Unravelling the Impact of Potentially Toxic Elements and Biochar on Soil: A Review

Article · May 2022

DOI: 10.1016/j.envc.2022.100540

1 author:

Maeti George
National University of Lesotho
7 PUBLICATIONS **37** CITATIONS
SEE PROFILE

Environmental Challenges 8 (2022) 100540

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

Unravelling the impact of potentially toxic elements and biochar on soil: A review

Maeti George

Department of Environmental Health, National University of Lesotho, Roma, 180, Lesotho

ARTICLE INFO

Keywords:
Potentially toxic elements
Biochar
Soil properties
Soil remediation
Microbial communities

ABSTRACT

Industrial activities, urbanization and mismanagement of toxic waste, have caused global environmental degradation. Biochar has lately gained considerable recognition and popularity for remediation of contaminated soil. Even though it is organic in nature, biochar may need further processing in order to safely remove contaminants, for soil augmentation and to enhance its treatment efficiency. In this study, areas that have been under-researched regarding safe precautionary measures in biochar preparation, and biochar safety towards soil environment, have been reviewed. The review has determined that, in order for biochar to have minimal negative impact on soil and its microorganisms, soil type and concentration of contaminants to be treated have to be pre-determined. Furthermore, the groups of microorganisms that are not tolerant to long-term application of biochar have to be known. Biochar itself may sometimes be a source of contaminants due to its substrate or method of its preparation, therefore prior biological tests should be done. Variations in experimental and climatic conditions have to be considered prior to reporting on how soil behaves when conditioned or treated with biochar. Furthermore, long-term field research should also be considered in order to provide different insights on biochar suitability to soil amelioration. Further areas of research are also identified, for holistical reporting of biochar and impact on the environment.

1. Introduction

With increase in agricultural activities, urbanization, and industrialization driven by economic development and population growth, there is enormous disposal of potentially toxic element- laden waste and effluent into the environment. Coupled with disposal of toxic waste, is the quantities (Anake et al., 2009) with which they are generated. Toxic substances are also sometimes reactive and explosive even in low concentrations (Ayangbenro and Babalola, 2017). Potentially toxic elements (PTEs) are toxic, while also conservative and persistent in the environment (Girma, 2015; Ayangbenro and Babalola, 2017; Suman et al., 2018). They are not degradable and tend to linger in the environment longer than other pollutants. They accumulate (Ayangbenro and Babalola, 2017) in the receiving environment and bio-magnify through food chains (Adhikari et al., 2004), enabling them to move across from one compartment of the environment to the other. However, not all potentially toxic elements bio-magnify, but those that bio-magnify include mercury. Of greatest concern is the species form in which the PTEs reach the receiving environment, which in most cases they are bio-available (Kaasalainen and Yli-Halla, 2003; D'Amore et al., 2005) while also toxic and jeopardizing crop production through phytotoxic properties (Girma, 2015).

Soil pollution does not only impact negatively on crops produced from it, but also on humans who consume the crops (He et al., 2019; Wu et al., 2020). Land pollution subsequently minimizes the size of available soil for crop production, and extensively pollutes air and water through secondary pollution. Contaminated water bodies, on the other hand, compromise water availability, which is already threatened by climatic changes and over abstraction due to population growth. The problem is grave where environmental policies and laws are in existence but are not implemented and enforced, putting at risk, humans and ecosystems' health (Alam et al., 2003; Zietz et al., 2003). Polluted land and compartments of the environment that were polluted, need phytoremediation in order to stop translocation of pollutants, or to bring to a halt recycling of PTEs through decomposition of vegetation that might have stored pollutants in their leaves and stems. Remediation of soil and water will also minimize consumption of contaminated food and water, thus minimizing transfer of pollutants into the various trophic levels in food chains.

2. Methodology

The study engaged a systematic review of literature in order to answer the research questions on impact of PTEs and biochar on soil. The review process took eleven months, and focussed on articles from MDPI, Elsevier, Wiley and Springer publishers (Fig. 1), being the reputable publishers of interest. Furthermore, focus was on topics that were related to

---

E-mail address: maetigeorge@gmail.com

https://doi.org/10.1016/j.envc.2022.100540
Received 13 February 2022; Received in revised form 28 April 2022; Accepted 29 April 2022

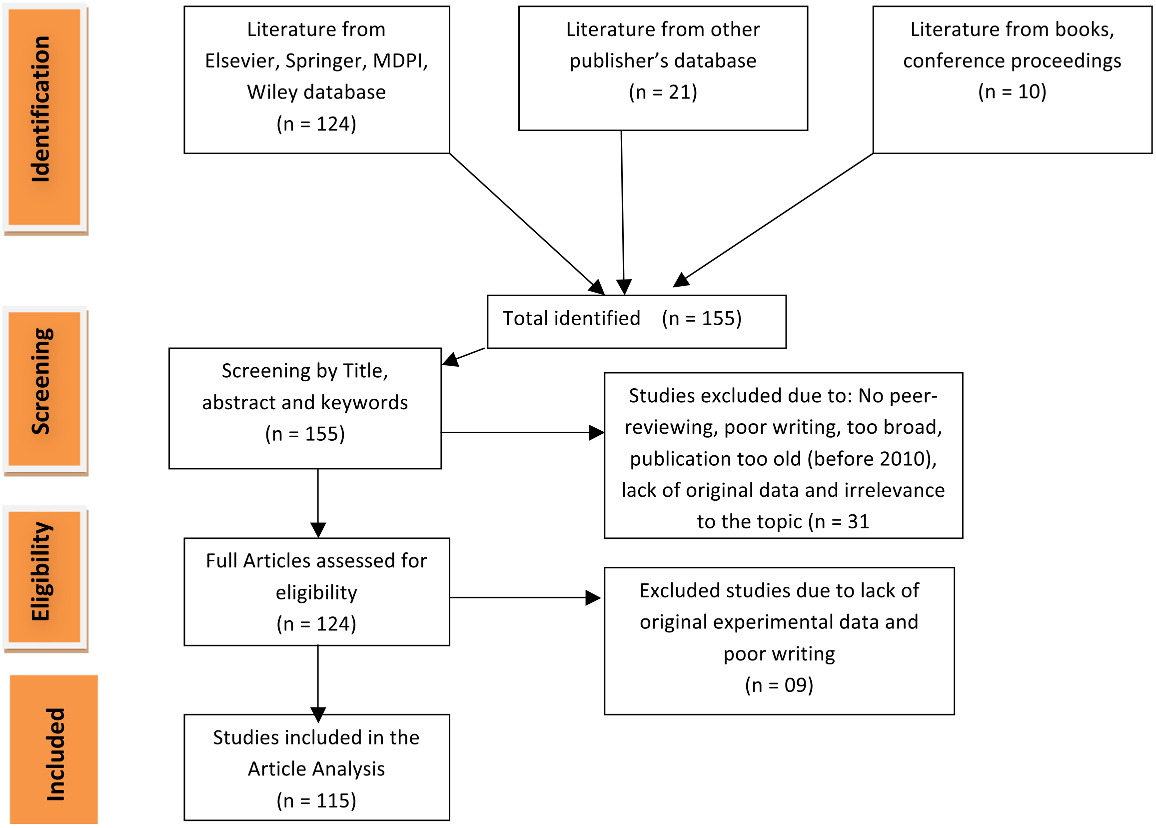

Fig. 1. Flow diagram showing number of articles identified, screened and included in the Review article (Adapted from: Page et al., 2021).

Table 1
Number of articles used in the review for each topic.

