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Biochar enhanced phytostabilization of heavy metal contaminated mine tailings: A review

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Mining activities has generated large amounts of mine tailings each year, and these tailings usually contain high concentrations of heavy metal pollutants, which not only cause serious damage to the local and surrounding soil ecosystems, but also harm human health *via* the transmission of food chain. Phytoremediation is treated as environmentally friendly, long-term effective and low-cost restoration method. However, tailing soil acidification, low organic matter content, poor water holding capacity and compaction make plant struggle to survive. Biochar, a soil conditioner can promote plant growth by improving the physical, chemical and biological properties of soil, thus strengthening the ability of phytoremediation in the contaminated tailings. This review elaborates how the physicochemical properties of biochar affect phytoremediation; and summarized how the raw materials of biochar affect the physicochemical characteristics. Finally, the future research directions are prospected.

KEYWORDS

biochar, phytoremediation, heavy metal, mine tailings, soil

1 Introduction

Mining industries is considered the basis of many industrial sectors because it provides energy and raw materials for many others. However, some studies indicated that the increasing demand and low production rate of mine concentrate result in more than 14 billion tons of mine discard waste and tailings are generated in the process of mineral exploitation every year (Adiansyah et al., 2015). Mine tailings usually contain high contamination of heavy metals (HMs) such as cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), chromium (Cr), cobalt (Co), mercury (Hg), nickel (Ni), and arsenic (As) (Maboeta et al., 2018). These HMs may infiltrate river and soil around mines through wet deposition and leakage from mine tailings ponds (Kowitwiwat and Sampanpanish, 2020). HMs in soil can not only decreasing the number of soil beneficial microorganisms by hamper their enzymatic and metabolic activities, but also having a fatal effect on invertebrates and reptiles by stimulate the formation of reactive oxygen species (Ahmed et al., 2022). This will lead to the destruction of the soil ecosystem balance and the reduction of soil microbial biodiversity. What's more, HMs can enter and accumulate in surrounding people through the food chain, respiratory inhalation, skin contact and other routes of exposure (Cheng et al., 2020). Some HMs have strong toxic to human organs even in trace amounts, which increases the risk of serious physical diseases and mental illness (Ayuso-Alvarez et al., 2019; Li et al., 2019; Chen et al., 2020). People living downstream of mine tailings may develop nervous system disturbance, pneumonia, kidney inflammation, sesophageal, liver and other cancers attributed to long-term consumption of vegetables, rice and drinking water contaminated with upstream HMs (Shu et al., 2018; Zhao et al., 2022). Considering the potential ecological environment destruction, health hazards and economic losses caused by untreated tailings, it is essential to rehabilitate tailings to lessen its risks.

At present, the developed tailings remediation technology can be divided into physical treatment, chemical remediation and bioremediation. Compare with bioremediation, physical treatment and chemical remediation are costly and usually affect soil properties, fertility, and biodiversity (Shah and Daverey, 2020). For example, during vitrification the tailings soil is melted at high temperatures (>1,300°C) and forms a glass matrix after rapid cooling, which effectively immobilizes various heavy metals (Hu et al., 2021). But the high energy consumption caused by high temperature will make the treatment very costly, not suitable for large-scale tailings remediation, and the remediated tailings lose ecological function which cannot be used for plant cultivation. Phytoremediation in bioremediation is considered to be an environmentally friendly, long-term effective and low-cost method (Praveen and Pandey, 2020). Phytoremediation includes phytoextraction, phytovolatilization, phytoimmobilization and phytostabilization (Liu et al., 2018). Generally, phytoremediation can mainly be divided into two broad techniques: phytoextraction, which relies on the excessive uptake of heavy metals by plants from the soil and their accumulation in branches, shoots and leaves, and phytostabilization, which stabilizes heavy metals to a harmless state by immobilizing them in the soil through the plant root system (Liu et al., 2018). At present, phytostabilization is widely used to stabilize heavy metals in tailings and generally regarded as an effective method to achieve long-term tailings remediation. This remediation technology contributes to the restoration of ecosystem functions, give tailings a certain landscape value and reduce the risk of exposure to HMs of human (Zalesny et al., 2021). The biomass materials obtained from phytoremediation can be used to produce biomass fuels such as bioethanol, biodiesel and biogas, which have good economic value (Sameena and Puthur, 2021). However, due to extreme pH values, high salinity, low organic matter content, low water retention capacity, and high concentrations of HMs make plant are struggle to survive and growth in tailing soil (Wang et al., 2017). This situation makes phytoremediation usually has a longer restoration cycle compared to physical and chemical remediation, which limits the application of phytoremediation. Therefore, how to improve the physicochemical and biological properties of tailings soil to make it suitable for plant growth is of great significance to improve the efficiency of phytoremediation.

