35	–	129	31	Yang et al. (2015)
Cassava stems—0 %		Day 60	–	7.04	–	33	27	
Cassava stems—10 %		Day 60	–	7.85	–	142	34	
Cassava stems—20 %		Day 60	–	7.77	–	282	43	

addition, biochar could ameliorate compaction by over 10 % (Peake et al. 2014), decrease bulk density from 1.47 to 1.44 mg m^{-3}, and increase porosity from 0.43 to 0.44 m^3 m^{-3} (Nelissen et al. 2015). Overall, the improved physical properties of soil, such as bulk density, water holding capacity, and aggregation ability, may increase the retention of both water and nutrients, which benefit to soil fertility directly.

The application of biochar could increase soil pH value. Wang et al. (2014) reported that rice husk biochar increased the tea garden soil (acid soil) pH from 3.33 to 3.63. The agricultural soil pH increased by almost 1 pH unit for biochar treatment which produced from mixed hardwood (*Quercus* spp. and *Carya* spp.) (Laird et al. 2010). The increase of soil pH could change the form of nutrients and facilitate some elements adsorption of the root. Cation exchange capacity is indirect measures of the capacity of soils to retain water and nutrients. Laird et al. (2010) indicated that the biochar treatments significantly increased cation exchange capacity by 4 to 30 % and relative to the controls. Similarly, cation exchange capacity of the highly weathered soil was increased from 7.41 to 10.8 cmol kg^{-1} after biochar treatment, which produced from *Leucaena leucocephala* (Jien and Wang 2013). Moreover, the increase in the amount of exchangeable cations in the amended soils suggested an improvement in soil fertility and nutrient retention, which may be attributed to the high specific surface area and a number of carboxylic groups of the biochar (Cheng et al. 2006). The amounts of the extractable nutrient elements (e.g., Na, K, Ca, and Mg) could be increased after biochar application. Wang et al. (2014) indicated that the amounts of the extractable K, Ca, Na, and Mg approximately increased by ranging from 60 to 670 % after biochar addition. For example, the K content of soil increased from 42 to 324 mg kg^{-1} (Wang et al. 2014). In addition, biochar treatment could increase base saturation percentage from 6.4 to 26 % and saturated hydraulic conductivity from 16.7 to 33.1 cm h^{-1}, decrease soil erosion rate from 1458 to 532 g m^{-2} h^{-1} (Jien and Wang 2013), and increase total C from 2.27 to 2.78 % and total N from 0.24 to 0.25 % and available P from 15.7 to 15.8 mg kg^{-1} (Jones et al. 2012). These improvements in soil chemical properties could increase soil fertility by increasing the nutrient contents and availability.

However, changes of soil physical or chemical properties were not always detected. For instance, Jones et al. (2012) indicated that soil electrical conductivity (from 46 to 43 μS cm^{-1}) and bulk density (from 1.04 to 1.08 g cm^{-1}) were not significantly influenced after 3 years of biochar addition in a UK field trial. Even the same experiment, in the first year application of biochar, it seems to ameliorate soil physical quality to some extent, including increasing porosity, decreasing soil bulk density, and improving soil aggregation (Nelissen et al. 2015). However, Nelissen et al. (2015) did not observe the difference between hydraulic conductivity and plant available water capacity in the second year after biochar application. Additionally, over 2 years, biochar application did not have a significant impact on soil chemical properties, except for organic carbon content and C: N ratios (Nelissen et al. 2015). These results suggested that the influences of biochar on soil physical and chemical properties are varied with different application conditions. Long-term field trials need to be conducted to test whether soil properties can be influenced permanently through biochar application. Overall, the improvements of soil properties could directly or indirectly increase nutrient contents and availability and decrease nutrient leaching, which are known as mechanisms for the increase of soil fertility.

