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THEMATIC ISSUE

Remediation via biochar and potential health risk of heavy metal contaminated soils

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Abstract

The serious damage to human health caused by soil heavy metals (HMs) pollution has always been a major problem in the field of public health. Although HMs pollution of soils has been efficiently remediated using biochar, the potential specific human health risks and their pathogeny during production and application are not known. The review provides a comprehensive summary of the current status, sources, and human health hazards of HMs contaminated soils; the physicochemical properties of biochar and its effects on the bioavailability of soil HMs; and the mechanisms and potential human health risks in using biochar for soil remediation. The results show that the interaction mechanisms between the biochar and soil HMs depend on the feedstock of biochar and pyrolysis temperature; biochar applications can directly or indirectly affect the bioavailability of HMs; several potential specific health risks such as dust pneumoconiosis, cytotoxicity, and respiratory diseases may be caused in the processes of biochar preparation and soil HMs remediation; additional recommendations are proposed for future research in areas, where significant knowledge gaps exist. This information can provide a meaningful reference for health management departments to formulate soil health prevention strategies.

Keywords Biochar · HMs pollution · Influencing factors · Potential health risk · Remediation

Introduction

Soil is the source of food needed for human survival, the core of the terrestrial ecosystem, and the root of the food chain. However, many heavy metals (HMs) are easily processed and stored in the soil (Proshad et al. 2020; Cetin et al. 2022). Currently, soil HMs pollution has become more and more serious and frequent disease-causing incidents are occurring. HMs have been determined to result in many disorders in humans such as cancer, cardiovascular disease, chronic anemia, cognitive impairment, nervous system depression, kidney damage, and skin and bone-related illnesses (Solenkova et al. 2014; Khalid et al. 2017; Shen et al. 2019; Zhang et al. 2020b). Because the large amount of cultivated land has been contaminated by HMs, dietary exposure has become the most important way for people to be exposed to HMs (Xiong et al. 2014). Therefore, the remediation of HM-contaminated soil has gradually attracted people's attention and become a research hotspot in the field of soil and environment.

Recently, based on the severely HM-contaminated soil situation, several remediation measures have been applied, including chemical remediation (immobilization techniques and soil washing), bioremediation (phytoremediation and microbial assisted), and physical remediation (soil replacement, soil isolation, vitrification, and electrokinetic) (Liu et al. 2018; Wang et al. 2020). Nevertheless, these methods have deficiencies or limitations, such as complex mechanisms, low efficiency, high costs, poor realization, a short duration, and a high risk of secondary pollution (Lahori et al. 2017; Buaisha et al. 2020). Currently, biochar amendment is

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considered to be one of the more promising in-situ remediation techniques. It causes less damage to the environment and may offer an available solution to the problem of soil pollution (Palansooriya et al. 2020).

Biochar is a type of fine-grained porous carbon-containing solid material, which is synthesized from waste biomass in a closed container through pyrolysis under oxygen-limited conditions (Qin et al. 2020). As a new type of environmentally functional material, biochar has multiple uses, including soil improvement, soil carbon sequestration, greenhouse gas emission reduction, environmental pollution restoration, and pathogen resistance (Zhang et al. 2013; Ye et al. 2017). Thus, biochar is the best choice for remediating HM-contaminated soil, and it can reduce the biological activity and toxicity of HMs such as Lead (Pb), Cadmium (Cd), and Copper (Cu) (Ndirangu et al. 2019; Panahi et al. 2020). However, compared with the advantages of biochar in the remediation of HMs contaminated soils, there are few in-depth studies on potential specific health risks. Although some studies have also revealed the negative effects of pollutant residues (e.g., HMs, polycyclic aromatic hydrocarbons (PAHs), cresols, formaldehyde, xylenols and acrolein) in biochar, remediation via biochar and potential specific health risk of HMs contaminated soils are rarely reported (Keiluweit et al. 2012; El-Naggar et al. 2019; He et al. 2019). Therefore, this review aims to clarify the mechanism, bioavailability, potential specific health risks and influencing factors of biochar remediation of HMs contaminated soil, which will provide a basis for health management departments to formulate soil health prevention strategies.

The objectives of this review were to summarize (1) the sources, current status, and health hazards of HMs in soil; (2) the effects of feedstock and pyrolysis temperature on the characteristics of biochar; (3) the effects of biochar on remediation mechanism and bioavailability of soil HMs; and (4) the potential health risks and pathogeny factors in biochar preparation and remediation.

