Chapter

Effects of Biochar in Soil and Water Remediation: A Review

Adelaide Perdigão and José Luís da Silva Pereira

Abstract

In the last decades increased global environmental concerns to water and soils pollution. The main concerns are related to the contamination of the ecosystem, food security, and human health since many of the contaminants present in soil and water (residues of pesticides and antibiotics, genes of resistance to antibiotics, and heavy metals) are absorbed by plants and enter the food chain. Remediation of the contaminated water and soil to ensure sustainable water supply and food production is urgently needed. The use of biochar can have a positive effect on this remediation process. There are several studies that demonstrate the biochar's ability to block/reduce the contaminating effect of pesticides, antibiotic residues, antibiotic resistance genes, and heavy metals. The objective of this chapter is to carry out a comprehensive review of the effect of using biochar on the availability/transmission of these contaminants to the soil and food supply chain.

Keywords: antibiotics, biochar, environment, food, human health, heavy metals

1. Introduction

Currently, water and soil pollution is a global concern due to its negative effect on ecological safety and health risks [1, 2]. Soil contamination through inorganic and organic contaminants is a well-known problem [1, 3]. Contamination of agricultural soils is due to the long-term application of pesticides, fertilizers, plastic film, wastewater irrigation, sewage application, and other activities [4]. Organic contaminants, such as organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), phthalate esters (PAEs), and polycyclic aromatic hydrocarbons (PAHs), are characterized by high toxicity, persistence, and bioaccumulation in the environment [5]. Soil is a major reservoir for a variety of pollutants and is a secondary emission source of contaminants to groundwater and surface water [4].

In the last years has been increasing interest amongst the scientific community in the development of technologies to remediate contaminated sites [6]. Soil remediation techniques are categorized as physical, chemical, or biological, based on the specific nature of the remediation mechanism employed [1]. Physical and chemical methods are costly, inefficient, and result in further pollution, especially in the case of chemical methods [1]. Adsorption is one of the most efficient biological methods for removing contaminants from water and wastewater [7]. The mechanism and capacity of adsorption are influenced by many factors: physicochemical properties of the adsorbent; type and nature of the adsorbate; the related affinity of the adsorbate for the adsorbent; and process conditions.

Therefore, the use of biological materials derived from organic material is considered an eco-friendly and sustainable approach [8]. The application of proper amendments such as biochar is a known efficacious and environmentally friendly method for reducing the availability and mobility of potentially toxic elements in contaminated soil via *in situ* immobilization [3, 9]. Biochar is a sensible and robust material for the enhancement of soil fertility and management of contaminated soils for sustainable agriculture and mitigation of climate change [1, 10]. Is a carbon-rich material that can be prepared from various organic waste feedstocks [1], like from various biomass, both woody (primarily residues from forestry and trees) and non-woody (agricultural crops and residues, animal waste, urban and industrial solid waste). The term biochar is used to designate carbonaceous materials, produced from biological sources, due to the incomplete combustion of fossil fuels and vegetation and constitute an important carbon sink due to their stability to microbial and chemical degradation [11]. Thus, biochar is a porous carbonaceous material largely containing carbon jointly with the inorganic components of the biomass utilized, such as alkali and alkaline earth metals.

For these organic wastes to be transformed into biochar, they are subjected to pyrolysis, gasification, or hydrothermal carbonization. These are the most common methods for biochar preparation [12, 13]. Biochar properties are highly dependent on the temperature (300–1000°C), time of pyrolysis, final acidity, and feedstock from which the biochar is made [14]. According to the residues types, biochar can present diverse physiochemical properties biochar's content of volatile matter, dissolved organic matter, ash, and carbon [1, 15]. Additionally, the pyrolysis condition may influence the physicochemical and chemical properties of biochar [16, 17]. However, there are characteristics that are always present, such as rich carbon content, high cation exchange capacity, large surface area, and stability structure [1, 13]. These characteristics, namely specific surface area, porosity, and cation exchange capacity, are responsible for the high adsorption capacity that gives it the ability to remove organic pollutants and heavy metals [13]. Also, the solution pH has a great influence on the adsorption capacity of biochars [16]. Moreover, biochar will improve the soil's biological activities, nutrient retention, water-retention capacity, an increase of pH value, and amount of soil organic matter.

In last year's, the utilization of biochar has been widely used in environmental applications such as soil remediation and water remediation. According to Krasucka et al. [7] the use of "green", low cost, or sustainable biochar for contaminant sorption yields economic and environmental benefits, furthermore, agrees with global trends in generating a circular economy and sustainable development. Biochar has been a common material for environmental contamination due to the widespread availability of its raw materials, its simple preparation process, low cost, and strong adsorption performance [18].

The application of biochar can improve soils that pose abiotic stresses because of the presence of heavy metals, salt, or organic contaminants [1]. Biochars produced from pyrolysis of biomass materials have received worldwide attention due to their broad usage in contaminant adsorption, soil remediation, and wastewater treatment [19]. Biochar application can reduce the bioavailability and mobility of soil pollutants including pesticides, antibiotics, heavy metal, and antibiotic resistance genes in soil microorganisms [20].

