Critical Reviews in Biotechnology

ISSN: 0738-8551 (Print) 1549-7801 (Online) Journal homepage: http://www.tandfonline.com/loi/ibty20

The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review

Haipeng Wu, Cui Lai, Guangming Zeng, Jie Liang, Jin Chen, Jijun Xu, Juan Dai, Xiaodong Li, Junfeng Liu, Ming Chen, Lunhui Lu, Liang Hu & Jia Wan

To cite this article: Haipeng Wu, Cui Lai, Guangming Zeng, Jie Liang, Jin Chen, Jijun Xu, Juan Dai, Xiaodong Li, Junfeng Liu, Ming Chen, Lunhui Lu, Liang Hu & Jia Wan (2016): The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review, Critical Reviews in Biotechnology, DOI: 10.1080/07388551.2016.1232696

To link to this article: http://dx.doi.org/10.1080/07388551.2016.1232696

Published online: 17 Oct 2016.

CRITICAL REVIEWS IN BIOTECHNOLOGY, 2016
http://dx.doi.org/10.1080/07388551.2016.1232696

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review

Haipeng Wu[a,b,c], Cui Lai[a,b], Guangming Zeng[a,b], Jie Liang[a,b], Jin Chen[c], Jijun Xu[c], Juan Dai[c], Xiaodong Li[a,b], Junfeng Liu[a,b], Ming Chen[a,b], Lunhui Lu[a,b], Liang Hu[a,b] and Jia Wan[a,b]

[a]College of Environmental Science and Engineering, Hunan University, Changsha, PR China; [b]Key Laboratory of Environmental Biology and Pollution Control (Hunan University), Ministry of Education, Changsha, PR China; [c]Changjiang River Scientific Research Institute, Wuhan, PR China

ABSTRACT
Compost and biochar, used for the remediation of soil, are seen as attractive waste management options for the increasing volume of organic wastes being produced. This paper reviews the interaction of biochar and composting and its implication for soil amendment and pollution remediation. The interaction of biochar and composting affect each other's properties. Biochar could change the physico-chemical properties, microorganisms, degradation, humification and gas emission of composting, such as the increase of nutrients, cation exchange capacity (CEC), organic matter and microbial activities. The composting could also change the physico-chemical properties and facial functional groups of biochar, such as the improvement of nutrients, CEC, functional groups and organic matter. These changes would potentially improve the efficiency of the biochar and composting for soil amendment and pollution remediation. Based on the above review, this paper also discusses the future research required in this field.

ARTICLE HISTORY
Received 15 January 2016
Revised 25 February 2016
Accepted 1 April 2016
Published online 14 October 2016

KEYWORDS
Waste; compost; pyrolysis; soil restoration; contamination remediation; organic materials

Introduction

Due to ever-increasing production of farm, livestock and poultry products for human consumption and biosolids for municipal wastewater treatment, a large volume of organic wastes are generated from these industries.[1–3] These organic wastes include crop residues, animal manures, municipal solid wastes, biosolids, etc. The large volumes produced must be treated or utilized in a manner that conforms to environmental regulations, including safe disposal onto land.[2,4] Compost and biochar, used for the restoration of soil have few negative effects on the environment, and are regarded as attractive waste management options.[1,5]

Composting is an bio-decomposition, self-heating and aerobic process of organic waste, and it has advantages over other disposal strategies because it reduces the volume of waste by 40–50% and provides a product that can be used as a material for soil pollution remediation, as a soil conditioner or as a good-quality fertilizer.[6,7] A compost bioremediation strategy relies on mixing the organic pollution contaminated substances with other necessary materials, and the pollutants are degraded by the active microflora.[8,9]

Biochar is a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment.[10] Organic wastes are important raw materials of biochar. Biochar is used in carbon sequestration, soil amendment, carbon farming, climate change mitigation and soil pollution remediation.[11–18] The production technology is robust, simple and appropriate for many regions of the world.[14] Biochar generally increases soil nutrient availability, microbial activity, soil organic matter, water retention and crop yields in soils, while decreasing its fertilizer needs, greenhouse gas emissions, nutrient leaching, erosion, pollutant bioavailability and pollutant mobility.[19–25]

Composting and biochar also has influences on each other's properties. The interaction of biochar and composting has been reported in recent years.[26] The surface of biochar is modified during the composting process due to biotic and abiotic oxidation and sorption of compost-derived organic compounds.[27,28] Addition of biochar could obviously effect the physico-chemical process and the microbial community during

CONTACT Guangming Zeng zgming@hnu.edu.cn College of Environmental Science and Engineering, Hunan University, Changsha, PR China; Jie Liang liangjie@hnu.edu.cn Key Laboratory of Environmental Biology and Pollution Control (Hunan University), Ministry of Education, Changsha, PR China

composting,[29,30] and the composition and quality of the end product.[31] The interaction of biochar and composting should now be the focus of further study if we want to maximize the potential benefits of both.[32,33]

The interaction of biochar and composting (or compost) could provide methods for improving the effectiveness of biochar and compost for soil amendment.[33] Borchard et al. [34] reported that composting increases the surface reactivity of biochars for Cu(II) sorption due to their uptake of compost-derived organic matter. Composted biochar (Bced, without compost) and Biochar-compost (BCing, biochar and biomass mixed then composting) had the greater capacity for reducing the bioavailability and mobility of Cd, Cu, Zn and Pb than that of biochar, compost and biochar and compost mixed amendment material (B + C). Also, BCing had the greater capacity for reducing the ecological risk of Cd, Cu, Zn and Pb than that of biochar, compost, B + C, Bced.[33]

This review focuses on the interaction of composting and biochar and the implications of the interaction for soil amendment and pollution remediation. With an increasing amount of literature on this field, in this review we aim to: (1) discuss the effect of composting on biochar and effect of biochar on composting; (2) review the combined remediation of biochar and composting (or compost) on soil heavy metal pollution, organic pollution and soil degradation; and (3) identify the immediate research needs arising and the future research directions.