Sources, current status, and health hazards of HM-contaminated soil

Sources and current status of HM-contaminated soil

Originating from natural and anthropogenic sources, HMs pose potential risks to ecosystems and human health due to their acute and chronic toxicity, environmental persistence, and bioaccumulation (Lv et al. 2014; Wu et al. 2018). Among them, the primary anthropogenic sources include industrial, agricultural, domestic, traffic, and e-waste pollution. Recently, with the rapid continuous development of industrialization and urbanization, and human activities such as industrial and agricultural activities, mining and smelting of minerals, urban garbage disposal, sewage irrigation, unreasonable application of pesticides and fertilizers, and discharge of motor vehicle exhaust, a lot of HMs have entered the soil in various forms (e.g., gas, water, and solid waste type) (Yang et al. 2018; Cetin and Jawed 2022). Li et al. (2015, 2016, 2022) confirmed that the sources of HM pollution were industrial activities, agricultural and natural sources. However, different sources of pollution lead to different types of HMs contaminated soils. For instance, coal-fired power plants can easily cause soil mercury (Hg) pollution (Rai et al. 2019), while HM components from electronic waste and highway traffic are complex, including Pb, Cd, Chromium (Cr), Iron (Fe), Manganese (Mn), Nickel (Ni), Hg, Arsenic (As), Cu, Zinc (Zn), Aluminum (Al), and Cobalt (Co) (Zeng et al. 2016; Abderrahmane et al. 2021). Moreover, the natural source is caused by the high content of HMs in the parent material itself, which is also called high geological background region and mainly distributed in karst areas such as southwestern and central-southern China (Kong et al. 2018; Wen et al. 2020). This phenomenon causes the source of the HMs in the karst soil to exhibit a superposition effect, and the pollution is the most serious in these areas. Besides, some natural disasters may also cause HM pollution in soil. For example, HMs from rich depositional zones migrate into the soil due to weathering and decomposition of minerals (Grantcharova and Fernández-Caliani 2021). According to all sources of HMs, approximately 22,000 tons of Cd, 939,000 tons of Cu, 783,000 tons of Pb, and 1,350,000 tons of Zn are released annually around the world, respectively (Oves et al. 2012).

Soil contaminated by HMs is a major environmental concern. There are approximately 6000, 2500, and 100,000 km^2 of HM-contaminated soil sites in the United States, Europe, and China, respectively (Teng et al. 2010). Pb, Cd, Hg, and Ni are the most common HM pollutants in contaminated soils worldwide (Jaskulak et al. 2020). According to the Bulletin of the National Survey of Soil Pollution by the Ministry of Environmental Protection of China, the total excess rate of soil points in China is 16.1%. Moreover, the over-standard rates of Pb, Cd, Cu, and Zn were 0.9%, 2.1%, 7.0%, and 1.5%, respectively (Cui et al. 2019). Among them, Cd and Hg are the main pollutants in vegetables, and their mean concentrations are 177.63% and 100.50% of those of the natural background values, respectively (Sawut et al. 2018). Similar studies have also shown that fruits and vegetables in many regions contain high levels of Cd, and Cd-carrying rice and maize are the most dangerous foods for human health (Zheng et al. 2020). Because HM-contaminated soils are characterized by concealment, hysteresis, long-term, irreversibility, and complexity, they pose a risk to the environment and human well-being (Gong et al. 2018). Therefore, there is an urgent need for timely and effective implementation of remediation measures for HM-contaminated soils to promote public health and well-being.

Health hazards of HM-contaminated soil

HM-contaminated soil is a worldwide issue for human health and nourishment. Currently, approximately 19% of arable agricultural land has been polluted by HMs and metalloids in China (Zhao et al. 2015). HMs can cause various types of damage to creatures and plants. In general, the HMs in agricultural soil easily accumulate in food and vegetables, so residents will experience chronic toxicity and disorders after long-term exposure to low doses (Xiong et al. 2016), which will result in serious public health effects.