Biochar is a kind of carbon-rich material with high specific surface area, abundant pore structure and various surface functional group which has been proven to have positive effects on soil physical, chemical and biological properties (Marcińczyk and Oleszczuk, 2022). In recent years, many researchers have noticed that the combination of biochar and phytoremediation can play a more active role in tailings remediation. Biochar addition to tailings soil can improves soil structure, increases tailings soil fertility and reduces the bioavailability of heavy metals, providing a better environment for the establishment of stable plants, thus improving the efficiency of phytoremediation. The mechanism of biochar assisted phytoremediation in mine tailings remediation and the effects of different biochar types are summarised in short in this paper. We aim to provide suggestions and references for future research by reviewing past related research.

2 Soil physical properties improvement

Tailings are produced by crushing and grinding during the beneficiation process, and it usually consists of sand, fine grained minerals, water and high concentrations of heavy metals (Sun et al., 2018; Pérez et al., 2021). The composition of the tailings determines its poor soil structure, poor water retention, limited nutrient retention, and susceptibility to water erosion (Macdonald et al., 2017). Therefore, biochar can improve the physicochemical and biological properties to promote plant survival and growth if it is used as a soil amendment before the establishment of plants in tailings soils. Most of the experiments reported are potted experiments under greenhouse conditions, in which tailings soil is mixed with a certain mass fraction of biochar in pots, and resistant plants are sown in the pots to study the effect and mechanism of biochar-enhanced phytoremediation by comparing with control leases. This section discusses the research results of biochar to improve soil structure, enhance soil water holding capacity and reduce soil erosion and its related mechanisms.

2.1 Soil structure

Soil structure, the basis of soil material exchange and energy transfer, is the material carrier regulating soil water, fertilizer, air and heat, which has an important influence on plant growth (Šimanský et al., 2019; Shi et al., 2022). Good soil structure can helps plant roots to breathe and absorb water and nutrients. Adding biochar to soil can improve soil structure by decreasing soil bulk density, increase total soil porosity, and promoting the stability of soil aggregates (Islam et al., 2021).

2.1.1 Soil bulk density

Soil bulk density is an indicator of soil compaction, which not only directly affects soil porosity and pore size, but also affects soil aeration, available water, plant available nutrients and microbial activity (Alghamdi, 2018). High soil compaction can inhibit plant growth by affecting plant photosynthetic rate, transpiration rate, stomatal conductance and enzyme activity, resulting in a significant decrease in plant biomass (leaf number, dry mass of stem, leaves and roots) (Grzesiak et al., 2013; Wang et al., 2019). Xiu et al. (2019) found that 3% biochar addition can reduce soil bulk density by 9.93%. Biochar can reduce soil volume density through a variety of mechanisms. Firstly, the bulk density of biochar is much lower than the average bulk density of soil, so mixing biochar with soil can reduce the overall density of soil through dilution effect (Garcia-Perez et al., 2022). Secondly, the abundant hydroxyl and carboxyl groups on the surface of biochar make it have the ability to combine with soil particles to form soil pores (Ayaz et al., 2022). Finally, the increase in organic carbon concentration caused by biochar addition can promote bioturbation, thereby reducing soil bulk density (Blanco-Canqui, 2021).

2.1.2 Soil pore structure

Soil pore structure plays an important role in soil function, affecting not only nutrient transport, air exchange and water storage, but also plant root extension and microbial activities (Yang et al., 2022). The movement of gas and water in soil is mainly affected by the number of pores, the size distribution of pore structure and other geometric features (Fan et al., 2020). Wang et al. (2020) discovered that 3% biochar addition can compared with the control group, soil micropores (5–30 μm) was significantly increased by 12.71%. The increase in total porosity in soil is usually attributed to the highly porous internal structure of biochar particles (Zhou et al., 2018). Besides, biochar can increases the volume of micropores by filling the pores between soils (Herawati et al., 2021). Finally, the accumulation or rearrangement between biochar and surrounding soil particles can also create new pores (Yang and Lu, 2021).

2.1.3 Soil aggregate

Soil aggregate is the basic unit of soil structure and the material basis of soil fertility, which plays an important role in soil structure stability (Tian et al., 2020). Aggregate stability affects many soil properties and processes, including carbon and nitrogen cycling, water and nutrient storage and transport, root penetration and development, and soil erosion (Heikkinen et al., 2019; Fan et al., 2021). Hu et al. (2021) observed that the stability of soil aggregates increased with the increase of biochar application rate. The mean weight diameter of aggregates increased by 49.77%, 78.34%, and 187.56% with the dosage of 2.5%, 5%, and 7% biochar. The addition of biochar brought with a large input of soluble salt like Na^+,K^+,Ca^{2+}, and Mg^{2+}(Burrell et al., 2016). Increased electrolytes in the soil contribute to the stability of soil aggregates by promoting flocculation of clay particles and binding of individual soil particles to aggregates (Phocharoen et al., 2018). Biochar is rich in organic carbon, which can promote the formation of soil humus, and the short-range attraction exerted by humus can dominate the interaction of clay particles, thus improving the stability of soil aggregates (Huang et al., 2016). Improved soil conditions are conducive to microbial growth and reproduction, and exocytic exudates (binding agents, polysaccharide, and glycoprotein) produced by fungi and bacteria can bond soil particles into large aggregates (Rabbi et al., 2020; Fan et al., 2021).