3.2 Influencing factors of biochar function

Some factors are needed to be considered for the application of biochar into the soil. The improvement of nutrient availability is dependent on the increase of soil pH caused by biochar addition, especially P and K (Atkinson et al. 2010). Deenik et al. (2010) and Spokas et al. (2011) indicated that biochar with high volatile matter content, which produced at higher temperature, contributed to N immobilization and microbial activity reduction which could inhibit plant growth. It is possible that the effects of biochar amendment depend on soil properties, especially soil texture and mineralogy. Moreover, (Peake et al. 2014) reported that the effect of biochar on field capacity and available water capacity varied across different soil types, and these effects were modified slightly but significantly in relation to specific soil properties. Furthermore, different biochar application rates were recommended for various texture soils because of the difference of soils' buffering capacity (Butnan et al. 2015). They indicated that the low application rate (1 %) of Thai traditional kiln biochar made from *Eucalyptus camaldulensis* was appropriate for the coarse-textured soil, which had low buffering capacity. However, the higher rate (2 %) of biochar was recommended for fine textured soil, which had higher buffering capacity compared to coarse-textured soil. Besides, Jones et al. (2012) demonstrated that biochar had no effect on the growth of maize but did enhance the growth and nutritional quality of the subsequent grass crop. The possible reason may be the differences in rooting depth. These aspects indicated that biochar function was highly related to pyrolysis temperatures, soil and plant types, and application rates. It is crucial to understand the underlying influencing factors of biochar function for choosing the optimum biochar for each particular soil, both maximizing soil productivity and minimizing deleterious environmental effects.

4 Adsorption and release of nutrients from biochar

4.1 Adsorption of nutrients and application as slow-release fertilizer

Many studies showed that biochar had the potential to sorb nutrients. Nitrate adsorption capacity of biochar produced from bamboo at 900 °C was approximately 1.2 mg g^{-1}, which was relatively higher than that of activated carbon (about 0.9 mg g^{-1}) (Mizuta et al. 2004). Yao et al. (2012) indicated that biochars could effectively sorb nitrate by 3.7 %, ammonium by 15.7 %, and phosphate by 3.1 %. However, the adsorption capacity of nutrient may be greatly influenced by biochar's properties, including pH, surface acidic groups, and ion exchange capacity (Yao et al. 2012; Morales et al. 2013). Therefore, it is crucial to understand the underlying mechanisms of nutrient sorption. The mechanisms describing the adsorption capacity of polar and apolar compounds are attributed to chemisorption, including hydrophobic bonding (Zhang et al. 2013), π-π electron donor-acceptor interactions resulting from fused aromatic carbon structures (Swiatkowski et al. 2004), and weak unconventional H-bonds (Conte et al. 2013). For example, the mechanisms attributed to adsorption of NH_4^+ onto biochar surfaces include physical adsorption (van der Waals adsorption) (Zhang et al. 2015), NH_4^+ attraction to negatively charged surfaces (Zheng et al. 2013), NH_4^+ reacting with acidic functional groups to form amides and amines (Spokas et al. 2012), NH_4^+ binding to cationic species sites on the surface of biochars (Hale et al. 2013), and π-π electron donor-acceptor interactions (Zhu and Pignatello 2005). Dissimilarly, biochar could not independently sorb the added P. Biochar affected P availability by interaction with other organic and inorganic components in the soil, including organic matter or other base cations in the soil (Xu et al. 2014).

Though there were little field trials focused on the study of biochar as slow-release fertilizer, many laboratory studies investigated the nutrients availability with biochar application. A clearer understanding of not only sorption but also desorption is indispensable because they are the processes that along with nutrients mineralization, controlling soil solution nutrients concentration, enhancing nutrients bioavailability. The influencing factors, which affect nutrients desorption, such as soil types, feedstocks, pyrolysis conditions, and biochar application rates, are needed to be considered. In the black soil, the average percentage of desorbed P were 36, 37, 39, and 41 % for the 0, 1, 5, and 10 % biochar application rates, respectively (Xu et al. 2014). Moreover, differences of P desorption were presented among black soil (24.6 mg kg^{-1}), brown soil (82.5 mg kg^{-1}), and fluvo-aquic soil (27.7 mg kg^{-1}) when the biochar application rates and P loading were 10 % and 240 mg L^{-1} (Xu et al. 2014). *Ingá* biochar made by slow pyrolysis at 400, 500, and 600 °C could release P by 32, 28, and 69 mg kg^{-1}, respectively. Moreover, they indicated that *Ingá* biochar could desorb P by 75 mg kg^{-1} in the first step, while *Embaúba* biochar could desorb P by 310 mg kg^{-1} and *Lacre* biochar could desorb P by 258 mg kg^{-1} (Morales et al. 2013). In addition, Zhang et al. (2015) demonstrated that desorption of NH_4^+ in biochars was greater than activated biochars which ranged from 18 % for biochar (made at 600 °C) at 2.7 mg L^{-1} to 31 % for biochar (made at 450 °C) at 5.1 mg L^{-1}. Desorption of NO_3^- in activated biochar treatment (4–5 mg L^{-1}) was higher than that of biochars (0–4 mg L^{-1}) (Zhang et al. 2015). These phenomena may be induced by the differences of the soil pH and the activity or availability of cations (Al^{3+}, Fe^{3+}, and Ca^{2+}) that interact with nutrients in biochars. Therefore, biochar has great potential as slow-release fertilizer. In order to better manage soil nutrients for maximum bioavailability, further investigation should focus on the methods which can measure nutrients availability of desorbed nutrients from biochar or soil, such as isotope analysis.