TOPIC	No. of Articles
Biochar effects on soil organisms	23 (27%)
Application of biochar in soil remediation	20 (18%)
Biochar effect on soil fertility	6
Biochar effects on nutrient retention	4
Biochar effects on leaching reduction	4 (12%)
Biochar and water retention/Water Holding Capacity	11 (10%)
PTE effects in soils	9 (8%)
PTE effects on microbial communities	8 (7%)
Biochar effect on soil bulk density	8 (7%)
Effect of biochar pyrolysis temperature preparation on	7 (6%)
contaminant removal	8 (7%)
Effect of biochar preparation method on & impact on contaminant removal	
PTE and soil toxicity	6 (5%)
Type of biochar feedstock on its adsorption properties	4 (4%)
How biochar age affects biochar performance	3 (3%)
Biochar and application rate	1 (1%)

effect of PTEs on the environment (soil and microbial communities), impact of biochar application onto the environment (soil, microorganisms, soil fertility, nutrient retention and leaching reduction, water retention, soil bulk density) as shown in Table 1. Scientific literature was guided by relevant articles' titles, abstract and keywords from such studies, and further refined to that one supported by laboratory experimental results for short and long-term studies. Bias was minimized by consideration of other databases. Screening method excluded articles that were not peer reviewed. Articles that were poorly written and too broad for the scope of this manuscript were also excluded. Furthermore, exclusion criterion included articles published before the year 2010 (for biochar) this being the period when the biochar topic had not yet attracted broad research that is also suitable for this manuscript. However, a few articles published between 2000 and 2010 were researched and included for the purposes of extracting data on PTEs.

3. Results

The review utilized 155 articles, from which 124 were identified as having original data, topic-related and peer-reviewed (Table 1) and thus used for the review. From the 124 screened articles, nine were either too broad for the scope of this manuscript or were poorly-written, and this brought the total number of articles used in this review to 115. A majority of the articles (21%) focussed on effects of biochar on soil microorganisms, followed by 18% that were on application of biochar in soil remediation, 13% on biochar effect on soil fertility, nutrient retention and leaching reduction, whereas the other 10% were on water holding capacity of biochar. The remaining articles covered effects of PTEs on soil (8%), on microbial communities (7%), biochar effect on soil bulk density (7%), biochar preparation methods on contaminant removal (6%), impact of biochar pyrolysis temperature on contaminant removal (6%), and PTEs and soil toxicity (5%). Ageing biochar's effect on its performance was covered by 3% of the articles, whereas the role played by type of feedstock used for biochar preparation on absorption properties was covered by 4% of the articles. It is worth noting that some articles used in this review covered more than one topic.

4. Effect of potentially toxic elements on the environment

Toxic substances are not only a nuisance to the receiving environment, but their toxicity cuts across to other spheres of the environment. Properties and effects of these PTEs in different environmental set-ups (soil, soil microbial communities and vegetation) are shown below.

Table 2
Effects of biochar on water retention for sandy soil (fine) and coarse soil under different environmental conditions.

	Soil type	climate	Pyrolysis temperature	Water retention	Reference
Biochar	Sandy	Desert	N/A	Repulsion	Abel et al. (2013)
		*	N/A	High + high AWC	Busscher et al. (2010); Basso et al. (2013); Głąb et al. (2016); Atkinson (2018),
		Other		* High	Abel et al. (2013); Bruun et al. (2014); Baiamonte et al. (2015)
				**No connection	Jeffery et al. (2015)
		N/A	High	High	Mao et al. (2019)
		N/A	Low	Hydrophobic	Kameyama et al. (2019); Li et al. (2021)
	* Coarse	N/A	N/A	High	Atkinson (2018)
Hydrochar	Sandy	N/A	N/A	repulsion	Abel et al. (2013)

AWC: Available Water Content.
*Conflicting for soil type.

4.1. Potentially toxic element effects in soils

Globally, availability of land for crop production has been drastically reduced due to pollution by PTEs. This has negative sequences on the ever growing population since the food demand is not met, leading to starvation, malnutrition and health risks since some communities feed on contaminated food. Health risks are due to direct consumption of contaminated food or indirectly through irrigation with contaminated water. Moreover, while producing crops on polluted soil is the only available option for communities with contaminated soil, their productivity is reduced since photosynthesis is inhibited, leading towards stunted growth that is evident by withheld leaf shoot and root development. PTEs bind onto soil, making them available to crops grown on polluted soil. Soil contamination by PTEs is more severe than that of other segments of the environment due to their recalcitrance and subsequent persistence in soil (Thangavel and Subbhuraam, 2004). PTEs reduce soil pH, and at very low pH some plant nutrients such as magnesium, calcium, phosphorus and nitrogen are unavailable for plant growth (Miah et al., 2005; Jackson et al., 2014). This subsequently results in high bioavailability of PTEs within such environments for plant uptake (McBride, 1995) and subsequently reduction in plant development and death in extreme cases.

PTE extraction from soils raises a concern regarding their mobility and transfer from abiotic to biotic sectors of the environment. Biotic segments here refer to vegetation and animals that rely on soil for productivity and feeding, respectively, being agents of PTEs transportation through food chains. Soil structure plays a significant role in determination of toxic substances from point of pollution and dispersal to non-polluted segments of the environment, especially groundwater. However, topography and other climatic factors like rain are drivers in the transfer of pollutants into open water bodies. Microbial activity is also reduced since most plants and their microorganisms survive better within pH range of 6 to 7.5 (Isirimah et al., 2003; Miah et al., 2005; Jackson et al., 2014).

Human populace depending on agricultural productivity from prepolluted soils is at the highest risk of PTE pollution. On the other side, PTEs are not only readily available for plants, but also affect their biomass development growth (Singh et al., 2016) through inhibition of nutrient absorption and photosynthesis, genetic structure (Nagajyoti et al., 2010) and soil microbial community and diversity (Xie et al., 2016; Chu, 2018).

4.2. Potentially toxic element effects on microbial communities

Microbial organisms are responsible for soil carbon, nitrogen, phosphorus and sulphur recycling. Furthermore, these organisms are responsible for biochemical reactions in soil, while also sensitive to soil contaminants, and often used as soil quality and pollution indicators (Chu, 2018). PTEs are an example of soil contaminants that alter microbial community composition, their effect on enzymatic activity and overall soil microbial activities (Giller et al., 1998b; Xie et al., 2016; Chu, 2018). A shift in microbial population due to PTE contamination constitutes a threat to soil microbial communities and their activities (Gülser and Erdoğan, 2008; Chu, 2018) amongst them soil organic matter decomposition (Maslin and Maier, 2000). However, a study by Yao et al. (2003) showed that there is an increase in tolerance of some microbes like arbuscular mycorrhizal fungi (Mora et al., 2005) to long term PTEs pollution. PTE tolerant microbes could be used in soil remediation due to detoxification mechanisms that they have developed (Xie et al., 2016). PTE uptake further takes place during enhancement of plant biomass that would ultimately speed up PTE extraction. This is accomplished with utilization of plant growth promoting rhizobacteria (PGPR) (Becerra-Castro and Prieto, 2011).