2.2 Water holding capacity

Soil water holding capacity (SWHC) is one of the most important factors in the soil properties because they affect the plant available water that supports plant physiological activities such as photosynthesis and transpiration (Atkinson and Aitkenhead, 2018). Basso et al. (2013) found that the addition of biochar increased soil water holding capacity by 23% relative to the control. The study by Ghassemi-Golezani and Farhangi-Abriz (2022) found that the mechanism of biochar in increasing soil water holding capacity may be related to its specific physical and chemical properties such as high specific surface area and porosity. Biochar affects soil water holding capacity through various mechanisms, but the increase of micropores structure and total soil porosity are considered to be the main mechanisms (Bikbulatova et al., 2018). The macropore (>80 μm) contribute to facilitate the rapid flow of water through the soil under the action of gravity but micropores (5–30 μm) can hold water by capillary forces (Li et al., 2021; Zhao and Hu, 2021). At the same time, the relatively high hydrophilicity of some biochar and the abundant oxygen-containing functional groups on the surface can also increase soil water retention (Zhang et al., 2019a). In addition, the addition of biochar will improve the aggregation and stability of soil aggregates, thus affecting the water retention capacity of soil (Batista et al., 2018). Finally, the increase of soil organic matter caused by biochar addition can slow down soil evaporation and water infiltration (Lal, 2020).

2.3 Soil erosion and nutrient loss

Tailings usually have a loose structure and a large accumulation slope, resulting in erosion or even crumbling and landslides when subjected to heavy rainfall during the rainy season (Wang et al., 2017). Soil erosion will cause the already inadequate fertility of the tailings soil to continue to decline, especially a large loss of organic matter in the soil. The loss of rich nutrients in the soil means that there are not enough nutrients for plant growth. Biochar is considered to have the potential to improve soil lose and nutrient retention (Crews and Rumsey, 2017). Hseu et al. (2014) noted that with the increase of biochar application rate, soil loss decreased significantly. Under extreme rainfall events, biochar incorporation could reduce soil loss content by at least 35%. Increase in soil surface roughness and improvement in soil properties, including porosity, aggregate stability, organic matter concentration and hydraulic conductivity, are considered to be the main factors in reducing soil erosion (Blanco-Canqui, 2021). Rubin et al. (2020) noted that 10% woody biochar reduced cumulative ammonium leaching by 65% and nitrate leaching by 92%. The reduction in inorganic nitrogen leaching may mainly be due to retention and adsorption on the surface area and pore space of the biochar (Feng et al., 2020). Peng et al. (2021) discovered that the application of 4% corn stover biochar can reduce the accumulation of leached total phosphorus by 20.2% compared to the control soil. Biochar affects phosphorus leaching losses directly or indirectly by adsorption of phosphorus, increasing phosphorus retention in the soil and promoting assimilation of phosphorus by plants (Yang et al., 2021a).

3 Soil chemical properties improvement

Extreme pH, low levels of nutrients and high concentrations of heavy metals in tailings soils limit plant germination, growth and development. Biochar has stable chemical properties, can exist in soil for a long time, and has the potential to improve soil chemical properties for a long time. Biochar enhances phytoremediation by neutralizing soil pH, providing nutrient support, and reducing heavy metal bioavailability. In this section of this paper, the research results and related mechanisms of biochar in improving soil pH and fertility and reducing heavy metal bioavailability are discussed.

3.1 Soil pH

The pH of tailings is keep low in normal or natural condition due to the large amount of acidic wastewater produced by tailings, especially sulfide tailings (Yin et al., 2021; Saedi et al., 2022). Acidification of tailings soil can lead to the mobility of heavy metals and toxicity to plants increased, and lead to plant deficiency of P, Ca, K, Mg, and Mo (Dai et al., 2017). Many studies have reported a significant increase in soil pH after biochar application (De la Rosa et al., 2022). Aamer et al. (2020) observed that 2% biochar application increased soil pH from 5.48 to 6.11. There are three main mechanisms by which biochar raises soil pH and reduces exchange acidity: first, the carbonate or oxide formed during pyrolysis can reacts with H^+; then the high pH of biochar itself can neutralize the acid in the soil; finally, various functional groups such as hydroxyl and carboxyl groups on the surface of biochar can absorb H^+ too (Lu et al., 2022).

The addition of biochar not only increased soil pH, but also enhanced soil pH buffering capacity (pHBC). The pHBC is important for maintaining the stability of soil properties and the stability of the whole ecosystem because it affects many soil reaction processes, such as the mineralization of organic matter; the activity of soil microorganisms and the available form of heavy metals (Dvorackova et al., 2022). Shi et al. (2017) discovered that 5% application of corn stover biochar increased the pHBC by 86.34%. The mechanism of biochar enhancing soil pHBC may be through increasing soil cation exchange capacity (CEC) and soil organic matter content (SOM) (Dai et al., 2017).