2. Soil and water contaminants

Soil is one of the main resources that human beings rely on to survive, and also the material repository of biogeochemical cycles. The remediation of contaminated soils, in order to protect human health and achieve sustainable development, has become the goal of the scientific community. Remediating contaminated soils to protect human health and to achieve sustainable development has become a desirable goal [21].

The main soil contaminants that most concern society are the following: pesticides, antibiotic residues, antibiotic resistance genes (ARGs), and heavy metals.

2.1 Pesticides

Pesticide is any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest (insects, mice, and other animals, weeds, or microorganisms) [11]. Pesticides are widely used to prevent or control the growth of crop pests in agricultural practices. Their leaching and accumulation in the soil and water is a threat to the environment and human health.

Pesticides are one of the persistent organic pollutants due to their recalcitrant, persistent, and bioaccumulative nature and due to their ability to be carried for long distances to affect remote uninhabited parts of the globe [11].

The *in situ* application of an adsorbent amendment in contaminated soils is a new and cost-effective alternative for remediation of pesticide-contaminated soils [11]. Biochar has been reported efficient for the reduction of pesticides bioavailability in a soil environment with additional benefits of increased soil fertility [22], giving you adsorption potential.

The strong adsorption potential of biochar has resulted in decreased availability of various agrochemicals (insecticides, fungicides, acaricides, and others) used for pest control in various crops [1]. The effect of biochars on the fate of pesticide contaminants in soil depends on the biochars type and properties, which in turn is affected by the feedstock and pyrolysis conditions [22]. Pesticide adsorption on biochars was affected by their aromaticity, polarity, pore-volume, pore diameter, pH, and surface acidity [23]. More porous structures and higher surface area will result in higher sorption capacities [24]. Studies carried out by Liu et al. [25] showed that an increase in pyrolysis temperature results in a larger pore volume and surface area. The pore volume of biochar increased from 0.056 to 0.099 $cm^3\ g^{-1}$ with a temperature from 500 to 900°C, while surface area increased from 25.4 to 67.6 $m^2\ g^{-1}$ [26]. The composition of biochar also affects its properties. For example, the surface area of plant biochar (112–642 $m^2\ g^{-1}$) such as oak wood, maize stover, and pine needle is generally much higher than that of pig manure (3.32–20.5 $m^2\ g^{-1}$), and biosolid biochar (50.9–94.2 $m^2\ g^{-1}$) such as poultry and turkey litter [25, 27, 28], similarly, pine needle biochar shows higher porosity (0.076–1.90 $cm^3\ g^{-1}$) than biosolid biochar (0.053–0.068 $cm^3\ g^{-1}$) derived at 500–700°C [28]. In general, it can be stated that feedstock with high lignin content produces biochar with macroporous structures, while feedstock with high cellulose content mainly produces biochar with microporous structures [24].

The pyrolysis temperature of biochars produced from various biomasses (biosolids, agricultural residues, and animal manure) also interferes with its pH, generally, the increase in temperature results in a higher pH of the biochar, and higher pH of biochar can accelerate the hydrolysis of organophosphorus and carbamate pesticides in the soil through alkali catalysis mechanism [24].

Biochar increases microbial activity by providing available carbon and other nutrients which ultimately accelerate the biodegradation of pesticides in soil [22].

Several studies have been performed to investigate the effect of biochar addition for pesticide remediation. Biochar proved to be efficient in the sorption of pesticides such as atrazine, terbuthylazine, pyrimethanil, or bentazone [29–32]. Using biochar irreversible adsorption of pesticides to soils has been as shown due to entrapment into biochar micropores, surface-specific adsorption, and partitioning into condensed structures [11]. Adsorption of triazine herbicides by biochar was primarily affected by the mesoporosity and microporosity of biochars [33]. Liu et al. [34] compared plant (soybean, corn stalk, and rice stalk) and manure (poultry, cattle, and pig) derived biochars for atrazine adsorption and concluded that, in general, plant-based biochars were more effective in removing atrazine and the removal efficiency increased with elevation in high temperatures treatments and biochar pH.

When studying the application of biochar for sulfamethazine absorption in soils treated with and without biochar derived from an invasive cucumber plant (*Sicyos angulatus* L.), it was found that, after the application of biochar, 86% of the sulfamethazine was reduced in the soil enriched with 5 mg kg^{-1}, whereas only 63% of sulfamethazine was reduced in soil enriched with 50 mg kg^{-1} of sulfamethazine pesticide [35]. Vithanage et al. [36] also used cucumber biochar (*Sicyos angulatus* L.) for sulfamethazine removal in clayey and sandy sand soils under different conditions of pH and sulfamethazine loads. High temperature pyrolyzed biochar (700°C) showed a high degree of sulfamethazine retention. Maximum sulfamethazine retention was observed at pH 3.0, possibly due to π-π electron donor-acceptor interactions and electrostatic cation exchange. As the pH rises to 5.0–7.0, cation exchange was the main sorption mechanism. Biochar was able to maintain up to 89% and 82% increase in sulfamethazine retention in sandy loam and sandy clay soil, respectively.