Effect of biochar on composting

Physico-chemical properties of composting

Temperature was the main parameter used to indicate the performance of the composting process.[25,35] Usually, the composting process was divided into four different phases according to temperature changes and these four phases successively were: mesophilic phase ($< 45\,°C$), thermophilic phase ($> 45\,°C$), cooling ($45\,°C \sim$ room temperature) and maturation phase (room temperature).[36] Many studies found significantly higher temperatures (Figure 1) (especially during the thermophilic phase) [25,26,29,37–40] and a longer duration of the thermophilic phase [41,42] for the composting with the addition of biochar than that of without biochar. Another study found composting with the addition of biochar maintained higher temperatures for a slightly shorter period and entered the cooling phase more rapidly than composting without biochar.[25] Zhang et al. [43] studied the effects of different percentages of biochar on the physical and chemical characteristics of composted green waste and on the growth and nutrition of the ornamental plant *Calathea insignis*,

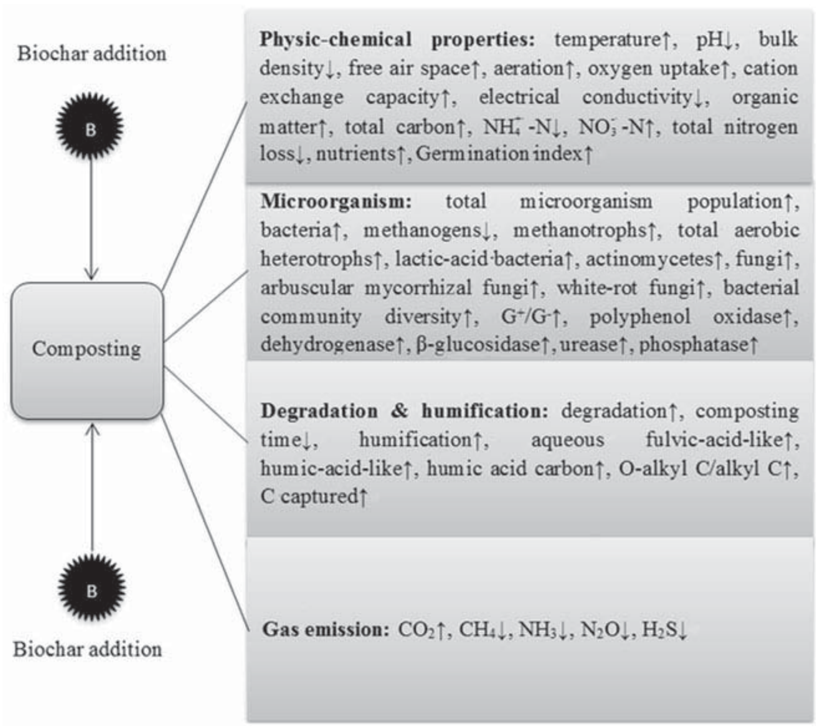

Figure 1. The effect of biochar addition on composting. G+/G−: Gram-positive to Gram-negative ratio; ↑: increase or enhance; ↓: decrease.

and argued that the optimum combination not only improved the particle-size distribution and adjusted the bulk density, porosity and water-holding capacity into ideal ranges but also decreased pH and electrical conductivity (EC). It also increased macro- and micronutrient content and the microbial biomass (C and N) of the growth media. The presence of biochar in the raw material of composting decreased bulk density and increased free air space and aeration of the compost.[29,30,42] Another study reported that the presence of biochar resulted in an increasing of 21–37% in oxygen uptake rates on the first day of sludge aerobic incubation of composting, due to the higher nano-porosity and surface area of the biochar.[44] The cation exchange capacity (CEC) was greater during composting during the treatments with biochar than that without bochar.[42] The EC increased significantly after the active phase during composting and this increase was faster during the treatment without biochar than with biochar.[25] Biochar could decrease the moisture content during composting, which was the result of change in aeration.[25,37,40] However, another study found that the moisture content decreased during the composting in the treatment without biochar whereas it remained close to, or slightly higher than, the initial value in the treatment with biochar, and argued that biochar had an effect on the water holding capacity and retained more water during composting.[39] This difference was induced by the differences in reaction conditions.

Biochar also increased the organic matter and the total carbon of composting.[29,37,45] Most of the studies found that biochar addition increased the C/N ratio because of the recalcitrant carbon derived from the added biochar.[25,26,29,37,41,44] However, two other studies found no significant difference in the C/N ratio between the composting containing biochar and that without biochar.[38,39] This difference was the result of the difference in the raw material C/N. Biochar accelerated organic matter degradation and ammonia formation during the thermophilic phase and enhanced nitrification during the maturation phase.[46] The NH_4^+–N content was lower during the composting containing biochar than that without biochar.[25,42] However, the NO_3^-–N content was higher in the composting containing biochar than that without biochar.[38,42] Hua et al. [47] found that incorporation of biochar into composting material could significantly lessen the total nitrogen loss and mobility of heavy metals during sludge composting. The Germination Index, generally used to evaluate the maturity and toxicity of the compost, was greater in composting containing biochar than that without biochar.[26,42]

Microorganisms during composting

Many studies demonstrated that biochar can increase the population of microorganisms, such as total microorganism, bacteria, lactic-acid bacteria, total aerobic heterotrophs, actinomycetes, fungi, arbuscular mycorrhizal fungi, and so on, in a composting system.[42,48–51] This was because biochar could provide the limited amount of water-soluble carbon and other soluble compounds, low C/N ratio, an extra source of energy, microporous space and carriers for these microorganisms. However, Jindo et al. [29,41] reported that biochar had significantly-lower microbial biomass during composting. This difference may be the result of different substrate water-soluble C/N ratios.

Biochar also changed the microbial community structure during composting.[29,52] It increased the bacterial community diversity in a composting system.[26,49] The fungal communities were also affected and some fungi, such as white-rot fungi increased, so that humification could take place more efficiently.[41] Jindo et al. [29] also found that biochar increased the Gram-positive to Gram-negative ratio of composting at different sampling times. Biochar induced a decrease of methanogens and an increase of methanotrophs (*pmoA*) during the most active phase of composting, and the methanogens/methanotrophs ratios obtained in the composting piles with biochar were twofold lower than in the pile without biochar during the thermophilic phase.[53]

Biochar could affected the activity of enzymes as a result their protection by association with organic complexes of high molecular weight, the proton exchange pathway, or other interaction mechanisms.[41] It increased the activity of dehydrogenase, β-glucosidase, urease, phosphatase and polyphenol oxidase, and the enzymes involved in lignin degradation, humification, carbon mineralization and dissolved organic carbon export.[41,42]