4.2 The retention of soil nutrients by biochar

Some researches indicated that incorporation of biochar into soil effectively reduced N_2O emission from different soils. For instance, Rondon et al. (2005) reported that 50 % reduction of N_2O emissions was found under soybean systems while 80 % decrease of N_2O emissions was found for grass systems. Similarly, biochars treatment could decrease N_2O emissions from 1768 to 45–699 μg N_2O-N m^{-2} h^{-1} (Wang et al. 2013) and suppress N_2O emissions between 21.3 and 91.6 % (Stewart et al. 2012). However, there were several studies reported that no effect (Cheng et al. 2012) or even increase (Clough et al. 2010) was detected on N_2O emissions after the application of biochar. The retention of nutrients by biochar could be dependent on biochar pyrolysis temperature, soil types, fertilizer doses, and soil water contents.

Biochar's chemical and physical properties are greatly dependent on pyrolytic temperatures, and then the adsorption of nutrients would be influenced by biochar application. The reduced N_2O emissions is attributed to the content of polycyclic aromatic hydrocarbons in the low-temperature biochars (300–400 °C), but not in the high-temperature biochars (>500 °C), while biochars produced at 200 °C contained a relatively large amount of phenolic compounds and markedly reduced N_2O emission (Wang et al. 2013). The potential explanations for the effects of pyrolysis temperature on nutrients' immobilization have mainly focused on dissimilarities of biochar's volatile compounds, surface area, and porosity (Azargohar and Dalai 2008).

Feedstocks, biochar application rates, fertilizer, and soil types should also be considered as noticeable factors for changing stabilization of nutrients. Nelissen et al. (2014) reported that N_2O emission approximately decreased by ranging from 60 to 90 % and NO emission approximately decreased by ranging from 30 to 90 % after biochars treatment, which were produced from willow, pine, and maize. Moreover, the cumulative N_2O-N emissions could be decreased by ranging from 53.9 to 83.5 % for the biochars applications ranging from 1 to 20 %, respectively (Stewart et al. 2012). Besides, when urea and fertilizers were applied, N_2O emissions were decreased in all biochar treatments compared to the control with an average of 53 % (from 618 to 295 μg N kg^{-1}) and 84 % (from 3356 to 529 μg N kg^{-1}), respectively (Nelissen et al. 2014). These results demonstrated that the influence of fertilizer types on nutrients' fixing cannot be neglected. Soil types should be considered as another influencing factor on immobilization of nutrients. For instance, (Rondon et al. 2005) reported that biochar decreased N_2O emissions by 50 and 80 % under soybean and grass systems, respectively. Nevertheless, the application of biochar was not absolute to reduce the loss of nutrients. For example, Scheer et al. (2011) reported that the cattle feedlot waste biochar had no significant effect on N_2O emission from red Ferrosol. Similarly, Clough et al. (2010) also documented that fluxes of N_2O from the biochar plus urine treatment were higher, compared to urine alone during the first 30 days, but there was no significant difference after 50 days. Consequently, in order to choose suitable biochar types for various soil types, it is significant to clear the potential mechanisms which should be responsible for the immobilization of nutrients.

Recently, abiotic interactions in the biochar-amended soils is ascribed to the potential explanations or mechanisms for the N_2O mitigation, including changes of pH, water penetration and decrease of bulk density, improvement of nutrients availability and soil structure, and increase of sorption capacity (Spokas et al. 2009; Singh et al. 2010; Taghizadeh-Toosi et al. 2011, 2012). Nelissen et al. (2014) hypothesized that the most likely mechanisms reducing NO emissions included the following parts: (i) stimulated NH_3 volatilization, (ii) biotic N immobilization, and (iii) non-electrostatic sorption of NH_4^+. The underlying mechanism that ammonia could be used as nutrient is likely the reversibility of ammonia trapping through the formation of ammonium salts (Taghizadeh-Toosi et al. 2011). Therefore, biochar may store nutrients and be used as slow-release fertilizer. However, the main mechanisms underlying the enhancement of nutrients availability with biochar application deserve further determination in order to improve the qualities of agriculture soils.