HMs has the characteristics of toxicity, bioenrichment, concealment, and biodegradation resistant in the natural environment (Wu et al. 2016). For instance, Pb, Hg, Cd, Cr and As are the "five toxic elements" that pose a great threat to human health even at low concentrations (Costa et al. 2020). Many toxic HMs continuously increase and amplify their toxicity through enrichment in the food chain (Walker et al. 2004). In addition, most toxic HMs can invade the human body through drinking water, food, skin contact, and other pathways to threaten human health directly or indirectly (Cheng et al. 2020; Zhao et al. 2022). When the amount of HMs in the body exceeds the safe dosage, they can cause serious damage to the human liver, kidneys, digestive system, and nervous system, even leading to a higher risk of cancer in humans (Chungu et al. 2019). For example, Wang et al. (2011) reported that long-term environmental exposure to Cd and Pb may increase the risk of death from all types of cancer, including stomach, esophageal, and lung cancer. A previous study also indicated that the damaging effects of persistent Hg exposure within the US population may cause a significant increase over time in the proportion of related neurodevelopmental and neurodegenerative diseases (Laks 2009). According to the World Health Organization (WHO), 494,550 deaths and 9.3 million disability-adjusted life years were lost due to long-term human exposure to Pb in 2015 (Forsyth et al. 2019). The world-famous Itai–Itai Disease and Minamata Disease are two of the four major public health hazards in Japan, and they are caused by Cd and Hg pollution, respectively (Inaba et al. 2005; Eto et al. 2010). Methylmercury (Me–Hg) is an organic form of Hg that mainly affects the central nervous system (Tchounwou et al. 2003). Its bioaccumulation and toxicity are much higher than those of inorganic forms of Hg. The specific damage to tissues and organs caused by each HM is listed in Table 1.

Characteristics of biochar used for HM remediation

Recently, biochar remediation of HM-contaminated soil has become a research hotspot. Biochar can effectively adsorb and immobilize HMs, which make it difficult for them to migrate and transform. Due to the differences in the actual uses of biochar, the different characteristics of biochar are controlled to varying degrees by the pyrolysis temperature and the types of feedstocks (Das et al. 2021). Pyrolysis is an essential process in the preparation of biochar. With the development of biochar application, distinctive sorts of pyrolysis techniques have been steadily developed, including slow pyrolysis, fast pyrolysis, flash pyrolysis, microwave-assisted pyrolysis, vacuum pyrolysis, gasification, hydropyrolysis, and intermediate pyrolysis (Tripathi et al. 2016). Each method differs in terms of the reaction temperature, residence time, and heating rates in the reactor. The pyrolysis technique is usually selected according to the intended use of the biochar, and the pyrolysis temperature is closely associated with the changes in the structure and

Table 1 Specific damage to tissues and organs caused by each HM

Heavy metals	Health effects	References
Cu	Wilson's disease and Indian childhood cirrhosis, Chronic copper toxicity, primarily affects the liver	Stern et al. (2007)
Pb	Lead encephalopathy, lead poisoning (including toxicity of the nervous, hematopoietic, renal, endocrine, and skeletal systems, with the CNS as the primary target organ); impairment of cognitive functions (especially in children)	Marjorie et al. (2014)
Cd	Kidney damage, skeletal damage, Itai-Itai disease, cardiovascular diseases (e.g., coronary artery disease), emphysema, anemia, chronic pulmonary diseases, osteoporosis and fractures, metabolic disorders, teratogenic, carcinogenic, and mutagenic diseases	Jarup(2003), and Solenkova et al. (2014)
As	Skin cancer, kidney damage, carcinoma of the bladder, lung cancer, hyperpigmentation, keratosis and vascular disease	Jarup (2003), and Marjorie et al. (2014)
Cr	Carcinogenic, allergic dermatitis or eczema, mutagenic, carcinogenic, and teratogenic	Zhang et al. (2020b)
Hg	Central nervous system defects, cardiovascular disease, kidney damage, lung damage, genotoxic, erethism, carcinogenic and teratogenic. The consequences of mercury poisoning include mental retardation, cerebral palsy, seizures and ultimately death	Tchounwou et al. (2003)
Zn	Affects the immune system, anemia, emaciation, and anorexia	Shen et al. (2019)

physicochemical properties of the biochar (Tomczyk et al. 2020). Among them, slow pyrolysis is the most common used and economic type of pyrolysis. Fast pyrolysis is the most effective method of producing biofuels. In addition, gasification is a direct oxidation process, the primary products of which include combustible gases such as hydrogen, carbon monoxide, and methane (Kambo and Dutta 2015).

The feedstock used for biochar production has a wide range of sources, including various straw crops (corn, wheat, barley and rice straw), organic waste, sewage sludge, animal manure (swine, dairy and cattle manure), plant residues (peanut, pecan, switchgrass, coconut coir, hazelnut shells and sugarcane bagasse), and brewery byproducts (Manolikaki and Diamadopoulos 2020). These feedstocks include components such as lignin, cellulose, hemicellulose, and inorganic minerals. The quality of the feedstock is one of the primary factors that affect the final performance of the biochar. For example, compared with biochar produced from plants, animal manure biochar has a stronger ability to adsorb HMs (Higashikawa et al. 2016). In general, the feedstock type and pyrolysis temperature are the main factors that determine the physicochemical properties of the biochar, which can lead to differences in the composition ratio of the elements, richness of the functional groups (FGs), pH, specific surface area (SSA), cation exchange capacity (CEC), stability, and adsorption properties. In addition, these properties (primary and secondary properties) also influence the capacity of the biochar to remediate HM-contaminated soil (Fig. 1).

