Chapter 2

Biochar: The Black Diamond for Soil Sustainability, Contamination Control and Agricultural Production

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Abstract

Production of biochars from agricultural wastes reduces significantly the volume and weight of the wastes, and hence, it can be considered as a promising means for managing the agricultural wastes. Biochar has received great interest during the last few years, due to its beneficial role to mitigate CO_2 emission through enhancing the long-term carbon sequestration. The effects of biochar on soil properties vary widely, depending on the characteristics of soil and the biochar. Most types of biochars are of alkaline nature and of high C content. Addition of biochar to the soil can improve the cation exchange capacity enrich soil with the nutrients and enhance the microbial growth, and improve some soil physical properties such as water retention and aggregation. For contamination control, biochars have proven to be a suitable tool for controlling the contaminants in the environment. The high surface area, porous structure, alkaline nature, and the presence of functional groups characterized the biochar as alternative option for the remediation of heavy metal contaminated waters and soils. However, there is a lack of knowledge regarding the effects of biochar in the presence of mineral and/or organic fertilizers on the plant growth and nutrient transformation in soils. In addition, biochar is successfully used for treating the acid soils; therefore, future studies are needed to investigate the neutralization of alkaline performance of biochar to be used safely in alkaline soils.

Keywords: biochar, soil, mineral fertilizers, contaminants, environmental management

1. Introduction

The increasing demand for food and the fertilizers (inorganic and organic) is a day fact. Mineral fertilizers are of great importance for food production. Accordingly, the world demand for mineral fertilizers has increased during the last few decades to meet the increased demand for agricultural products in response to the growing population [1]. However, several studies indicated that mineral fertilizers contain various amounts of heavy metals as impurities [1, 2]. Consequently, the addition of large amounts of mineral fertilizers to the soil for long periods may result in the accumulation of heavy metals in soils and plant grown thereon, as confirmed by previous studies [1, 3].

Intensive researches have been performed to overcome the infertility problems of the agricultural soils. The addition of organic residues in forms of compost, manure, and other organic forms has proven to be suitable alternative options for mineral fertilization. However, these materials need to be applied intensively due to their low nutritive contents and rapid degradation rate. Biochar is a charcoal produced from the pyrolysis of biomass at relatively low temperature (<700°C) [4]. Biochar has received great interest during the last few years, due to its beneficial roles in environmental management. Several beneficial objectives could be achieved through biochar application for environment, that is, waste management, energy production, soil improvement, maximizing agricultural production, contamination control (soils and waters), and greenhouse gases (GHGs) mitigation [5–10].

2. Production and characterization of biochars derived from different wastes

2.1. Historical view of the biochar

Biochar production is an ancient practice over that past 70 centuries in the Egyptian societies. It seems that the production of biochar was not the main target, the Egyptian societies used the liquid wood tars to embalm the bodies of their dead, and the liquid preserving agent was produced from charring processes [11]. Similarly, the use of biochar as soil amendment first began over the past 2,500 years in South America (terra preta), the place which named "the black earth." Biochar is created both naturally by forest fires and by human through burning bits for different practices, that is, cooking and manufacturing. Terra preta is a famous soil located in the Amazon Basin. The acidic condition of terra preta in the past due to the toxic levels of exchangeable aluminum hindered the agricultural production; however, the continuous accumulation of biochar in the soils led to enrich the soil in calcium and phosphate and elevated pH level in comparison with the surrounding soils. In addition, terra preta soil contains about 50 Mg ha^{-1} carbon in a form of biochar within approximately 1 m depth [12]. Consequently, aluminum toxicity in this soil was neutralized, and soil status in terms of physical, biological, and chemical features has been modified that made it one of the most fertile soils over the world. The promising benefits of biochar have alerted the sign for researchers in the past to determine the positive performance of biochar, for example, the role of biochar for improving vegetative growth and enhancing soil fertility has been studied by Trimble [13] and Retan [14]. Due to the several benefits of biochar, many researches and extension initiatives of biochar have been established all over the world in order to spread the knowledge and cooperation of biochar and its applications, for example,

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the Australia New Zealand Biochar Research Network (www.anzbiochar.org/project.html), the US Biochar Initiative (http://biochar-us.org/biochar-research), the European Biochar Research Network (http://cost.european-biochar.org/en), the UK Biochar Research Center (http://www.biochar.ac.uk/), the China Biochar Network (http://www.biochar-international.org/chinanetwork), the Japan Biochar Association (http://www.geocities.jp/yasizato/JBA.htm), the New Zealand Biochar Research Centre (http://www.massey.ac.nz/massey/learning/colleges/college-of-sciences/research/agriculture-environment-research/soil-earth-sciences/biochar-research-centre/biochar-research-centre_home.cfm) and the Biochar India (www.biocharindia.com).

2.2. Production of biochar

2.2.1. Biomasses for biochar production

The rapid population growth led to subsequent increases in food production, and consequently, large amounts of organic residues are produced annually [8]. Therefore, it is essential to recycle their organic residues effectively. Various types of biomass have been used for biochar production, including: (i) agricultural and forestry by-products, that is, wood chips, straw, nut shells, rice hulls, tree bark, wood pellets, and switch grass, (ii) industrial by-products, that is, sugar cane bagasse, paper sludge, and pulp, (iii) animal wastes such as chicken litter, dairy and swine manure, and (iv) sewage sludge. Producing the biochar from biomass, especially wastes offer an excellent way for the recycling of wastes into beneficial materials. Pyrolysis treatment reduces the volume of biomasses by 44–90 and 75–80% and weight by 44–93 and 71–77% [8, 15].

2.2.2. Production technologies of biochar

Biochar is produced through the pyrolysis process, in which the biomasses are burned in the absence of oxygen. As mentioned above, the main objective of biochar production is to use it as a soil amendment or for usage in other aspects such as remediation and industrial technologies. The process is closely similar to those of gasification; however, in case of gasification, the process is performed in two steps, firstly, the biomass is heated to around 600°C, and hydrocarbon gases and tar are evaporated; secondly, char is gasified by reaction with oxygen, hydrogen, and steam under high temperature. However, in case of pyrolysis, the biomass is burned in the absence of oxygen along the production time. There are many important secondary products upon producing the biochar, including a synthetic gas that can be used to generate electricity and bio-oil, which can be used as diesel fuel. As shown in **Table 1**, biochar can be produced through fast and slow pyrolysis techniques; the main difference between them is the heating rate and the amount of the produced bio-oil.