5. Application of biochar in soil remediation

Biochar is produced from agricultural residuals that are organic in nature like animal manure, woodchips (Thornley et al., 2009; Ahmad et al., 2014); and material that is non-agricultural in production like sewage sludge. It is produced under reducing thermochemical conditions by decomposition and transformation of plant material (Meyer et al., 2011; Chen et al., 2020), under low oxygen conditions (Lehmann and Joseph, 2012; Sohi, 2012). It is also defined as 'a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment' (IBI, 2013). This is an environment-friendly soil amendment (Lehmann and Joseph, 2012) and remediation technology (amongst others), that uses adsorption and has become popular due to high adsorption capacity (even for organic pollutants), high specific surface area (SSA), and high carbon content, thus increasing soil fertility (Shaaban et al., 2018; Yu et al., 2019), oxygen-containing functional groups SFG (Ahmad et al., 2014), surface chemistry and physical and chemical resistance (Crini et al., 2019). The product is also porous (Atkinson et al., 2010) and has high cation exchange capacity (CEC). When applied to soil, the porous nature increases soil water retention (Abel et al., 2013). However, other authors suggest otherwise, as shown in Section 5.4 on water retention. It was suggested that biochar modification could contribute towards an increase in pore spaces, SSA and SFG (Tan et al., 2016; Dai et al., 2017).

Adding to the slow pyrolysis method used for biochar production, biomass can alternately undergo hydrothermal carbonisation (HTC) utilizing hot compressed water (Kambo and Dutta, 2015). Hydrochar has physicochemical properties which make it applicable at different environmental conditions. Nevertheless, notice of exchangeable usage of the two - biochar and hydrochar, is observed, despite different engineering and preparation methods used (Dieguez-Alonso et al., 2018). One of the differences between the two is that hydrochar has lower surface area and micro-porosity than biochar (Kambo and Dutta, 2015). Biochar has a pH that ranges from 7.1 to 10.5 (Lehmann et al., 2011), and when added to soil it increases the pH of acidic soil (Van Zwieten et al., 2010). This creates an enabling environment for some PTE adsorption (Yuan et al., 2011; Gai et al., 2014). However, preparation method of biochar contributes towards a change in biochar pH where hydrothermal carbonization results in biochar of low pH (Magdziarz et al., 2020)

5.1. Application of biochar in soil remediation

While biochar may be proposed as a solution to soil contaminant reduction, its application should not be universal since some biochar production led to the formation of toxicants (Godlewska et al., 2021) and contaminants like volatile organic carbons (VOCs) and nanoparticles, and could conversely add contaminants to soil. VOCs are largely a result of incomplete combustion of raw materials that produce biochar. There is therefore a high possibility of the toxic contaminants accumulation in plant tissues, and subsequent risk to human health if soil is intended for crop production. Emerging contaminants negatively impact on soil microorganisms. Some of these contaminants are bioavailable (Zheng et al., 2019) and pose health problems for communities that rely on conditioned soil for crop production. The problem is severe where biochar contamination was a result of its source or raw material used for its production, for example sewage sludge from non-residential sources. However, the levels of toxicity of such biochar can be determined through biological tests on soil prior to bioremediation. Such tests include seed germination and analysis of microorganisms like earthworms (Zheng et al., 2019). Further investigations and research should cover mechanisms with which biochar affects plant growth due to biochar-plant nutrient linkage.

5.2. Biochar effects on soil organisms

Microorganisms improve soil quality through processes like nutrient transformations and carbon cycling. Increment of biochar benefits soil in modifying its chemical and some physical characteristics. However, selection of biochar is essential since some could be toxic as a result of their origin (Verheijen et al., 2009). High rates of biochar application to sandy soils have been reported to decrease microbial activity in soil, while also reducing organic matter decomposition (Brtnicky et al., 2021). However, in studies by Liang et al. (2008), Grossman et al. (2010) and Lehmann et al. (2011) an increase in soil microbial community was observed through application of biochar.

A study by Skjemstad et al. (2002) has shown limitations in utilization of biochar as a source of energy for some microorganisms, but this observation has been reproached by Kuzyakov et al. (2009) where biochar stimulated some species of dormant soil microorganisms. However, Gul et al. (2014) have associated microorganism abundance with type of feedstock from which biochar originates, where manure or crop residue biochar was better in enhancement of microorganism abundance than that from wood. Dai et al. (2021) reported that labile C supplies carbohydrates to some microorganisms and increased their population size. Ezawa et al. (2002) and Lehmann et al. (2011) also observed that due to its porous nature, biochar may also be habitable to some microorganisms, thus stimulating them. Macropores are associated with habitat provision for microorganisms (Alkharabsheh et al., 2021). The other likelihood for a change in microbial activity and abundance after biochar application could be availability of labile substrates and sorption of bacteria onto biochar (Ezawa et al., 2002) and increase in soil pH (Gul et al., 2014; Liu et al., 2020). Availability of labile substrates could be a question of the feedstock from which specific biochar has been processed. Furthermore, abundance of other microorganisms like amoebas, bacterivorous and herbivorous nematodes was negatively impacted, with herbivores requiring a higher biochar addition for positive microbial abundance (Liu et al., 2020). Additionally, there was no significant response of soil fauna to biochar application in a study by Lee (2021). Undoubtedly, the aspect of microorganism and biochar compatibility is one of the research areas that need further investigation. Laboratory studies that would address this gap should look into a variation of biochar types - produced from different feedstock at different pyrolysis temperature, and with different application rates. Biochar age should also be considered and investigated on different microorganism species, on varied soil types, and most importantly, under controlled experiments and at different environmental and climatic conditions. However, some studies have identified a link between biochar age and soil properties, as well as with microorganisms health. Biochar from grassy and woody feedstock changed their pH and became acidic, a condition that stabilized pH of soil amended with such biochar (Mukherjee et al., 2014).

Due to their sensitivity to a pH change brought by biochar, earthworms tend to respond negatively, especially when applied at high rates (Weyers and Spokas, 2011) of about 10 to 20% (w/w). Not only did a change in pH affect earthworms, but, in the same study *E. fetida* species was used, where the biochar water holding capacity led to loss in earthworm weight at a 10% (w/w) application rate. Furthermore, in a study by Anyanwu et al. (2018), biochar that was 90 days old negatively affected growth of *E. eugeniae* earthworm species. This has shown that other negative impacts of biochar onto organisms could be a result of its toxicity from ageing, where it undergoes biological and physicochemical changes (Mukherjee et al., 2014; Kavitha et al., 2018) that lower its affinity for contaminants.

An increase in medicinal plant biomass (Liu et al., 2016) resulted from application of biochar made from pinewood. Furthermore, a study by Alvarez-Campos et al. (2018) showed biomass increase of sugarcane plant after application of rice hull-based biochar, whereas *Zea mays* biomass increased due to coconut husk biochar (Gonzaga et al., 2018). However, Anyanwu et al. (2018) articulated that plant roots and shoot biomass respond differently to rice husk biochar application rate, biochar age and contact time. The study showed that *O. sativa* shoot biomass increased in growth for all ages of biochar, whereas its roots did not increase for varied dosage and age or exposure time. In the same study, *S. lycopersicum* species showed a decreasing shoot response to ageing biochar. This was opposed to observations by Makoto et al. (2010) and Noguera et al. (2010), who showed that both rice (Noguera et al., 2010) root biomass and root length increased after addition of forest fire biochar on Gmelin larch (Makoto et al., 2010). These instinctively show significance of biochar feedstock, crop type, application rate and biochar age, together with growing climatic conditions and species variation.

Some organisms are less tolerant to long-term application of biochar due to toxicity that results from its method of preparation and ageing process (Mukherjee et al., 2014). Further studies need to be taken regarding the level of organisms' tolerance to long-term application of biochar. Adding to these, it is imperative that sources of potentially toxic elements, their reaction while in the environment with other substances, effects and harm that they may cause on organisms be known (Zhao and Kaluarachchi, 2002), in order to ensure effective remediation. Without a doubt, this implies that biochar preparation method and level of soil degradation are also issues to be looked into prior to soil amendment. The latter is significant since biochar application has been found to be more effective for degraded soil. It is thus concluded that biochar application has both beneficial and detrimental impacts on soil biota (Domene, 2016), and levels at which these can have lethal effects have to be one of research issues.

