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Review

The Remediation Mechanisms and Effects of Chemical Amendments for Heavy Metals in Contaminated Soils: A Review of Literature

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Abstract

Many countries around the world are suffering from serious problems associated with soil heavy metal pollution, especially developing countries. Heavy metal contaminants in soils mainly result from soil natural weathering and anthropogenic activities such as industrial and agricultural activities, coal-burning as well as transportation. It is widely acknowledged that heavy metal pollution may lead to the deterioration of soil environmental quality and the loss of soil ecological functions. Therefore, the control and remediation for soil heavy metal pollution need to be urgently carried out to guarantee human health and food security. To date, soil amendments are increasingly employed to remediate heavy metal contaminated soils. In recent years, the research progress at an international scale is reviewed with regard to soil amendments used for the remediation of heavy metal polluted soils by laboratory and field-scale studies. A summary is provided with soil amendment types, metal stabilization mechanisms, as well as the influences of soil amendment application on soil properties. At last, future research prospects are put forward to broaden the development of this field. It is expected to provide valuable references for the research and practice of heavy metal stabilization in polluted soils.

Keywords: heavy metals, soil amendments, remediation mechanism, soil properties

Introduction

Due to the detrimental effects on human health and the soil ecosystem, soil pollution with heavy metals has received growing attention worldwide [1]. Heavy metals have a considerable range of pollution sources, mainly including geologic and anthropogenic sources. Based on the recent literature reviews, mining and smelting activities are regarded as the primary causes of heavy metal pollution in soils [2-3]. Due to their non-degradation, toxic metals are difficult to be removed through the natural process once

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entering the soils. At present, the basic principles of soil remediation are classified into two categories [4]. One approach is that toxic heavy metals are removed from contaminated soils via physical, chemical and biological technologies to reduce their contents, and the other approach is that their mobility and toxicity are reduced by the application of soil amendments during stabilization [5-6]. Compared with other techniques, such as soil replacement, electrochemical remediation, phytoremediation and microbial remediation, chemical stabilization technology with convenient, low cost, and efficient advantages can be applied to soil remediation projects at larger scales [7].

Currently, there remain some limitations in chemical stabilization technology used for heavy metal polluted soils, since this technology only changes the chemical species of heavy metals and reduces their toxicity in soils through physicochemical reactions, but can not completely remove them. It should also be noted that the stabilized heavy metals might be re-released, when the environmental conditions change [8]. In addition, the selection, combination and application of soil amendments for different contaminated soil and site types are important parts of stabilization remediation projects. Many previous investigations have revealed that amendment application can not only show significant remediation effects on heavy metals in soils, but also effectively improve soil environment and restore ecological systems [9-11].

Based on the above backgrounds, this study mainly focuses on the current pollution situation of heavy metals and introduces their source pathways and potential environmental hazards in soils worldwide. Besides, the recent research progress is comprehensively reviewed in terms of stabilization mechanisms, as well as the types of soil amendments and their effects on soil physicochemical and biological properties. Finally, the current technical challenges and future research directions are presented to provide scientific references for remediation of heavy metal contaminated soils.

Results and Discussion

The Current Situation of Heavy Metal Pollution Worldwide

Heavy metal pollution in soils remains an environmental problem worldwide, and has posed a serious threat to public health [12]. For example, Mamat et al. evaluated the human health risk posed by heavy metals in farmlands of 146 cities in China, and the results demonstrated that Cr contributed 98.5% to health risks [13]. Currently, there are more than 5 million sites worldwide, covering 20 million hectares of contaminated land with heavy metals [14]. In Europe, millions of hectares of soil are also contaminated with heavy metals, which accounts for around 37.3% of the total European land area [15] In the US, more than 100,000 sites are associated with heavy metal contamination [16], and nearly 600,000 hectares of land have suffered from heavy metal pollution [7]. In Italy, 57 contaminated sites with heavy metals are preferentially concerned nationwide, one-sixth of which are located in the Campania region with a total area of 345,000 hectares [17]. In France, 5759 contaminated or potentially contaminated sites are identified, 60.1% of which are contaminated with heavy metals [18]. In Japan, the area of heavy metal contaminated farmlands are 470,000 hectares [19]. There are about 2600 abandoned mines in South Korea, nearly 50.0% of which are due to heavy metal pollution [20]. Moreover, the number of abandoned metal mine sites in Canada, Japan, and the UK ranges from 5,000 to 10,000 [21]. In Australia, there are about 50,000 abandoned mine sites nationwide.