The use of biochar in water pesticides remediation also proved to be efficient. Mandal et al. [23] affirm that rice straw biochars are efficient to adsorb atrazine and imidacloprid from water and have great potential as the next-generation low-cost adsorbent to prevent contamination of groundwater and minimize the environmental impact caused by the pesticides.

However, biochar application studies for contaminated soil remediation have mainly been conducted in laboratories, greenhouses, or small plot experiments, so large-scale field experiments are needed before implementing remediation projects on an operational scale [11]. Resuming, it can be concluded that pyrolysis temperature affects biochar properties and consequently pesticide sorption capacity. Biochar from high pyrolysis temperatures increases pesticide sorption in soils, reducing their soil mobility and bioavailability.

2.2 Antibiotic residues

The widely abuse of antibiotics has led to unpredictable residue releasing in the ecosystem and caused a series of environmental problems [37]. The ecological toxicity of antibiotics is a subject of growing concern because residues of antibiotics in the environment may pose adverse effects on the ecosystem [19]. Thus, antibiotics have a very low degradation rate in the natural environment and can persist for long periods [38]. Residues of antibiotics are detected in wastewater, liquid manure, surface waters, groundwater, soil and plants, drinking water, and food [7]. The application of animal manure in agricultural land is a major way through which antibiotics enter soils that are used for food production; subsequently, they can be transported to other environmental compartments and enter the food chain [39]. The behavior of antibiotics and their transport in manure is related to their physicochemical properties as well as the abiotic properties of the environment.

The content of antibiotic residues in environmental samples (water, sediment, and soil) is seasonal, in the autumn the amounts of tested drugs were higher than in the summer because higher temperatures causing degradation of the drug and frequent rainfall increases the dilution [7]. Irrespective of the different dissipation pathways for antibiotics in manure, adsorption is one of the key processes controlling the fate, mobility, and reactivity of antibiotics [12]. Adsorption is predominantly, especially in the removal of antibiotics from the environment [7].

Really, the residues of the antibiotics cannot remove effectively in traditional biological wastewater treatment facilities [37]. The methods for antibiotics removal from water include bio-electrochemical systems, heterogeneous photocatalytic method, advanced oxidation process, microbiological method, and adsorption method [40]. Biochars are highly adsorptive with the potential for sequestration of environmental organic contaminants and proved suitable for mitigating effects of antibiotics residues in manure, which effects propagate when manure is added to the soil [39].

Biochar strongly sorbs several antibiotics, including oxytetracycline, ciprofloxacin, tetracycline hydrochloride, doxycycline hydrochloride, and fluoroquinolone [16] in an aqueous solution. The efficiency of removal of the three antibiotics increased with increasing biochar dosage up to 1.2 g L^{-1}. In experimental studies developed by Peng et al. [41], on the adsorption of seven antibiotics in the environmental concentration of aqueous solutions by carbon-based materials have been observed and showed that the carbon-based materials have good adsorption properties for antibiotics in the actual concentration of environments, by which the highest removal efficiency of antibiotics can be up to 100%.

Biochar produced at high pyrolytic temperatures had greater adsorption capacity for antibiotic residues [17]. The efficiency of removal of tetracycline hydrochloride, doxycycline hydrochloride, and ciprofloxacin was enhanced with increasing pyrolysis temperature and biochar dosage [7, 14]. In studies developed by Zeng et al. [16], the best adsorption was obtained with biomass pyrolyzed at 700°C. Regarding antibiotic adsorption, the characteristics of the biochar produced play an essential role, namely its sorption parameters, aromaticity, hydrophilicity, and group density surface oxygen functionals or ash content [7].

2.3 Antibiotic resistance genes

Antibiotic resistance genes (ARGs) are the means through which bacteria become super antibiotic-resistant bacteria [42]. In last year's dissemination and persistence of antibiotic resistance genes (ARGs), received increasing concerns like one of the biggest threats to global public health and food security [43, 44]. The spread of antibiotic-resistant pathogens is a growing problem in the world is considered a type of emerging contaminant.

According to World Health Organization [45] antibiotic resistance is one of the most critical human health challenges of the next century and heralded the need for "a global strategy to contain resistance". In agreement with the last UN Global Environmental Outlook [46] ARGs as classified as the main pollutants for water sources, and call for the application of effective policies for its control in water bodies worldwide. Soil amendments with animal manure are potential sources of ARGs in soil, water, and plants [47]. Animal manures, commonly applied to the soil, support the spread of ARGs from soil to humans via the food chains [44, 48]. Remediation of agricultural soils polluted with ARGs is important for protecting food safety and human health [20, 44].