3.2 Soil fertility

Poor nutrients in tailings are one of the main constraints to phytoremediation. The addition of biochar can directly or indirectly increase soil fertility, thus increasing germination, early growth, root and stem length, and chlorophyll content of plants (Shamim et al., 2018).

3.2.1 Soil organic matter

SOM, such as humus and humus-like substances, can be mineralized to release nutrients for assimilation by plants and microorganisms (Ding et al., 2016). SOM plays an important role in maintaining soil quality and sustaining soil ecosystems, and its content affects many physical and chemical properties of the soil, such as aggregate stability, water retention capacity, and pH (Simansky et al., 2016). However, most tailings are severely deficient in organic matter, with many tailings having less than 1% organic matter (Lin et al., 2021a; Qin et al., 2022). Li et al. (Hua et al., 2014) found that soil improvement by biochar could effectively increase soil organic matter, and the degree of impact increased with the increase of biochar. The addition of 8% biochar could increase organic matter content by 41%–75%. Biochar can reduce the decomposition of soil organic matter and thus promote carbon sequestration in low organic carbon soils (Fatima et al., 2020). Liu et al. (2022b) found that 1% addition of wheat straw biochar reduced CO_2 emissions from soil organic matter mineralization by 28%. Biochar is rich in organic compounds, especially unstable organic compounds, which affect soil organic matter by providing a usable energy source for microbial metabolism, growth and reproduction (Liu et al., 2022a). In addition, biochar can stabilize the organic matter content of the soil by inhibiting the mineralization of organic matter. Biochar can forming stable organic-inorganic complexes through adsorbing labile OC, and controlling β-Glucosidase activity related to soil organic matter degradation, thereby promoting the formation and stabilization of soil SOM (Luo et al., 2020; Liu et al., 2022b). Although biochar incorporation can increase the biomass of soil microorganisms, the increased efficiency of microbial utilization of unstable C can protect SOC and promote carbon sequestration (Fatima et al., 2020). Finally, biochar has a huge specific surface area, rich pore structure and functional groups such as hydroxyl and carboxyl groups, which make it have a strong adsorption capacity and can improve the ability of soil to adsorb and retain organic matter (Cen et al., 2021).

3.2.2 Cation exchange capacity

CEC represents the ability of soil to retain positively charged ions and is the main source of soil buffering capacity (Razzaghi et al., 2021). CEC can be used as an index to evaluate the ability of soil to retain and release nutrients, such as ammonium, nitrate, P, Mg, and Ca (Mattila and Rajala, 2022). Kaur and Sharma (2019) noticed that the addition of 10% biochar could significantly increase soil CEC by 26.54%–33.18%. The main mechanism of increasing CEC by adding biochar may be that the surface negative charge and charge density of biochar increase the negative charge density of soil (Hailegnaw et al., 2019). In addition, biochar surface oxidation functional groups such as carboxylic acids, lactones and phenols contribute to increasing the negatively charged biochar density (Domingues et al., 2020). SOM is a rich source of soil negative charge, and the addition of biochar can enhance soil CEC by increasing soil organic matter especially humic acid (Šimanský et al., 2017). The increase in soil pH after the addition of biochar may lead to deprotonation of functional groups of minerals, resulting in more negative charges, contributing to the improvement of CEC (Hailegnaw et al., 2019).

3.2.3 N and P

On the one hand the tailings are deficient in nitrogen and phosphorus, on the other hand the plant available forms of these nutrients are easily lost through leaching, conversion to gaseous forms and in precipitation reactions (Gul and Whalen, 2016). Biochar improves soil nitrogen retention and provides more effective phosphorus, while reducing soil losses of nitrogen and phosphorus, thereby promoting plant growth and nutrient uptake. Xu et al. (2016) found that application of 2%, 4%, and 8% corn stover biochar reduced total leached N accumulation by 18.8%, 19.5%, and 20.2%. Gonzaga et al. (2022) observed that the addition of sludge biochar increased the availability P concentration from 60.20 to 124.36 mg kg^{-1} in bulk soils and from 192.9 to 245.9 mg kg^{-1} in the rhizosphere. Biochar improves soil nitrogen fixation and reduces soil nitrogen fixation losses through mechanisms such as biotic (increases in microbial biomass and activity) and abiotic (adsorption of NO_3^-, NH_4^+ and organic nitrogen by biochar) nitrogen fixation, enhanced nitrogenation, reduced leaching, and denitrification (Asadyar et al., 2021). Although these processes may reduce plant utilization of N for a short period of time, recent evidence suggests that N adsorbed by biochar can eventually be used by plants (Bai et al., 2015). Soil N may be mineralized to inorganic N when there is not enough N in the soil for plant use or microbial activity (Liu et al., 2017). At the same time, biochar improves the nitrogen use efficiency of plants, thereby promoting plant growth (Sathe et al., 2021). Biochar contains various organic and inorganic forms of P that can be used as a source of these nutrients to provide available P to the soil (Sui et al., 2022). In addition, biochar can activate soil endogenous phosphorus by affecting P-related complexation and metabolic effects, and increase the content of available P in soil (Yang et al., 2021b). Biochar can also improve soil phosphorus retention by adsorbing phosphorus and releasing it gradually to make it available to plants (Matin et al., 2020).