Similarly, heavy metal pollution in China is also serious. According to related reports, more than 30.0 % of farmlands in southern China are contaminated with heavy metals such as Cr, Cd, Pb, As and Hg [22-23]. It is reported that about one-sixth of farmlands (45 million hectares) in China have been polluted with heavy metals in varying degrees, of which 14.5 % are lightly contaminated, 1.5% are moderately contaminated and 0.7% are severely contaminated, respectively [3, 24]. The cultivated area (20 million hectares) contaminated with Cd and Pb is estimated to about 20.00% [25]. A related study reported that about 1.5 million hectares of land are also contaminated with heavy metals due to mining activities in China, and the area of contaminated soil is increasing at a rate of 46,700 hectares per year [26]. Another survey showed that among the 1.4 million hectares of wastewater-irrigated land in China, 64.8% of the land is polluted with heavy metals, accounting for 16.0% of the total cultivated area [27]. In addition, Yang et al. reported that heavy metal contents in surface soils at 10 smelter contaminated sites exceeded the permissible limits recommended by the Chinese Environmental Quality Standard for Soils (GB15618-1995) [28]. Thus, it can be seen that heavy metal pollution in soils has been received wide attention globally.

Source Identification of Heavy Metals Pollution

Heavy metal pollutants in soils are mainly emanated from geologic and anthropogenic processes. The natural sources include soil parent material and weathering, while anthropogenic sources are dominantly controlled by industrial emissions, mining, and smelting activities, coal combustion and sewage irrigation, as well as fertilizer and pesticide application [29]. These anthropogenic activities have resulted in large amounts of toxic heavy metals entering into the soil environment through various pathways [30-31]. For example, Qian et al. reported that after 48 and 35 years, the enrichment levels of Cd and Zn in fertilized soil would reach the risk screening values of soil environmental quality standards in China (GB15618-2018), respectively, based on the dynamic mass balance model [32]. Lee et al. investigated the effects of a zinc smelter on nearby soils in Korea and found that the migration depth of heavy metals in the soil reached 0.6 m. The results also have indicated that the emissions and deposition of smelter-derived dust contributed 49.0-83.0 % to heavy metal pollution in surface soil [33]. In addition, Liu et al. collected a total of 1772 surface soil samples from 135 large open-pit coal mining areas in China and found that the Cd, Cu and As concentrations also exceeded the risk screening values in China (GB15618-2018) [34]. It is also reported that through various industrial activities, Cd, Zn, Cu, and Pb release reaches about 2.2×10^{-4}, 3.5×10^{-5}, 9.39×10^{-5}, 7.38×10^{-5} metric tons, respectively, during the last few decades [35].

Considering the expensive costs and technical challenges of soil remediation, controlling the sources of heavy metal contamination in soils is regarded as the most effective strategy. Therefore, the sources of heavy metal pollution must be quantitatively identified to effectively reduce the remediation cost and workload [36]. Currently, positive matrix factorization (PMF) models and isotope tracing techniques have been widely used to identify the sources of heavy metal pollution. For example, Yang et al. used the PMF model to determine the sources of heavy metal pollution in 125 farmlands in Jiangsu and Zhejiang provinces, and reported that anthropogenic activities contributed 59.7% and 67.9% to heavy metal pollution, respectively [37]. Fei et al. applied PMF and GeoDetector models to investigate the sources of heavy metals in 2150 topsoils in Hangzhou, and the results suggested that the contribution of agricultural activities, industrial activities and soil parent materials to heavy metal pollution are 63.4%, 19.8% and 16.8%, respectively [38]. Wu et al. used the modified PMF model to analyze the source characteristics of heavy metals in 140 farmlands in Tianjin and found that irrigation, atmospheric deposition and sludge application contributed 26.6%, 19.6% and 2.9% to heavy metal pollution, respectively [39]. Similarly, a recent study by He et al. reported that in Baiyin City, a typical mining city in China, the percentage contribution of anthropogenic heavy metals in farmlands in the mining areas, Yellow River irrigation area, as well as sewage irrigation areas of West Dagou and East Dagou was about 85.0%, 41.0%, 88.0%, and 76.0%, respectively [40]. These published studies can provide valuable information for the pollution control, risk management and remediation projects of heavy metals in soils.