Biochar amendments have proven able to decrease the relative abundance of multiple subtypes of antibiotic resistance genes (ARGs) [19] because could affect their dissemination and fate in the environment [49]. Recently, a few studies also attempted to use biochar to alleviate ARG pollution in soil [49, 50]. Several studies demonstrated that biochar efficiently mitigated ARG pollution to some extent in soils [51] but not all the biochars consistently showed a positive effect.

In studies developed by Chen et al. [20] reported that biochar of rice straw application apparently reduced the abundance of 131 ARGs in non-planted soil, but little effect was found in a *Brassica chinensis* L. planted soil. In this study, soils were amended with or without 0.5% biochar (w/w). The addition of dissolved biochar effectively inhibited the increase of the conjugative transfer frequency of ARGs between bacteria in studies developed by Liu et al. [18] and Lian et al. [49] affirm that the replication of ARGs was also greatly inhibited after interacting with biochar.

Cui et al. [52] found that wheat straw biochar increased the abundance of tet and sul genes in a soil-plant system. These studies showed the uncertainties about the effectiveness of biochar in remediating soil ARG pollution. This uncertainty is related to the properties of the biochar, as the properties of biochar may affect the conjugative transfer of ARGs between bacteria namely feedstock and pyrolytic conditions [53]. Also, the number of heavy metals and antibiotics present in the soil determines the evolution of ARGs in the soil [44, 52], being interesting the development of biochars with excellent adsorption capacities of heavy metals and antibiotics to prevent soil pollution by ARGs [44].

Relative to heavy metals and other organic pollutants the interaction between biochar and ARGs is much less explored [49]. Therefore, further studies are needed to confirm the effect of different biochar on ARGs and even develop alternative strategies to improve the efficiency of biochar in the remediation of ARG soil pollution.

2.4 Heavy metals

Soil contamination with heavy metals has become a global environmental-health concern [1, 14, 54]. Their high level in the soil cause hazardous effects on soil quality, fertility, food safety, and human health [14]. The entry of soil-borne heavy metals into the food chain depends on the amount and source of heavy metals input, the properties of the soil, the rate and magnitude of uptake by plants [6].

The main aim for researchers and environmentalists is to stop the entry of metals and metalloids into the food chain for better human health [8]. Indiscriminate waste disposal practices have led to significant build-up in soils of a wide range of heavy metals [6]. Sources of heavy metals in soil could be anthropogenic activities, such as mining and smelting, wastewater irrigation, exhaust emissions, and sludge applications [6, 55].

Heavy metals could impact soil fertility, microbial activities, biodiversity, crop yields and pose risks to human health due to dietary exposure [6]. Biochar serves as a faster, more efficient, and environmentally friendly alternative to heavy metals in the agricultural soil [14].

The ability of biochar to remediate soil contaminated by heavy metals is linked to their facility to immobilize pollutants [55]. Immobilization is the conversion of soluble and potentially soluble forms of heavy metals to geochemically stable solid phases. Adsorption, ion exchange, complexation, and precipitation are the major mechanisms reducing heavy metal bioavailability in soils [15, 56, 57]. Biochar could reduce the bioavailability of heavy metals in the soil through cation exchange, complexation, and other related effects [15]. the addition of biochar to soil binds and/or precipitates heavy metals in soil and reduces their accumulation in plants [58].

The remediation effect depends on the characteristics of both biochar and soil and their interactions [6, 55]. Biochar applications could decrease the mobility/bioavailability of heavy metals in soils and their accumulation in plants [55].

The evolution of heavy metals in soil solutions altered by different biochars under vibrant redox conditions is a challenge and more investigation is necessary to comprehend the influence of the biochar on the dynamic forces of the heavy metals contaminated soils [1]. There are several studies that demonstrate the effectiveness of biochar in the treatment of soils contaminated by heavy metals. Thus, studies developed by Zeng et al. [16] reported that maize straw biochar reduced the availability of Cd in soil by transforming this heavy metal into a state of lower availability. Using apricot shell and the apple tree derived biochar [9] found that the labile fractions of Cd in smelter-contaminated soil decreased. Also, in studies developed by [59] using biochar from sewage sludge, this one showed up effective in immobilizing non-essential heavy metals for plants. Li et al. [60] applied 3% of soybean-straw-derived biochar (hydrothermal carbon at 350°C) to the As and Cd co-contaminated farmland soil, which reduced the bioaccumulation of As in rice plants by 88% and the treatment effects on Cd were similar. A field experiment made by Zheng et al. [61] for Cd, showed that, when the application rates of soybean-straw-derived biochar and rice-straw-derived biochar were 20 ton ha^{-1}, the content of Cd in rice roots, rice shoots, rice husks, and rice grains decreased by 25.0–44.1% and 19.9–44.2%, and 46.2–70.6% and 25.8–70.9%, respectively.