3.3 Heavy metal bioavailability

Exposure to high concentration of heavy metals in tailings will lead to the gradual reduction of plant biomass and photosynthetic activity, which has a serious stress on the survival, growth or reproduction of colonizing plants (Ibrahim et al., 2022). The addition of biochar can reduce the uptake of heavy metals by plants by significantly reducing the mobility and bioavailability of heavy metals, thereby alleviating plant stress and promoting plant growth. Ibrahim et al. (2022) discovered that the addition of 4% *Casuarina* biochar could decreased the concentrations of Cd, Cu, Pb, and Zn by 37.2%, 40.2%, 89.2%, and 35.5% in the shoot, and by 25.7%, 32.3%, 85.0%, and 25.2% in the root. Biochar can directly adsorb and fix heavy metals in tailings. The abundant functional groups, porous structure, and ionic charge on the surface of biochar contribute to the fixation of cationic metals in the soil by co-precipitation, surface functional groups complexation, ion exchange, physical adsorption and π-π-electron interactions (Jia et al., 2022). The improvement of soil by biochar, including the increase of soil pH, is an important factor affecting the bioavailability of heavy metals in soil. The increase of pH value promotes the transformation of heavy metals from exchangeable state to bound state and other stable forms (Irshad et al., 2020). In addition, tailings are rich in oxides such as silica, whose charge depends on pH (Fashola et al., 2019). The increase of pH lead to the deprotonation of acidic functional groups (hydroxyl and carboxyl groups, etc.) of tailing particles, resulting in more negative charges of tailing particles, thus enhancing the adsorption capacity of tailing for heavy metals (Yan et al., 2021c). Finally, biochar affects the redox potential of heavy metals, for example, biochar converts

Cr^{6+} to Cr^{3+} which is less toxic and mobile by continuously transferring electrons (Xu et al., 2020; Narayanan and Ma, 2022).

4 Soil biological properties improvement

In recent years, many researchers have found that tailings native microbial communities can enhance plant tolerance and improve plant colonization in tailings soils (Gazitua et al., 2021). Microorganisms in tailings soils can affect the physical and chemical properties of plant roots and influence the uptake of nutritions and heavy metals by plants (Shen et al., 2022). Application of biochar can enhance phytoremediation by influencing microbial abundance and diversity. This section discusses the role of microorganisms in phytoremediation and the findings and related mechanisms of the action of biochar in enhancing microbial activity and abundance.

4.1 Role of microorganisms in phytoremediation

Microorganisms especially root microorganisms play a crucial role in the process of tailings phytoremediation, such as decomposition of organic matter and conversion of plant available nutrients, formation and stabilization of soil aggregates, fixation of heavy metals, and suppression of plant diseases (Bhanse et al., 2022). Microorganisms can mineralize organic matter, converting organic nitrogen and organic phosphorus into orthophosphate anions ($HPO_4^{2-}$and $H_2PO_4^{1-}$) and inorganic nitrogen ($NO^{3-}$and NH^{4+}), the major forms of nitrogen and phosphorus that are absorbed by plants (Richardson et al., 2009). Soil microorganisms can bind to soil particles through mycelium or play the role of as binder for soil aggregate in soil particles by secreting insoluble extracellular compounds (Ren et al., 2022). Microorganisms reduce tailings heavy metal bioavailability through direct and indirect mechanisms, including intracellular and extracellular chelation, enzymatic transformation, methylation, alkylation and metal dealkylation, and adsorption of polymers from the cell surface (Fashola et al., 2019). Besides, the addition of biochar can lead to antagonism, competition or parasitism between microorganisms and pathogens in soil by improving soil physicochemical conditions and controlling soil microbial community structure (Gao et al., 2019). The reduction in the number of pathogens can reduce plant morbidity and inhibit the damage to plants. Finally, root microorganisms induce the activities of peroxidase enzymes such as catalase (CAT), peroxidase (POD), peroxidase and polyphenol oxidase (PPO) to improve plant tolerance to heavy metals (Benidire et al., 2021).

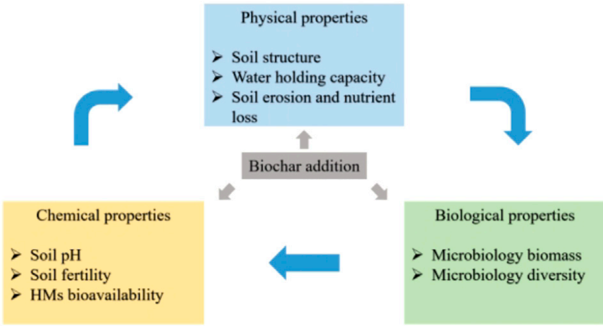

FIGURE 1
The improvement of soil physical, chemical and biological properties caused by biochar addition.