The Potential Hazards of Heavy Metal Pollution

Since soil is an important part of the food production system, heavy metal pollution in soils has received attention from governments and the public worldwide. According to relevant studies, 13.9% of food production in China is influenced by heavy metal pollution [41]. Numerous studies have also shown that heavy metal pollution caused the deterioration of soil quality and the loss of soil biochemical functions. For example, soil structure is destroyed by mining activities and there is bare vegetation in mining polluted soils due to the presence of high metal concentrations [42]. Heavy metal contamination has significant effects on the transformation and decomposition of soil nutrients. For example, Enya et al. indicated that heavy metals have an inhibitory effect on the decomposition of soil organic matter. Soil enzyme activities are considered as an indicator of soil quality, which plays an important role in maintaining soil health and fertility [43]. For example, Liu et al. found that heavy metals have led to the denaturation of the proteins in soil enzymes and the formation of metal complexes with enzyme substrates, which further have resulted in a decrease in the sucrase, protease, and urease activities [44]. In addition, microbial activity, biomass and community structure in soils can also be used as biological indicators to evaluate soil health [45]. For example, Chen et al. observed that long-term heavy metal pollution reduced soil microbial activity and biomass by 3.0-45.0% and 21.0-53.0%, respectively [46]. Bai et al. reported that combined heavy metal pollution caused by a Pb/Zn smelter in China explained 30.6% of the variation in soil bacterial community structure [47].

In recent decades, many previous studies have also suggested that excessive accumulation of heavy metal pollutants can cause serious ecological and human health hazards through soil-crop-human systems. For example, Neaman et al. collected 182 soil samples in the Valparaiso region of central Chile and determined Cu, As, Pb, and Zn contents in soils, and showed that 11.0% and 48.0% of soil contaminated with Cu and As posed the potential risks to the plants and earthworms, respectively, while 25.0% of soil samples severely threatened human health [48]. He et al. investigated the effects of Pb pollution on children's health due to coal mining activities in China, and found that the blood Pb levels of children differed significantly by age and sex, and the mean blood Pb levels in 229 children (0-6 years old) was 31.77 μg/L, of whom 19.2 % and 0.4% were higher than 50 μg/L and 100 μg/L, respectively [49]. Lu et al. collected 440 paddy soil and rice samples in a typical rice production area of China, and the findings indicated that the pollution levels of Cd in 99.0% of soil samples and 68.9% of rice samples were higher than the permissible limits of the Chinese standards [50]. Similarly, Li et al. studied the effect of Pb smelting activities in China on the heavy metal accumulation in the soil-wheat-human system, and the results showed that as the distance from the smelter decreased, the contents of heavy metals absorbed by nearby residents through the consumption of wheat increased [51]. Therefore, there is an urgent need to remediate heavy metal contaminated soils and mitigate their potential health hazards.

Chemical Stabilization Remediation of Heavy Metals in Soils

Currently, physical, chemical and biological remediation techniques are widely used for heavy metal-contaminated soils worldwide. These technologies have their advantages, disadvantages and applicable scopes and their remediation principles, efficiency and costs vary in different conditions. Among them, chemical stabilization remediation techniques have been developed to remediate large-scale heavy metal contaminated sites because of their simple operation, low cost, and high efficiency [52-53]. Based on a recent investigation, the utilization rate of this technology in China has reached 48.5% in 2017-2018 [54]. This chemical remediation technology relies on the addition of soil amendments to improve soil physicochemical properties, and effectively reduce the mobility and toxicity of heavy metals through various physicochemical reactions, such as adsorption, ion exchange, precipitation, complexation, and redox reactions, and ultimately reduce their harmful effects on animals, plants, and humans [55-57]. For example, Mu et al. prepared a silica-iron amendment from acid leached copper residue by thermochemical activation to remediate heavy metal contaminated soils. The results indicated that the better immobilization effects of the amendment for Cd, Cr, and Pb were mainly due to soil pH change and the chemisorption, co-precipitation, and ion exchange induced by Fe, Si, and Ca [58]. However, the stabilized heavy metal pollutants may become mobile again, under dynamic environmental conditions, such as deposition event, freezing-thawing cycles, wetting-drying alternation and natural weathering [59]. For example, Liu et al. showed that atmospheric deposition near lead/zinc (Pb/Zn) smelters reduced the effectiveness of metal stabilization remediation in contaminated soils by 22.9-57.5% [60]. Therefore, the chemical stabilization effects of soil amendments for heavy metals in contaminated soils need to be evaluated and tracked periodically [61].