2.2.3. Development of biochar production

Figure 1 shows the development of biochar production. The people used to simply gather piles of agricultural wastes and cover them and burn them slowly with limited air. They have

Parameter	Biochar production		
	Fast pyrolysis	Slow pyrolysis	Gasification
Temperature	~500°C	~400°C	600–1800°C
Heating rate	up to 1000°C min^{-1}	Slow 5–30°C min^{-1}	–
Time	Few seconds	Hours ~ days	–
Aeration	Oxygen free	Oxygen free or limited	Oxygen limited
Biochar	~12%	~35%	~10%
Syngas	~13%	~35%	~85%
Bio-oil	~75%	~30%	~5%

Data obtained from Roos [16].

Table 1. Differences between gasification and pyrolysis processes.

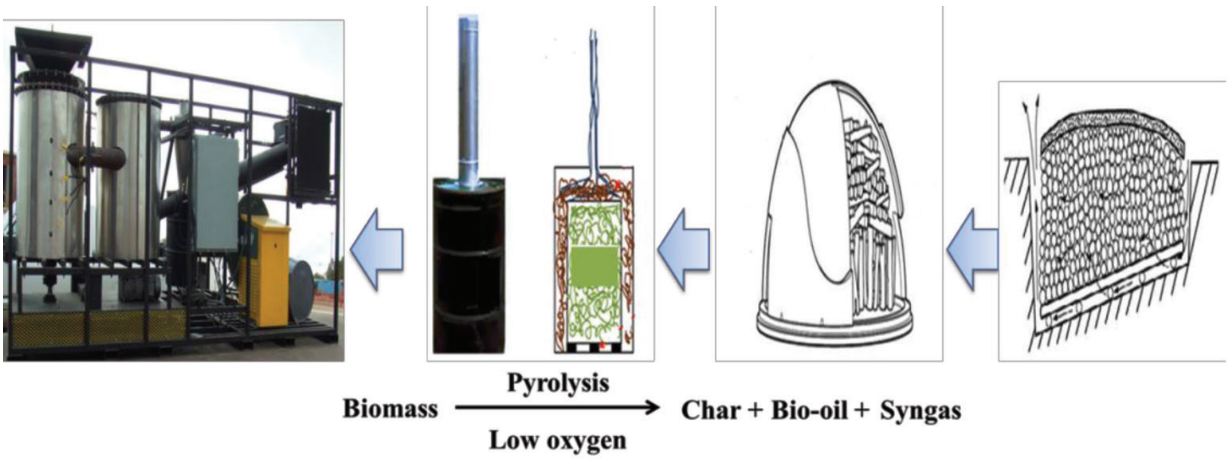

Figure 1. Development of biochar production. Images obtained from Lehmann and Joseph [4], Abdelhafez et al. [7].

used several ways to exclude air penetration into burning places, such like covering with soil particles. This traditional method is still used today in developing countries; however, considerable amounts of smokes and almost half amount of carbon dioxide in the original biomass are released into the atmosphere. Briefly, biomasses were put together tightly and covered with a layer of soil in a large pit kiln then a small part of the biomass was burned up. To achieve a successful pyrolysis process, people used to make small holes in the soil surface to provide amount of air uniformly in order to maintain a productive balance between burning and pyrolysis. The pit kiln has some disadvantages, that is, the release of almost 50% of C into the atmosphere and the high ash content of the produced biochar. To overcome these problems, brick kilns were developed to achieve more control for aeration. These kilns were better insulated and allowed a better airflow control, which allowed higher biochar yields and lower ash contents of the produced biochar. The above-mentioned techniques are in situ biochar production units, where the biochar was made at places where suitable raw material was abundant. By beginning of the 1930s, transportable, cylindrical metal kilns were developed in Europe and became popular in the 1960s, in developing countries. They are often made out of oil drums and are more easily to handle than traditional pits. The sealed container allows a high control of airflow, and the biochar can easier be recovered [17]. The portable kilns are still used in developing countries in the small farms and have been used experimentally by Abdelhafez et al. [8, 9] in China and Egypt, respectively. However, the traditional methods may contaminate the environment due to the emitted syngas and bio-oils. Therefore, advanced instruments have been developed successfully to eliminate the emitted syngas and bio-oil and to use them as by products by using specific condensers for gas and bio-oil collection.

2.3. Differences between biochar and charcoal

Man used to create charcoal instinctively for heating, industry and production beginning from the creation. Both biochar and charcoal contain high carbon materials; however, there are some major differences as follows [4]:

(i) Charcoal is produced primarily as a source of energy, while biochar is manufactured as a soil amendment for improving soil fertility, carbon (C) sink, or water filtration.

(ii) Wood is the major source of charcoal production; however, biochar can be produced from any biomass.

(iii) The carbonization trend of biochar is not complete as in charcoal; consequently, charcoal contains much ash content compared to the biochar.

Carbon is present in the biochar in a form of six C atoms linked together. The formation of graphite is more likely to occur when the C atoms arranged together without O or H ions. However, in case of biochar, graphite does not form because the arranged atoms of carbon are corrupted by O and H ions; as a result, C atoms are arranged irregularly according to the type of biomass used for biochar production and temperature of pyrolysis [4].