The ability of biochar to immobilize heavy metals is related to its ability to change soil pH, biochar typically contains alkaline components, which can considerably improve soil pH [58]. For example, Van Poucke et al. [62] showed a significant negative correlation between the pH value increase and the soil exchangeable Cd content after biochar application. In studies developed by Fang et al. [63] was found that the addition of sludge-derived biochar to contaminated soil could increase the soil pH and reduce the effective concentration of Pb, Cd, Ni, and Cr in soil.

Studies developed by Li et al. [64] evidenced that the heavy metal concentrations in biochar were diluted by adding antibiotic mycelial residue, which led to lower toxic inputs to the environment, moreover, heavy metals were transformed to more stable fractions after co-pyrolysis. Liu et al. [18] confirm that the addition of dissolved biochar is an effective measure to control copper pollution in water, as the combination of humic acid-like components in dissolved biochar with Cu(II) significantly reduces the concentration of Cu(II) in water.

The hydrological conditions in the natural field can influence the effect of biochar on the stabilization of contaminated soil [65]. Studies developed by dos Santos et al. [66], showed the biochar efficiency in removal methylene blue from water. About 83% of methylene blue removal was achieved within 30 minutes of equilibration time.

Braghiroli et al. [67] showed that biochar high aromaticity and porosity are essential for the sorption of organic contaminants, while the presence of oxygen-containing functional groups and optimum pH are crucial for the sorption of inorganic contaminants, especially metals. Thus, biochar can be proficiently adopted for metals adsorption from polluted water [68], showing to be a promising option for the treatment of contaminants in water, but further research is required to evaluate its performance with real effluents containing contaminants of emerging concern [67].

3. Conclusions

Biochar is widely used in wastewater treatment and soil remediation and shows great potential in ameliorating the toxicological effect of antibiotics, pesticides, antibiotic resistance genes, and heavy metals. Biochar efficacy for reducing the availability and mobility of potentially toxic elements in soil and water is dependent on the properties and chemical structure of the contaminants, as well as the adsorption process conditions; however, it is primarily dependent on biochar physicochemical properties. Biochar properties are predominantly determined by the feedstock type used and pyrolysis temperature. Hence, to obtain an efficient and selective biochar adsorbent, it is essential to select appropriate feedstocks and production conditions. However, research gaps still exist in the development of practical methods for preparing and applying different biochars that target specific heavy metals, and more research is needed to expand knowledge in this area.

Acknowledgements

This research was funded by National Funds by FCT—Portuguese Foundation for Science and Technology, under the project UIDB/04033/2020 and UIDB/00681/2020, CERNAS-IPV.

Conflict of interest

The authors declare no conflict of interest.

Author details

Adelaide Perdigão[1,2]* and José Luís da Silva Pereira[2,3]

1 CERNAS-IPV Research Centre, Polytechnic Institute of Viseu, Viseu, Portugal

2 Agrarian School of Viseu, Polytechnic Institute of Viseu, Viseu, Portugal

3 CITAB—Centre for the Research and Technology of Agro-Environmental and Biological Sciences, University of Trás-os-Montes and Alto Douro, Vila Real, Portugal

*Address all correspondence to: aperdigao25@gmail.com

References

[1] Murtaza G, Ditta A, Ullah N, Usman M, Ahmed Z. Biochar for the management of nutrient impoverished and metal contaminated soils: Preparation, applications, and prospects. Journal of Soil Science and Plant Nutrition. 2021;**21**(3):2191-2213

[2] Rostami S, Azhdarpoor A. The application of plant growth regulators to improve phytoremediation of contaminated soils: A review. Chemosphere. 2019;**220**:818-827

[3] Moradi N, Karimi A. Fe-modified common reed biochar reduced cadmium (Cd) mobility and enhanced microbial activity in a contaminated calcareous soil. Journal of Soil Science and Plant Nutrition. 2021;**21**(1):329-340

[4] Sun J, Pan L, Tsang DCW, Zhan Y, Zhu L, Li X. Organic contamination and remediation in the agricultural soils of China: A critical review. Science of the Total Environment. 2018;**615**:724-740

[5] Sun J, Pan L, Zhan Y, Lu H, Tsang DCW, Liu W, et al. Contamination of phthalate esters, organochlorine pesticides and polybrominated diphenyl ethers in agricultural soils from the Yangtze River Delta of China. Science of the Total Environment. 2016;**544**:670-676

[6] Bolan N, Kunhikrishnan A, Thangarajan R, Kumpiene J, Park J, Makino T, et al. Remediation of heavy metal(loid)s contaminated soils—To mobilize or to immobilize? Journal of Hazardous Materials. 2014;**266**:141-166

[7] Krasucka P, Pan B, Sik Ok Y, Mohan D, Sarkar B, Oleszczuk P. Engineered biochar—A sustainable solution for the removal of antibiotics from water. Chemical Engineering Journal. 2021;**405**:126926

[8] Mehmood S, Wang X, Ahmed W, Imtiaz M, Ditta A, Rizwan M, et al. Removal mechanisms of slag against potentially toxic elements in soil and plants for sustainable agriculture development: A critical review. Sustainability. 2021;**13**(9):5255