Remediation of HM-contaminated soil using biochar

Interaction mechanisms of biochar and HMs in soil

The diversity of feedstocks and pyrolysis conditions are the fundamental reasons that directly lead to the differences in the mechanisms by which biochar and HMs interact. In general, adsorption and immobilization are the major mechanisms by which biochar removes HMs (Ndirangu et al. 2019). Specifically, the mechanism combines with and adsorbs the HMs through physical (physisorption and electrostatic attraction) and chemical (precipitation, ion exchange, the complexation of oxygen-containing FGs with π electrons, and reducing forms) reactions (Fig. 2) (Zhang et al. 2013; Cheng et al. 2020). Compared with activated carbon, the characteristics of biochar are very similar to those of natural soil. Hence, the ability of biochar to adsorb or immobilize HMs is essentially affected by its physicochemical properties, for example, its large SSA, abundant FGs, high pH, and large pore size (Higashikawa et al. 2016). Moreover, the application of biochar can increase the pH of the soil, so that the HMs can be effectively immobilized in the soil, which is one of the important mechanisms of biochar remediation of HMs (Houben et al. 2013b).

Physical mechanism

Physical mechanism is the basic mechanism of biochar remediation of HMs contaminated soil, which includes physical adsorption and electrostatic attraction. Since physical adsorption is controlled by intermolecular forces, it is usually reversible. The physical adsorption of Cd by biochar is mainly determined by its SSA and pore size distribution