2.4. Physicochemical characteristics of biochar

All biochars are black but are not created equal and are not of the same physicochemical characteristics. Both the types of biomass and pyrolysis conditions play important roles for identifying the characteristics of the produced biochars [5, 18]. The produced material of biochar is a solid, structured, carbonaceous material and exhibits a high surface area [19], low oxygen and hydrogen contents [20], and little amount of nutrients [21, 22]. The physical characteristics of the produced biochar depend mainly on the type of biomass and the pyrolysis conditions, in terms of, heating rate, highest temperature of burning, pressure, burning time and the characteristics of burning vessel. It is well known that organic materials start to decompose after 120°C; hemicellulose compounds decompose at 200–260°C, and lignins decompose at 240–350°C [23]. Biochar has proven to be a suitable tool for the removal of heavy metals from aqueous solutions [10] due to the presence of macrospores with an average pore size of 51–138 m^2 g^{-1} [24],. The presence of functional groups on the surface of biochar candidate it for the removal of organic and inorganic contaminants from aqueous solutions. Abdelhafez and Li [10] demonstrated that the spectrums of sugar cane and orange peel biochars are quite similar; both biochars exhibited absorption bands on 3448.13 and 3429.4 cm^{-1} corresponding to C─OH functional groups; around 1637.27 and 1384.85 cm^{-1}, there were C═O and C─C bands and the adsorption bands on 1101.43 cm^{-1} present the C─O, C─C, and C─OH bands. Therefore, both biochars had the ability to adsorb Pb(II) ions from aqueous solutions. During the pyrolysis of biomass, heating causes some nutrients to be volatilized, especially at the surface of the material, while other nutrients become concentrated in the remaining biochar. In case of wood-rich materials, carbon (C) begins to volatilize around 100°C, N above 200°C, S above 375°C, and potassium (K) and P between 700°C and 800°C. The volatilization of magnesium (Mg), calcium (Ca), and manganese (Mn) occurs at temperatures above 1000°C [25, 26]. Therefore, biochar contains much amount of alkali metal ions causing its liming performance when it is applied to the soils [8, 9]. As shown in **Table 2**, more than 80% of the produced biochars is C, while nitrogen contents are relatively low because most of nitrogen in the feedstock starts to be volatile at temperature above 200°C. Therefore, the nitrogen contents of biochars derived from agricultural wastes are quite low. However, the nitrogen content of sewage sludge biochar seems to be higher than the agricultural wastes biochars [15]. Furthermore, most of the stated biochars characterized by its high pH values, and this could be attributed to the presence of alkaline metal ions, that is, Ca, Mg, and K, which are stable and does not volatile in the biomass during the production of biochars. The previous studies demonstrated that increasing the pyrolysis time and temperature led to increase the surface area and pours structure of the produced biochar [27, 28]. Similarly, the pH of the produced biochar depends on the pyrolysis temperature and time; by increasing the pyrolysis temperature, the pH of the produced biochars increased to reach 11.5 in some studies [29]. A point to note that, biochar has a liming effect when it is applied to the soil; therefore, possible increment in soil acidity (pH) might occur [8]. In addition, adsorption of macronutrients (N, P and K) on the surfaces of biochar might hinder its uptake by the growing plants. Applying biochar to the soils has been found to increase the bioavailability and plant uptake of phosphorus (P), alkaline metals and some trace metals [30], but the mechanisms for these increases are still a matter of speculation. Moreover, the benefits of biochar for the removal of organic and inorganic contaminants from water are well documented [31, 32]. However, to date, only limited studies are available on biochar effects combined with different mineral and organic fertilization levels on soil properties and plant growth. The behavior of biochar is not equal for all elements; some studies have reported that biochar has the potential for the stabilization of Pb in shooting range and metal smelter contaminated soils [7, 10]. Abdelhafez et al. [7, 8]. illustrated the beneficial effect of biochar for soil improvement and Pb remediation in a military shooting range and metal smelter contaminated soils. Moreover, it was found that biochar increased the bioavailability of Cu (shooting range soil) and As (metal smelter soil). Therefore, the chemical behavior of biochar with heavy metal ions is not constant and needs to be investigated.

Feedstock	Temperature	pH	%							CEC, cmolc kg^{-1}	C/N ratio	%		H/C ratio	O/C ratio	SSA, $m^2 g^{-1}$	Reference
			C	N	P	S	Ca	Mg	K			O.M	Ash				
Peanut hull	500.00	8.60	82.00	2.70	0.30	0.10	–	–	–	–	30.37	–	9.30	0.44	0.03	200.00	[5]
Sugar cane bagasse	<500	8.63	74.02	1.00	0.24	–	0.17	0.32	2.00	69.62	74.02	87.80	12.21	0.42	0.23	92.30	[10]
Orange peel	<500	8.75	66.36	2.13	0.25	–	1.04	0.28	1.86	68.28	31.15	88.80	11.17	0.65	0.32	0.20	
Cattle waste	380.00	8.20	62.10	0.10	–	–	–	–	–	39.00	621.00	–	25.60	1.90	0.27	–	[15]
Sewage sludge	380.00	8.50	38.30	5.20	–	–	–	–	–	0.50	7.37	–	44.90	0.94	0.25	–	
Oak wood	600.00	6.38	87.50	0.20	–	–	–	–	–	75.70	489.00	–	0.01	0.33	0.07	642.00	[33]
Corn stover	350.00	9.39	60.40	1.20	–	–	–	–	–	419.30	51.00	–	11.40	0.75	0.29	293.00	[34]
	600.00	9.42	70.60	1.07	–	–	–	–	–	252.10	66.00	–	16.70	0.39	0.10	527.00	
Corn stalk	400.00	9.60	51.10	1.34	0.25	–	–	–	1.34	–	38.13	–	–	–	–	–	[35]
	500.00	10.10	48.40	0.55	0.44	–	–	–	2.65	–	88.00	–	–	–	–	–	
Wheat straw	425.00	10.40	46.70	0.59	–	–	1.00	0.60	2.60	–	79.15	–	20.80	–	–	–	[36]
Coco peat	500.00	10.30	84.40	1.02	0.03	0.27	0.06	2.30	–	–	82.75	–	15.90	0.41	0.10	13.70	[37]
Coconut charcoal	<500	8.86	76.50	0.20	–	–	–	–	–	–	426.60	–	2.90	0.12	–	–	[38]
Pine wood	<500	8.47	53.20	0.40	–	–	–	–	–	–	143.40	–	65.70	0.35	–	–	
Eucalyptus deglupta	350.00	7.00	82.40	0.57	0.06	0.03	–	–	–	4.69	144.56	–	0.20	–	0.12		[39]
Hard wood saw dust	500.00	–	63.80	0.22	–	0.01	–	–	–		290.00	–	22.80	0.60	0.14	1.00	[40]
Chinese pine	600.00	8.38	66.67	2.21	–	–	–	–	–	31.58	30.17	–	12.50	0.58	0.31	–	[41]

Table 2. Physicochemical characteristics of different types of biochar.

3. The beneficial effect of biochars derived from different wastes on soil fertility

3.1. Fresh organic matter versus biochar as soil amendment

Soil organic carbon is originated by photosynthesis under highly reduced conditions (estimated by 600 mV) which are presented in leaf chloroplast [42]. Such fresh materials are probably the most reduced fraction when added to soils, acting as electron pumps to more oxidized species [43]. Generally, organic residues are used as amendments to improve soil quality and productivity [44].

The organic amendments that persist longer in soil might exert high impacts on soil physicochemical reactivity [45]. In deep soil layers, organic materials are relatively more stable than in the surface ones due to the absence of fresh organic carbon, an essential source of energy for soil microbes [46]. Probably, compounds that contain less oxygen (lower electron richness) are less easily decomposed than do compounds having comparable size, solubility, and molecular complexity [47].

Specific mechanisms might guarantee stabilization of organic C in soil, for example, biotic exclusion which might take place through adsorption of organics and aggregation with soil minerals forming mineral-bound OM [48]. Also, preservation of recalcitrant (stable) compounds might stabilize organic C [49]. It is thought that the recalcitrant compounds are present in organic materials in much higher proportions than those classified as labile [50].

Pyrolysis is the converting of unstable organic matter into more stable forms (biochar) that can be applied to soils [51]. This can be attained by heating carbon bearing solids in the absence of oxygen [52] to produce porous materials of low density [53] and more stable forms of carbon [54] which are more resistant to biodegradation as compared to fresh organic materials. Biochars' half-life in soil is relatively long [55].