[9] Ali A, Shaheen SM, Guo D, Li Y, Xiao R, Wahid F, et al. Apricot shell- and apple tree-derived biochar affect the fractionation and bioavailability of Zn and Cd as well as the microbial activity in smelter contaminated soil. Environmental Pollution. 2020;**264**:114773

[10] Pereira JLS, Figueiredo V, Pinto AFMA, Silva MEF, Brás I, Perdigão A, et al. Effects of biochar and clinoptilolite on composition and gaseous emissions during the storage of separated liquid fraction of pig slurry. Applied Sciences. 2020;**10**(16):5652

[11] Morillo E, Villaverde J. Advanced technologies for the remediation of pesticide-contaminated soils. Science of the Total Environment. 2017;**586**: 576-597

[12] Guo M, Song W, Tian J. Biochar-facilitated soil remediation: Mechanisms and efficacy variations. Frontiers in Environmental Science. 2020;**8**:183

[13] Wang J, Wang S. Preparation, modification and environmental application of biochar: A review. Journal of Cleaner Production. 2019;**227**: 1002-1022

[14] Awad M, Liu Z, Skalicky M, Dessoky ES, Brestic M, Mbarki S, et al. Fractionation of heavy metals in multi-contaminated soil treated with biochar using the sequential extraction procedure. Biomolecules. 2021;**11**(3):448

[15] Xu C, Zhao J, Yang W, He L, Wei W, Tan X, et al. Evaluation of biochar pyrolyzed from kitchen waste, corn straw, and peanut hulls on immobilization of Pb and Cd in

contaminated soil. Environmental Pollution. 2020;**261**:114133

[16] Zeng Z, Tian S, Liu Y, Tan X, Zeng G, Jiang L, et al. Comparative study of rice husk biochars for aqueous antibiotics removal. Journal of Chemical Technology and Biotechnology. 2018;**93**(4):1075-1084

[17] Ahmad M, Lee SS, Rajapaksha AU, Vithanage M, Zhang M, Cho JS, et al. Trichloroethylene adsorption by pine needle biochars produced at various pyrolysis temperatures. Bioresource Technology. 2013;**143**:615-622

[18] Liu X, Wang D, Wang L, Tang J. Dissolved biochar eliminates the effect of Cu(II) on the transfer of antibiotic resistance genes between bacteria. Journal of Hazardous Materials. 2022;**424**:127251

[19] He G, Jiang X, Yao L, Liu G, Yang Y, Jiang Y, et al. Effects of tetracycline on nitrogen and carbon cycling rates and microbial abundance in sediments with and without biochar amendment. Chemosphere. 2021;**270**:129509

[20] Chen Q-L, Fan X-T, Zhu D, An X-L, Su J-Q, Cui L. Effect of biochar amendment on the alleviation of antibiotic resistance in soil and phyllosphere of *Brassica chinensis* L. Soil Biology and Biochemistry. 2018;**119**: 74-82

[21] Cheng M, Zeng G, Huang D, Lai C, Xu P, Zhang C, et al. Hydroxyl radicals based advanced oxidation processes (AOPs) for remediation of soils contaminated with organic compounds: A review. Chemical Engineering Journal. 2016;**284**:582-598

[22] Varjani S, Kumar G, Rene ER. Developments in biochar application for pesticide remediation: Current knowledge and future research directions. Journal of Environmental Management. 2019;**232**:505-513

[23] Mandal A, Singh N, Purakayastha TJ. Characterization of pesticide sorption behaviour of slow pyrolysis biochars as low cost adsorbent for atrazine and imidacloprid removal. Science of the Total Environment. 2017;**577**:376-385

[24] Liu Y, Lonappan L, Brar SK, Yang S. Impact of biochar amendment in agricultural soils on the sorption, desorption, and degradation of pesticides: A review. Science of the Total Environment. 2018;**645**:60-70

[25] Liu Y, Yao S, Wang Y, Lu H, Brar SK, Yang S. Bio- and hydrochars from rice straw and pig manure: Inter-comparison. Bioresource Technology. 2017;**235**:332-337

[26] Chen T, Zhang Y, Wang H, Lu W, Zhou Z, Zhang Y, et al. Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sewage sludge. Bioresource Technology. 2014;**164**:47-54

[27] Cantrell KB, Hunt PG, Uchimiya M, Novak JM, Ro KS. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresource Technology. 2012;**107**:419-428

[28] Li H, Dong X, da Silva EB, de Oliveira LM, Chen Y, Ma LQ. Mechanisms of metal sorption by biochars: Biochar characteristics and modifications. Chemosphere. 2017; **178**:466-478

[29] Wang H, Lin K, Hou Z, Richardson B, Gan J. Sorption of the herbicide terbuthylazine in two New Zealand forest soils amended with biosolids and biochars. Journal of Soils and Sediments. 2010;**7**:283-289

[30] Dairy-Manure Derived Biochar Effectively Sorbs Lead and Atrazine|Environmental Science &