4.2 Microbial abundance and diversity

Biochar application can significantly promote the growth of soil microorganisms, increase the abundance of microbial communities and affect the diversity of microbial communities (Hua et al., 2021). Li et al. (2022) found that adding 2% tobacco stalk biochar could increase the microbial biomass of carbon and nitrogen in soil by 87.28% and 54.33%. Yang et al. (2022) found that the use of 1% rice straw biochar prepared at 550°C increased the Shannon diversity index and decreased the Simpson index. In biochar modified soil, the Shannon index of bacteria increased by 3.1% and Simpson index decreased by 29.0%, and the Shannon index of fungi increased by 22.6% and Simpson index decreased by 69.2%. The addition of biochar will bring unstable carbon derived from the pyrolysis of incomplete biomass, which is preferentially used by soil microbial communities, thus stimulating the growth, activity and reproduction of microorganisms (Plaza et al., 2016; Luo et al., 2020). Second, the porous structure and large surface area of biochar provide habitat for soil microorganisms, protecting them from desiccation and predation by large soil organisms (Poveda et al., 2021). Final, biochar can play an indirect role in microbial abundance by altering other environmental factors, such as soil pH and heavy metal availability (Yang et al., 2022). An overview of the improvements in the physical, chemical and biological properties of the soil resulting from the addition of biochar is shown in Figure 1.

5 Plant biomass and roots

Plant biomass and roots play an important role and can significantly affect phytoremediation efficiency (Niu et al., 2021). This section discusses the role of plant biomass and roots in phytoremediation along with the findings and the associated mechanisms of the role of biochar in enhancing plant biomass and promoting root development.

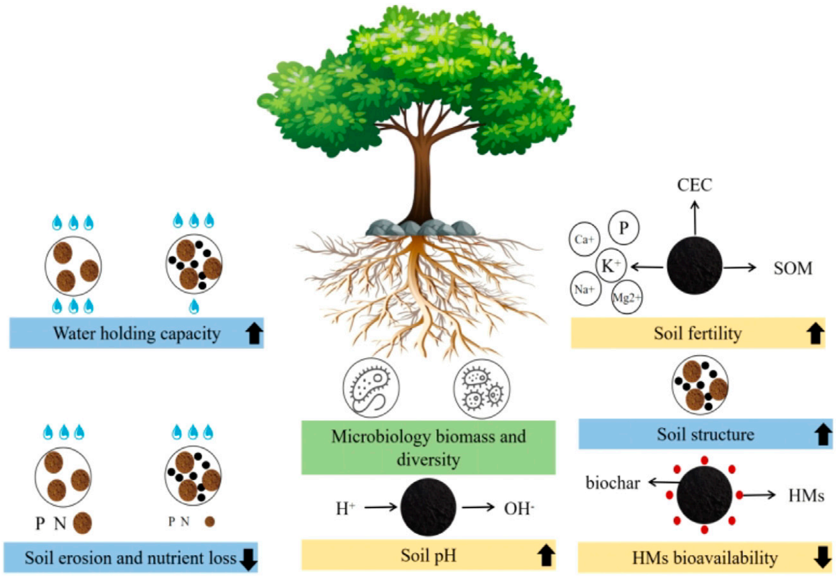

FIGURE 2
The improvement in plant growth due to the addition of biochar.

5.1 Role of plant biomass and roots in phytoremediation

Plant biomass is a key factor affecting phytoremediation potential. The increase of plant biomass can dilute the content of heavy metals in plant tissues to reduce their damage (Cheng et al., 2020). Besides, roots play an important role in plant growth because well-developed roots are better able to absorb and transfer water and nutrients from the soil, contributing to above-ground growth. The enhanced photosynthesis of aboveground leaves can provide sufficient nutrients for root growth, thus forming a virtuous cycle. Phytoremediation efficiency is strongly dependent on the nature of root secretions, because root secretions, including hydrogen ions, organic acid anions, phytochelators, enzymes, and carbon-containing metabolites, which can promote complex formation and reduce heavy metal toxicity through chelation or hydrogen bonding (Yang et al., 2020). These roots secretions also attract beneficial rhizosphere growth-promoting bacteria, which facilitate plant growth under stress (Liu et al., 2021).