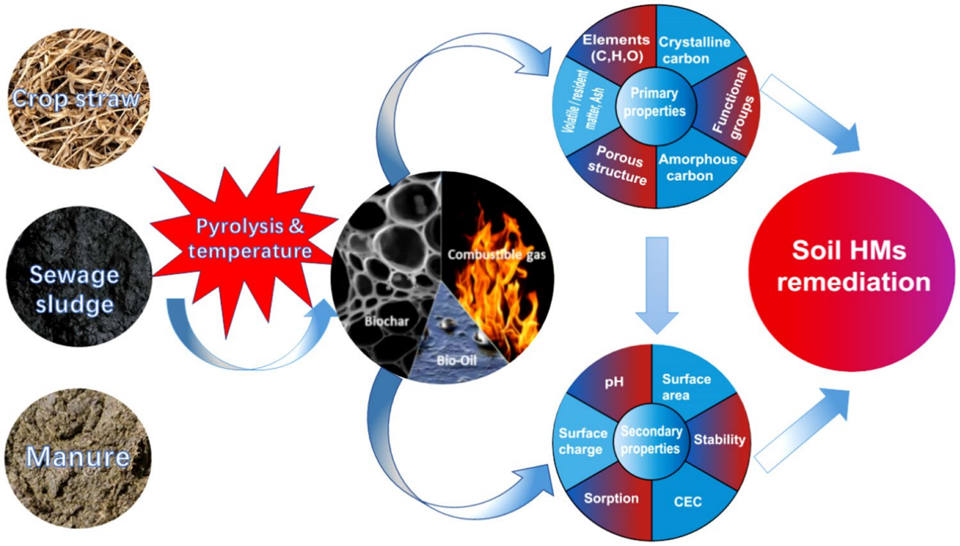

Fig. 1 Effects of biochar properties on the remediation of HM-contaminated soil

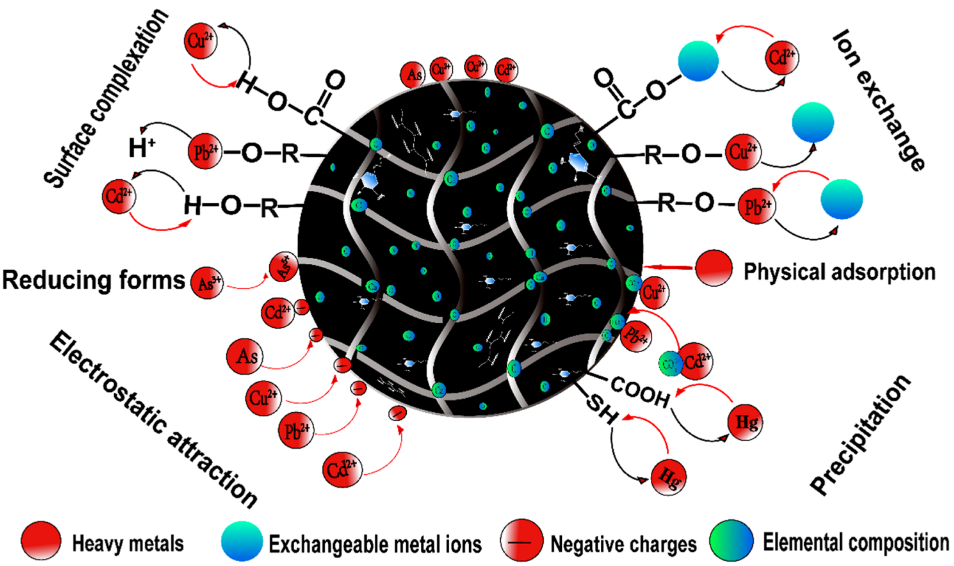

Fig. 2 Interaction mechanisms of biochar particles and HMs in soil

(Yang et al. 2019). Electrostatic attraction is largely driven by the surface charges of biochar and promotes the sorption of HMs on sites with hetero-charges (Zheng et al. 2021). Uchimiya et al. (2011) believed that the main mechanism of soil Cu immobilization is the electrostatic attraction between the heterogeneously charged Cu and biochar. For instance, the more negative surface charge of double-low canola straw biochar leads to more electrostatic adsorption of Cu(II), and the less negative zeta potential on the Cu(II)-adsorbed biochar results in the Cu(II) being solely adsorbed via the formation of surface complexes (Tong et al. 2011). Similarly, Li et al. (2017) also emphasized that electrostatic interaction is an important mechanism for As and Cr(III) removal using biochar. However, Xu and Zhao (2013) reported that both electrostatic and non-electrostatic mechanisms contribute to the enhanced Cd(II), Pb(II), and Cu(II) sorption of biochar, but the increase in the percentage of Cd(II) sorption caused by biochar was much greater than those of the Cu(II) and Pb(II) sorption. Therefore, it is particularly important to investigate the remediation mechanism of different biochars for different HMs.

Chemical mechanism

Ion exchange, complexation, precipitation, and reducing forms play an important part in HM contaminated soils for remediation by biochar (Lian and Xing 2017). Cao et al. (2011) reported that the passivation of HMs via biochar may be dominated by ion exchange and surface complexation. Negatively charged sites substituted by cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, etc.) are considered ion-exchange locations for HMs on biochar, and the CEC is considered as the main indicator of chemisorption HMs (Gholizadeh and Hu 2021). High CEC can improve the ion exchange between biochar and HMs cations. However, the CEC gradually decreased with the increase in temperature. When the pyrolysis temperature was 250–300 °C, the CEC of biochar showed a maximum value (Lee et al. 2010). The surface of biochar with oxygen-containing FGs (e.g., –COOH, –COH, –OH, etc.) are abundant, which form stable complexes with HM ions (Park et al. 2011). For example, Samsuri et al. (2013) confirmed that the complexation of As with oxygen-containing FGs controlled the adsorption of As on biochar. Similarly, biochar binds to Pb through complexation and cation exchange (Jiang et al. 2012). Dong et al. (2011) found that complexation is the key mechanism of Cr immobilization using biochar amendment.

The alkaline substances contained in biochar (e.g., CO_3^{2-}, $PO_4^{3-}$and OH^- etc.) are easily co-precipitated with HM cations (Pb(II) and Cd(II)) to form insoluble phosphates and carbonates (Cheng et al. 2020). In particular, soil pH and biomass feedstocks are key factors controlling the concentration of Cd and Pb in a soil solution (Wang et al. 2018b, 2019b). For instance, the soil pH increased from 5.11 to 7.51 under the application of chicken manure biochar, and the Cd was precipitated as $CdCO_3$ within this pH range (Park et al. 2011). Moreover, biochar derived from dairy manure is rich in PO_4^{3-} ions, which easily react with Pb to produce a stable precipitate [$Pb_5(PO_4)_3(OH)$] (Cao et al. 2011). Xu et al. (2013) also indicated that the precipitation reaction of phosphate or carbonate with Pb, Cu, Zn, and Cd is the mechanism of biochar adsorption of HMs. In addition, the mechanism of biochar stabilization of mercury is controlled by the fact that FGs such as carboxyl, thiol, and sulfoxide groups, can react with Hg^+ to form precipitate complexes and enable the retention/filtration of particulate Hg in the porous structure of biochar (Wang et al. 2019a). Due to the variability of the valence state in the environmental medium, As is prone to chemical reduction reaction. Wang et al. (2017) found that the application of biochar increases the abundance of Fe-reducing bacteria, and the As(V) adsorbed on Fe oxides is reduced to As(III), thereby enhancing the mobility and toxicity of the As in the soil. Similarly, the FGs on the surfaces of biochar can provide π-electrons to promote the reduction of As(V) to As(III), which ultimately enhances the mobility and toxicity of As (Choppala et al. 2016). Furthermore, the mobility of As increases with increasing soil pH, and the application of alkaline biochar increases the soil pH, which has raised some concerns and challenges concerning the application of biochar in As-contaminated soil (Beesley et al. 2011). However, it has been documented that modified biochar can effectively immobilize As and reduce its mobility. For example, Fe-biochar and Mn-biochar can oxidize and adsorb As (Yin et al. 2017). Therefore, the properties of different HMs should be fully considered to achieve the best biochar restoration effect.