Technology [Internet]. Disponível em: https://pubs.acs.org/doi/abs/10.1021/es803092k [citado 29 de Setembro de 2021]

[31] Cabrera A, Cox L, Spokas K, Hermosín MC, Cornejo J, Koskinen WC. Influence of biochar amendments on the sorption–desorption of aminocyclopyrachlor, bentazone and pyraclostrobin pesticides to an agricultural soil. Science of the Total Environment. 2014;**470-471**:438-443

[32] Reduced plant uptake of pesticides with biochar additions to soil—ScienceDirect [Internet]. Disponível em: https://www.sciencedirect.com/science/article/pii/S0045653509004226 [citado 29 de Setembro de 2021]

[33] π+−π Interactions between (Hetero) aromatic Amine Cations and the Graphitic Surfaces of Pyrogenic Carbonaceous Materials|Environmental Science & Technology [Internet]. Disponível em: https://pubs.acs.org/doi/abs/10.1021/es5043029 [citado 29 de Setembro de 2021]

[34] Liu N, Charrua AB, Weng C-H, Yuan X, Ding F. Characterization of biochars derived from agriculture wastes and their adsorptive removal of atrazine from aqueous solution: A comparative study. Bioresource Technology. 2015;**198**:55-62

[35] Rajapaksha AU, Vithanage M, Lim JE, Ahmed MBM, Zhang M, Lee SS, et al. Invasive plant-derived biochar inhibits sulfamethazine uptake by lettuce in soil. Chemosphere. 2014;**111**:500-504

[36] Vithanage M, Rajapaksha AU, Tang X, Thiele-Bruhn S, Kim KH, Lee S-E, et al. Sorption and transport of sulfamethazine in agricultural soils amended with invasive-plant-derived biochar. Journal of Environmental Management. 2014;**141**:95-103

[37] Li H, Hu J, Yao L, Shen Q, An L, Wang X. Ultrahigh adsorbability towards different antibiotic residues on fore-modified self-functionalized biochar: Competitive adsorption and mechanism studies. Journal of Hazardous Materials. 2020;**390**:122127

[38] Huang A, Yan M, Lin J, Xu L, Gong H, Gong H. A review of processes for removing antibiotics from breeding wastewater. International Journal of Environmental Research and Public Health. 2021;**18**(9):4909

[39] Ngigi AN, Ok YS, Thiele-Bruhn S. Biochar affects the dissipation of antibiotics and abundance of antibiotic resistance genes in pig manure. Bioresource Technology. 2020;**315**:123782

[40] Wang H, Lou X, Hu Q, Sun T. Adsorption of antibiotics from water by using Chinese herbal medicine residues derived biochar: Preparation and properties studies. Journal of Molecular Liquids. 2021;**325**:114967

[41] Peng B, Chen L, Que C, Yang K, Deng F, Deng X, et al. Adsorption of antibiotics on graphene and biochar in aqueous solutions induced by π-π interactions. Scientific Reports. 2016;**6**(1):31920

[42] Identification and quantification of bacterial genomes carrying antibiotic resistance genes and virulence factor genes for aquatic microbiological risk assessment—ScienceDirect [Internet]. Disponível em: https://www.sciencedirect.com/science/article/pii/S0043135419309340 [citado 29 de Setembro de 2021]

[43] Hernando-Amado S, Coque TM, Baquero F, Martínez JL. Defining and combating antibiotic resistance from one health and global health perspectives. Nature Microbiology. 2019;**4**(9):1432-1442

[44] Zheng H, Feng N, Yang T, Shi M, Wang X, Zhang Q, et al. Individual and

combined applications of biochar and pyroligneous acid mitigate dissemination of antibiotic resistance genes in agricultural soil. Science of the Total Environment. 2021;**796**:148962

[45] Antibiotic resistance [Internet]. Disponível em: https://www.who.int/news-room/fact-sheets/detail/antibiotic-resistance [citado 29 de Setembro de 2021]

[46] UN Environment, editor. Global Environment Outlook—GEO-6: Healthy Planet, Healthy People. 1st ed. Cambridge: Cambridge University Press; 2019. Disponível em: https://www.cambridge.org/core/product/identifier/9781108627146/type/book [citado 9 de Fevereiro de 2021]

[47] Xu Y, Li H, Shi R, Lv J, Li B, Yang F, et al. Antibiotic resistance genes in different animal manures and their derived organic fertilizer. Environmental Sciences Europe. 2020;**32**(1):102

[48] Lu Y, Li J, Meng J, Zhang J, Zhuang H, Zheng G, et al. Long-term biogas slurry application increased antibiotics accumulation and antibiotic resistance genes (ARGs) spread in agricultural soils with different properties. Science of the Total Environment. 2021;**759**:143473

[49] Lian F, Yu W, Zhou Q, Gu S, Wang Z, Xing B. Size matters: Nano-biochar triggers decomposition and transformation inhibition of antibiotic resistance genes in aqueous environments. Environmental Science & Technology. 2020;**54**(14):8821-8829