Stabilization Effects of Soil Amendments on Heavy Metals in Soils

The wide application of organic and inorganic soil amendments in soil remediation has continued to be a hot topic in the past 20 years, and more than 3000 related papers have been published [62]. To date, organic amendments generally include biochar, sludge, compost and livestock manure. Moreover, inorganic amendments mainly involve clay minerals, lime-based materials, metal oxides, metal sulfides, silicates, phosphate, iron-based materials [62-63]. Table 1 summarizes some examples of recent studies evaluating the stabilization effectiveness of soil amendments for heavy metals. These previous studies have indicated that the remediation efficiency of soil amendments are related to the following factors: the conditions of soils and experiments, the application amount and types of amendments, the duration of stabilization, the geochemical behaviors of heavy metals, and the degree of heavy metal contamination.

Stabilization Mechanisms of Heavy Metals by Soil Amendments

Adsorption and ion exchange: Heavy metals are immobilized by soil amendments via ion exchange and adsorption, thereby reducing their toxicity and bioavailability. For example, Khadhar et al. used principal component analysis to study the factors affecting the metal mobility in sludge-amended soils, which found that Cd, Zn, Pb, and Cu preferentially accumulated in organic-rich surface horizons and clay layers of soils, mainly due to the decisive role of adsorption [81]. Liao et al. studied the stabilization effects of nanohydroxyapatite (n-HAP) on V and found that the hydroxy radical in n-HAP can form coordination compounds with V and adsorb it to the hydroxyapatite surface [82]. Meanwhile, the phosphate added to the soil was readily bound to V, which reduced the V mobility [82]. Moreover, Liu et al. applied mineral amendments to reduce the reducible fraction of Tl in soils, which was due to the increase in soil pH and the ability of Fe-Mn oxides to adsorb Tl. Another reason was that Tl from the exchange fraction was transferred to the reducible fraction and then the residual fraction [83]. Li et al. found that in calcareous soils, soluble phosphate and calcium for Pb stabilization was dominated by an adsorption-exchange mechanism, that is, Pb(II) was adsorbed on the insoluble phosphate surface, which exchanged with calcium in calcium-phosphorus compounds to form calcium-lead subcrystalline minerals [84].

Co-precipitation: After alkaline materials such as sepiolite adding to soils, an increase in soil pH resulted in the adsorption sites with negative charges increasing, which prompts the precipitation of hydroxide or carbonate, thereby reducing the metal toxicity [9]. Phosphate-containing minerals also have a strong ability to immobilize heavy metals. For example, Wang et al. found that phosphate groups in phosphate-modified palygorskite form metal phosphate precipitates, which played an important role in heavy metal immobilization. In addition, heavy metal ions can co-precipitate with iron-containing compounds in amendment treatment [85]. For example, Lin et al. applied iron oxide nanoparticles to stabilize Cd in polluted soils and found that Cd and Fe (II) on the surface of Fe minerals might undergo co-precipitation reactions during microbial and chemical Fe (II) oxidation [70]. Similarly, Cao et al. used a surface modification of silica nanoparticles with mercaptopropyl trimethoxysilane and ferrous sulfate to immobilize soil Cd, Pb and As, and found that these

Table 1. The stabilization effects of soil amendments for heavy metals in polluted soils.