5 Biochar, microorganisms, and fertility

Biochar has been shown not only to improve soil physicochemical properties but also to change soil biological properties (Pietikäinen et al. 2000; Lehmann et al. 2006; Kim et al. 2007; O'neill et al. 2009; Grossman et al. 2010; Liang et al. 2010). These changes could ameliorate soil structure, containing increasing organic/mineral complexes (aggregates) and pore spaces (Rillig and Mummey 2006), enhance nutrient cycles, which include the increase of nutrient retention and immobilization, as well as the decrease of nutrient leaching (Steiner et al. 2008b), thus promote plant growth (Warnock et al. 2007). Besides, microorganisms, such as rhizosphere bacteria and fungi, may facilitate plant growth directly (Schwartz et al. 2006; Compant et al. 2010). In summary, changes in microbial community composition or activity induced by biochar may affect nutrient cycles and plant growth, as well as the cycling of soil organic matter (Wardle et al. 2008; Kuzyakov et al. 2009; Liang et al. 2010). This section gives an overview of the influence of biochar properties, such as organic and inorganic composition or surface properties, on microbial community.

5.1 Influence of biochar on microorganisms community

There are growing interests in the application of biochar as a means to manage soil biota, and small changes of soil biota induced by biochar application are of equally strong concern. Some mechanisms may explain how biochar could affect microorganisms in soils: (1) changes in nutrient availability; (2) changes in other microbial communities; (3) alterations in plant-microbe signaling; and (4) habitat formation and refuge from hyphal grazers. Microbial properties are largely affected by the soil food web. Furthermore, the trophic structure of the soil food web highly depended on the quantity, quality, and distribution of organic matter. Despite the slow rates of production of soil organic matter compared with other flows in the carbon cycles, its relative stability for microbial decomposition facilitates soil organic matter accumulation.

5.1.1 Influence of biochar on microbial abundance

Domene et al. (2014) indicated that microbial abundance could increase from 366.1 (control) to 730.5 μg C g^{-1} after an addition of 30 t ha^{-1} biochar. Similarly, microbial abundance increased by 5–56 % with the increase of corn stover biochar rates (from 0 to 14 %) for the different preincubation times (2–61 days) (Domene et al. 2015). Some possible reasons may be responsible for the increase of microbial abundance, such as higher availability of nutrients or labile organic matter on biochar surface (Pietikäinen et al. 2000; Bruun et al. 2012), less competition (Lehmann et al. 2011), the enhanced habitat suitability and refuge (Pietikäinen et al. 2000; Warnock et al. 2007), the increased water retention and aeration (Wardle et al. 1999; Schimel et al. 2007), or positive priming (Zimmerman et al. 2011).

Furthermore, nutrient and carbon availability can affect microbial abundance. This influence was greatly varied with the different types of biochar and the special microorganisms group. It can be considered that symbiotic relationships with biota through changing nutrient supplies were formed from the different demands of the plant. Similar explanations may hold for the effect of C supply increasing by exudation or root turnover in the rhizosphere and C as energy sources for heterotrophic microorganisms (Lehmann et al. 2011). Consequently, the influence on microbial abundance was dissimilar with the different sphere of biochar additions, including rhizosphere and bulk soil. On the other hand, under nutrient-limiting conditions, microbial abundance may be increased due to the greater nutrient availability after biochar application (Taylor 1951). The possible reasons were biochar-driven improvements in nutrient retention or the release of nutrient by the biochar (Lehmann et al. 2011). Some recent researches seem to demonstrate that the following aspects can dominate the influence of nutrient and C availability on microbial biomass, (i) the existing nutrient and C availability in soil; (ii) the additive amount of nutrient and C; and (iii) the properties of microorganisms.

The pH of soils may change, after biochar additions, because of the acidity or basicity of biochar. Different living conditions will be formed for microorganisms with different pH of biochar. For example, Aciego Pietry and Brookes (2008) indicated that microbial biomass C increased from about 20 to 180 μg biomass C g^{-1} soil and microbial biomass ninhydrin-N increased from about 0.5 to 4.5 μg ninhydrin-N g^{-1} soil with rising pH values from 3.7 to 8.3 under otherwise identical environmental conditions, which demonstrated that the rising soil pH could increase microbial biomass. Moreover, there are different influences on different microbial abundance if pH values are changed. With the increase of pH up to values around 7, bacterial populations were possible to increase, whereas, no change in fungi abundance was observed (Rousk et al. 2010). Similar to nutrient and C changes, the pre-existing soil pH, the direction, and magnitude of change will also largely affect the level of pH changes.