Degradation and humification of composting

Addition of biochar improved the humification and organic matter degradation during composting.[42,46] Biochar addition at 3% could reduce the composting time of poultry manure by 20%.[46] Fluorescent excitation and emission matrix indicated that the concentrations of aqueous fulvic-acid-like and humic-acid-like compounds were, respectively, 13–26% and 15–30% higher in the composting as a result of the addition of biochar, than those in the control without biochar.[44] Biochar promoted the neo-synthesis of humic acids and it intensified the humification of pig manure during the 74 days of humification, which was indicated by the following: (1) the increased content of humic acid carbon in the composting with addition of biochar was 16.9% more than that of the control; (2) spectroscopic analyzes show a higher O-alkyl C/alkyl C ratio and aromaticity in the composting with the addition of biochar during the thermophilic phase, and peak intensities of fulvic-like and humic-like substances were achieved faster than the composting without biochar.[54] The organic matter of the poultry manure–biochar mixture was characterized by a high polymerization degree of the humic-like substances, with a relatively high proportion of humic acids in relation to fulvic acids.[31] At the end of the composting process, the humic acid fraction represented more than 90% of the alkali extractable fraction, reflecting the intense humification of this material.[31] Scanning electron microscope analysis indicated that the dense microstructure on the sludge surface disintegrated into fragments with organic fraction degraded and water lost the composting with addition of biochar.[44] The effects of biochar on composting also contained: (1) humic substance extraction captured a carbon increase by 10%, and (2) water-soluble C decreased by 30%, due to an enhanced degradation rate and/or the sorption of these labile compounds by biochar.[41] Ngo et al. [55] reported that the presence of biochar induced a protection of the organic matter against chemical oxidation, suggesting that biochar increased the carbon sequestration potential of compost.

Gas emission of composting

Biochar increased CO_2 emission during composting, which was the result of higher decomposition of DOC and microbial activity was stimulated by biochar.[30,37–40,56] For example, biochar induced a significant increase in CO_2 respiration rates from poultry litter, and the first respiration maxima increased by 44% and total respiration increased by 28%.[30] Conversely, Chowdhury et al. [37] found that the cumulative CH_4 losses were much lower for the composts containing biochar than those without biochar . Similarly, the emission of NH_3 during composting was reduced by biochar addition.[37–40] The NH_3 emissions during composting was lower by up to 64% if poultry litter was mixed with biochar (w/w, 20%), and total N losses were reduced by up to 52%.[40] Wang et al. [25] also found that reduction of biochar (by 25.9%) led to total N_2O emission over the total composting period of pig manure, wood chips and sawdust mixture composting treatment. Biochar (w/w, 5% and 20%) also reduced H_2S emission by 58% and 71% during poultry litter composting.[40] The changes of these gase emissions may be connected due to the changes of microbigams during the composting induced by biochar and the decreases of NH_3 and H_2S would reduce the foul smell of composting.[50]

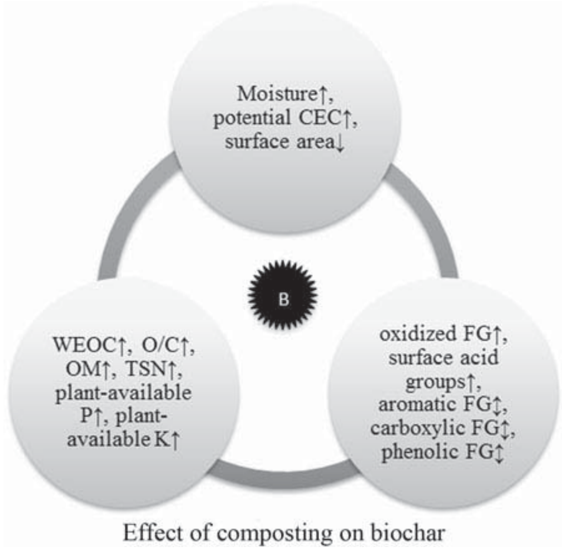

Figure 2. The effect of composting on biochar. CEC: cation exchange capacity; WEOC: water extractable organic carbon; O/C: O/C ratio; OM: organic matter, TSN: total soluble nitrogen; FG: functional group; ↑: increase; ↓: decrease; ↕: some increase and others decrease.

Effect of composting on biochar

The studies of this field focussed on the effect of composting on the characteristics of biochar (Figure 2). Prost et al. [28] elucidated the effect of composting on chemical and physical properties of two different types of biochars (charcoal and gasification coke). They found that the moisture, water-extractable organic carbon, total soluble nitrogen, plant-available phosphorus, plant-available potassium and potential CEC were increased during the composting because biochar absorbed water, organic matter and nutrients from the leachate of composting. Composting of hardwood shavings or chicken litter increased the CEC of biochar (by 2.2–6.5 times) probably due to thermophilic oxidation.[57] Other studies also found composting increased the moisture, water-extractable organic carbon and CEC of biochar.[33] Calculation of the O/C ratio by energy-dispersive X-ray spectroscopy demonstrated the anticipated increasing values from fresh biochars (0.13) to Bced (0.40), which was caused by composting the mixture of straw, draff, horse manure and maize silage.[58]

The composting decreased the surface area of biochar due to the clogging of micropores by adsorbing compost-derived materials. It also might facilitate biochar surface oxidation biotically by the co-metabolic decay or the high microbial activity during the

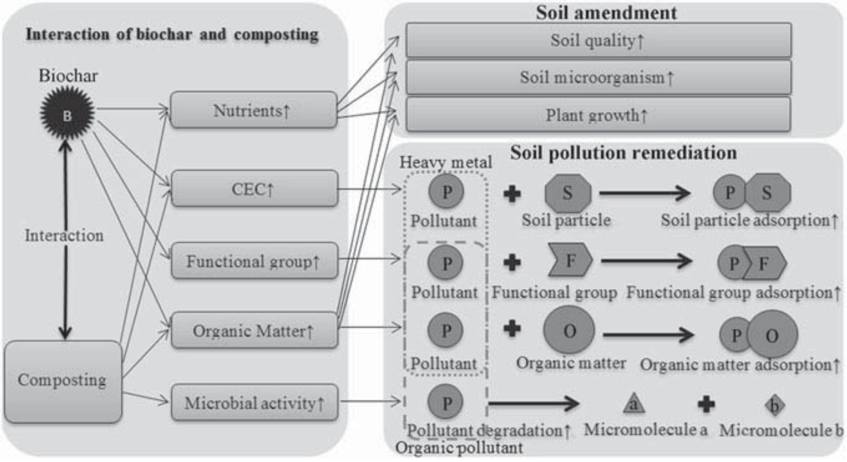

Figure 3. The potential implications of the interaction of biochar and composting for soil amendment and pollution remediation. CEC: cation exchange capacity; ↑: increase or enhance.