5.3. Biochar effect on soil fertility, nutrient retention and leaching reduction

Environmentalists and soil scientists have opted for utilization of organic forms of soil fertility due to negative effects of synthetic fertilizers (Adesemoye and Kloepper, 2009). Upon adsorption onto biochar surface, PTEs can be converted from inorganic to organic forms, and in this manner, soil fertility improves (Chen et al., 2020). Furthermore, converted forms can be biodegradable and thus pose no threat to the receiving environment. This conversion facilitates bioavailability for crops (Lahori et al., 2017; Wang et al., 2018). Other mechanisms employed during PTE adsorption include complexation and cation exchange. A positive charge on biochar surface has also made it possible for adsorption of PTEs from soil (Weiner et al., 2013; Ahmad et al., 2018) reducing their mobility, a preliminary process that hinders leaching of these PTEs into nearby water bodies. However, biochar application still relies on biochar preparation methods and soil type (Yu et al., 2013; Zhang et al., 2019) for efficiency. Furthermore, owing to raw material from which it is processed, biochar may itself be a source of soil contaminants (Verheijen et al., 2009). Some studies have shown that biochars from animal manure, solid waste like bagasse and woodchips (Thornley et al., 2009; Nanda et al., 2016) and domestic sewage could be safer than those from industrial sewage. This could be due to some PTEs (Wang and Wang, 2019) present in the latter. On the other hand, sewage laden with PTEs like Cu and Zn could be an advantage for increment of soil fertility since these PTEs are micronutrients (Wang et al., 2020).

Mechanisms through which biochar improves soil fertility could be through nutrient absorption (Blanco-Canqui, 2019), which subsequently reduces their leaching into nearby water bodies (Hua et al., 2009; Ding et al., 2010). However, for fertility improvement purposes, soil of high pH (Novak et al., 2014; Scott et al., 2014) could have its fertility reduced, even though some researchers have associated prolonged nitrate residence time in plant roots with its confinement within biochar pores. Furthermore, literature on exact mechanisms employed to prohibit leaching, especially that of nitrates, is scant. For effective adsorption process, the choice of raw material used for biochar production, and other production conditions like pH, pyrolysis temperature (Kavitha, et al., 2018), have to be taken into consideration. Some studies have associated high pyrolysis temperature with increased biochar surface area (Downie et al., 2011; Hossain et al., 2011; Lu et al., 2013; Chen et al., 2014) and porosity, relating these properties with nutrient retention. This might be due to quinones and aromatics which have a higher potential to perform as electron acceptors (Chintala et al., 2016). High pyrolysis temperature was further asserted to support reduced nitrate leaching (Borchard et al., 2019), while other researchers established that leaching is minimal even for biochar produced at pyrolysis temperatures that are not necessarily low (Bu et al., 2019; Sanford et al., 2019). pH determines the adsorbent's surface charge, and extent of functional group dissociation (Salam et al., 2011; Yang and Cui, 2013). The macropores (of > 50 nm) of biochar are a result of raw materials from which it originates, whereas micropores and mesopores < 2 nm and 2 to 50 nm respectively, are a result of thermochemical processes under its production (Zabaniotou et al. 2008). It is therefore of utmost importance that raw material is selected in accordance with specific target pollutants and nutrients to be removed from soil, or even those that need to stay within soil (nutrients) for its fertility.

5.4. Biochar and water retention

Agricultural activities consume 70% of water globally. In order to conserve water, one of the approaches is organic improvement of soil through biochar application so that it retains more water against losses like evaporation. However, several researchers are adamant that biochar water retention potential relies on feedstock from which it is derived and is selective on soil types. Regarding type of feedstock, Kavitha et al. (2018) showed that hydraulic properties of woodchip biochar were better than that derived from dairy manure. In a study by Abel et al. (2013), both biochar and hydrochar had shown a higher potential for retention for sandy soil. The study also showed that with hydrochar application there was a possibility of water repellence. Other studies of similar nature have reported that addition of biochar to sandy soil increased the soil water retention and available water capacity (AWC) (Busscher et al., 2010; Basso et al., 2013; Głąb et al., 2016; Atkinson, 2018), whereas Abel et al. (2013), Bruun et al. (2014) and Baiamonte et al. (2015) reported an increase in water retention only. Baiamonte et al. (2015) further suggested that an increase in water retention is directly proportional to increase in amount of biochar applied for soil amendment. However, with regard to soil type, Atkinson (2018) reported that water retention capability is closely linked to coarse soils. On the contrary, research by Jeffery et al. (2015) suggested that there was no significant increase in water retention after biochar was applied to sandy soil, even though there was a connection between at least 99% of the biochar's internal pore spaces with the surface and hence some chances of improvement in water retention. Furthermore, the same study and another by Kameyama et al. (2019) suggest that biochar produced at high temperatures seems to be hydrophobic. Mao et al. (2019) also reiterated significance of high pyrolysis temperature in soil water retention. Li et al. (2021) concurred with other findings from these studies and reported on the hydrophobic nature of biochar, and that its further treatment could alter it to hydrophilic.

Moreover, the method of biochar application within soil has been questionable. In this regard, deep-banding method was utilized by Blackwell et al. (2009) in order to minimize loss of biochar through wind erosion, without affecting crop yield. This method was proven to be more appropriate than uniform top mixing for soil water retention. This study further recommended intense research to confirm that biochar application enhances water retention. It is with such findings, that it is proposed that the use of different feedstock in biochar production is tested against water retention capability for verification of these observations, alongside processes used to produce biochar.

Climatic condition dynamics should also be explored, since soil water repulsion was more pronounced due to hydrophobic nature of soil particles (Abel et al., 2013) for regions like deserts, or those that are facing water scarcity. It is still not clear whether effectiveness of biochar and hydrochar application relies on available water capacity or pore space within each soil type, variation in climatic conditions, or a combination of all these factors. This is substantiated by Basso et al. (2013) that, it is not only biochar pore space (Van Zwieten et al., 2009) that plays a role in water retention of soils. Further studies could explore linkage amongst these factors.

Clearly soil type has to be taken into consideration in order to ascertain whether biochar has an effect on soil water retention, in order to avoid contradictory results. It is also important for each study to elaborate on experimental design, age of biochar, climatic conditions under which the research was undertaken, duration of the study and all other variables that could have an impact on biochar efficiency.

5.5. Biochar effect on soil bulk density

One of the properties of biochar is low bulk density (BD), which helps decrease that of soil and improve its structure (Pituello et al., 2018). Biochar lowers BD by influencing soil aggregation (Toková et al., 2020), especially for sandy loam and clay soils (Ouyang et al., 2013; Soinne et al., 2014). Other biochar properties that decrease soil bulk density include its active surface area and porosity, in combination with soil properties (Toková et al., 2020). The study by Toková et al. (2020) further suggests that efficiency of biochar in decreasing soil bulk density was observed when applied together with some fertilizer. Furthermore, Verheijen et al. (2019) reported on selective efficiency and decrease in soil bulk density for different soil types. The study revealed that lowest biochar application (about 1%) decreased sandy soil bulk density, whereas sandy loam soil was responsive after at least 5% of biochar application. Li et al. (2019) established that the question of biochar effectiveness in promoting soil lies in its particle size and rate of application. The similar trend was observed by other researchers (Abel et al., 2013; Koide et al., 2015) in terms of biochar concentration, highlighting the need for extensive research on the relationship between biochar particle size and soil type. However, big and small soil aggregates are prone to water erosion, with small particles being easily eroded by wind (Li et al., 2019). Furthermore, frequent application (3%) rate leads to soil erosion (Li et al., 2019) due to low water-stable aggregate content and saturated hydraulic conductivity (K_{sat}). However, some complexity resulted in the same study because even though high biochar application rate led to soil erosion, the effect of different biochar particle size on water-stable aggregates and (K_{sat}) was unclear. The effect of biochar on soil erosion progression has to be holistically researched along with its particle size, frequency of application, and soil type to be amended.

