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Biochar From Different Sources To Control Heavy Metal Toxicity To Soil Microorganisms And Plant

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Abstract

Heavy metal stress has the unfavorable effect of disrupting soil fertility and plant growth. Heavy metals have extremely harmful biological consequences. In drought stress, biochar, a carbon-rich material, reduces stress by enhancing plant growth, biomass, nutrient uptake, and improving gaseous exchange. Biochar keeps moisture and nutrients in the soil, inhibits dangerous bacteria, absorbs heavy metals and pesticides, avoids soil erosion, raises soil pH, enhances cationic exchange, and increases soil fertility. The formation of reactive oxygen species is frequently induced by heavy metal stress. However, biochar alters the scavenging enzymes that scavenge reactive oxygen species (ROS) and provides an efficient electron transfer route to combat the damaging effects of ROS in plants. Biochar is seen to be a useful tool for managing agricultural production and environmental challenges. The possible significance of biochar in alleviating heavy metal stress is discussed in this review.

Introduction

Heavy metals contamination is a severe problem in the soil and causes effect on crop development. These metals can be transferred and concentrated into plants tissues from the soil. Their effects can cause serious problems on plants themselves and may become a health problem for human and animals. China has a population of over 1.355 billion and is one of the few countries in the world where use of untreated waste water and sewage sludge to agriculture production has become a common and wide spread practice. Generally, release of domestic and industrial effluents to nearby agriculture fields without any treatment is a common practice for crop production in China.

Biochar is a product of thermal decomposition of biomass in the absence of oxygen produced by the process called pyrolysis. Biochar has been found to be biochemically recalcitrant as compared to un-charred organic matter and possesses considerable potential to enhance long-term soil carbon pool (Lehmann et al., 2006). Biochar has been shown to improve water holding capacity, soil structure and water retention, enhance nutrient availability and retention, ameliorate acidity, and reduce aluminum toxicity to plant roots and soil micro biota (Glaser et al., 2002). Bioavailability of heavy metals in soil can be reduced by various immobilization and stabilization techniques using an organic or biological product such as biochar and biosolids (Mohan et al., 2010). Biochar application remediates the heavy metal contaminated soil by preventing heavy metal leaching into water channel and by reducing its availability to plants (Xinde and Harris, 2010). Biochar has shown a great affinity for heavy metals and their sorption capacity is comparable with other biosorbents. Sorption capacity of soil can be improved by the biochar application, due to its impact on the transportation, toxicity and fate behavior of metals in the soil (Glaser et al., 2002; Lehmann et al., 2002). Heavy metals are not biodegradable, and persist for a long time in contaminated soils. It is expensive and time consuming to remove heavy metals from contaminated soils (Cui and Zhang, 2004). Stabilization of heavy metals in situ by adding soil amendments such as lime and compost is commonly employed to reduce the bioavailability of metals and minimize plant uptake (Bolan et al., 2004). Biochar can be a good option for immobilizing heavy metals in the contaminated soils, and to improve the quality of the contaminated soils by significantly reducing the uptake of heavy metals by plants.

A lot of research has been conducted in advanced countries in order to determine the effects of biochar on heavy metals availability and sorption in soil, however work is very limited in Chinese soils. In China we have lot of crop and animal waste material which is applied as such on soil and cause pollution problem. It will worth to convert it into biochar which will reduce carbon dioxide emission in the air from these wastes. As heavy metals contaminated soil area is increasing in China due to untreated disposal of industrial and municipal waste. The heavy metals are entering in the food chain and causing human health problem. So keeping in view of the above mentioned points a study is designed to evaluate the effect of biochar on heavy metals immobilization in the soil to reduce their uptake by plants. In this research project we will investigate the effect of biochar made from different available materials on heavy metals immobilization in the soil to reduce their uptake by plants and also the effect of different biochar to reduce heavy metal toxicity to soil micro-organisms and their activities. The specific objectives of this study are: (1) To quantify the effect of different biochar at different levels to reduce heavy metals toxicity to soil microorganisms and their activity. (2) To evaluate the effect of biochar made from different feedstock to reduce heavy metals uptake by plants. (3)To elucidate the effect of different biochar on crop growth and yield in heavy metals contaminated soil.