Microbial abundance could be increased after microorganisms sorb to biochar surfaces, which render them less susceptible to leaching in soil. Hydrophobic attraction, electrostatic forces, and precipitates forming are involved in the main processes of adsorption to biochar (George and Davies 1988). Moreover, biochar, containing a well-developed pore structure, may provide living environment for microorganisms. Both bacteria and fungi are hypothesized to be better protected against predators or competitors by exploring pore habitats in biochar (Ezawa et al. 2002; Saito and Marumoto 2002; Thies and Rillig 2009).

Biochar could be used to sorb toxins and chemical signals which would hinder microbial growth. Pollock (1947) indicated that biochar could arrest the growth-inhibiting substances. Furthermore, high-temperature biochars have been found to have a stronger adsorption on compounds that are toxic to microorganisms (Chen et al. 2009; Kasozi et al. 2010). Additionally, the humidity may influence largely on microbial abundance. Microorganisms would be stressful in soil of periodic drying which may induce the dormant or even dead (Schimel et al. 2007). Biochar has great water holding capacity because of the large surface area, which could promote the growth of microorganisms. However, further conclusions cannot be obtained only from the original materials and properties of biochar. There is a speculation that bacterial cells or growth-regulating compounds may play an important role in sorption.

5.1.2 Influence of biochar on microbial composition and structure

Addition of biochar may cause some changes in microbial community composition and structure; thus, trophic relationships are likely to be changed. Prayogo et al. (2014) used canonical variate analysis to examine the effect of treatment on the structure of microbial community. They indicated that the first canonical variate analysis axis accounting for 75.5 % of the variance and the second axis representing 24.6 % of the variation, which suggested a significant changes in microbial community structure after biochar application. Biochar would be expected to cause a shift in the fungus: bacteria ratio, since fungi could be better placed to degrade lignin contained within biochar. Furthermore, changes in microbial community composition may be associated in some shifts in pH induced by the application of biochar (Prayogo et al. 2014). Nevertheless, few researches have focused on the biological significance of the shift in pH induced by biochar. Besides, the diversity of microorganisms could be increased or decrease after addition of biochar to soil. For instance, bacterial diversity was increased by as much as 25 % in biochar-rich Terra preta soils compared to unmodified soils in both culture-independent (Kim et al. 2007) and culture-dependent (O'Neill et al. 2009) studies. However, compared to the unmodified soils, lower diversity of archaea (Taketani and Tsai 2010) and fungi (Jin 2010) were found in Terra preta and a biochar-amended temperate soil, respectively. This information indicates that different microbial groups respond in different ways after biochar application into soil.

5.2 Influence of biochar on microbial activity

In agroecosystems, decomposer microorganisms could enhance nutrient release from soil organic matter to the rhizosphere of crop, which are essential for the inputs of nutrients and the sustainable crop production (Bardgett 2005). There are some indexes, such as different enzymes and metabolism rates, which can be used as means to assess the soil biological activity. With the increase of biological activities and community shifts, the retention of N and P were enhanced (Pietikäinen et al. 2000; Thies and Rillig 2009; Lehmann et al. 2011); thus, these processes may increase plant nutrient availability in nutrient-limited agroecosystems (Major et al. 2010). With application of chicken manure biochar from 0 to 15 %, soil dehydrogenase activity increased from 2.75 to 8.96 mg TPF kg^{-1} 24 h^{-1} (Park et al. 2011). Paz-Ferreiro et al. (2012) indicated that, compared to the control, phosphomonoesterase increased by 70.8 % after the treatment of sewage sludge biochar at a rate of 4 %. Possibly, the increases of organic N- and P-mineralizing enzymes are attributed to the plant uptake of N and P and growth of fine roots as well as hairs into biochar pores. However, Domene et al. (2014) found that no significant changes in microbial activity, when measured as basal respiration and feeding rates, indicated that net microbial processing of organic C did not change with application of biochar but rather with differences in soil texture. This result was in agreement with other long-term studies under field conditions were no change or even lower respiration rates (Woolf and Lehmann 2012). Therefore, it is possible that the increased microbial activity highly rely on the easily mineralizable organic content of fresh biochars.

5.3 Impact of biochar on functional ecology of microorganisms

Additions of biochar may either increase or decrease many soil processes, such as C mineralization (Kuzyakov et al. 2009; Liang et al. 2010), denitrification and methane oxidation (Yanai et al. 2007; Van Zwieten et al. 2009), and nutrient transformations (Deluca et al. 2009). Numerous reasons may be responsible for these effects, such as altered C sources or nutrient availability and sorption of inorganic and organic compound. Moreover, various enzymes activity, different water retention and infiltration properties or changes in pore architecture may have effects on microbial functional ecology. In other words, alterations of soil processes could be considered as a result of the changes of microbial community structure, abundance, activity, and metabolism.