degradation of available carbon, as well as abiotically by the elevated temperatures during composting.[28,59–61] Additionally, the adsorption of organic matter could increase the oxidized functional groups on the surface of biochar.[33,62] The results of FTIR spectroscopy disclosed that aerobic composting can promote the formation of surface acid groups on bamboo charcoal, and these surface acid groups may deprotonate and react with NH_4^+ to form stable complexes.[49] Wiedner et al. [58] found that the relative contribution of surface functional groups (aromatic, carboxylic and phenolic) of different biochar had different effects: (1) composting with a mixture of straw, draff, horse manure and maize silage decreased the percentage of aromatic and phenolic, and increased the percentage of carboxylic of wood chips biochar (produced at ~550 °C); (2) composting with a mixture of straw, draff, horse manure and maize silage decreased the percentage of carboxylic, and increased the percentage of phenolic of green cutting biochar (produced at ~800 °C); and (3) composting with a mixture of chaffed lob and biowaste decreased the percentage of phenolic, and increased the percentage of aromatic and carboxylic of wood chips biochar (produced at ~450 °C). The change of biochar surface induced by composting improved its adsorption of copper (II).[34]

Implication of the interaction for soil amendment and pollution remediation

The interaction of biochar and composting had influences on each other's properties, such as increase of nutrients, CEC, functional group and organic matter of biochar and the rise of nutrients, CEC, organic matter and microbial activities of composting. These changes would potentially improve the efficiency of biochar and composting for soil amendment and pollution remediation (Figure 3). In soil amendment, the increase of nutrients and organic matter of biochar and composting would probably improve soil quality and microorganism and help in plant growth. In soil pollution remediation, the rise of CEC biochar and composting would likely enhance the adsorption ability of soil particle for heavy metal pollutant. The increase of functional groups in biochar would improve the adsorption ability of functional group for heavy metal or organic pollutant. The rise of organic matter in biochar and composting would enhance the adsorption ability for heavy metals and organic pollutants. The enhancing of microbial activity would enhance microbial degradation of organic pollutants. These induced the studies concerning the implications of the interactions of biochar and composting for soil amendment and pollution remediation as following:

Implication of the interaction for soil amendment

As shown in Table 1, many publications reported the effectiveness of B + C on soil amendment. B + C had an obvious different effect on soil physico-chemical properties,[64,66,68,74] gas emission,[63,65,67,70,73,75] microbial properties,[63,65] enzymes [63] and plant growth.[67,69,71,72,73] Suddick and Six [73] reported that the average emissions of soil N_2O, amended with B + C, was less than those of soil enhanced with biochar, or with compost and amended with nothing. Fernandez et al. [65] found that the microbial biomass carbon to TOC ratio of soil enhanced with B + C was higher than that of soil enhanced with biochar and lower than that of soil with compost. Schulz and Glaser found that B + C increased plant height, biomass and seed number and these increases were greater that

Table 1. Studies regarding the implication of biochar and composting (or compost) combined amendments for soil amendment.

	Study indicators	Reference
B + C	Soil respiration; MBC; MBC/SOC; metabolic quotient; C mineralization; enzyme (α-Glu, β-Glu, β-Xyl, NA-β-Glu, Acid phos, Leucine) activities	[63]
	pH; exchangeable acidity, Al, Fe, Ca; TP; available P; soluble-P; $AlPO_4$-P; $FePO_4$-P; redundant soluble-P; Ca-P; TOP	[64]
	sizes and decomposition rates of stable and labile C pools; CO_2 emission; TC; TOC; IC; MBC; MBC/TOC	[65]
	Total N, Total P, Total K, height increase, girth increase, root/shoot, mean weight diameter of plant; organic carbon, TN, pH, EC, extractable P, extractable K, extractable Ca, extractable Mg of soil	[66]
	water content; N_2O, CO_2, CH_4 emission; biomass yield of *Lolium perenne*; NO- 3; NH+ 4	[67]
	TOC; TN; C/N; Plant-available Al, K, Na, Mg, P, Ca; CEC; base saturation; pH; water content;	[68]
	crop yield; economic valuation	[69]
	pH; DOC; NH+ 4-N; NO- 3-N; net N mineralization rate; N_2O, CO_2 emission; N_2O/N_2;	[70]
	plant height and biomass; numbers of plants and harvested seeds per pot; TOC; black C; CEC; plant-available Ca, Mg, K, Na, Mn; exchangeable acidity; pH; P, N leaching	[71]
	TC; TN; C/N; Biomass production, N uptake, withdrawal (grains); mineral N fertilizer remaining in the soil and crop	[72]
	pH; TC; TN; C/N; PO- 4-P;K; Na; Ca; Mg; Zn; Mn; Fe; Cu; fresh weight yield of Swiss chard; N_2O emission; water filled pore space; NO- 3-N; NH+ 4-N	[73]
	NH+ 4-N; NO- 3-N; mineral N;	[74]
	N_2O, CO_2 emission; NH+ 4-N; NO- 3-N; DOC;	[75]
BCed	OM; CEC; NH+ 4-N; NO- 3-N; pH; P; K; Ca; Mg; O_2 consumption; N_2O, CH_4, CO_2 emission	[27]
BCing	water holding capacity; plant-available N; maize yield; pH; EC; Ca; K; Mg; Na; CEC; PO- 4-P; TN; maize N, P, Ca, K, Mg, Na uptake; Total N, P, K, Mg, Ca, Na, Mn, Cu, Ni, Zn, Co, Cr, Pb, Cd of maize plant;	[76]
	pH; salt; Na^+; soil organic carbon; bulk density; CEC; TN; available K; available P; spikes, grain weight spikes, thousand grain weight of wheat; wheat grain weight	[77]
	crop yield; economic valuation	[69]
	TOC; IC; TN; NO- 3; NH+ 4; Al; Ca; K; Mg; Na; P; pH; EC; seed weight of oat	[78]
	grapevine growth analysis; grape must analysis; infection rate of *Plasmopara viticola* and *Oidium tuckerii*; grape constitutes	[79]

B + C: biochar and compost mixed amendment material; Bced: composted biochar and without compost; BCing: biochar and biomass mixed and then composting.

those of biochar and lower than that of compost, they also found that B + C increased plant number and this increase was greater than that of biochar and compost.[71]

Bced also had different effects on soil enhancement. However, only Borchard et al. [27] studied the effect of Bced on agricultural (planting corn and soybean) soil amendment. They found that the application of Bced induced soil had more N_2O and CH_4 emission, less CO_2 emission and similar O_2 consumption than that of the soil with biochar. They also found that Bced induced more soil SOM, CEC, pH, P, K, Ca, Mg, NH_4^+–N and NO^- 3–N than that of biochar. There was no paper which recorded the effects of Bced on soil microbial properties, enzymes and plant growth. These indicators, such as soil microbial biomass and soil microbial community structure, are sensitive to local changes in the environmental conditions and anthropogenic activity and are critical to the global ecosystem.[21,80–83]