6. Conclusion

The burgeoning interest of soil scientists and environmentalists on soil remediation should consider possible risks associated with biochar preparation methods and long-term application. There is a need to consider practicality and applicability challenges of biochar application at large scale, since previous tests had been done on small-scale and at high application rates. Furthermore, remediation methods have proved to be challenging when species forms of potentially toxic elements to be treated are unknown.

A majority of the reviewed studies have not addressed issues of biochar produced from various feedstock, biochar of different age, respond of roots and shoots together (for same plant), exposure time of plants to biochar, varied soil type, and other properties of biochar like water holding capacity, and hence a discrepancy in their reporting. Risks associated with its long-term application, even in degraded soils should be identified and mitigation measures employed. This does not exempt research from observing variations of experimental and environmental (climatic) conditions when tests like water retention and other variables that are influenced by biochar application are performed, at both small and large-scale. The other gap in biochar application is the extent to which it affects the environment (soil and its biota) for both short-term and long-term application due to type of feedstock used, method of preparation, and soil type to be amended. This study therefore suggests that a variety of experimental design and experimental variables be brought together, together with long-term analysis at different climatic conditions.

Resulting from this review, application of biochar on soil that is intended for crop production may degrade it, resulting in further risk in relation to food security, and leaching of contaminants into water bodies. Biochar changes its physical, chemical and biological properties, when applied and re-applied. As one of the mitigation measures, it is suggested that preliminary soil type tests be performed in order to establish response of various soil types to biochar. Even though biochar utilization was initially chosen due to low costs, it should be noted that there might be extra costs related to processing requirements and availability of reactors, through which there might be compromised production as costs increase.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G., 2013. Impact of biocharand hydrochar addition on water retention and water repellency of sandy soil. Geoderma 183–191. doi:10.1016/J.GEODERMA.2013.03.003, 202-203.

Adesemoye, A., Kloepper, J., 2009. Plant–microbes interactions in enhanced fertilizer-use efficiency. Appl. Microbiol. Biotechnol. 85, 1–12. doi:10.1007/s00253-009-2196-0.

Adhikari, T., Manna, M., Singh, M., Wanjari, R., 2004. Bioremediation measure to minimize heavy metals accumulation in soils and crops irrigated with city effluent. Food Agric. Environ. 2, 266–270.

Ahmad, M., Rajapaksha, A., Lim, J., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y., 2014. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99, 19–33.

Ahmad, Z., Gao, B., Mosa, A., Yu, H., Yin, X., Bashir, A., Ghoveisi, H., Wang, S., 2018. Removal of Cu (II), Cd (II) and Pb(II) ions from aqueous solutions by biochars derived from potassium-rich biomass. J. Clean. Prod. 180, 437–449.

Alam, M., Snow, E., Tanaka, A., 2003. Arsenic and heavy metal contamination of vegetables grown in Santa village, Bangladesh. Sci. Total Environ. 308, 83–96.

Alkharabsheh, H., Seleiman, M., Battaglia, M., Shami, A., Jalal, R., Alhammad, B., Almutairi, K.F., Al-Saif, A., 2021. Biochar and its broad impacts in soil quality and fertility. Nutr. Leach. Crop Prod. 11, 1–29. doi:10.3390/agronomy11050993.

Alvarez-Campos, O., Lang, T., Bhadha, J., McCray, J., Glaz, B., Daroub, S., 2018. Biochar and mill ash improve yields of sugarcane on a sand soil in Florida. Agric. Ecosyst. Environ. 253, 122–130. doi:10.1016/j.agee.2017.11.006.

Anake, W., Adie, G., Osibanjo, O., 2009. Heavy metal pollution at municipal solid waste dumpsites in Kano and Kaduna states in Nigeria. Bull. Chem. Soc. Ethiop. 23 (1), 281–289.

Anyanwu, I., Alo, M., Onyekwere, A., Crosse, J., Nworie, O., Chamba, E., 2018. Influence of biochar aged in acidic soil on ecosystem engineers and two tropical agricultural plants. Ecotoxicol. Environ. Saf. 153, 116–126. doi:10.1016/j.ecoenv.2018.02.005.

Atkinson, C., 2018. How good is the evidence that soil-applied biochar improves water-holding capacity? Soil Use Manag 34 (2), 177–186 doi:10.111/SUM.12413.

Ayangbenro, A., Babalola, O., 2017. A new strategy for heavy metal polluted environments: a review of microbial biosorbents. Int. J. Environ. Res. Public Health 14 (94), 1–16. doi:10.3390/ijerph14010094.

Baiamonte, G., De Pasquale, C., Marsala, V., Cimo, G., Alonzo, G., Crescimanno, G., Conte, P., 2015. Structure alteration of a sandy-clay soil by biochar amendments. J. Soils and Sediments 15, 816–824. doi:10.1007/s11368-014-0960-y.

Basso, A., Miguez, F., Laird, D., Horton, R., Westgate, M., 2013. Assessing potential of biochar for increasing water-holding capacity of sandy soils. GCB Bioenergy 5 (2), 132–143. doi:10.1111/gcbb.12026.

Becerra-Castro, C., Prieto Prieto-Fernández, A., Álvarez-Lopez, V., Monterroso, C., Cabello-Conejo, M., Acea, M.J., Kidd, P., 2011. Nickel solubilizing capacity and characterization of rhizobacteria isolated from hyperaccumulating and non-hyperaccumulating subspecies of alyssum serpyllifolium. Int. J. Phytorem. 13, 229–244. doi:10.1080/15226514.2011.568545.

Blackwell, P., Krull, E., Butler, G., Herber, A., Solaiman, Z., 2009. Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. Aust. J. Soil Res. 48, 531–545.

Blanco-Canqui, H., 2019. Biochar and water quality. J. Environ. Qual. 48 (1), 2–15. doi:10.2134/jeq2018.06.0248.

Borchard, N., Schirrmann, M., Cayuela, M., Kammann, C., Wrage-Mönnig, N., Estavillo, J., Novak, J., 2019. Biochar, soil and land-use interactions that reduce nitrate leaching and N2O emissions: a meta-analysis. Sci. Total Environ. 2354–2364.

Brtnicky, M., Datta, R., Holatko, J., Bielska, L., Gusiatin, Z., Kucerik, J., Hammerschmiedt, T., Danish, S., Radziemska, M., Mravcova, L., Fahad, S., Kintl, A., Sudoma, M., Ahmed, N., Pecina, V., 2021. A critical review of the possible adverse effects of biochar in the soil environment. Sci. Total Environ. 796, 1–18. doi:10.1016/j.scitotenv.2021.148756.

Bu, X., Su, J., Xue, J., Wu, Y., Zhao, C., Wang, L., 2019. Effect of rice husk biochar addition on nutrient leaching and microbial properties of Calcaric Cambisols. J. Soil Water Conserv. 74, 172–179.

Busscher, W., Novak, J., Evans, D., Watts, D., Niandou, M., Ahmedna, M., 2010. Influence of pecan biochar on physical properties of a Norfolk loamy sand. Soil Sci. 175 (1), 10–14.