3.2. Effect of biochar on soil properties

Biochar is used as an amendment to improve soil properties. It improves soil-water holding capacity [56, 57], saturated hydraulic conductivity [58], increases cation exchange capacity (CEC) [8, 59], decreases bulk density [60], and minimizes the loss of nutrients and other agricultural chemicals in soil run-off [4]. It also decreases soil penetration resistance and increases aggregation and infiltration [61]. On the other hand, biochar does not show any significant effect on soil porosity either directly through pore contribution, or indirectly through improving aggregate stability [62]. Besides, applications of biochar increase soil electrical conductivity (EC) in addition to its high contents of phosphorus and nitrogen [63].

3.3. Effect of biochar on the plant growth and soil biota

The main roles of biochar for enhancing plant growth are directly through its nutrients contents, and indirectly through its effects on nutrients use efficiency. Biochar serves as energy provider [64] for wheat [65], rice [36], maize [6], soy bean [66], and spring barley [67]; thus, it improves root density, crop growth, and productivity [68]. It was found that chicken manure-derived biochar increased the dry weights of the shoot and root of the Indian mustard by 353 and 572% upon its application to soil at a rate of only 1% [69]. Even biochar produced from wastewater sludge increased the productivity of cherry tomatoes by 64% as compared to the control [63]. Thus, such amendment is recommended for low-fertile and degraded soils [4] as well as highly weathered soil [70]. The zone of plant rhizosphere becomes larger with application of biochar [71]. Moreover, biochar increases plant resistance toward biotic stresses [72]. Some types of biochar amendments are rich in nutrients [73], and on the other hand, it minimizes the leaching of nutrients from soil, i.e., nitrate [74], ammonium, and probably phosphate [75]. However, the majority of biochars produce ethylene which is an inhibitor for soil microbes [68], beside of the released organic molecules which might suppress activities of some beneficial soil biota [76].

4. Biochar: alternative option for soil sustainability

Using biochar as a soil amendment can fulfill three main targets, that is, increasing plant productivity, thus achieving food security [4], improving soil properties, and disputing land degradation [77] beside of minimizing the change of climate [78]. Moreover, biochar changes organic wastes into value-added biochar which acts as sorbents for eliminating contaminants in wastewater [79]. As mentioned above, the transformation of terra preta soil into a high fertile soil due to biochar addition is a great evidence of the role of biochar for soil sustainability. The recycling of agricultural wastes into benefit materials guarantees the sustainability of agricultural lands.

5. Biochar and the environmental change

5.1. Effect of biochar on CO_2 emissions

Soils can store more carbon than do plants or atmosphere [47]. Globally, soil organic matter (SOM) contains about three times as much carbon as either the atmosphere or terrestrial vegetation [80]. In soils of low N content, CO_2 is the dominant greenhouse gases (GHGs) component [81]. Accordingly, strategies that migrate excess CO_2 from atmospheric air might be more important than reducing equivalent emissions of CO_2 to air [64]. The promising approach in lowering CO_2 from air is biochar [78]. Thus, biochar could be considered as the geo-engineering solution to control climate change [82] probably by means of carbon sequestration [83], thus minimizing the emissions of the greenhouse gases [84] while supplying energy and improving the productivity of the cultivated crops [64]. Roberts et al. [84] found that 62–66% of CO_2 emissions could be sequestered within biochar. Accordingly, adopting biochar technologies can offer financial incentive in emission trading markets [82].

5.2. Effect of biochar on CH_4 and N_2O emissions

Pyrolysis process serves also in reducing emissions of the other GHGs such as methane (CH_4) and nitrous oxide (N_2O) when amended to agricultural soils and pastures [64]. Biochar decreases the emissions of CH_4 and, therefore, increases the stock of soil organic carbon [85]. This probably takes place through suppressing the oxidation of ambient CH_4 [51]. On the other hand, the emissions of CH_4 might increase in rice paddy soil amended with biochar [36].

The effect of biochar on the transformation processes of nitrogen (N) in soil is not well defined [86]. Probably, biochar reduced GHGs emissions only in neutral to acidic soils with high N content [87]. In this concern, emissions of N_2O as well as leaching ammonium from soil could be reduced when using biochar rather than fresh organic material as soil amendments [86]. Generally, biochar suppresses production of N_2O [54]. It is found that 10.7–41.8% of the total emissions of N_2O decreased with application of biochar at rates of 20 and 40 Mg ha^{-1}, respectively [87]. Similar results show that soil N_2O fluxes decreased up to 79% in soils amended with biochar as compared to the control [88]. In an experiment conducted by Mukherjee et al. [89], it was found that 92% of the cumulative N_2O emissions reduced when amending soils with biochar. Even under the reduced conditions of the rice paddy soil, biochar can also minimize the emission of N_2O [36]. Such reductions might be attributed to the oxidative reactions that take place on the surfaces of biochar with ageing [86]. Accordingly, reductions of the emissions of N_2O owing to application of biochar to soils improve the GHGs-to-yield ratio conditions [90].

Others found no significant differences in emissions of both CO_2 and N_2O from soils owing to application of biochar as compared to nonamended soils [56]. Likewise, Mukherjee et al. [89] found that the total cumulative emissions of CH_4 and CO_2 emissions were not affected significantly by amending soils with biochar. It is worthy to mention that biochar production itself can increase, to some extent, the greenhouse gases emitted to the atmosphere; however, more studies are needed to fulfill this point of study and to lessen GHGs emitted during production process.

6. The beneficial role of biochar for contamination control of soils and waters

6.1. Biochar as means for decontaminating soils from heavy metals and pesticides

Biochars produced at relatively high temperature pyrolysis are more efficient in sorption of organic contaminants, whereas those produced at low temperatures are more efficient for removing heavy metals [102]. At low temperature, the produced biochar is of acidic nature, whereas those produced at high temperature were of alkaline nature [91]. This approach offers a new safe solution for decontaminating soil pollution [92]. Generally, biochars are efficient in reducing the phytoavailability of many organic pollutants in soil, that is, (1) herbicides, for example, atrazine and acetochlor [51], Fluometuron and 4-chloro-2-methylphenoxyacetic acid [93], (2) pesticides, for example, pyrimethanil [94], atrazine [95], simazine [96], azoxystrobin [97], (3) fungicides, that is, tricyclazole in alluvial paddy soil [98] in addition to (4) phenols [99], thus controlling their toxicity and transfer in soil [100]. Immobilization of these organic residues might be take place because of the high affinity and ability of biochar to sequester such organics [101]. High temperature pyrolysis biochar is characterized by its high

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surface area, high micro-porosity, and hydrophobicity [102], and thus, combined adsorption and partition mechanisms might take place with the herbicide, pesticides, and the fungicide on carbonized and noncarbonized fractions [96]. In case of phenols, its sorption might take place on the microspores surface area of the biochar in addition to sorption on the carboxylic and lactonic groups [99]. Sorption affinity with the organic contaminants is found irreversible [94] and can increase with decreasing solid/solution ratio [96].