BCing also had different effects on soil amendment. Schulz et al. [78] demonstrated the positive influence of BCing on plant growth and soil properties and TOC, oat plant height, biomass production and seed weight were increased with rising biochar amount in BCing raw material, and they also considered that composting is a good way to overcome biochar's inherent nutrient deficiency, which makes it a suitable technique to help refine farm-scale nutrient cycles. Other studies also found that amendment of BCing in conjunction with a pyroligneous solution from wheat straw could be an effective option to alleviate the salt stress and improve crop productivity in salt affected croplands.[77] Besides, BCing was economically viable within every cropping season in a maize mono-cropping system.[69] However, Schmidt et al. [79] found that biochar, compost and BCing did not show relevant effects on plant growth parameters of vine or vine health, and only found minor effects on grape quality that were present in the first year though not in the second and third year. Also, the performance of BCing was better than that of biochar. They thought that the effectiveness of these amendments were lower than other similar studies partly due to the favorable, unrestrictive soil and climatic conditions.[79] All these studies focus on plant growth and partly on soil physico-chemical properties.[76] However, there are no publications about the effects of BCing on soil gas emission, microbial properties and enzymes which were important for the ecological system.[20,21,81,83,84]

Implication of the interaction for soil pollution remediation

The interaction of biochar and composting had influences on each other's adsorption/desorption properties for a pollutant. For example, amendment with a mixture of compost and biochar endows the alluvial soil with high adsorptive properties (from $K_{fads(soil)} = 9.26$ to $K_{fads(mixture)} = 17.89$) without impeding the slow release of tricyclazole.[85] Composting obviously improved the adsorption affinity coefficient nearly by a factor of 5 for biochar in the adsorption experiment of copper (Cu(II)).[34] However, Dechene et al. [86] found that composting did not obviously affect adsorption or

Table 2. Studies regarding the implications of biochar and composting (or compost) combined amendments for soil pollution remediation.

	B + C	BCed	BCing	Reference
Sorption effectiveness		Cu(II)		[34]
		polar herbicides and herbicide metabolites		[86]
	tricyclazole			[85]
Soil pollution remediation effectiveness	As, Cd, Cu, Pb, Zn, PAHs			[88]
	As, Cd, Cu, Pb, Zn			[89]
			Zn, Cu, PAHs	[90]
	Cu, Pb			[32]
	Cd, Cu, Pb, Zn			[91]
			Cu	[92]
	Co, Cu, Ni, Pb, Zn			[93]
	Cu, Pb, Zn			[94]
	Cd, Cu, Pb, Zn	Cd, Cu, Pb, Zn	Cd, Cu, Pb, Zn	[33]

B + C: biochar and compost mixed amendment material; Bced: composted biochar and without compost; BCing: biochar and biomass mixed and then composting.

desorption of polar herbicide (imazamox) and three herbicide metabolites (methyl-desphenyl-chloridazon, metazachlor oxalic acid, metazachlor sulfonic acid) of biochar and thought that these anionic compounds were rather repulsed by the net negative charge of biochar and Bced.[87]

As shown in Table 2, the efficiency studies of biochar and composting (or compost) combined amendments for soil pollution remediation mainly were focus on that of B + C. As a result of the changes in raw materials, production condition, ratio and the application of biochar and compost amounts, concentrations and kinds of pollution and fertility, pH and soil SOM, the results of studies had some differences.[91,93] However, in general, the main viewpoints agreed with that efficiency of B + C for soil pollution remediation are between that of biochar and compost.[32,33,89,88,94]

There were few studies that focused on the efficiency of Bced or BCing for soil pollution remediation. Only Zeng et al. [33] systematically studied the efficiency of corn core biochar, straw compost, B + C, Bced and BCing for reducing Cd, Cu, Zn, and Pb bioavailability, mobility and ecological risks in wetland soil, and they found that Bced and BCing had the greatest capacity for reducing the bioavailability and mobility of Cd, Cu, Zn Pb, and BCing had the greatest capacity for reducing the ecological risk of Cd, Cu, Zn and Pb. Hua et al. [90] reported that sludge composted with biochar significantly decreased the mobility of Zn, Cu and polycyclic aromatic hydrocarbons, compared with the composted sludge without biochar, with lower absorption and less accumulation of pollutants by the plants. The sludge composted with biochar in this study contained only 7% (w/w) biochar, and this study focus on the application of compost which was improved by little biochar. The increase of biochar probably induced greater capacity for soil pollution remediation. In stark contrast, another study argued that biochar, compost and BCing had no significant effect on Cu immobilization in soil.[92] This difference was a result of the difference of raw material biochar and compost together with soil properties.

On the whole, there were insufficient papers reporting on the application of Bced and BCing in soil organic pollutions remediation or soil combined pollution of heavy metal and organic pollutant remediation. The interaction of biochar and composting could enhance composting microbial activities and improve adsorption of biochar. This would improve the effectiveness of biochar and compost for the degradation of organic pollutant and the adsorption of heavy metals and organic pollutants. Besides, composting (mixed contaminated soil and raw materials of compost then composting) was another effective amendment for soil organic pollutions.[95] The addition of biochar may change the efficiency of composting for soil organic pollutions remediation, and there are no reports on this matter.

Conclusion and future research needs

Interaction of biochar and composting had influences on each other's properties. Biochar could affect the physico-chemical properties, microorganisms, degradation and humification and gas emission of composting, such as the rise of nutrients, CEC, organic matter and microbial activities. Composting could change the physico-chemical properties and facial functional groups of biochar, such as the increase of nutrients, CEC, functional group and organic matter. These changes would potentially improve the efficiency of biochar and compost for soil amendment and pollution remediation.

Based on the above review, the following is recommended for the future research:

1. Biochar (activated by steam/acid/KOH) has captured the increasing attention of researchers because of its improved properties.[96–98] The effects of activated biochar (which probably has greater ability for promoting composting than that

of fresh biochar) on physico-chemical properties, microbigams, degradation, humification and gas emission of composting needs further study.