Effect of biochar on bioavailability of HMs in soil

The bioavailability of HMs is defined as the number of HMs in the soil able to interact with the organisms that inhabit the soil environment. After biochar is applied to the soil, it mainly affects the occurrence form of the HMs in the soil through direct sorption or indirectly by changing the composition and properties of the soil, thereby affecting the bioavailability and mobility of the HMs in the soil. The bioavailability of HMs is greatly affected by many factors, including the soil pH, type of biochar, aging time of the biochar, rhizosphere environment, and microbial biomass (Katayama et al. 2010). At present, there is a great deal of evidence that increasing the soil pH by applying biochar can effectively reduce the bioavailability of HMs. For example, Huang et al. (2020) found that biochar increased the soil pH by 0.31, and reduced the diethylenetriaminepentaacetic acid (DTPA) extractable Pb, Cd, Zn, and Cu contents by 23.8%, 11.9%, 5.27%, and 14.3%, respectively. Biochar mainly reduces the bioavailability of soil HMs through its superior sorption capacity, immobilization, and rapid physical and chemical reactions (Park et al. 2011). However, the effect of biochar on the immobilization of HMs is reduced under the effects of long-term biological factors, which cause a reversible reaction to occur regarding the bioavailability of HMs (Wang et al. 2021a). In addition, the bioavailability of HMs decreases as the application level of biochar increases. For example, Houben et al. (2013a) reported that the incorporation of 1% biochar reduced the extractable Cd, Zn, and Pb concentrations by 14, 15% and 29%, respectively. The reductions reached 44%, 52%, and 76% in the presence of 5% biochar, and 71%, 87%, and 92% in the presence of 10% biochar for Cd, Zn, and Pb, respectively. Similarly, the presence of biochar can improve the plant root environment and enhance the soil water retention capacity to promote plant growth and nutrient absorption. The roots are the first metal barrier, stabilizing the metals on the cell wall and the extracellular carbohydrates of the rhizosphere, thereby avoiding the Cd and Zn toxicity of plants (Cheng et al. 2020).

Potential health risks of and protective measures using biochar for remediation of HM-contaminated soil

Although biochar has been applied widely to the soil to remove HMs and other contaminants, the strong sorption of biochar may have some disadvantages due to no selectivity to pollutants (Ye et al. 2017). For example, biochar also easily adsorbs toxic and hazardous chemicals such as pesticides and herbicides, and it may cause secondary pollution (Safaei Khorram et al. 2016). Even though the huge SSA of biochar makes it an efficient adsorbent of various organic and inorganic pollutants (Xie et al. 2015), biochar is affected by its environmental media conditions to produce chemical, physical and biological changes, which can reduce the affinity of biochar for pollutants and release them into the environment, thereby increasing the risk of exposure of organisms (Godlewska et al. 2021). Zhang et al. (2013) found that the interactions between organic and inorganic substances at the adsorption sites of biochar cause the available sites to be blocked and reduce the number of pollutants adsorbed. Moreover, biochar can only change the form of HMs in the soil when they are amended, but the total amount remains unchanged. Therefore, biochar ages over time and releases some of the absorbed HMs, which enter the body through the food chain, inhalation, and skin contact. Among them, digestive exposure through the consumption of vegetables, fruits, rice, and other foods is the major pathway (> 90%), which will inevitably increase the potential health risks (Xiong et al. 2014; Wang et al. 2021a, b).