5.2 Plant biomass and roots

Biochar addition promotes plant biomass increase and root development. Ren et al. (2021) found that the application of biochar not only increased the total root area by 91.35%, but also increased the net photosynthetic rate by 77.3% and the total biomass by 72.5%. Biochar-induced improvement in root growth and development is associated with improved soil structure and enhanced availability of nutrients (Chang et al., 2021). In addition, it has recently been found that the addition of biochar can also change the gene expression of plants, downregulating the biosynthesis pathway defense genes and up-regulating the growth promoting genes (Li et al., 2016). Finally, biochar can inhibit pathogen growth, survival, virulence and activity by inducing systemic plant defense responses, improving soil nutrient availability, regulating soil microbial community structure, and adsorbing enzymes and organic acids produced by pathogenic microorganisms (Alaylar et al., 2021; Hou et al., 2022). Figure 2 shows the improvement in plant growth due to the addition of biochar.

6 Effects of different biochar characteristics and used dosage

6.1 Characteristics of biochar

Many researchers have confirmed that different biochar feedstock type, preparation process and used dosage can have varying degrees of impact on the improvement of physical, chemical and biological properties. The previous sections has explained in detail how the physicochemical properties of biochar determine its potential to enhance phytoremediation. But the physicochemical properties of biochar are directly affected by the type of biomass raw material and pyrolysis conditions. Therefore, the comparison of biochar prepared from different raw materials and under different pyrolysis conditions is the basis for the application of biochar to enhance the phytoremediation of tailings pollution.

6.1.1 Feedstock type

By summarizing relevant studies, it can be found that the mainly biomass sources of biochar preparation are crop residues, forestry biomass and organic solid waste, mainly including straw, seed husk, pericarp, wood chips, bark, branches, animal waste and sludge. Plant biomass is normally characterized by low ash content, high calorific value, high bulk density and small void fraction, while organic solid waste is generally characterized by high ash content, low calorific value, low bulk density and high void fraction (Jafri et al., 2018). Sludge biochar have been targeted for particular focus because of its phosphorus-rich properties, but there is a risk of contamination with heavy metals remaining in it after preparation (Zhang et al., 2021).

In general, the specific surface area and porosity of organic solid waste biochar are much smaller than that of plant biochar, which are mainly related to the release of volatiles during pyrolysis: excessive ash will block pores, especially micropores, resulting in a decrease in surface area and porosity (Ji et al., 2022). Compared with cellulose and hemicellulose, lignin is more stable in the pyrolysis process, so lignin-rich biomass will produce biochar with macroporous structure, while cellulose-rich biomass mainly produces biochar with microporous structure (Li et al., 2017). The larger volatile substances content of plant-based biochar compared with organic solid waste biochar at relatively low temperature is due to the presence of hemicellulose and cellulose (Li et al., 2018). Organic solid wastes often contain a large number of inorganic minerals, and the precipitation of soluble alkali metal salts and mineral components in the pyrolysis process leads to the increase of organic solid waste biochar ash and pH value (Xu et al., 2022). Biochar derived from organic solid waste showed more CEC and oxygenated surface functional groups than biochar derived from plants, possibly because the alkali metals in the raw material promoted the generation of oxygenated surface functional groups (Murtaza et al., 2022). Compared with biochar from non-woody materials, wood biochar has lower ash content but higher C content, aromaticity and stability because carbon compounds such as lignin, which are rich in the raw material, are not easily degraded during pyrolysis (Xu et al., 2022). The content of N and P in organic solid waste biochar such as manure is usually high, which may be due to the high content of protein and free amino acid in the raw material, and the decomposition of protein and free amino acid will release N and P (Ji et al., 2022).

6.1.2 Pyrolysis conditions

Among many pyrolysis conditions that affect the physicochemical properties of biochar, such as pyrolysis temperature, heating rate, residence time and pyrolysis atmosphere, pyrolysis temperature is one of the most influential factors (Shaaban et al., 2014). In general, biochar prepared at higher temperatures has higher C content, specific surface area, pore volume, ash, aromaticity and thermal stability, while biochar prepared at lower temperatures has more O and H content, yield, hydrophilic, volatile substances, acidic functional groups, available nitrogen and CEC (Zhao et al., 2017).

Higher pyrolysis temperature is conducive to the release of volatile substances from the raw material and the formation and volatilization of intermediate melt, thus forming more micropore volume and larger specific surface area, but also leads to the decrease of biochar production (Shaaban et al., 2014). Because more water and oxygen-containing groups are removed during pyrolysis, biochar prepared at high pyrolysis temperature has high C content, aromaticity, stability and low hydrophilicity (Lin et al., 2021b). The increase in ash content at high pyrolysis temperature is due to the combustion of organic matter and the residue of inorganic components (Tomczyk et al., 2020). The increase in pH with increasing temperature is mainly due to more alkali metal salt in ash produced during pyrolysis, and additional support is provided by the appearance of basic functional groups, the disappearance of acidic functional groups and the release of alkali metal salts from the raw material (Murtaza et al., 2022). Due to the dehydration and deoxygenation of biomass raw materials, the content of oxygen-containing functional groups is low (Tomczyk et al., 2020). The CEC of biochar depends on the nature and distribution of oxygen-containing functional groups on the surface of biochar, so the CEC of biochar decreases with the increase of pyrolysis temperature (Liang et al., 2016). The phosphorus contents of biochar increased with the increase of pyrolysis temperature, mainly because high temperature caused the decomposition of biomass structure, resulting in higher residual phosphate (Yang and Lu, 2021). The continuous decrease of N content in biochar with the increase of pyrolysis temperature is due to the high temperature leads to the escape of N element in the form of non-coagulable forms such as HCN and NH_3 or organic N in the coagulable liquid phase (Xu et al., 2021).