2. Effect of Bced and BCing on farmland, wetland and grassland soil amendment (especially on soil microbial properties, gas emission, enzymes and plant growth).
3. Efficiency of Bced and BCing for organic pollutions remediation or combined pollution of heavy metal and organic pollutant remediation in farmland, wetland and grassland soil.
4. Composting (mixed contaminated soil and raw materials of compost before composting) was one effective amendment for soil organic pollutions. The addition of biochar may change the efficiency of composting for soil organic pollutions remediation – this requires further research.
5. Biochar and composting combined amendments, as well as other organic amendments (ex. biochar), could decrease bioavailability of pesticides. This may cause an increase in the consumption of pesticides. The enhanced ecological risks induced by an increase in the consumption of pesticides is worthy of attention.

Disclosure statement

The authors report no declarations of other interest.

Funding

This article was financially supported by CRSRI Open Research Program [CKWV2015203/KY], National Natural Science Foundation of China [51521006, 51378190, 51479072, 51408206], and Program for Changjiang Scholars and Innovative Research Team in University [IRT-13R17].

References

[1] Farrell M, Jones DL. Critical evaluation of municipal solid waste composting and potential compost markets. Bioresour Technol. 2009;100:4301–4310.

[2] Park JH, Lamb D, Paneerselvam P, et al. Role of organic amendments on enhanced bioremediation of heavy metal(loid) contaminated soils. J Hazard Mater. 2011;185:549–574.

[3] Thangarajan R, Bolan NS, Tian G, et al. Role of organic amendment application on greenhouse gas emission from soil. Sci Total Environ. 2013;465:72–96.

[4] Zeng G, Chen M, Zeng Z. Risks of neonicotinoid pesticides. Science. 2013a;340:1403.

[5] Beesley L, Moreno-Jiménez E, Gomez-Eyles JL, et al. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environ Pollut. 2011;159:3269–3282.

[6] Lu L, Zeng G, Fan C, et al. Diversity of two-domain laccase-like multicopper oxidase genes in streptomyces spp.: identification of genes potentially involved in extracellular activities and lignocellulose degradation during composting of agricultural waste. Appl Environ Microbiol. 2014b;80:3305–3314.

[7] Zeng G, Huang D, Huang G, et al. Composting of lead-contaminated solid waste with inocula of white-rot fungus. Bioresour Technol. 2007;98:320–326.

[8] Semple KT, Reid BJ, Fermor TR. Impact of composting strategies on the treatment of soils contaminated with organic pollutants. Environ Pollut. 2001;112:269–283.

[9] Zeng G, Yu Z, Chen Y, et al. Response of compost maturity and microbial community composition to pentachlorophenol (PCP)-contaminated soil during composting. Bioresour Technol. 2011;102:5905–5911.

[10] Ahmad M, Rajapaksha AU, Lim JE, et al. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere. 2014;99:19–33.

[11] Betts AR, Chen N, Hamilton JG, et al. Rates and mechanisms of Zn2+ adsorption on a meat and bonemeal biochar. Environ Sci Technol. 2013;47:14350–14357.

[12] Huang B, Li Z, Huang J, et al. Adsorption characteristics of Cu and Zn onto various size fractions of aggregates from red paddy soil. J Hazard Mater. 2014a;264:176–183.

[13] Khan S, Chao C, Waqas M, et al. Sewage sludge biochar influence upon rice (Oryza sativa L) yield, metal bioaccumulation and greenhouse gas emissions from acidic paddy soil. Environ Sci Technol. 2013;47:8624–8632.

[14] Mohan D, Sarswat A, Ok YS, et al. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent-a critical review. Bioresour Technol. 2014;160:191–202.

[15] Sohi SP. Agriculture. Carbon storage with benefits. Science. 2012;338:1034–1035.

[16] Teixido M, Hurtado C, Pignatello JJ, et al. Predicting contaminant adsorption in black carbon (biochar)-amended soil for the veterinary antimicrobial sulfamethazine. Environ Sci Technol. 2013;47:6197–6205.

[17] Woods WI, Falcao NPS, Teixeira WG. Biochar trials aim to enrich soil for smallholders. Nature. 2006;443:144.

[18] Zeng G, Chen M, Zeng Z. Shale gas: surface water also at risk. Nature. 2013b;499:154.

[19] Abit SM, Bolster CH, Cai P. Influence of feedstock and pyrolysis temperature of biochar amendments on transport of Escherichia coli in saturated and unsaturated soil. Environ Sci Technol. 2012;46:8097–8105.

[20] Hale SE, Jensen J, Jakob L, et al. Short-term effect of the soil amendments activated carbon, biochar, and ferric oxyhydroxide on bacteria and invertebrates. Environ Sci Technol. 2013;47:8674–8683.

[21] Lu L, Huggins T, Jin S, et al. Microbial metabolism and community structure in response to bioelectrochemically enhanced remediation of petroleum hydrocarbon-contaminated soil. Environ Sci Technol. 2014a;48:4021–4029.

[22] Mao JD, Johnson RL, Lehmann J, et al. Abundant and stable char residues in soils: implications for soil fertility and carbon sequestration. Environ Sci Technol. 2012;46:9571–9576.

[23] Masiello CA, Chen Y, Gao X, et al. Biochar and microbial signaling: production conditions determine effects on microbial communication. Environ Sci Technol. 2013;47:11496–11503.

[24] Schmidt MWI, Torn MS, Abiven S, et al. Persistence of soil organic matter as an ecosystem property. Nature. 2011;478:49–56.

[25] Wang C, Lu H, Dong D, et al. Insight into the effects of biochar on manure composting: evidence supporting the relationship between N2O emission and denitrifying community. Environ Sci Technol. 2013;47: 7341–7349.

[26] Wei L, Shutao W, Jin Z, et al. Biochar influences the microbial community structure during tomato stalk composting with chicken manure. Bioresour Technol. 2014;154:148–154.

[27] Borchard N, Spokas K, Prost K, et al. Greenhouse gas production in mixtures of soil with composted and noncomposted biochars is governed by char-associated organic compounds. J Environ Qual. 2014;43:971.

[28] Prost K, Borchard N, Siemens J, et al. Biochar affected by composting with farmyard manure. J Environ Qual. 2013;42:164–172.

[29] Jindo K, Sanchez-Monedero MA, Hernandez T, et al. Biochar influences the microbial community structure during manure composting with agricultural wastes. Sci Total Environ. 2012a;416:476–481.

[30] Steiner C, Melear N, Harris K, et al. Biochar as bulking agent for poultry litter composting. Carbon Manag. 2011;2:227–230.

[31] Dias BO, Silva CA, Higashikawa FS, et al. Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. Bioresour Technol. 2010;101: 1239–1246.

