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The Research Progress on Biochar Adsorption of Heavy Metals and Its Practical Application in Phytoremediation

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Abstract. Soil pollution by heavy metals has become an urgent problem, and we should develop some efficient methods for remediation. Phytoremediation is an environmentally friendly and gentle remediation technology, which uses plants to remove or stabilise pollutants in soil. However, it also has some disadvantages, such as low biomass production and poor heavy metal uptake. Moreover, plants themselves are very sensitive to heavy metal pollution, which affects their growth. Biochar, which is produced by the pyrolysis of biomass under low oxygen conditions, has a strong ability to adsorb heavy metals through physical adsorption and other mechanisms. It also has a positive effect on improving soil properties and enhancing the efficiency of phytoremediation. This essay hopes to summarise the current research on the interaction mechanisms between biochar and heavy metals, the effects of biochar on the improvement of phytoremediation, and provide a future research guideline for the sustainable use of biochar in the remediation of heavy metal-contaminated soil.

Keywords: biochar, heavy metal adsorption, phytoremediation, soil remediation, synergistic effect

1. Introduction

The continuous and progressively more challenging problem of heavy metal soil contamination continues to threaten ecosystem functions, food safety and human health. As a result of discharging heavy metals through industrial emissions, mining activities, agricultural runoff, and urban waste disposal large-scale accumulation of toxic metals such as lead (Pb), cadmium (Cd), arsenic (As), and chromium (Cr) in arable lands, large areas of land that cannot be used for cultivation or habitation [1,2]. In response, phytoremediation has emerged as a promising, cost-effective, and aesthetically acceptable strategy for in-situ soil restoration. This approach employs plants to extract, stabilise, or detoxify contaminants. However, the ability to remediate contaminated soil using hyperaccumulators is limited because hyperaccumulators grow relatively slowly, there is limited bioavailability of heavy metals to the plant from the soil and hyperaccumulators can cause phytotoxicity, which can lead to reduced survival of hyperaccumulators and reduced ability for hyperaccumulators to remediate contaminated soil [3-5].

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In such a context, biochar, a carbon-rich solid residue produced from the pyrolysis of biomass materials at reduced oxygen availability, has emerged as a potentially viable candidate for the improvement of phytoremediation capacity. Because of the biochar have various mechanisms which mentions above can provide a strong retention properties for variety of heavy metal ions [6]. Added to this such active retention properties, letting biochar into the phytoremediation system holds the prospect of improving the conditions of the polluted ecological environment through the development of a more favourable and eco-friendly site for plant growth and also can improve soil physical structure, water-holding capacity, and microbial habitat. In this case, the incorporation of biochar represents a novel collaborative attempt to resolve the problems of phytoremediation [2,7].

Nevertheless, most existing studies address biochar's adsorption mechanisms and agronomic benefits separately. There still lack of a systematic integration of its direct stabilisation effects with indirect synergistic roles in plant–microbe systems, and practical guidelines for matching biochar types with specific plant species remain insufficient. Therefore, this review aims to summarise the interaction mechanisms between biochar and heavy metals, explain the synergistic effects of biochar on phytoremediation efficiency, and provide a compatibility framework for selecting biochar–plant combinations. This review bridges the gap between biochar material science and phytoremediation ecology, offering actionable guidance for field-scale remediation.

2. Biochar adsorption mechanisms for heavy metals

The strong ability of biochar is to adsorb and stabilise heavy metals in soil, which is primarily attributed to the combined action of physical and chemical adsorption mechanisms. Reference [3] points out its inherent physicochemical properties serving as the fundamental basis at 2011.

Physical adsorption is a reversible process, which is driven by physical forces. It's mainly relying on biochar's large specific surface area and pore structure to trap heavy metal ions and lock them into the soil [6]. This mechanism enables in short-term, though the molecules can run out off the soil when the conditions change (like pH changes, etc). Physical adsorption can quickly reduce the mobility of heavy metals and mitigate their immediate environmental risks.

In contrast, chemical adsorption is a more stable and irreversible process, involving reactions between heavy metal ions and active functional groups (e.g., carboxyl and hydroxyl groups) on the biochar surface [2]. There are three key reactions that support this chemical adsorption include ion exchange, surface complexation, and precipitation, which are crucial for the long-term stabilisation of heavy metals in soil [7,8]. To explain more specifically, ion exchange mainly means by exchanging the heavy ions in soil with harmless ions in biochar. Second, surface complexation means letting heavy metals ions form a stable complexes with functional groups. Lastly, is precipitation. Precipitation is a process that letting heavy metal ions form water-insoluble precipitates on the surface of biochar. Together, these two adsorption mechanisms contribute to biochar's excellent performance in heavy metal retention, laying a foundation for its application in soil remediation.