Use of biochar for detoxifying metal toxicity

Soil contamination due to toxic metals has been considered one of the major environmental issue due to its adverse effects on animals, human and soil health. The pollution includes sources such as industrial and domestic effluents poses serious threat for crop production particularly in developing countries where untreated effluents are used to irrigate agricultural lands. According to an estimate, more than 35500 ha land of China is irrigated with raw sewage effluents. These sources of contamination results in accumulation of organic and inorganic pollutants in soil due to continuous application of such effluents (Xin et al., 2000). Heavy metals in soil and water are of major concern due to their persistence in the environment. Their complete destruction is not possible biologically, however they can be transformed from one oxidation state to another in order to decrease their adverse effects (Garbisu and Alkorta, 2001; Gisbert et al., 2003). Bioavailability of metals and their toxicity to crop plants depend on their chemical forms in soil. Metals can exist in following fractions in soil: i) water soluble and exchangeable, ii) Fe-Mn oxide-bound, iii) carbonate-bound, iv) organic-matter bound and v) residual forms (Abollino et al., 2006). Among these fractions bioavailable forms are water-soluble and exchangeable, Fe-Mn oxide bound, carbonate- and organic matter-bound are considered to be potentially bioavailable, while the residual fraction is not considered to be available for plants or microorganisms (Yang et al., 2013). Metal fractions and their bioavailability in soil are strongly influenced by soil physic-chemical factors such as pH, texture, cation exchange capacity, redox potential and organic matter (Spark, 2005). Heavy metals have hazardous effects not only on plants but also on human beings such as hematological, neurological, reproductive, developmental, hypertension and cancer.

Biochar has been found to sorb heavy metals and reduce their uptake by plants like cadmium, lead and chromium. Biochar amendment can also influence soil pH, natural organic matter and metal speciation in subsequent so, its use for inorganic contaminants have contradicting effects on mobility, bioavailability and toxicity of different elements (Beesley et al., 2010). Solubilization of heavy metals of raw sewage sludge is reduced by applying biochar prepared from the sewage sludge as compare to the application of sewage sludge as such in the soil which can cost more for its transportation (Mendez and Gasco, 2005). Biochar application can remediates the toxic metal contaminated soil by preventing heavy metal leaching into water channel and by reducing its availability to plants (Xinde and Harris, 2010).

The successful completion of this study would be helpful for reducing the problem of heavy metal toxicity in soil to plants. Many harmful impacts of heavy metals on human health could also be minimized. The use of contaminated soils for crop production will enhance the socio-economic condition of the people of the region in one hand and also play role in strengthening the economy of the country on the other hand. The use of biochar for detoxifying metal toxicity could promote some local industry like the preparation of biochar on commercial basis. The use of contaminated soils by this technology may prove helpful for enhancing crop yield and productivity, therefore can improve socio-economic conditions of the country through reduction of imports of food items.

Mechanisms of biochar-microbe interaction in soil

Biochar modifies the soil bacteria to fungal ratio and soil enzyme activity, as well as reshaping the microbial community structure (Ahmad et al., 2016). Even if the overall microbial activity and biomass remain unchanged, biochar application can drastically alter the microbial community structure. Gene copy counts are a more sensitive metric than microbial biomass for interpreting microbial responses to biochar application in soils (Chen et al., 2013). Ergosterol extraction, quantitative real-time polymerase chain reaction (q-PCR), fluorescence in situ hybridization (FISH), phospholipid fatty acid quantitation (PLFA), molecular fingerprinting of 16S rRNA gene fragments using denaturing gradient gel electrophoresis (DGGE) and terminal restriction fragment length polymorphism (TRFLP), and high-throughput sequencing (also known as next-generation sequencing) are among the techniques used to test microbial activity (Mackie et al., 2015, Rousk et al., 2009). Under treatment with biochar, changes in the relative abundances of Acidobacteria, Actinobacteria, Gemmatimonadetes, and Verrucomicrobia are regularly found using high-throughput sequencing (Nielsen et al., 2014). Metagenomics sequencing of microbial genes can achieve function annotation indicated by changes in soil microbial community structure with better precision to the species level (Jäckel et al., 2004). This is necessary to understand the impacts of biochar on soil remediation (Chen et al., 2013). Because the mechanisms behind biochar's impacts on microorganisms and related soil functions and processes are still unknown, this review concentrates on a synthesis of many potential pathways based on published studies.

Biochar has a wide range of effects on microbial activity, with seven different pathways being established in the central circle. (1) biochar provides shelter for soil microbes with pore structures and surfaces (Quilliam et al., 2013a); (2) biochar supplies nutrients to soil microbes for their growth with those nutrients and ions adsorbed on biochar particles (Joseph et al., 2013); (3) biochar triggers potential toxicity with VOCs and environmentally persistent free radicals (Fang et al., 2014a); (4) biochar modifies microbial habitats by improving soil properties that are essential for microbial growth (including aeration conditions, water content, and pH) (Quilliam et al., 2013a); (5) Biochar disrupts microbial intra- and inter-specific communication between microbial cells by a combination of sorption and the hydrolysis of signalling molecules (Yang et al., 2016b); (6) biochar disrupts microbial intra- and inter-specific communication between microbial cells (Gao et al., 2016, Masiello et al., 2013); Biochar may contain compounds that act as microbial communication signals; and (7) biochar improves the sorption and breakdown of soil pollutants while lowering their bioavailability and toxicity to bacteria (Stefaniuk and Oleszczuk, 2016). The postulated mechanisms involving biochar-microbe interactions need to be tested further, and research should focus on the relationship between biochar-microbe interaction mechanisms and their environmental impacts.