[50] Ding J, Yin Y, Sun A-Q, Lassen SB, Li G, Zhu D, et al. Effects of biochar amendments on antibiotic resistome of the soil and collembolan gut. Journal of Hazardous Materials. 2019;**377**:186-194

[51] Ye M, Sun M, Zhao Y, Jiao W, Xia B, Liu M, et al. Targeted inactivation of antibiotic-resistant *Escherichia coli* and *Pseudomonas aeruginosa* in a soil-lettuce system by combined polyvalent bacteriophage and biochar treatment. Environmental Pollution. 2018;**241**: 978-987

[52] Cui E-P, Gao F, Liu Y, Fan X-Y, Li Z-Y, Du Z-J, et al. Amendment soil with biochar to control antibiotic resistance genes under unconventional water resources irrigation: Proceed with caution. Environmental Pollution. 2018;**240**:475-484

[53] Liu X, Wang D, Tang J, Liu F, Wang L. Effect of dissolved biochar on the transfer of antibiotic resistance genes between bacteria. Environmental Pollution. 2021;**288**:117718

[54] Rizwan MS, Imtiaz M, Zhu J, Yousaf B, Hussain M, Ali L, et al. Immobilization of Pb and Cu by organic and inorganic amendments in contaminated soil. Geoderma. 2021;**385**:114803

[55] He L, Zhong H, Liu G, Dai Z, Brookes PC, Xu J. Remediation of heavy metal contaminated soils by biochar: Mechanisms, potential risks and applications in China. Environmental Pollution. 2019;**252**:846-855

[56] Cheng S, Chen T, Xu W, Huang J, Jiang S, Yan B. Application research of biochar for the remediation of soil heavy metals contamination: A review. Molecules. 2020;**25**(14):3167

[57] Boni MR, Marzeddu S, Tatti F, Raboni M, Mancini G, Luciano A, et al. Experimental and numerical study of biochar fixed bed column for the adsorption of arsenic from aqueous solutions. Water. 2021;**13**(7):915

[58] Wei L, Huang Y, Huang L, Huang Q, Li Y, Li X, et al. Combined biochar and soda residues increases maize yields and decreases grain Cd/Pb in a highly Cd/Pb-polluted acid Udults soil.

Agriculture, Ecosystems and Environment. 2021;**306**:107198

[59] Chagas JKM, de Figueiredo CC, da Silva J, Paz-Ferreiro J. The residual effect of sewage sludge biochar on soil availability and bioaccumulation of heavy metals: Evidence from a three-year field experiment. Journal of Environmental Management. 2021;**279**:111824

[60] Li G, Khan S, Ibrahim M, Sun T-R, Tang J-F, Cotner JB, et al. Biochars induced modification of dissolved organic matter (DOM) in soil and its impact on mobility and bioaccumulation of arsenic and cadmium. Journal of Hazardous Materials. 2018;**348**:100-108

[61] Zheng R, Chen Z, Cai C, Tie B, Liu X, Reid BJ, et al. Mitigating heavy metal accumulation into rice (*Oryza sativa* L.) using biochar amendment—A field experiment in Hunan, China. Environmental Science and Pollution Research. 2015;**22**(14):11097-11108

[62] Van Poucke R, Ainsworth J, Maeseele M, Ok YS, Meers E, Tack FMG. Chemical stabilization of Cd-contaminated soil using biochar. Applied Geochemistry. 2018;**88**:122-130

[63] Fang S, Tsang DCW, Zhou F, Zhang W, Qiu R. Stabilization of cationic and anionic metal species in contaminated soils using sludge-derived biochar. Chemosphere. 2016;**149**: 263-271

[64] Li C, Xie S, You F, Zhu X, Li J, Xu X, et al. Heavy metal stabilization and improved biochar generation via pyrolysis of hydrothermally treated sewage sludge with antibiotic mycelial residue. Waste Management. 2021;**119**: 152-161

[65] Shentu J, Li X, Han R, Chen Q, Shen D, Qi S. Effect of site hydrological conditions and soil aggregate sizes on the stabilization of heavy metals (Cu, Ni, Pb, Zn) by biochar. Science of the Total Environment. 2022;**802**: 149949

[66] dos Santos KJL, dos Santos GEDS, de Sá ÍMGL, Ide AH, Duarte JLDS, de Carvalho SHV, et al. Wodyetia bifurcata biochar for methylene blue removal from aqueous matrix. Bioresource Technology. 2019;**293**:122093

[67] Braghiroli FL, Bouafif H, Neculita CM, Koubaa A. Activated biochar as an effective sorbent for organic and inorganic contaminants in water. Water, Air, and Soil Pollution. 2018;**229**(7):230

[68] dos Santos GEDS, Lins PVDS, Oliveira LMTDM, da Silva EO, Anastopoulos I, Erto A, et al. Layered double hydroxides/biochar composites as adsorbents for water remediation applications: Recent trends and perspectives. Journal of Cleaner Production. 2021;**284**:124755