In general, the potential health risks associated with biochar remediation are closely related to its production (feedstock and pyrolysis temperature), packaging, storage, transportation, distribution, and application (Table 2). At the same time, the toxic substances adsorbed by each process have a cumulative effect, which ultimately exacerbates the harmful effects on the human body. For example, Buss and Masek (2016) found that the content of volatile organic compounds is high in the process of biochar pyrolysis, and its initial release exceeds the occupational exposure limit. Moreover, the toxins contained in the feedstock may cause biochar to become harmful under pyrolysis conditions (Keiluweit et al. 2012). Meanwhile, biochar prepared at high temperature is more likely to release adsorbed HMs during the aging process, which becomes a source of secondary pollution and a high potential environmental risk and

Table 2 Potential human health risks of biochar prepared from different feedstocks

Feedstocks	Pyrolysis temperatures	Experimental design	Outcome measures	Results (health risks)	Authors/key references
Crops straw	250, 400, and 600 °C	In vitro cell experiment	Inhalable particle (PM_{10}), biochar dust or powder carrying HMs	Dust pneumoconiosis, cytotoxicity, respiratory health effects	Hamatui et al. (2016), Sigmund et al. (2017), Zama et al. (2018), Zhang et al. (2019b), Saletnik et al. (2021)
Wood (sawdust)	250–700 °C	In vitro cell experiment	$PM_{2.5}$ carrying contaminants, infiltration and aquifer pollution, PAHs	Dust pneumoconiosis, cytotoxicity, respiratory health effects, human cancer risk	Safaei Khorram et al. (2016), Lyu et al. (2016), Sigmund et al. (2017), Torres et al. (2017), Wang et al. (2019c)
Animal manure	200–800 °C	Laboratory experiment	Bacteria, pathogens	Disease risk via the fecal–oral route, neurotoxic effect	Smith et al. (2009), Wang et al. (2021b)
Sewage sludge	600 °C	A field experiment	Pathogens, parasites, endocrine-disrupting compounds	Intestinal infectious diseases, teratogenesis	Zhang et al. (2019a), Capone et al. (2020), Zhang et al. (2021)
Plant residues	250, 400 and 600 °C	Laboratory experiment	PAHs in biochar	Carcinogenic, teratogenic, and mutagenic toxicities	Zhang et al. (2018); Wang et al. (2019c)

ecotoxicity (Zhang et al. 2020a). Therefore, controlling carbonization temperature is a necessary means to prevent biochar from producing large amounts of toxic substances. Ni et al. (2021) indicated that the residue of PAHs in rhizosphere soil amended by corn straw-derived biochar at 300 °C was the lowest.

In addition, biochar is mainly added to soil in the form of powder or particles, which causes the release of biochar dust when the soil is weathered and eroded. Meanwhile, biochar dust carrying toxic contaminants may migrate from the soil to other environmental media, such as groundwater or atmosphere, resulting in the expansion of the pollution range (Maienza et al. 2017). Ravi et al. (2020) revealed that at low wind speeds, the applied biochar particles are more likely to be worn by sand particles and transported out of the soil system by the wind, which results in higher fine particle emissions, deterioration of the air quality, and human health risks. Furthermore, biomass waste contains high levels of toxic pollutants, such as HMs, polycyclic aromatic hydrocarbons, dioxins, polychlorinated biphenyls, persistent organic pollutants, and pathogens (Ndirangu et al. 2019). These toxic substances are enriched during the preparation of biochar and are easily inhaled by the body along with the emitted fine biochar particles. In addition, the low density of biochar is prone to produce dust particles. These dust particles absorb toxic substances and are easily released into the air, thereby increasing the risk of human exposure to these pollutants through inhalation, ingestion and skin (He et al. 2019). Gabriel Sigmund et al. (2017) have also confirmed that biochar dust particles were cytotoxic to mouse fibroblast cells. Therefore, to reduce the risk of exposure, workers should take dust prevention measures to avoid secondary dust pollution during the production and use of biochar, such as wearing masks and mixing biochar with soil matrix.

Similarly, changes in the rhizosphere environment of plants weaken the HM immobilization effect of biochar, resulting in the re-released of adsorbed HMs into the soil (Houben and Sonnet 2015). Moreover, the application of biochar also increased the release of PAHs from plant root exudates (Wang et al. 2018a). In addition, during the aging of the biochar, it is easy for it to adsorb excessive dissolved organic carbon, which blocks the pore structure of the biochar, thereby reducing the number of adsorption sites and weakening its adsorption capacity (Luo et al. 2017). For instance, Li et al. (2018) found that the long-term application of aging biochar can enhance the bioaccumulation of pesticides such as acetochlor in corn and lead to increased health risks. Thus, if biochar containing highly toxic pollutants is used to remediate HM-contaminated soil, it may increase the bioaccumulation level of toxic substances in the food chain and increase the risk of human exposure. Therefore, it is important to carefully evaluate the potential damage to occupational health, environmental pollution, and food safety using biochar in the remediation of HM-contaminated soil (Fig. 3).