Biochars can also immobilize the phytotoxcity of heavy metals in soil forming less bioavailable organic bound fraction [69]. Biochar is of an alkaline nature, thus applying biochar to soils is associated with increases in soil pH [103]. The mechanism of immobilization might be a result of precipitation due to the rise in soil pH due to the application of the basic biochar or even by the electrostatic interaction on the carboxyl groups of the biochar [104] or through coordination by π electrons (C═C) of carbon [105].

Many experiments revealed the successfulness of biochar treatments on partitioning of heavy metals in soil, for example, Cd, Cu, and Pb [69]. Surprisingly, using biochar for decontaminating soils decreased the leachable fractions of Cd and Zn by 300 and 45-folds in compared to the untreated treatments [106]. In another experiment, it was found that treating soils with biochar removed Pb, Zn, and Cd by 97.4, 53.4, and 54.5%, respectively [107]. It is worthy to mention that the oxidized biochars, rich in carboxyl groups, showed higher affinity to immobilize Pb, Cu, and Zn than did the un-oxidized ones [104].

6.2. Biochar as a means of decontaminating heavy metals and organic residues from wastewater

Biochars act as sorbents for decontaminating wastewaters from heavy metals [79]. This might take place mainly through sorption on the surface functional groups of biochar [108], for example, oxygen-containing carboxyl, hydroxyl, and phenolic surface functional groups [109]. The kinetics of adsorption followed pseudo second order [10, 110]. The stability of heavy metals by biochar correlated significantly with the oxygen-containing functional groups of the biochar [108] with maximum adsorption attained within the pH range 5.0–6.0 [110]. Digested dairy waste biochar and digested whole sugar beet biochar were found to be efficient in removing Pb^{2+}, Cu^{2+}, Ni^{2+}, and Cd^{2+} from wastewater [111]. Also, biochars can efficiently remove organic contaminants from wastewaters. It was found that the fast pyrolysis pine wood biochar could remove salicylic acid and ibuprofen from solutions [112].

Biochar can also effectively remove phosphate from wastewater [113]. This probably takes place on the colloidal and nano-sized MgO particles on its surface [114]. Most of the sorbed phosphate is bioavailable and can be added to soils as slow release P-fertilizers [115]. Moreover, 60% of the sorbed phosphate can be desorbed within 24 h [116].

Treating biochar hydrothermally with H_2O_2 increased its affinity to remove heavy metals from aqueous solutions because this treatment increased the oxygen-containing functional groups [117]. Another type of biochar is chitosan-modified one which is a low-cost synthesized biochar efficient for immobilizing heavy metal in the environment [118]. Also, a graphene/biochar composite is a safe economic adsorbent that can decontaminate heavy metals through surface complexation with C─O, C C, ─OH, and O C─ groups [119].

7. Conclusion and future challenges of biochar

The previous demonstration showed that biochar plays an important role in environmental management and soil sustainability. Several beneficial roles of biochar have been observed. Biochar improves soil fertility and plant growth, mitigates the greenhouse gasses, and could be used successfully for the remediation of soils and waters from contaminants. However, several research questions are still unknown and need intensive researches, that is, the effect of biochar on minerals and/or organic fertilizers use efficiency and the neutralization of alkaline performance of biochar to be used safely in alkaline soils. In addition, the stability of biochar in the amended soils needs a sustainable experiment to determine exactly the degradation rate of different types of biochars.

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References

[1] Abdelhafez AA, Abbas HH, Abd-El-Aal RS, Kandi NF, Li J, Mahmoud W. Environmental and health impacts of successive mineral fertilization in Egypt. Clean-Soil, Air and Water. 2012;**40**(4):356-363

[2] Milinovic J, Lukic V, Nikolic-Mandic S, Stojanovic D. Concentrations of heavy metals in NPK fertilizers imported in Serbia. Pesticide Phytomedicine. 2008;**23**:195-200

[3] Huang S, Jin J, He P. Effects of different patterns of land use on status of heavy metals in agricultural soils. Better Crops. 2009;**93**:20-22

[4] Lehmann J, Joseph S. Biochar for environmental management: An introduction. In: Lehmann J, Joseph S. (Eds.), Biochar for Environmental Management: Science and Technology. London: Earthscan; 2009. pp. 1-12

[5] Novak JM, Lima I, Xing B, Gaskin JW, Steiner C, Das KC, Ahmedna M, Rehrah D, Watts DW, Busscher WJ, Schomberg H. Characterization of designer biochar produced at

different temperatures and their effects on a loamy sand. Annals of Environmental Science. 2009;**3**(1):195-206

[6] Major J, Rondon M, Molina D, Riha SJ, Lehmann J. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant and Soil. 2010;**333**:117-128

[7] Abdelhafez AA, Lee SS, Ok YS. Effects of biochar on soil quality and heavy metal bioavailability in a military shooting range soil. Korean Society of Soil and Ground Water Environment (KOSSGE). 2010; pp. 236. Korea

[8] Abdelhafez AA, Li J, Abbas MHH. Feasibility of biochar manufactured from organic wastes on the stabilization of heavy metals in a metal smelter contaminated soil. Chemosphere. 2014;**117**:66-71

[9] Abdelhafez AA, Abbas MHH, Hamed MH. Biochar: A solution for soil Pb pollution. The 8th International Conference for Development and the Environment in the Arab World Assiut University, Egypt. 2016; pp. 89-103

[10] Abdelhafez AA, Li J. Removal of Pb(II) from aqueous solution by using biochars derived from sugarcane bagasse and orange peel. Journal of the Taiwan Institute of Chemical Engineers. 2016;**61**:367-375

[11] Emrich W. Handbook of charcoal making. The traditional and industrial methods. D. Reidel Publishing Company - Dordrecht, Holland; 1985

[12] Verheijen FGA, Jeffery S, Bastos AC, van der Velde M, Diafas I. Biochar Application to Soils—A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. EUR 24099 EN. Luxembourg: Office for the Official Publications of the European Communities; 2009. 149 p

[13] Trimble WH. On charring wood. Plough, the Loom and the Anvil. 1851;**3**:513-516

[14] Retan GA. Charcoal as a means of solving some nursery problems. Forestry Quarterly. 1915;**13**:25-30

[15] Shinogi Y, Yoshida H, Koizumi T, Yamaoka M, Saito T. Basic characteristics of low-temperature carbon products from waste sludge. Advances in Environmental Research. 2003;**7**(3):661-665

[16] Roos CJ. Clean Heat and Power Using Biomass Gasification for Industrial and Agricultural Projects, U.S. Department of Energy Olympia; 2010. ss: 1-9