3. Biochar adsorption on typical heavy metals and influencing factors

When it comes to cleaning up the polluted environments, especially in the context of phytoremediation, biochar has shown a significant ability to absorb the heavy metals. Different types of biochars has different reactions to heavy metals, making it a broad-spectrum tool in the remediation efforts. Studies indicate that biochar is highly effective in adsorbing cationic heavy metals like lead (Pb^{2+}) and cadmium (Cd^{2+}). The process mainly involves surface complexation and

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precipitation. Similarly, [6] found that adding biochar to soil can significantly reduced the bioavailability of Cd^{2+}, which in turn could helped lower its buildup in hyperaccumulator plants, thus reducing its toxicity.

However, biochar tends to struggle with anionic heavy metals like arsenic (As) and chromium (Cr^{6+}). Although biochar did not perform well, modifying -- by treating it with acids or loading it with metal oxides (e.g. Fe, Mn), or introducing functional groups -- can greatly enhance its ability to capture these anions [2,9].

There are several factors that influence how well biochar can adsorb heavy metals. The first is the intrinsic properties of the biochar itself. The type of biomass it originates from (like crop residues or woody materials), the temperature at which it's pyrolysed, and any modifications made to the biochar all play critical roles. For example, higher pyrolysis temperatures can boost the biochar's surface area and porosity, improving its physical adsorption capability. Reference [3] also indicated in 2011 that chemical modifications can introduce more active groups that enhance chemical bonding with heavy metals.

From the perspective of the external environment, the conditions in the soil where biochar is applied can also significantly affect its performance, such as soil pH, ion concentration and so on. For instance, in alkaline soils, heavy metal ions may precipitate on the surfaces of biochar, while high levels of competing cations can limit biochar's ability to selectively adsorb the target heavy metals [5].

4. Representative original research cases on plant-biochar compatibility

The matching of willow (a typical tolerant tree species) with nano-micro biochar and iron/manganese modified biochar in multi-heavy metal contaminated soil. The main innovation is the researcher aim to solve the bottleneck of low survival rate and poor remediation efficiency of trees in both acidic and alkaline heavy metal-contaminated soil, and exploring the synergistic coupling effect between different biochar types and willow growth as well as heavy metal remediation [2]. The results showed that adding biochar significantly reduced the bioavailability of Cu, Pb, Cd, Mn and Zn in the soil, while also increasing the biomass and root development of willow, meaning the trees grew better and took up less toxic metals.

Low-cadmium accumulating maize varieties with calcium-modified biochar in the alkaline cadmium-contaminated farmland soil. Its core innovation is integrating the biochar modification technology with the low-heavy metal accumulating plant selection, focusing on solving the dual problems of cadmium accumulation in crops and soil ecological degradation in alkaline cadmium-contaminated farmland [1,5]. The field trial found that this combination cut down Cd accumulation in maize grains by more than half, and also improved the diversity of soil microbes, which helps keep the soil healthy.

Apart from the willow and low-cadmium maize that mentioned above, there are also some other common plant–biochar combinations that work well in real remediation projects, such as sunflower with lychee biochar and alfalfa with olive stick biochar. Their core advantages are summarised in Table 1 below.

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Table 1. Compatibility between common phytoremediation plants and biochar types

Plant Type	Plant Type	Target Heavy Metal	Core Advantages of Matching
Willow (tolerant tree species)	Nano-micro biochar, iron/manganese modified biochar	Cu, Pb, Cd, Mn, Zn	High plant survival rate, strong adaptability to acid/alkaline soil, efficient reduction of heavy metal bioavailability.
Low-cadmium accumulating maize	Calcium-modified biochar	Cd	Reduced crop cadmium accumulation, improved soil microbial diversity, suitable for safe utilization of farmland.
Sunflower	Lychee branch biochar	Pb, Cd, As, Zn	Increased biomass and metal accumulation in leaves/receptacles, reduced metal concentration in seeds [10].
Alfalfa	Olive stick biochar	Cu, Zn	Reduced metal uptake in roots/shoots, improved CEC and microbial activity, alleviated oxidative stress [11].

5. Conclusion

This review systematically summarises the current understanding of biochar's mechanisms for heavy metal adsorption and its synergistic role in phytoremediation. There are some key findings. Biochar stabilises heavy metals through combined physical adsorption (porosity, surface area) and chemical mechanisms (ion exchange, complexation, precipitation, redox reactions), with the latter providing long-term stability. Biochar is highly effective for cationic metals (Pb^{2+}, Cd^{2+}, Cu^{2+}) but requires modification for anionic metals (As, Cr). Biochar indirectly enhances phytoremediation by improving soil properties (pH, CEC, water retention), promoting beneficial microbial colonisation, and alleviating oxidative stress in plants, and can also decline the soil degradation. Also, matching appropriate biochar types with specific plant species can significantly improves remediation efficiency.

The theoretical significance of this review lies in integrating direct adsorption mechanisms with indirect plant–microbe synergies, while its practical value provides a compatibility framework for field applications. Future research should prioritise long-term field trials to evaluate biochar's stability and ecological safety, development of targeted modification strategies for specific metal mixtures, and establish a standardised protocols for biochar selection and application rates. With continued innovation, biochar-assisted phytoremediation is expected to become a sustainable, cost-effective solution for restoring heavy metal-contaminated soils worldwide.

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