The mineralization or oxidation of biochar itself will be influenced by the changes of microbial properties. However, these soil processes depend on some aspects, including the amounts of available C sources, the sorption of organic C of easy degradation, the existing of stable biochar, or the effect of pH and phenolic materials on microbial community. For instance, non-pyrolyzed C rather than labile C additions could enhance the mineralization of biochar (Liang et al. 2010). What is more, changes in microbial community caused by biochar additions may also increase mineralization of other soil C. Wardle et al. (2008) found that a greater decomposition of soil C was generated by greater microbial biomass in the presence of biochar. However, this has generally not been observed beyond an initial greater mineralization after fresh biochar additions (Hamer et al. 2004; Wardle et al. 2008; Zimmerman et al. 2011), indicating that various reasons of C loss could be converted into physical export of C, changes in pH or nutrient contents (Lehmann and Sohi 2008). Therefore, biochar mineralization may depend on the proportion of labile C and the nutrient contents in the biochar.

Additionally, biochar may facilitate the microbially mediated transformation of nutrients in soil. Ball et al. (2010) reported that nitrification was increased by biochar additions to forest soil and explained by sorption of phenolics that would otherwise inhibit nitrification and an increase in ammonia-oxidizing bacteria (Deluca et al. 2006). Additionally, Bailey et al. (2010) found that activity of alkaline phosphatase, aminopeptidase, and N-acetylglucosaminidase increased with biochar application. The possible reason was that plant uptake of N and P, and growth of fine roots and root hairs into biochar pores stimulated the production of organic N- and P-mineralizing enzymes. The families of *Bradyrhizobiaceae* (*Rhodoblastus*, *Rhodopseudomonas*, *Bradyrhizobium*, and *Nitrobacter*) and *Hyphomicrobiaceae* (*Rhodoplanes*, *Starkeya*), which can utilize N_2, NO_3^-, or NH_3 through N_2 fixing or denitrification, increased after biochar addition and were intimately involved in C and N cycling (Anderson et al. 2011). Moreover, microorganisms could generate ethylene in fresh biochar, which may be linked to the decreases of N_2O and CO_2 emissions (Spokas et al. 2010). Therefore, after biochar treatment, the improvements of microbial functional processes could decrease the emissions of gaseous nutrients, increase the retention of nutrients, and facilitate nutrients cycling.

6 Negative effects of biochar on soil biota

Negative, null, or positive effects of biochar on soil microbial community may depend on the biochar and soil type. Organic pyrolytic products, such as phenolics and polyphenolics, may be present in biochar and are harmful for soil microorganisms. Warnock et al. (2007) indicated that mycorrhizae and total microbial biomass decreased after biochar application. Gell et al. (2011) and Ennis et al. (2012) reported that the decrease in microbial abundance and activities might be also expected with an enhanced retention of toxic substances, such as heavy metals and pesticides, and the release of pollutants from biochar, such as bio-oil and polycyclic aromatic hydrocarbons. It is not valid to conclude that a special biochar which has positive effects on one soil biota would also have similar effects on others. For example, Rillig et al. (2010) reported that hydrochar could be beneficial to arbuscular mycorrhizae but may hinder plant growth. Several factors are likely to be responsible for the negative effects of biochar on soil biota, including the volatile matters, properties of biochar as well as salts, such as Cl or Na. Turner (1955) reported withering of the petioles and discoloration of the leaves of clover plants after using biochar without washing procedures to remove organic and inorganic matters. Moreover, some biochars might pose a direct risk to soil biota and their functions

(Liesch et al. 2010) and may explain some of the decreased crop yields reported in literatures. These may be short-term effects that need to be taken seriously in consideration and be evaluated for their suitability as a soil amendment.