[17] FAO Forestry Department, editor. Simple Technologies for Charcoal Making. 2nd ed. Rome: FAO; 1987

[18] Chen B. Yuan M. Enhanced sorption of polycyclic aromatic hydrocarbons by soil amended with biochar. Journal of Soils and Sediments. 2011;**11**:62-71

[19] Bird MI, Ascough PL, Young IM, Wood CV, Scott AC. X-ray microtomographic imaging of charcoal. Journal of Archaeological Science. 2008;**35**:2698-2706

[20] Abdullah H, Wu H. Biochar as a fuel: 1. Properties and grindability of biochars produced from the pyrolysis of mallee wood under slow-heating conditions. Energy and Fuels. 2009;**23**:4174-4181

[21] Gaskin JW, Steiner C, Harris K, Das KC, Bibens B. Effect of low temperature pyrolysis conditions on biochar for agricultural use. Transactions of the ASABE. 2008;**51**:2061-2069

[22] Agblevor FA, Beis S, Kim SS, Tarrant R, Mante NO. Biocrude oils from the fast pyrolysis of poultry litter and hardwood. Waste Management. 2010;**30**:298-307

[23] Sjöström E. Wood Chemistry: Fundamentals and Applications. 2nd ed. San Diego, CA: Academic Press; 1993

[24] Laine J, Yunes S. Effect of the preparation method on the pore size distribution of activated carbon from coconut shell. Carbon. 1992;**30**:601-604

[25] Neary DG, Klopatek CC, DeBano LF, Folliott PF. Fire effects on belowground sustainability: A review and synthesis. Forest Ecology and Management. 1999;**122**:51-71

[26] Knoepp JD, DeBano LF, Neary DG. Soil Chemistry, RMRS-GTR 42-4. Ogden, UT: US Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2005

[27] Keiluweit M, Kleber M, Sparrow MA, Simoneit BR, Prahl FG. Solvent-extractable polycyclic aromatic hydrocarbons in biochar: Influence of pyrolysis temperature and feedstock. Environmental Science and Technology. 2012;**46**(17):9333-9341

[28] Bird MI, Wurster CM, de Paula Silva PH, Bass AM, de Nys R. Algal biochar—Production and properties. Bioresource Technology. 2011;**102**(2):1886-1891

[29] Yuan JH, Xu RK, Zhang H. The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresource Technology. 2011;**102**(3):3488-3497

[30] Houben D, Evrard L, Sonnet P. Mobility, bioavailability and pH-dependent leaching of cadmium, zinc and lead in a contaminated soil amended with biochar, Chemosphere. 2013;**92**:1450-1457

[31] Liu XH, Zhang XC. Effect of biochar on pH of alkaline soils in the loess plateau: Results from incubation experiments. International Journal of Agriculture and Biology. 2012;**14**:745-750

[32] Pellera FM, Giannis A, Kalderis D, Anastasiadou K, Stegmann R, Wang J-Y, Gidarakos E. Adsorption of Cu(II) ions from aqueous solutions on biochars prepared from agricultural by-products. Journal of Environmental Management. 2012;**96**:35-42

[33] Nguyen B, Lehmann J. Black carbon decomposition under varying water regimes. Organic Geochemistry. 2009;**40**:846-853

[34] Nguyen B, Lehmann J, Hockaday WC, Joseph S, Masiello CA. Temperature sensitivity of black carbon decomposition and oxidation. Environmental Science and Technology. 2010;**44**:3324-3331

[35] Feng Y, Xu Y, Yu Y, Xie Z, Lin X. Mechanisms of biochar decreasing methane emission from Chinese paddy soils. Soil Biology and Biochemistry. 2012;**46**:80-88

[36] Zhang A, Cui L, Pan G, Li L, Hussain Q, Zhang X, Zheng J, Crowley D. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. Agriculture, Ecosystems and Environment. 2010;**139**:469-475

[37] Lee Y, Park J, Ryu C, Gang KS, Yang W, Park Y, Jung J, Hyun S. Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500°C. Bioresource Technology. 2013;**148**:196-201

[38] Erin N, Yargicoglu EN, Sadasivam BY, Reddy KR, Spokas K. Physical and chemical characterization of waste wood derived biochars. Waste Management. 2014;**36**:256-268

[39] Rondon MA, Lehmann J, Ramírez J, Hurtado M. Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with biochar additions. Biology and Fertility of Soils. 2007;**43**(6):699-708

[40] Fabbri D, Torri C. Spokas KA. Analytical pyrolysis of synthetic chars derived from biomass with potential agronomic application (biochar): Relationships with impacts on microbial carbon dioxide production. Journal of Analytical and Applied Pyrolysis. 2012;**93**:77-84

[41] Liu XH, Han FP, Zhang XC. Effect of biochar on soil aggregates in the loess plateau: Results from incubation experiments. International Journal of Agriculture & Biology. 2012;**14**:975-979

[42] Macías F, Camps Arbestain M. Soil carbon sequestration in a changing global environment. Mitigation and Adaptation Strategies for Global Change. 2010;**15**:511-529

[43] Chesworth W. Redox, soils and carbon sequestration. Edafologia. 2004;**11**:37-43

[44] Melero S, Porras JCR, Herencia JF, Madejon E. Chemical and biochemical properties in a silty loam soil under conventional and organic management. Soil and Tillage Research. 2006;**90**:162-170

[45] Wander M. Soil Organic Matter Fractions and their Relevance to Soil Function. Soil Organic Matter in Sustainable Agriculture. CRC Press USA, Fred Magdoff and Ray R. Weil; 2004

[46] Fontaine S, Barot S, Barre P, Bdioui N, Mary B, Rumpel C. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature. 2007;**450**:277-280

[47] Kleber M. What is recalcitrant soil organic matter. Environmental Chemistry. 2010;**7**: 320-332

[48] Lützow M, Kögel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, Flessa H. Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions—A review. European Journal of Soil Science. 2006;**57**:426-445

[49] Lützow M, Kögel-Knabner I, Ludwig B, Matzner E, Flessa H, Ekschmitt K, Guggenberger G, Marschner B, Kalbitz K. Stabilization mechanisms of organic matter in four temperate soils: Development and application of a conceptual model. Journal of Plant Nutrition and Soil Science. 2008;**171**:111-124

[50] Davidson EA, Janssens IA. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature. 2006;**440**:165-173

[51] Spokas KA, Koskinena WC, Bakera JM, Reicoskyb DC. Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. Chemosphere. 2009;**77**:574-581

[52] Brown R. Biochar production technology. In: Lehmann J, Joseph S, editors. Biochar for Environmental Management: Science and Technology. London: Earthscan; 2009. pp. 127-146