[32] Karami N, Clemente R, Moreno-Jimenez E, et al. Efficiency of green waste compost and biochar soil amendments for reducing lead and copper mobility and uptake to ryegrass. J Hazard Mater. 2011;191:41–48.

[33] Zeng G, Wu H, Liang J, et al. Efficiency of biochar and compost (or composting) combined amendments for reducing Cd, Cu, Zn and Pb bioavailability, mobility and ecological risk in wetland soil. RSC Adv. 2015;5:34541–34548.

[34] Borchard N, Prost K, Kautz T, et al. Sorption of copper (II) and sulfate to different biochars before and after composting with farmyard manure. Eur J Soil Sci. 2012;63:399–409.

[35] Gong JL, Wang B, Zeng GM, et al. Removal of cationic dyes from aqueous solution using magnetic multi-wall carbon nanotube nanocomposite as adsorbent. J Hazard Mater. 2009;164:1517–1522.

[36] Fogarty AM, Tuovinen OH. Microbiological degradation of pesticides in yard waste composting. Microbiol Rev. 1991;55:225–233.

[37] Chowdhury MA, de Neergaard A, Jensen LS. Potential of aeration flow rate and bio-char addition to reduce greenhouse gas and ammonia emissions during manure composting. Chemosphere. 2014;97:16–25.

[38] Khan N, Clark I, Sanchez-Monedero MA, et al. Maturity indices in co-composting of chicken manure and sawdust with biochar. Bioresour Technol. 2014;168: 245–251.

[39] Malińska K, Zabochnicka-Świątek M, Dach J. Effects of biochar amendment on ammonia emission during composting of sewage sludge. Ecol Eng. 2014;71: 474–478.

[40] Steiner C, Das KC, Melear N, et al. Reducing nitrogen loss during poultry litter composting using biochar. J Environ Qual. 2010;39:1236.

[41] Jindo K, Suto K, Matsumoto K, et al. Chemical and biochemical characterization of biochar-blended composts prepared from poultry manure. Bioresour Technol. 2012b;110:396–404.

[42] Zhang L, Sun X. Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar. Bioresour Technol. 2014;171: 274–284.

[43] Zhang L, Sun X-y, Tian Y, et al. Biochar and humic acid amendments improve the quality of composted green waste as a growth medium for the ornamental plant Calathea insignis. Sci Hortic. 2014b;176:70–78.

[44] Zhang J, Lu F, Shao L, et al. The use of biochar-amended composting to improve the humification and degradation of sewage sludge. Bioresour Technol. 2014a;168:252–258.

[45] Xu P, Zeng GM, Huang DL, et al. Use of iron oxide nanomaterials in wastewater treatment: a review. Sci Total Environ. 2012;424:1–10.

[46] Sanchez-Garcia M, Alburquerque JA, Sanchez-Monedero MA, et al. Biochar accelerates organic matter degradation and enhances N mineralisation during composting of poultry manure without a relevant impact on gas emissions. Bioresour Technol. 2015;192: 272–279.

[47] Hua L, Wu W, Liu Y, et al. Reduction of nitrogen loss and Cu and Zn mobility during sludge composting with bamboo charcoal amendment. Environ Sci Pollut Res Int. 2009;16:1–9.

[48] Douds DD, Lee J, Uknalis J, et al. Pelletized biochar as a carrier for AM fungi in the on-farm system of inoculum production in compost and vermiculite mixtures. Compost Sci Util. 2014;22:253–262.

[49] Hua L, Chen Y, Wu W, et al. Microorganism communities and chemical characteristics in sludge-bamboo charcoal composting system. Environ Technol. 2011;32:663–672.

[50] Otterpohl R. Boosting compost with biochar and bacteria. Nature. 2012;486:187–188.

[51] Yoshizawa S, Tanaka S, Ohata M, Mineki S, Goto S, Fujioka K, Kokubun T. Composting of food garbage and livestock waste containing biomass charcoal. Proceedings of the International Conference and Natural Resources and Environmental Management Kuching; 2005; Sarawak, Malaysia.

[52] Zhang Y, Zeng GM, Tang L, et al. A hydroquinone biosensor using modified core-shell magnetic nanoparticles supported on carbon paste electrode. Biosens Bioelectron. 2007;22:2121–2126.

[53] Sonoki T, Furukawa T, Jindo K, et al. Influence of biochar addition on methane metabolism during thermophilic phase of composting. J Basic Microbiol. 2013;53:617–621.

[54] Wang C, Tu Q, Dong D, et al. Spectroscopic evidence for biochar amendment promoting humic acid synthesis and intensifying humification during composting. J Hazard Mater. 2014;280:409–416.

[55] Ngo PT, Rumpel C, Ngo QA, et al. Biological and chemical reactivity and phosphorus forms of buffalo manure compost, vermicompost and their mixture with biochar. Bioresour Technol. 2013;148:401–407.

[56] Fan T, Liu Y, Feng B, et al. Biosorption of cadmium(II), zinc(II) and lead(II) by Penicillium simplicissimum: isotherms, kinetics and thermodynamics. J Hazard Mater. 2008;160:655–661.

[57] Khan N, Clark I, Sanchez-Monedero MA, et al. Physical and chemical properties of biochars co-composted with biowastes and incubated with a chicken litter compost. Chemosphere. 2015;142:14–23.

[58] Wiedner K, Fischer D, Walther S, et al. Acceleration of biochar surface oxidation during composting?. J Agric Food Chem. 2015;63:3830–3837.

[59] Feng Y, Gong J-L, Zeng G-M, et al. Adsorption of Cd (II) and Zn (II) from aqueous solutions using magnetic hydroxyapatite nanoparticles as adsorbents. Chem Eng J. 2010;162:487–494.

[60] Hamer U, Marschner B, Brodowski S, et al. Interactive priming of black carbon and glucose mineralization. Org Geochem. 2004;35:823–830.

[61] Kuzyakov Y, Subbotina I, Chen H, et al. Black carbon decomposition and incorporation into soil microbial biomass estimated by 14C labeling. Soil Biol Biochem. 2009;41:210–219.

[62] Pietikainen J, Kiikkila O, Fritze H. Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. Oikos. 2000;89:231–242.

[63] Bamminger C, Marschner B, Jüschke E. An incubation study on the stability and biological effects of pyrogenic and hydrothermal biochar in two soils. Eur J Soil Sci. 2014;65:72–82.

[64] Ch'ng HY, Ahmed OH, Majid NM. Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. Scientific World Journal. 2014;2014:506356.

[65] Fernandez JM, Nieto MA, Lopez-de-Sa EG, et al. Carbon dioxide emissions from semi-arid soils amended with biochar alone or combined with mineral and organic fertilizers. Sci Total Environ. 2014;482–483:1–7.