7 Discussions

The performances and mechanisms of biochar in the improvement of soil fertility could be divided into four parts. Firstly, biochar could be used as a source of nutrients to increase soil fertility, due to the initial addition of soluble nutrients contained in the biochar and the mineralization of the labile fraction of biochar which contain organically bound nutrients. Moreover, the potential of biochar as nutrients source may mainly depend on the feedstock and pyrolysis temperatures. For instance, lower pyrolysis temperature may relatively increase the availability of N and P, while higher pyrolysis temperature may relatively increase the availability of K. Therefore, it is possible that biochar could be designed for specific end use. Secondly, biochar could improve soils' physical and chemical properties. Though the long-term experiments are still scarce, biochar could possibly be part of a long-term adaptation strategy. The main reason is that biochar could improve soils physical properties including the increase of porosity and water storage capacity. Actually, the improvements of soil properties (e.g., the increased aggregation capacity, pH, and cation exchange capacity) could increase soil fertility by increasing nutrient contents and availability and decreasing nutrient leaching. Moreover, biochar properties, application conditions, and soil properties determine biochar function. Thirdly, biochar could store nutrients and be used as slow-release fertilizer. Due to biochar's specific properties (e.g., pore structure and functional groups), the surplus nutrients (e.g., nitrate, ammonium and phosphate) could be stored onto biochar surface. Subsequently, biochar could slowly release nutrients because of biochar's desorption properties, which may reduce nutrients leaching and increase nutrient contents. Moreover, biochar could increase soil fertility by reducing the N_2O and NO emissions. Relatively, the low-temperature biochars could be more efficient for reducing N_2O emission. Fourthly, biochar could improve soil biological properties, including microbial abundance, structure, and activity. Biochar could improve microbial community by increasing nutrient availability, providing suitable shelter, and ameliorating living condition. The improved microbial community could facilitate nutrients cycling, which could decrease the emissions of gaseous nutrients and increase the retention of nutrients. In addition, biochar may have negative effects on microbial community, due to the harmful substances (e.g., phenolics and polyphenolics) contained in biochar.

The possible improvements of soil's properties and fertility after biochar application were shown in Fig. 3. On the one hand, the properties of soils, containing physical, chemical, and biological properties, could be improved after biochar treatment. Moreover, the improvement of soils properties is highly related to the specific physicochemical properties of biochar, such as high surface area, amount of functional groups, and the content of liming. For example, soil's cation exchange capacity may increase with the increase of carboxylic groups and surface area. The well-developed pore structure may not only enhance the capacity of water retention but

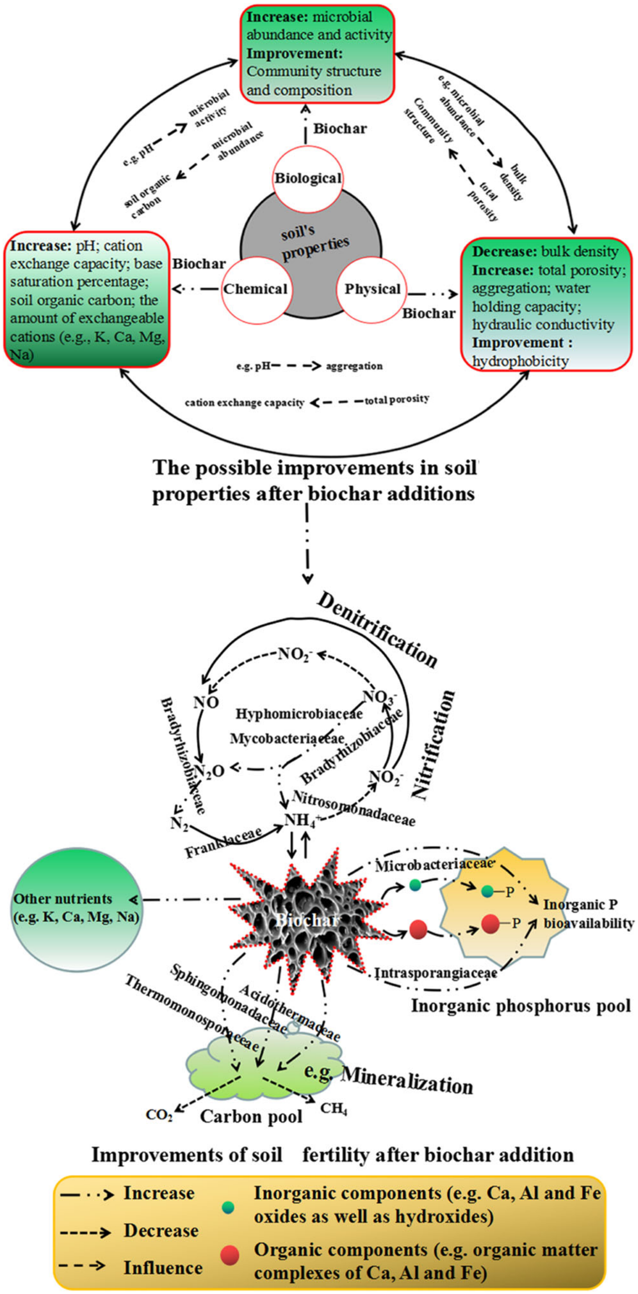


Fig. 3 The possible improvements of soil properties and fertility after biochar application

also provide a shelter for soil's microorganisms, thus nutrient retention and cycling could be improved. The content of liming contained in biochar may increase soil's pH values. On the other hand, biochar could increase plant nutrient availability in soils by releasing nutrients, retaining nutrients, reducing nutrients leaching, and mitigating gaseous N losses. Therefore, biochar has great potential in the improvement of soil fertility.