Chen, S., Chen, T., Xu, W., Huang, J., Jiang, S., Yan, B., 2020. Application research of biochar for the remediation of soil heavy metals contamination: a review. Molecules 25 (3167), 1–21. doi:10.3390/molecules25143167.

Chen, T., Zhang, Y., Wang, H., Lu, W., Zhou, Z., Zhang, Y., Ren, L., 2014. Influence of pyrolysis temperature on characteristics and heavy metal adsorptive performance of biochar derived from municipal sewage sludge. Bioresour. Technol. 164, 47–54.

Chintala, R., Subramanian, S., Fortuna, A., & Schumacher, T., 2016. Examining biochar impacts on soil abiotic and biotic processes and exploring the potential for pyrosequencing analysis. In T. Ralebitso-Senior, & C. Orr, Biochar Application (pp. 133-162). Elsevier. Retrieved from doi:10.1016/B978-0-12-803433-0.00006-0.

Chu, D., 2018. Effects of heavy metals on soil microbial community. IOP Conference Series: Earth and Environmental Science (pp. 1-6). IOP Publishing. doi:10.1088/1755-1315/113/1/012009.

Crini, G., Torri, G., Lichtfouse, E., Kyzas, G., Wilson, L., Morin-Crini, N., 2019. Dye removal by biosorption using cross-linked chitosan-based hydrogels. Environ. Chem. Lett. 17, 1645–1666. doi:10.1007/s10311-019-00903-y.

D'Amore, J., Al-Abed, S., Scheckel, K., Ryan, J., 2005. Methods for speciation of metals in soils: a review. J. Environ. Qual. 35 (5), 1707–1745. doi:10.2134/jeq2004.0014.

Dai, L., Fan, L., Liu, Y., Ruan, R., Wang, Y., Zhou, Y., Yu, Z., 2017. Production of bio-oil and biochar from soapstock via microwave-assisted co-catalytic fast pyrolysis. Bioresour. Technol. 225, 1–8.

Dai, Z., Xlong, X., Zhu, H., Xu, H., Leng, P., Tang, C., Xu, J., 2021. Association of biochar properties with changes in soil bacterial, fungal and fauna communities and nutrient cycling processes. Biochar 3, 239–254. doi:10.1007/s42773-021-00099-x.

Dieguez-Alonso, A., Funke, A., Anca-Couce, A., Rombolà, A., Ojeda, G., Bachmann, J., Behrendt, F., 2018. Towards biochar and hydrochar engineering—influence of process conditions on surface physical and chemical properties, thermal stability, nutrient availability, toxicity and wettablility. Energies 11 (496), 1–26. doi:10.3390/en11030496.

Ding, Y., Liu, Y., Wu, W., Shi, D., Yang, M., Zhong, Z., 2010. Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water, Air, Soil Pollut. 213 (1), 47–55. doi:10.1007/s11270-010-0366-4.

Domene, X., 2016. A critical analysis of meso- and macrofauna effects following biochar supplementation. In T. Ralebitso-Senior, & C. Orr, Biochar Application: Essential Soil Microbial Ecology (pp. 268-292). Barcelona, Spain: Elsevier. doi:10.1016/B978-0-12-803433-0.00011-4.

Downie, A., Van Zwieten, L., Smernik, R., Morris, S., Munroe, P., 2011. Terra preta australis: reassessing the carbon storage capacity of temperate soils. Agric., Ecosyst. Environ. 140, 137–147.

Ezawa, T., Yamamoto, K., Yoshida, S., 2002. Enhancement of the effectiveness of indigenous arbuscular mycorrhizal fungi by inorganic soil amendments. Soil Sci. Plant Nutr. 48, 897–900.

Gai, X., Wang, H., Liu, J., Zhai, L., Liu, S., Ren, T., Liu, H., 2014. Effects of feedstock and pyrolysis temperature on biochar adsorption of ammonium and nitrate. PLoS ONE 9, 1–19. doi:10.1371/journal.pone.0113888.

Giller, K., Witter, E., Mcgrath, S., 1998b. Toxicity of heavy metals to microorganisms and microbial processes in agricultural soils: a review. Soil Biol. Biochem. 30, 1389–1414. doi:10.1016/j.envint.2008.06.009.

Girma, G., 2015. Microbial bioremediation of some heavy metals in soils: an updated review. J. Res. Dev. Manag. 10, 62–73.

Głąb, T., Palmowska, J., Zaleski, T., Gondek, K., 2016. Effect of biochar application on soil hydrological properties and physical quality of sandy soil. Geoderma 281, 11–20.

Godlewska, P., Ok, Y., Oleszczuk, P., 2021. The Dark Side of Black Gold: ecotoxicological Aspects of Biochar and Biochar-Amended Soils. J. Hazard. Mater. 403, 1–21. doi:10.1016/j.jhazmat.2020.123833.

Gonzaga, M., Mackowiak, C., de Almeida, A., de Carvalho Junior, J., Andrare, K., 2018. Positive and negative effects of biochar from coconut husks, orange bagasse and pine wood chips on maize (Zea mays L.) growth and nutrition. Catena 162, 414–420 http://dx.doi.org/10.1016/j.catena.2017.10.018.

Grossman, J., O'Neill, B., Tsai, S., Liang, B., Neves, E., Lehmann, J., Thies, J., 2010. Amazonian anthrosols support similar microbial communities that differ distinctly from those extant in adjacent, unmodified soils of the same mineralogy. Microb. Ecol. 60, 192–205. doi:10.1007/s00248-010-9689-3.

Gul, S., Whalen, J., Thomas, B., Sachdeva, V., Deng, H., 2014. Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. Agric., Ecosys. Environ. 206, 46–59. doi:10.1016/j.agee.2015.03.015.

Gülser, F., Erdoğan, E., 2008. The effects of heavy metal pollution on enzyme activities and basal soil respiration of roadside soils. Environ. Monit. Assess. 145 (1–3), 127–133.

He, Y., Li, B., Zhang, K., Li, Z., Chen, Y., Ye, W., 2019. Experimental and numerical study on heavy metal contaminant migration and retention behavior of engineered barrier in tailings pond. Environ. Pollut. 252, 101–1018.

Hossain, M., Vladimir, V., Chan, K., Ziolkowski, A., Nelson, P., 2011. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. J. Environ. Manag. 92 (1), 223–228.

Hua, L., Wu, W., Liu, Y., McBride, M., Chen, Y., 2009. Reduction of nitrogen loss and Cu and Zn mobility during sludge composting with bamboo charcoal amendment. Environ. Sci. Pollut. Res. 16, 1–9. doi:10.1007/s11356-008-0041-0.

IBI, 2013. Standardized product definition and product testing guidelines for biochar that is used in Soil. Retrieved from International Biochar Initiative: http://www.biochar-international.org/sites/default/files/IBI_Biochar_Standards_V1.1.pdf.

Isirimah, N., Igwe, C., & Iwegbue, C., 2003. Important ions in soil environment. In Introductory Soil Chemistry and Biology for Agriculture and Biotechnology (pp. 34-97). Port Hartcourt: Osia International Publishers Ltd.

Jackson, C.R., Thompson, J.A., Kolka, R.K., 2014. Wetland Soils, Hydrology, and Geomorphology. In: Batzer, D., Sharitz, R. (Eds.), Ecology of Freshwater and Estuarine Wetlands Eds.. University of California Press, Berkeley, CA pp. 23-60https://www.fs.fed.us/nrs/pubs/jrnl/2014/nrs_2014_jackson_001.pdf.