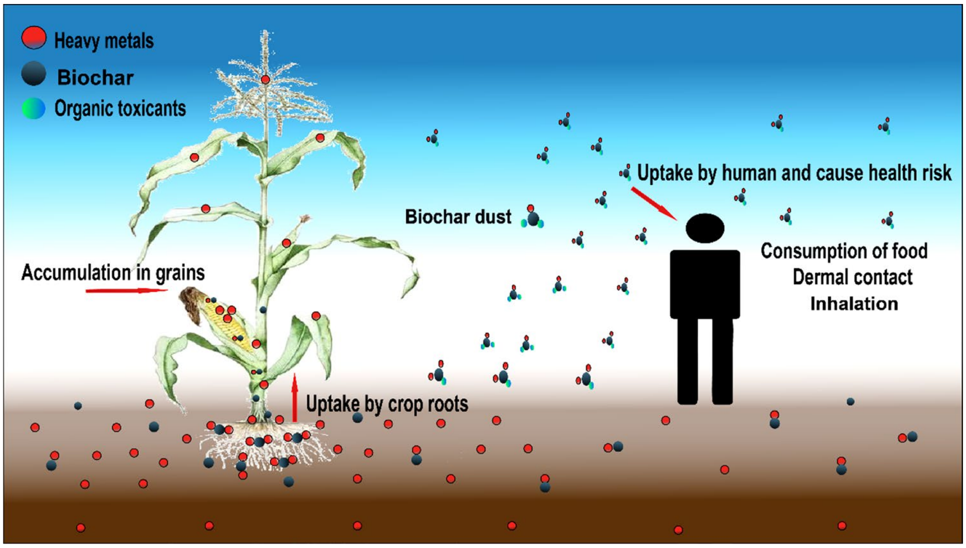

Fig. 3 Potential risks of using biochar in the remediation of HM-contaminated soil

Future perspectives

As a cost-effective and environmentally friendly agent, biochar has a broad prospect in soil HM remediation. However, the properties of biochar vary with the feedstocks and pyrolysis temperature, and they influence the interaction mechanisms between the biochar and soil HMs; In addition, there are several potential health risks in the processes of biochar preparation and soil HM remediation. Different kinds of feedstocks can be attributed to different health damages due to the lack of unified biochar production and application standards. For example, biochar derived from straw and wood is prone to dust and causes respiratory diseases, cytotoxicity, and dust pneumoconiosis among biochar dust-exposed workers (Hamatui et al. 2016; Sigmund et al. 2017; Torres et al. 2017). However, animal manure and sewage sludge-biochar are easy to carry bacteria and pathogens, which can adsorb toxic substances (e.g., HMs, PAH, and pesticides) and become a serious secondary source of pollution threatening human health (Safaei Khorram et al. 2016; Smith et al. 2009; Capone et al. 2020). Therefore, some effective protection measures and unified standards are necessary to make for biochar production and application to reduce the risk of biochar dust or particles carrying with pathogens exposure. This review summarizes the potential specific health risks of biochar production and application, which can provide an implicational reference for health management departments to make health prevention strategies and measures. However, the immobilization mechanism of biochar to different sources of HMs and the effect of environmental conditions on the release of HMs during biochar aging are still unclear. Meanwhile, it is also necessary to scientifically evaluate the use of biochar for the remediation of HM-contaminated soils and the extent of the potential human health risks after remediation. Thus, future research should be strengthened in the following aspects.

1. Biochar is inevitably influenced by the chemical, physical, and biological actions in the soil during the remediation of HM-contaminated soils. Therefore, it is necessary to understand the interaction mechanisms between biochar and HMs during the aging process.
2. The spatial differentiation of soil HMs is significant in high geological background areas. HMs from natural and anthropogenic sources have different activities and availabilities. However, the HM remediation mechanism of biochar in such high geological background areas is still unclear.
3. The stability of biochar is not only affected by the feedstock and pyrolysis temperature, but also by the soil environmental conditions. The remediation of HM-contaminated soil using biochar under special environmental conditions (dry–wet alternation or freeze–thaw alternation) requires further study.
4. There are several potential risks in the preparation and application of biochar. However, human health risk assessment for the remediation of HM-contaminated soils using biochar is still lacking.

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Data availability The data sets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Animal research Participation of animal subjects did not occur in this study.

Consent to participate All the authors participated in writing the manuscript.

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