6.2 Used dosage

The effects of biochar on tailing soil and plants are closely related to the amount of biochar added. Shi et al. (2022) found that the addition of appropriate amounts of biochar would improve soil structure, including increasing soil porosity, stabilizing soil triple comparison, promoting the formation of soil aggregates and improving the stability of aggregates. But if the application of biochar is too large, it may reduce the effect of soil structure improvement. Liu et al. (2020) noted the application of 5% biochar stimulated plant growth and recorded the maximum biomass. However, if the amount of biochar applied is higher than this level, biochar can inhibit plant growth. Excessive addition of biochar may inhibit plant

TABLE 1 Biochar application in phytoremediation.

Feedstock of biochar	Pyrolysis temperature (°C)	Dosage (%)	HMs	Plant	Result	References
Acacia wood	450	5	As and Mn	Mott dwarf Napier grass	The absorption and accumulation of As and Mn in the above-ground and underground parts decreased by 78.6% and 63.9% of As and 72.5% and 69.3% of Mn respectively.	Kowitwiwat and Sampanpanish (2020)
Cornstalk	500	5	Cd	Beta vulgaris	The Cd concentration of DTPA extraction in soil decreased by 16%, and the dry weight of plant roots increased by 267%.	Gu et al. (2020)
Lemongrass	450	4	Al, Cr, Cu, and Pb	Palmarosa	Biochar amendment significantly increased biomass disease and reduced heavy metal translocation factor.The translocation factors of Al, Cr, Cu, and Pb decreased by 69.5%, 3.6%, 14.2% and 83.1%, respectively.	Jain et al. (2020)
Wheat straw	520	1.5	Cd	Alfalfa	Alfalfa biomass increased by 239%, root biomass increased by 289.4%, and aboveground biomass increased by 221.8%. Cd concentration decreased by 23.2% in roots, but increased by 0.38% in aboveground parts.	Zhang et al. (2019b)
Lychee	500	5	Pb, Cd, As, and Zn	Sunflower	The biomass of sunflower plants and their roots, stems, leaves, containers and seeds increased by 64.7, 20.4, 32.8, 36.5, 75.1 and 230%, respectively and Pb, Cd, As, and Zn in sunflower rhizosphere soil decreased by 16.3%, 21.9%,17.0% and 24.5%, respectively.	Liu et al. (2020)

growth. This may be due to the too high water holding capacity of the soil and less oxygen in the pore space, which leads to the anaerobic state of plant roots (Chang et al., 2021). It is also possible that the adsorption capacity of biochar is too strong in the early stage, which slows the release of available nutrients in the later stage, resulting in a lack of fertilizer (Li et al., 2022). This is also may be related to the formation of toxic compounds during the charring process, such as polycyclic aromatic hydrocarbons (PAHs) (Mikajlo et al., 2022).

The reduced bioavailability of heavy metals through biochar application may be beneficial for the establishment of plant mulch in tailings soils for long-term phytostabilization (Forjan et al., 2018). Table 1 summarizes the research progress of biochar application in phytoremediation including different biomass sources, different pyrolysis conditions and different dosing rates.

7 Conclusion and future prospects

This article reviews how the addition of biochar causes changes in soil physical, chemical and biological properties, and how these changes have salutary effect on enhanced phytoremediation. The addition of biochar will simultaneously affect physical, chemical and biological properties, and these properties will also interact with each other to jointly strengthen the effect of phytoremediation. The application of biochar is beneficial to reduce the mobility and bioavailability of heavy metals in tailings, improve soil structure, enhance soil fertility, promote plant growth, and promote soil microbial activity. Therefore, in order to improve soil properties before large-scale biochar utilization, more extensive studies on biochar-soil-plant systems are needed to promote the effect of phytoremediation of heavy metal-contaminated soil, so as to enhance phytoremediation. Future research should focus on the following issues that need attention: First, at present, many studies are limited to laboratory scale and conducted under greenhouse conditions, so there is a lack of field studies to evaluate the ability of biochar to enhance. Second, microorganisms play an important role on phytoremediation, so more research should be emphasized on the biochar-soil-microbe-plant interaction. Third, whether the pollutants (PAHs and HMs) may carried by biochar, especially modified biochar, will cause secondary pollution to the environment is a problem worthy of attention.

Author contributions

YS and YZ performed the experiments and wrote the paper. HY, JS, JZ contributed to the Data analysis and picture drawing. XZ and BL conceived and designed the paper. XZ and YS supported the funding.

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Conflict of interest

Author JS was employed by the company Shandong Industry Research Environmental Technology Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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