Jeffery, S., Meinders, M.B., Stoof, C., Bezemer, T., van de Voorde, T., Mommer, L., van Groenigen, J., 2015. Biochar application does not improve the soil hydrological function of a sandy soil. Geoderma 251-252; 47–54. doi:10.1016/j.geoderma.2015.03.022.

Kaasalainen, M., Yli-Halla, M., 2003. Use of sequential extraction to assess metal partitioning in soils. Environ. Pollut. 126 (2), 225–233.

Kambo, H., Dutta, A., 2015. A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renewable Sustainable Energy Rev. 45, 359–378.

Kameyama, K., Miyamoto, T., Iwata, Y., 2019. The preliminary study of water-retention related properties of biochar produced from various feedstock at different pyrolysis temperatures. Materials (Basel) 12, 1732. doi:10.3390/ma12111732.

Kavitha, B., Reddy, P., Kim, B., Lee, S., Pandey, S., Kim, K.-.H., 2018. Benefits and limitations of biochar amendment in agricultural soils: a review. J. Environ. Manag. 227, 146–154. doi:10.1016/j.jenvman.2018.08.082.

Koide, R., Nguyen, B., Skinner, R., Dell, C., Peoples, M., Adler, P., Drohan, P., 2015. Biochar amendment of soil improves resilience to climate change. GCB Bioenergy 7 (5), 1084–1091. doi:10.1111/gcbb.12191.

Kuzyakov, Y., Subbotina, I., Chen, H., Bogomolova, I., Xu, X., 2009. Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biol. Biochem. 41, 210–219.

Lahori, A., Guo, Z., Zhang, Z., Li, R., Mahar, A., Awasthi, M., Shen, F., Sial, T.A., Kumhar, F., Wang, P., 2017. Use of biochar as an amendment for remediation of heavy metal-contaminated soils: prospects and challenges. Pedosphere 27, 991–1014.

Lee, S., 2021. Meso and Macrofauna Responses to Biochar in Urban Soils. University of Michigan.

Lehmann, J., Joseph, S., 2012. Biochar for Environmental Management: Science and Technology. Wiley, New York, USA.

Lehmann, J., Rillig, M., Thies, J., Masiello, C., Hockaday, W., Crowley, D., 2011. Biochar effects on soil biota – a review. Soil Biol. Biochem. 43, 1812–1836.

Li, L., Zhang, Y.-.J., Novak, A., Yang, Y., Wang, J., 2021. Role of biochar in improving sandy soil water retention and resilience to drought. Water 13 (407), 1–11. doi:10.3390/w13040407.

Li, Y., Zhang, F., Yang, M., Zhang, J., Xie, Y., 2019. Impacts of biochar application rates and particle sizes on runoff and soil loss in small cultivated loess plots under simulated rainfall. Sci. Total Environ. 649, 1403–1413. doi:10.1016/j.scitotenv.2018.08.415.

Liang, B., Lehmann, J., Solomon, D., Sohi, S., Thies, J., Skjemstad, J., Luizao, F.J., Engelhard, M.H., Neves, E.G., Wirick, S., 2008. Stability of biomass-derived black carbon in soils. Geochim. Cosmochim. Acta 72, 6069–6078. doi:10.1016/j.gca.2008.09.028.

Liu, A., Tian, D., Xiang, Y., Mo, H., 2016. Biochar improved growth of an important medicinal plant (Salvia miltiorrhiza bunge) and inhibited its cadmium uptake. J. Plant Biol. Soil Health 3 (2), 6.

Liu, M., Li, X., He, Y., Li, H., 2020. Aquatic toxicity of heavy metal-containing wastewater effluent treated using vertical flow constructed wetlands. Sci. Total Environ. 727, 138616.

Lu, H., Zhang, W., Wang, S., Zhuang, L., Yang, Y., Qiu, R., 2013. Characterization of sewage sludge-derived biochars from different feedstocks and pyrolysis temperatures. J. Anal. Appl. Pyrolysis 102, 137–143.

Magdziarz, A., Wilk, M., Wa̧drzyk, M., 2020. Pyrolysis of hydrochar derived from biomass–Experimental investigation. Fuel 267, 117246. doi:10.1016/j.fuel.2020.117246.

Makoto, K., Tamai, Y., Kim, Y., Koike, T., 2010. Buried charcoal layer and ectomycorrhizae cooperatively promote the growth of Larix gmelinii seedlings. Plant Soil 357, 143–152.

Mao, J., Zhang, K., Chen, B., 2019. Linking hydrophobicity of biochar to the water repellency and water holding capacity of biochar amended soil. Environ. Pollut. 253, 779–789.

Maslin, P., Maier, R., 2000. Rhamnolipid-enhanced mineralization of phenanthrene in organic-metal co-contaminated soils. Biorem. J. 4 (4), 295–308.

McBride, M., 1995. Environmental Chemistry of Soils. Oxford University Press, New York.

Meyer, S., Glaser, B., Quicker, P., 2011. Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environ. Sci. Technol. 9473–9483. doi:10.1021/es201792c.

Miah, M., Jahiruddin, M., Islam, M., Razia, S., 2005. Fertilizer Recommendation Guide. Bangladesh Agrcultural Research Council, Dhaka.

Mora, A., Calvo, J.J.O., Cabrera, F., Madejoin, E., 2005. Changes in enzyme activities and microbial biomass after "in situ" remediation of a heavy metal-contaminated soil. Appl. Soil Ecol. 28, 125–137.

Mukherjee, A., Zimmerman, A., Hamdan, R., Cooper, W., 2014. Physicochemical changes in pyrogenic organic matter biochar after 15 months of field aging. Solid Earth 5, 693–704.

Nagajyoti, P., Lee, K., Sreekanth, T., 2010. Heavy metal occurrence and toxicity for plants: a review. Environ. Chem. Lett. 8, 199–216.

Nanda, S., Dalai, A., Gökalp, I., Kozinski, J., 2016. Valorization of horse manure through catalytic supercritical water gasification. Waste Manage 52, 147–158. doi:10.1016/j.wasman.2016.03.049.

Noguera, D., Rondon, M., Laossi, K.-.R., Hoyos, V., Lavelle, P., de Carvalho, M., Barot, S., 2010. Contrasted effect of biochar and earthworms on rice growth and resource allocation in different soils. Soil Biol. Biochem. 42, 1017–1027.

Novak, J., Cantrell, K., Watts, D., Busscher, W., Johnson, M., 2014. Designing relevant biochars as soil amendments using lignocellulosic-based and manure-based feedstocks. J. Soil Sediments 14, 330–343.

Ouyang, L., Wang, F., Tang, J., Yu, L., Zhang, R., 2013. Effects of biochar amendment on soil aggregates and hydraulic properties. J. Soil Sci. Plant Nutr. 13 (4), 991–1002. doi:10.4067/S0718-95162013005000078.

Page, M., McKenzie, J., Bossuyt, P., Boutron, I., Hoffmann, T., Mulrow, C., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Syst. Rev. 10 (89), 372. doi:10.1136/bmj.n71.

Pituello, C., Dal Ferro, N., Francioso, O., Simonetti, G., Berti, G., Piccoli, I., Pisi, A., Morari, E., 2018. Effects biochar on the dynamics of aggregate stability in clay and sandy loam soils. Eur. J. Soil Sci. 69, 827–842.

Salam, O., Reiad, N., ElShafei, M., 2011. A study of the removal characteristics of heavy metals from wastewater by low-cost adsorbents. J. Adv. Res. 2 (4), 297–303. doi:10.1016/j.jare.2011.01.008.