[66] Ghosh S, Ow LF, Wilson B. Influence of biochar and compost on soil properties and tree growth in a tropical urban environment. Int J Environ Sci Te. 2014;12: 1303–1310.

[67] Kammann C, Ratering S, Eckhard C, et al. Biochar and hydrochar effects on greenhouse gas (carbon dioxide, nitrous oxide, and methane) fluxes from soils. J Environ Qual. 2012;41:1052–1066.

[68] Liu J, Schulz H, Brandl S, et al. Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions. J Plant Nutr Soil Sci. 2012;175:698–707.

[69] Mekuria W, Getnet K, Noble A, et al. Economic valuation of organic and clay-based soil amendments in small-scale agriculture in Lao PDR. Field Crop Res. 2013;149:379–389.

[70] Mukome FND, Six J, Parikh SJ. The effects of walnut shell and wood feedstock biochar amendments on greenhouse gas emissions from a fertile soil. Geoderma. 2013;200:90–98.

[71] Schulz H, Glaser B. Effects of biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. J Plant Nutr Soil Sci. 2012;175:410–422.

[72] Steiner C, Glaser B, Geraldes Teixeira W, et al. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. J Plant Nutr Soil Sci. 2008;171:893–899.

[73] Suddick EC, Six J. An estimation of annual nitrous oxide emissions and soil quality following the amendment of high temperature walnut shell biochar and compost to a small scale vegetable crop rotation. Sci Total Environ. 2013;465:298–307.

[74] Tammeorg P, Brandstaka T, Simojoki A, et al. Nitrogen mineralization dynamics of meat bone meal and cattle manure as affected by the application of softwood chip biochar in soil. Earth Env Sci Trans Royal Soc. 2013;103:19–30.

[75] Zhu K, Christel W, Bruun S, et al. The different effects of applying fresh, composted or charred manure on soil N2O emissions. Soil Biol, Biochem. 2014;74:61–69.

[76] Glaser B, Wiedner K, Seelig S, et al. Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. Agron Sustain Dev. 2014;35:667–678.

[77] Lashari MS, Liu Y, Li L, et al. Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain. Field Crop Res. 2013;144:113–118.

[78] Schulz H, Dunst G, Glaser B. Positive effects of composted biochar on plant growth and soil fertility. Agron Sustain Dev. 2013;33:817–827.

[79] Schmidt H-P, Kammann C, Niggli C, et al. Biochar and biochar-compost as soil amendments to a vineyard soil: Influences on plant growth, nutrient uptake, plant health and grape quality. Agr Ecosyst Environ. 2014;191:117–123.

[80] Huang J, Li Z, Zeng G, et al. Microbial responses to simulated water erosion in relation to organic carbon dynamics on a hilly cropland in subtropical China. Ecol Eng. 2013;60:67–75.

[81] Wu H, Zeng G, Liang J, et al. Effect of early dry season induced by the three Gorges dam on the soil microbial biomass and bacterial community structure in the Dongting Lake wetland. Ecol Indic. 2015;53:129–136.

[82] Wu H, Zeng G, Liang J, et al. Changes of soil microbial biomass and bacterial community structure in Dongting lake: impacts of 50,000 dams of Yangtze river. Ecol Eng. 2013;57:72–78.

[83] Xu HJ, Wang XH, Li H, et al. Biochar impacts soil microbial community composition and nitrogen cycling in an acidic soil planted with rape. Environ Sci Technol. 2014;48:9391–9399.

[84] Huang J, Li Z, Nie X, et al. Microbial responses to soil rewetting in erosional and depositional environments in relation to the organic carbon dynamics. Geomorphology. 2014b;204:256–264.
[85] Garcia-Jaramillo M, Cox L, Knicker HE, et al. Characterization and selection of biochar for an efficient retention of tricyclazole in a flooded alluvial paddy soil. J Hazard Mater. 2015;286:581–588.
[86] Dechene A, Rosendahl I, Laabs V, et al. Sorption of polar herbicides and herbicide metabolites by biochar-amended soil. Chemosphere. 2014;109: 180–186.
[87] Hu XJ, Wang JS, Liu YG, et al. Adsorption of chromium (VI) by ethylenediamine-modified cross-linked magnetic chitosan resin: isotherms, kinetics and thermodynamics. J Hazard Mater. 2011;185:306–314.
[88] Beesley L, Moreno-Jimenez E, Gomez-Eyles JL. Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. Environ Pollut. 2010;158:2282–2287.
[89] Beesley L, Inneh OS, Norton GJ, et al. Assessing the influence of compost and biochar amendments on the mobility and toxicity of metals and arsenic in a naturally contaminated mine soil. Environ Pollut. 2014;186:195–202.
[90] Hua L, Chen Y, Wu W. Impacts upon soil quality and plant growth of bamboo charcoal addition to composted sludge. Environ Technol. 2012;33:61–68.
[91] Kargar M, Clark OG, Hendershot WH, et al. Immobilization of trace metals in contaminated urban soil amended with compost and biochar. Water Air Soil Poll. 2015;226:119–119.
[92] Mackie KA, Marhan S, Ditterich F, et al. The effects of biochar and compost amendments on copper immobilization and soil microorganisms in a temperate vineyard. Agr Ecosyst Environ. 2015;201:58–69.
[93] Rodriguez-Vila A, Covelo EF, Forjan R, et al. Phytoremediating a copper mine soil with Brassica juncea L., compost and biochar. Environ Sci Pollut Res Int. 2014;21:11293–11304.
[94] Sizmur T, Wingate J, Hutchings T, et al. Lumbricus terrestris L. does not impact on the remediation efficiency of compost and biochar amendments. Pedobiologia. 2011;54:S211–S216.
[95] Chen M, Xu P, Zeng G, et al. Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: applications, microbes and future research needs. Biotechnol Adv. 2015;33:745–755.
[96] Gupta RK, Dubey M, Kharel P, et al. Biochar activated by oxygen plasma for supercapacitors. J Power Sources. 2015;274:1300–1305.
[97] Hadjittofi L, Prodromou M, Pashalidis I. Activated biochar derived from cactus fibres-preparation, characterization and application on Cu(II) removal from aqueous solutions. Bioresour Technol. 2014;159: 460–464.
[98] Rajapaksha AU, Vithanage M, Ahmad M, et al. Enhanced sulfamethazine removal by steam-activated invasive plant-derived biochar. J Hazard Mater. 2015;290:43–50.