Biochar provides habitat for microbes

One theory regarding biochar's microorganism benefits is that due to their pore structures, biochars can act as microbe shelters. Biochars have a higher per-unit-volume livable pore volume than soil (Quilliam et al., 2013a). Microbial living cells can cling to charcoal surfaces, and biochars with large specific surface areas can serve as microbe habitats (Abit et al., 2012). However, there is spatial variation in the colonisation of bacterial cells and fungal hyphae between the surface and internal pores of biochar (Quilliam et al., 2013a). Three phenomena can explain different microbial colonisation patterns on the surfaces and in the pores of biochar: 1) Biochar pores are less accessible to nutrients than natural soil pores, 2) biochar pores can be closed by soil organic matter (e.g., humic acids), and 3) hazardous chemicals such as PAHs may be found in biochar (particularly new biochar) (Kasozi et al., 2010, Quilliam et al., 2013a, Quilliam et al., 2013b). Microbial colonization on biochar surfaces and pores is also influenced by the ageing process, which is characterized by temporal heterogeneity. (Quilliam et al., 2013a). Bacterial cells from Geobacter metallireducens and Methanosarcina barkeri co-cultures can attach themselves to biochar surfaces in a matter of minutes. Adjusting the ageing periods of biochar can promote the colonization of soil microorganisms (both fungal hyphae and single bacterial cells) on surfaces and in the pores of biochar (Quilliam et al., 2013a).

Biochar provides nutrients to soil microbes

Because of its wide surface area, high pore volume, and negative surface charge, biochar contains a variety of nutrients (e.g., K, Mg, Na, N, and P) and enriches soil nutrients by sorption (Chathurika et al., 2016, Rodriguez-Vila et al., 2016). (Chen et al., 2012c). Cation exchange capacity (CEC) is a key indicator of a soil's ability to retain cationic nutrients while also providing nutrients for microbial activity. Biochar application improves soil CEC by increasing nutrient retention and reducing nutrient loss through leaching, both of which are advantageous to soil microbial activity (Lehmann, 2007b), especially for bacteria living in low-organic-matter soils (de Andrade et al., 2015). Biochar's nutritional conditions (measured by ash content) are mostly determined by its feedstock and pyrolysis temperatures. Biochars made from herbaceous material (crop wastes) and manure have a larger ash content than wood biochar, allowing them to provide more nutrients (Fig. 3A) (Akhter et al., 2015). For crop residue biochar and manure biochar, a distinct ascending relationship between ash content and pyrolysis temperatures has been discovered (Xu and Chen, 2013). Biochar nutrients can be released at varying rates into soils (Mukherjee and Zimmerman, 2013). Biochar can be used as a slow-release fertilizer in this situation, providing long-term advantages to soil fertility and microbial growth. Another reason biochar may provide nutrients to soil microbes is that it controls soil microbial processes that are necessary for nutrient cycle. Biochar, for example, might increase the quantity of rhizobacteria that can convert organic S and P into bio-available forms, promoting the growth of Lolium perenne (Fox et al., 2014), and is likely to stimulate the growth of other microorganisms that can only use inorganic S and P.

Biochar reduces the toxicity of contaminants to soil microbes

Biochar can reduce the toxicity of soil pollutants to soil microbes when used as a soil ameliorant (Koltowski et al., 2017). Willow biochar (pyrolyzed at 700 °C) can minimize microbe mortality while enhancing Folsomia candida reproduction in soils contaminated with heavy metals and organic pollutants (PAHs), as well as diminish the bacteria Vibrio fischeri leachate toxicity (Koltowski et al., 2017). The immobilization of soil contaminants (including heavy metals like Al, Cd, Co, Cr, Mn, and Ni, as well as organic pollutants like PAHs) on biochar and the resulting reduction in their bioavailability could be the primary reason for the reduced toxicity of soil contaminants to microbes and the increased microbial biomass (Seneviratne et al., 2017). Application of rice straw biochar (5 percent application rate) can result in a 68 percent increase in the organic-bound percentage of heavy metals (Cd, Cu, Pb, and Zn) (Lu et al., 2017). Reduced heavy metal load on N-fixing bacteria (Bradyrhizobium japonicum) could improve plant development even further (Seneviratne et al., 2017). Biochar interactions with soil microbes have more significant implications on the environmental fate of soil pollutants, including their immobilisation and degradation, which will be described in a later chapter of this review.