The influencing factors should be considered before biochar application into soils. These factors could be divided into three aspects, including biochar properties, application conditions, and soil properties. Biochar properties are mainly dependent on the feedstocks and pyrolysis conditions especially temperature. For example, as shown in Table 2, manure biochar may contain more P content than biochar produced from other feedstocks. In general, the pH value may increase with the increase of pyrolysis temperature. Effects of the application conditions (e.g., application rate and time) on the soil properties were presented in Table 3. Actually, most laboratory and field studies were focused on the short-term effects of biochars on soil properties. The long-term experiments and studies are crucial for evaluating the benefits of biochar as a sustainable material. Soil properties are highly related to the soil type. For instance, highly weathered soils are typically characterized by strong acidity, low clay activity, and poor fertility and are considered to be degraded soils. Dissimilarly, vertisol is a soil containing a large amount of expansive clay minerals, and it has high swelling pressure, exceptionally low hydraulic conductivity, poor soil structure, and deep crack cutting when it is dry and stick when it is wet. Therefore, the main influencing factors should be analyzed and the maximum benefits should be evaluated before biochars application into soils.

Many researches showed that the application of biochar presents an ideal method to improve soils fertilizer. However, some fundamental mechanisms and the utilization of biochar in agro-ecosystem are poorly understood. These knowledge gaps mainly include the following aspects:

(i) It is significant to understand the interactions between biochar and soil microbial communities, which may critically affect the release of CH_4 and N_2O from soil, especially included nutrient biogeochemical cycles.
(ii) Understanding the dynamic mechanisms of biochar incorporation into soil. Biochar application is restricted by many factors, such as biochar and soil type and application rates. Thereby, to clear the role of each influencing factor played on the applying of biochar is inevitable for the process of field trials. In fact, the mechanisms and influencing factors are usually co-existence when biochar application into soil. The following researches should focus on the interactions between biochar, soil, microbes, and plant roots after biochar application into soil.
(iii) The exact service life of biochar is still rarely understood. In other words, we should pay more attention to the decomposition rate of biochars in soil. Thus, we can choose biochar correctly and manage resources suitably.
(iv) The maximum adsorption and desorption capacity of biochar are needed to be determined in further researches. Biochars have indicated nonlinear adsorption and desorption of nutrients. With that in mind, the availability of mineral substance to plants and potential leaching of nutrient to the environment, which present in different biochars, are still unclear.
(v) Further studies should be focused on the combined application of several 'designed biochars' into soil. According to the main influencing factors and mechanisms, biochars could be produced purposefully. The combined application of several 'designed biochars' may increase the utilization efficiency of nutrients and manage soil specifically.

8 Conclusions

The application of biochar into soils has great potential for improving soils fertility and promoting plant growth. The choice of biochar managing various soils is flexible, because diverse biomass materials could be used as feedstocks of biochars and the feedstocks could be pyrolyzed at different temperatures. Moreover, biochar has huge surface area, well-developed pore structure, amounts of exchangeable cations and nutrient elements, and plenty of liming. Because of these properties, soil properties could be improved after biochar treatment. For instance, the huge surface area and well-developed pore structure may increase the water holding capacity and microbial abundance. The cation exchange capacity and availability of nutrients could be increased due to the amounts of exchangeable cations and nutrient elements. The increased pH of soils should be attributed to the plenty of liming contained in biochar. Therefore, improvements of soil physical, chemical, and biological properties promote the productivity of plant through increasing the amount of nutrient elements, enhancing availability of nutrient elements, reducing nutrient leaching, and mitigating gaseous nutrients losses.

These results of characterization analyses, column experiments and some field trials indicated that biochar could be designed or may have the potential to manage specific soil purposefully, through controlling the feedstock and pyrolysis conditions. Biochar can be a novel and feasible fertilizer directly or indirectly. This is not only because of the biochars' fertility but also their environmental and economic benefits. Despite the interests of using biochars to manage soils is increasing, some studies are also reported the negative effects and a number of research gaps as well as uncertainties still exist as discussed above in this review. In order to clear these knowledge gaps, further relevant investigations are inevitable in the following research, especially long-term experiments.

Acknowledgments This study was financially supported by the National Natural Science Foundation of China (Grant no. 41271332, 51478470, and 51521006).

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