[53] Beesley L, Moreno-Jiménez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental Pollution. 2011;**159**:3269-3282

[54] Spokas KA, Reicoky DC. Impacts of sixteen different biochars on soil greenhouse gas production. Annals of Environmental Science. 2009;**3**:179-193

[55] Verheijen FGA, Montanarella L, Bastos AC. Sustainability, certification, and regulation of biochar. Pesquisa Agropecuária Brasileira. 2012;**47**:649-653

[56] Karhu K, Mattila T, Bergström I, Regina K. Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity—Results from a short-term pilot field study. Agriculture, Ecosystems & Environment. 2011;**140**:309-313

[57] Lal AMAR. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy. 2013;**3**:313-339

[58] Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, Inoue Y, Shiraiwa T, Horie T. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Research. 2009;**111**:81-84

[59] Martin SL, Clarke ML, Othman M, Ramsden SJ, West HM. Biochar-mediated reductions in greenhouse gas emissions from soil amended with anaerobic digestates. Biomass and Bioenergy. 2015;**79**:39-49

[60] Mukherjee A, Lal R. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy. 2013;**3**:313-339

[61] Busscher WJ, Novak JM, Evans DE, Watts DW, Niandou MAS, Ahmedna M. Influence of pecan biochar on physical properties of a Norfolk loamy sand. Soil Science. 2010;**175**:10-14

[62] Hardie M, Clothier B, Bound S, Oliver G. Close D. Does biochar influence soil physical properties and soil water availability?. Plant and Soil. 2014;**376**:347-361

[63] Hossain MK, Strezov V, Yin Chan K, Nelson PF. Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). Chemosphere. 2010;**78**:1167-1171

[64] Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. Nature Communications 2010;**1**(56):1-9

[65] Baronti S, Alberti G, Delle Vedove G, Di Gennaro F, Fellet G, Genesio L, Miglietta F, Peressotti A, Vaccari FP. The Biochar option to improve plant yields: First results from some field and pot experiments in Italy. Italian Journal of Agronomy. 2010;**5**:3-11

[66] Mete FZ, Mia S, Dijkstra FA, Abuyusuf M, Hossain A.S.M.I. Synergistic effects of biochar and NPK fertilizer on soybean yield in an alkaline soil. Pedosphere. 2015;**25**:713-719

[67] Sun Z, Bruun EW, Arthur E, de Jonge LW, Moldrup P, Hauggaard-Nielsen H, Elsgaard L. Effect of biochar on aerobic processes, enzyme activity, and crop yields in two sandy loam soils. Biology and Fertility of Soils. 2014;**50**:1087-1097

[68] Spokas KA, Baker JM, Reicosky DC. Ethylene: Potential key for biochar amendment impacts. Plant and Soil. 2010;**333**:443-452

[69] Park JH, Choppala GK, Bolan NS, Chung JW, Chuasavathi T. Biochar reduces the bioavailability and phytotoxicity of heavy metals. Plant and Soil. 2011;348-439

[70] Lehmann J, Rondon M. Bio-char soil nanagement on highly weathered soils in the humid tropics. Biological Approaches to Sustainable Soil Systems. CRC Press -Taylor and Francis Group, LLC; 2006. pp. 517-529

[71] Prendergast-Miller MT, Duvall M, Sohi SP. Biochar-root interactions are mediated by biochar nutrient content and impacts on soil nutrient availability. European Journal of Soil Science. 2014;**65**:173-185

[72] Elad Y, Cytryn E, Harel YM, Lew B, Graber ER. The biochar effect: Plant resistance to biotic stresses. Phytopathologia Mediterranea. 2012;**50**:335-349

[73] Uchimiya M, Lima IM, Klasson KT, Wartelle LH. Contaminant immobilization and nutrient release by biochar soil amendment: Roles of natural organic matter. Chemosphere. 2010b;**80**:935-940

[74] Dempster DN, Jones DL, Murphy DV. Clay and biochar amendments decreased inorganic but not dissolved organic nitrogen leaching in soil. Soil Research. 2012;**50**:216-221

[75] Yao Y, Gao B, Zhang M, Inyang M, Zimmerman AR. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere. 2012;**89**:1467-1471

[76] Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota—A review. Soil Biology and Biochemistry. 2011;**43**:1812-1836

[77] Barrow CJ. Biochar: Potential for countering land degradation and for improving agriculture. Applied Geography. 2012;**34**:21-28

[78] Lehmann J. Bio-energy in the black. Frontiers in Ecology and the Environment. 2007;**5**:381-387

[79] Xu X, Cao X, Zhao L. Comparison of rice husk-and dairy manure-derived biochars for simultaneously removing heavy metals from aqueous solutions: Role of mineral components in biochars. Chemosphere. 2013;**92**:955-961

[80] Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kogel-Knabner I, Lehmann J, Manning DAC, Nannipieri PRasse DP, Weiner S, Trumbore SE. Persistence of soil organic matter as an ecosystem property. Nature. 2011;**478**:49-56

[81] Zheng J, Stewart CE, Cotrufo MF. Biochar and nitrogen fertilizer alters soil nitrogen dynamics and greenhouse gas fluxes from two temperate soils. Journal of Environmental Quality. 2012;**41**:1361-1370

[82] Cowie AL, Downie AE, George BH, Singh B-P, Van Zwieten L, O'Connell D. Is sustainability certification for biochar the answer to environmental risks? Pesquisa Agropecuária Brasileira. 2012;**47**:637-648

[83] Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems—A review. Mitigation and Adaptation Strategies for Global Change. 2006;**11**:395-419

[84] Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J. Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. Environmental Science and Technology. 2010;**44**:827-833

[85] Xie Z, Xu Y, Liu G, Liu Q, Zhu J, Tu C, Amonette JE, Cadisch G, Yong JWH, Hu S. Impact of biochar application on nitrogen nutrition of rice, greenhouse-gas emissions and soil organic carbon dynamics in two paddy soils of China. Plant and Soil. 2013;**370**:527-540

[86] Singh BP, Hatton BJ, Singh B, Cowie AL, Kathuria A. Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. Journal of Environmental Quality. 2010;**39**:1224-1235

[87] Zhang A, Liu Y, Pan G, Hussain Q, Li L, Zheng J, Zhang X. Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China plain. Plant and Soil. 2012;**351**:263-275

[88] Castaldi S, Riondino M, Baronti S, Esposito FR, Marzaioli R, Rutigliano FA, Vaccari FP, Miglietta F. Impact of biochar application to a Mediterranean wheat crop on soil microbial activity and greenhouse gas fluxes. Chemosphere. 2011;**85**:1464-1471

[89] Mukherjee A, Lal R, Zimmerman AR. Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil. Science of the Total Environment. 2014;**487**:26-36