Sanford, J., Larson, R., Runge, T., 2019. Nitrate sorption to biochar following chemical oxidation. Sci. Total Environ. 669, 938–947.

Scott, H., Ponsonby, D., Atkinson, C., 2014. Biochar: an improver of nutrient and soil water availability – what is the evidence? CAB Rev. 9 (19), 1–20. doi:10.1079/PAVSNNR20149019.

Shaaban, M., Zwieten, L., Bashir, S., Younas, A., Núñez-Delgado, A., Chhajro, M., Kubar, K., Ali, U., Rana, M., Mehmood, M., Hu, R., 2018. A concise review of biochar application to agricultural soils to improve soil conditions and fight pollution. J. Environ. Manag. 228, 429–440. doi:10.1016/j.jenvman.2018.09.006.

Singh, S., Parihar, P., Singh, V., Prasad, S., 2016. Heavy metal tolerance in plants: role of transcriptomics, proteomics, metabolomics, and ionomics. Front. Plant Sci. 6, 1–36. doi:10.3389/fpls.2015.01143, 1143.

Skjemstad, J., Reicosky, D., Wilts, A., McGowan, J., 2002. Charcoal carbon in U.S. agricultural soils. Soil Sci. Soc. Am. J. 66, 1249–1255.

Sohi, S., 2012. Carbon storage with benefits. Science 338 (6110), 1034–1035. doi:10.1126/science.1225987.

Soinne, H., Hovi, J., Tammeorg, P., Turtola, E., 2014. Effect of biochar on phosphorus sorption and clay soil aggregate stability. Geoderma 162–167. doi:10.1016/j.geoderma.2013.12.022, 219-220.

Suman, J., Uhlik, O., Viktorova, J., Macek, T., 2018. Phytoextraction of heavy metals: a promising tool for clean-up of polluted environment? Front. Plant Sci. 9. doi:10.3389/fpls.2018.01476, 1476.

Tan, X.-F., Liu, Y.-g., Gu, Y.-L., Xu, Y., Zeng, G.-m., Hu, X.-j., Liu, S.-b., Wang, X., Liu, S.-m., Li, J., 2016. Biochar-based nano-composites for the decontamination of wastewater: a review. Bioresour. Technol. 212, 318–333.

Thangavel, P., Subbhuraam, C., 2004. Phytoextraction: role of hyperaccumulators in metal contaminated soils. Proc. Indian Natl Sci. Acad. 70 (1), 109–130.

Thornley, P., Upham, P., Tomei, J., 2009. Sustainability constraints on UK bioenergy development. Energy Policy 37, 5623–5635. doi:10.1016/j.enpol.2009.08.028.

Toková, L., Igaz, D., Horák, J., Aydin, E., 2020. Effect of biochar application and re-application on soil bulk density, porosity, saturated hydraulic conductivity, water content and soil water availability in a silty Loam Haplic Luvisol. Agronomy 10 (1005), 1–17. doi:10.3390/agronomy10071005.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K., Downie, A., Rust, J., Joseph, S., Cowie, A., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant Soil 327, 235–246. doi:10.1007/s11104-009-0050-x.

Van Zwieten, L., Singh, B., Joseph, S., Kimber, S., Cowie, A., & Chan, K., 2009. Biochar and emissions of non-CO2 greenhouse gases from soil. In J. Lehmann, & S. Joseph, Biochar for Environmental Management (pp. 227-243). London: EarthScan.

Verheijen, F., Jeffrey, S.A.C.B., van der Velde, M., Diafas, I., 2009. Biochar Application to soils. A critical Scientific Review of Effects On Soil properties, Processes and Functions. Office for the Official Publications of the European Communities, Luxemburg.

Wang, J., Wang, S., 2019. Preparation, modification and environmental application of biochar: a review. J. Clean. Prod. 227, 1002–1022. doi:10.1016/j.jclepro.2019.04.282.

Wang, M., Zhu, Y., Cheng, L., Anderson, B., Zhao, X., Wang, D., Ding, A., 2018. Review on utilization of biochar for metal-contaminated soil and sediment remediation. J. Environ. Sci. 63, 156–173.

Wang, X., Guo, Z., Hu, Z., Zhang, J., 2020. Recent advances in biochar application for water and wastewater treatment: a review. PeerJ 1–34. doi:10.7717/peerj.9164.

Weiner, b., Baskyr, I., Poerschmann, J., Kopinke, F., 2013. Potential of the hydrothermal carbonization process for the degradation of organic pollutants. Chemosphere 92, 674–680.

Weyers, S., Spokas, K., 2011. Impact of biochar on earthworm populations: a review. Appl. Environ. Soil Sci. 1–12. doi:10.1155/2011/541592.

Wu, H., Liu, Q., Ma, J., Liu, L., Qu, Y., Gong, Y., Yang, S.H., Luo, T., 2020. Heavy metal(loids) in typical Chinese tobacco-growing soils: concentrations, influence factors and potential health risks. Chemosphere 245, 125591. doi:10.1016/j.chemosphere.2019.125591.

Xie, Y., Fan, J., Zhu, W., Amombo, E., Lou, Y., Chen, L., Fu, J., 2016. Effect of Heavy Metals Pollution on Soil Microbial Diversity and Bermudagrass Genetic Variation. Front. Plant Sci. 1–12. doi:10.3389/fpls.2016.00755.

Yang, X., Cui, X., 2013. Adsorption characteristics of Pb(II) on alkali treated tea residue. Water Resour. Ind. 3, 1–10. doi:10.1016/j.wri.2013.05.003.

Yao, H., Xu, J., Huang, C., 2003. Substrate utilization pattern, biomass and activity of microbial communities in a sequence of heavy metal-polluted paddy soils. Geoderma 115, 138–148. doi:10.1016/S0016-7061(03)00083-1.

Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., 2019. Biochar amendment improves crop production in problem soils: a review. J. Environ. Manag. 8–21. doi:10.1016/j.jenvman.2018.10.117.

Yu, L., Tang, J., Zhang, R., Wu, Q., Gong, M., 2013. Effects of biochar on soil methane emission at different soil moisture levels. Biol. Fertil. Soils 49, 119–128. doi:10.1007/s00374-012-0703-4.

Yuan, J., Xu, R., Zhang, H., 2011. The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresour.Technol 102, 3488–4397.

Zabaniotou, A., Stavropoulos, G., Skoulou, V., 2008. Activated carbon from olive kernels in a two-stage process: industrial improvement. Bioresour.Technol 99, 320–326.

Zhang, M., Riaz, M., Zhang, L., Xia, H., El-Desouki, Z., Jiang, C., 2019. Response of fungal communities in different soils to biochar and chemical fertilizers under simulated rainfall conditions. Sci. Total Environ. 691, 654–663.

Zhao, J., Kaluarachchi, J., 2002. Risk assessment at hazardous waste-contaminated sites with variability of population characteristics. Environ. Int. 28 (1–2), 41–53.

Zheng, H., Bingjie, L., Liu, G., Cai, Z., & Zhang, C., 2019. Potential toxic compounds in biochar: knowledge gaps between biochar research and biochar from biomass and waste. In Y. Ok, D. Tsang, N. Bolan, & J. Novak, Biochar from Biomass and Waste (pp. 349-384). Elsevier. doi:10.1016/B978-0-12-811729-3.00019-4.

Zietz, B., Dieter, H., Lakomek, M., Schnieder, H., Gaedtke, K., Dunkelberg, H., 2003. Epidemiological investigation on chronic copper toxicity to children exposed via the public drinking water supply. Sci. Total Environ. 302, 127–144.