Providence of soil contaminants under biochar-microbe interactions

a. Immobilization of contaminants by biochars

Biochar is a powerful sorbent that, through a variety of methods, immobilises organic pollutants and heavy metals (Ahmad et al., 2014). The interactions of biochar with organic pollutants are influenced by electrostatic attraction, polar and non-polar organic attraction to the carbonised phase of biochar, and partitioning to the non-carbonized phase of biochar (Huang and Chen, 2010). For the interaction of biochar with inorganic pollutants, ion exchange, anionic metal attraction, precipitation, and cationic metal attraction are effective processes (Xu and Chen, 2015). Biochar can sometimes be more effective than activated carbon at immobilising heavy metals., e.g., Pb precipitation (84–87 percent) in the form of –Pb9 (PO4)6 and Pb3(CO3)2, as well as surface sorption (13–16 percent) via C=C (-electron) and –O–Pb bonds through interactions with biochar, were found to be six times more effective (up to 680 mmol Pb kg1) by dairy manure-derived biochar than activated carbon in a study (Cao et al., 2009). Certain herbicides (such as simazine) sorb in micropores or on the surfaces of biochar, restricting their access to microbial cells, extracellular enzymes, and plants, as well as their leakage into groundwater (Jones et al., 2011). Biochar can be endowed with a hybrid sorption capability of organic pollutants and phosphate by simply adding iron oxide to it, making it a multifunctional material for agricultural and environmental purposes (Chen et al., 2011).

Recent research shows that biochar can alleviate aluminum (Al) toxicity by changing the speciation of Al(OH)2+ or Al(OH)3+, rather than by attracting Al3+ directly to negatively charged sites on charcoal (Qian and Chen, 2013). (Qian et al., 2013). Although there is rivalry sorption between Cd and Al, oxidation of biochar surfaces during the aging process can generate extra binding sites for heavy metals Cd and Al. (Qian et al., 2015). Si particles can reduce the amount of soil exchangeable Al and Si released from biochars can form Si-Al compounds in the epidermis of wheat roots, indicating that Si particles can reduce the amount of soil exchangeable Al and that Si released from biochars can form Si-Al compounds in the epidermis of wheat roots (Qian et al., 2016). The findings suggest that more research into the elemental makeup of biochar as well as its role in biogeochemical cycles of soil elements involving soil bacteria is required.

b. Impacts on contaminant transformation and indulgence

Biochars have been shown to operate as electron exchangers between microorganisms and contaminants, facilitating microbial breakdown. (Yu et al., 2015). Biochar can operate as a direct electron acceptor of acetate for microbial extracellular respiration and growth (Yu et al., 2015) and as an electron donor to drive the microbial reduction of the Fe (III) oxyhydroxide mineral ferrihydrite (Kappler et al., 2014). When biochar is reduced as a result of an electron transfer from Geobacter sulfurreducens, it can also act as an electron donor for other microbes' metabolism, catalysing biochemical activities (Yu et al., 2015). The presence of biochar significantly improved the degradation of pentachlorophenol (PCP) by a bacteria species (Geobacter sulfurreducens) that was previously unable to degrade PCP on its own; this improvement was attributed to biochar-facilitated electron transfer between microbial cells and the PCP molecule (Yu et al., 2015).

Conclusions

Heavy metals are poisonous to all living things. These have different levels of toxicity that affect plant development and regulation. Drought stress, on the other hand, poses a threat to plant growth and development. Both of these produce reactive oxygen species (ROS), which induce membrane lipid peroxidation and electrolytic leakage, lowering photosynthetic rate. Biochar aids in the modification of soil physiochemical characteristics. It improves soil water retention, water and mineral uptake, nutrient retention, heavy metal absorption, soil fertility, and microbiota enhancement. The biochar is linked to a decrease in Na+ uptake, mineral buildup, and stomatal conductance and phytohormone control. Overall, this analysis can help researchers better understand biochar-mediated tolerance mechanisms in plants under high stress. More research is needed to determine the effect of biochar in maintaining a healthy soil microbiome under a variety of environmental situations, including various pressures. More research is needed to confirm the role of biochar in drought and heavy metal stress mitigation. To fully comprehend the impact of biochar in plant growth, soil characteristics, and other environmental factors, detailed and timely research is required.

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