[90] Kammann C, Ratering S, Eckhard C, Müller C. Biochar and hydrochar effects on greenhouse gas (carbon dioxide, nitrous oxide, and methane) fluxes from soils. Journal of Environmental Quality. 2012;**41**:1052-1066

[91] Hossain MK, Strezov V, Chan KY, Ziolkowski A, Nelson PF. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. Journal of Environmental Management. 2011;**92**:223-228

[92] Zhang X, Wang H, He L, Lu K, Sarmah A, Li J, Bolan NS, Pei J, Huang H. Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. Environmental Science and Pollution Research. 2013;**20**:8472-8483

[93] Cabrera A, Cox L, Spokas KA, Celis R, Hermosín MC, Cornejo J, Koskinen WC. Comparative sorption and leaching study of the herbicides fluometuron and 4-chloro-2-methylphenoxyacetic acid (MCPA) in a soil amended with biochars and other sorbents. Journal of Agricultural and Food Chemistry. 2011;**59**:12550-12560

[94] Yu X, Pan L, Ying G, Kookana RS. Enhanced and irreversible sorption of pesticide pyrimethanil by soil amended with biochars. Journal of Environmental Sciences. 2010;**22**:615-620

[95] Cao X, Ma L, Gao B, Harris W. Dairy-manure derived biochar effectively sorbs lead and atrazine. Environmental Science and Technology. 2009;**43**:3285-3291

[96] Zheng W, Guo M, Chow T, Bennett DN, Rajagopalan N. Sorption properties of greenwaste biochar for two triazine pesticides. Journal of Hazardous Materials. 2010;**181**:121-126

[97] Sopeña F, Bending GD. Impacts of biochar on bioavailability of the fungicide azoxystrobin: A comparison of the effect on biodegradation rate and toxicity to the fungal community. Chemosphere. 2013;**91**:1525-1533

[98] García-Jaramillo M, Cox L, Knicker HE, Cornejo J, Spokas KA, Hermosín, MC. Characterization and selection of biochar for an efficient retention of tricyclazole in a flooded alluvial paddy soil. Journal of Hazardous Materials. 2015;**286**:581-588

[99] Han Y, Boateng AA, Qi PX, Lima IM, Chang J. Heavy metal and phenol adsorptive properties of biochars from pyrolyzed switchgrass and woody biomass in correlation with surface properties. Journal of Environmental Management. 2013;**118**:196-204.

[100] Smernik RJ. Biochar and sorption of organic compounds. In: Lehmann J, Joseph S, editors. Biochar for Environmental Management: Science and Technology. London: Earthscan; 2009. pp. 289-300

[101] Yu X, Ying G, Kookana RS. Reduced plant uptake of pesticides with biochar additions to soil. Chemosphere. 2009;**76**:665-671

[102] Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M, Lee SS, Ok YS. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere. 2014;**99**:19-33

[103] Peng X, Ye LL, Wang C, Zhou H, Sun B. Temperature and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an ultisol in southern China. Soil Tillage Research. 2011;**112**(2):159-166

[104] Uchimiya M, Bannon DI, Wartelle LH. Retention of Heavy Metals by Carboxyl Functional Groups of Biochars in Small Arms Range Soil. Journal of Agricultural and Food Chemistry. 2012;**60**:1798-1809

[105] Uchimiya L, Lima IM, Klasson KT, Chang S, Wartelle LH, Rodgers JE. Immobilization of heavy metal ions (CuII, CdII, NiII, and PbII) by Broiler litter-derived biochars in water and soil. Journal of Agricultural and Food Chemistry. 2010;**58**:5538-5544

[106] Beesley L, Marmiroli M. The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. Environmental Pollution. 2011;**159**:474-480

[107] Liang Y, Cao X, Zhao L, Arellano E. Biochar- and phosphate-induced immobilization of heavy metals in contaminated soil and water: Implication on simultaneous remediation of contaminated soil and groundwater. Environmental Science and Pollution Research. 2014;**21**:4665-4674

[108] Uchimiya M, Wartelle LH, Klasson KT, Fortier CA, Lima IM, Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. Journal of Agricultural and Food Chemistry. 2011;**59**:2501-2510

[109] Uchimiya M, Chang S, Klasson KT. Screening biochars for heavy metal retention in soil: Role of oxygen functional groups. Journal of Hazardous Materials. 2011;190:432-441

[110] Kołodyńska D, Wnętrzak R, Leahy JJ, Hayes MHB, Kwapiński W, Hubicki Z. Kinetic and adsorptive characterization of biochar in metal ions removal. Chemical Engineering Journal. 2012;**197**:295-305

[111] Inyang M, Gao B, Yao Y, Xue Y, Zimmerman AR, Pullammanappallil P, Cao X. Removal of heavy metals from aqueous solution by biochars derived from anaerobically digested biomass. Bioresource Technology. 2012;**110**:50-56

[112] Essandoh M, Kunwar B, Pittman Jr CU, Mohan D, Mlsna T. Sorptive removal of salicylic acid and ibuprofen from aqueous solutions using pine wood fast pyrolysis biochar. Chemical Engineering Journal. 2015;**265**:219-227

[113] Chen B, Chen Z, Lv S. A novel magnetic biochar efficiently sorbs organic pollutants and phosphate. Bioresource Technology. 2011;**102**:716-723

[114] Yao Y, Gao B, Inyang M, Zimmerman AR, Cao X, Pullammanappallil P, Yang L. Removal of phosphate from aqueous solution by biochar derived from anaerobically digested sugar beet tailings. Journal of Hazardous Materials. 2011;**190**:501-507

[115] Yao Y, Gao B, Chen J, Yang L. Engineered biochar reclaiming phosphate from aqueous solutions: Mechanisms and potential application as a slow-release fertilizer. Environmental Science and Technology. 2013;**47**:8700-8708

[116] Sarkhot DV, Ghezzehei TA, Berhe AA. Effectiveness of biochar for sorption of ammonium and phosphate from dairy effluent. Journal of Environmental Quality. 2013;**42**:1545-1554

[117] Xue Y, Gao B, Yao Y, Inyang M, Zhang M, Zimmerman AR, Ro KS. Hydrogen peroxide modification enhances the ability of biochar (hydrochar) produced from hydrothermal carbonization of peanut hull to remove aqueous heavy metals: Batch and column tests. Chemical Engineering Journal. 2012;**200**:673-680

[118] Zhou Y, Gao B, Zimmerman AR, Fang J, Sun Y, Cao X. Sorption of heavy metals on chitosan-modified biochars and its biological effects. Chemical Engineering Journal. 2013;**231**:512-518

[119] Tang J, Lv H, Gong Y, Huang Y. Preparation and characterization of a novel graphene/biochar composite for aqueous phenanthrene and mercury removal. Bioresource Technology. 2015;**196**:355-363

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