Amendments	Material	Heavy metals	Stabilization or immobilization	References
Organic	Biochar	Pb	The immobilization rate of Pb in agricultural soils was 87.0%,	[64]
	Sludge	Pb, Zn and Cd	15.0% sludge addition resulted in the leaching rates of Pb, Zn and Cd reducing by 84.0%, 64.0% and 76.0%, respectively	[65]
	Compost	Cr, Cd, Pb and Mn	Compost treatment led to the uptake of Cd, Cr, Pb and Mn by radish reducing by 32.5%, 50.3%, 44.5% and 42.3%, respectively	[42]
	Pig manure	Cd	Cd bioavailability decreased significantly with the increase of manure addition	[66]
Inorganic	Sepiolite	Cd, Pb and Zn	When 5.0% sepiolite was added, the leaching rates of Cd, Pb and Zn reduced by 61.0%, 61.0% and 70.0%, respectively	[67]
	Lime	Cd	The concentration of bioavailable Cd in soils and rice decreased by 12.9-18.2% and 28.5-56.2%, respectively	[68]
	Layered double hydroxide (LDH)	Cr (VI)	S-Mg-LDH, S-Ca-LDH, Mg-LDH and Ca-LDH treatments reduced the leaching of Cr (VI) by 75.4%, 72.4%, 86.6% and 75.9%, respectively	[69]
	Iron oxide nanoparticles	Cd	The exchange and carbonate bound fraction of Cd decreased by 14.2-83.5% and 18.3-85.8%, respectively	[70]
	Sodium Sulfide	Cd	The $CaCl_2$ extracted Cd concentration increased at the lower application of sodium sulfide, and decreased with the increase of sodium sulfide application.	[71]
	Silicon fertilizer	Cd, Cr, Cu, Pb, As and Hg	1) 3.2% silicon fertilizer reduced the contents of Pb, Cr and Cu in Chinese cabbage by 14.5%, 19.1% and 17.5%, respectively. 2) Hg content decreased by 22.3% when the application rate was 1.6%. 3) 0.8% silicon fertilizer treatment resulted in The content of arsenic decreasing by 7.9%.	[72]
	Nano Silicon Dioxide	Cd, Pb and As	The stabilization efficiency of Pb, Cd and As were 97.1%, 85.0% and 80.1%, respectively	[73]
	Calcium superphosphate	Cd, Pb and Zn	The application of calcium superphosphate decreased DTPA-extracted Pb and Cd by 1.4 to 10.7%, while DTPA-extracted Zn increased by 0.2 to 13.4%.	[74]
	Nano zero-valent iron (N-ZVI)	Cr (VI) and Cr_{total}	The stabilization efficiency of Cr (VI) and total Cr in the soil after two weeks of soil aging was 98.7% and 92.1%, respectively, in 5.0% of the vinegar residue loaded with N-ZVI.	[75]
	Fly ash	Cd	The bioavailable content of Cd decreased from 4.12 mg/kg to 1.92 mg/kg and the residual content was 2.48 times higher than that of the control, after 10.0% fly ash added to Cd-contaminated soil for 30 days	[76]
Combined	Chemical fertilizer, sheep manure and medicine residue	Cr, Pb, Cd, As and Hg	Compared with the medicine residue and fertilizer treatment groups, Cr, Pb, Cd, As and Hg in soils treated with sheep manure and fertilizer increased by 3.6%, 10.9%, 6.1%, 1.4% and 1.4%, respectively	[77]
	farmyard manure and lime	Cd	Compared to the controls, the content of the exchange fraction of Cd reduced by 44.1%	[78]
	Fertilizer, lime and seafoam	Cd and Pb	DTPA extracted Cd and Pb contents decreased by 46% and 68%, respectively	[79]
New material	New materials rich in Fe, Si and Ca	Cd	The uptake and accumulation of Cd by plants were effectively reduced	[80]

metals could be transferred to insoluble mercapto metal compounds and hardly soluble iron arsenate precipitate by modified nanosilica [73].

Complexation: Soil amendments contain chemicals or functional groups that play a dominant role in metal immobilization through surface complexation reactions. For example, Gao et al. prepared biochar by co-pyrolysis in rice straw with orthophosphate ($Ca(H_2PO_4)_2$-H_2O and KH_2PO_4) for soil remediation in Pb-Zn mining areas and found that orthophosphates in biochar readily complexed with heavy metals, thus reducing heavy metal activity [86]. Fan et al. prepared thiol-modified rice straw biochar to remediate Cd and Pb contaminated soil and found that the biochar selectively adsorbed Cd(II) and Pb(II) through surface complexation reactions [87]. Kameda et al. developed a metal adsorbent based on Fe and gypsum, and its stabilization mechanism for As was due to the formation of internal spherical surface complexes between As and ferrihydrite [88]. Likewise, Wang et al. found that humic acid greatly improved the immobilization ability of montmorillonite for heavy metals, because oxygen-containing functional groups in humic acid could promote the surface complexation reaction with heavy metals [89].

Redox effect: Immobilizers with redox effects reduce the mobility and toxicity of heavy metals by altering their valences. Fan et al. showed that the reduction in the lability and bioaccessibility of As could be attributed to the fact that amorphous FeOOH formed from Fe0 oxidation on the surface of zero-valent iron nanoparticles, and could adsorb or co-precipitation with As [90]. Some recent studies have shown that Cr (VI) with higher mobility and toxicity could be converted to Cr (III) with lower mobility and toxicity in contaminated soils. For example, Hou et al. found that the reduction played a dominant role in Cr immobilization within 0-30 days of the addition of nano-zero-valent iron to soil, which resulted in more Cr (VI) reduced to Cr (III) [91]. Chen et al. investigated the effects of co-pyrolysis treatment of rice straw with Cr-contaminated soil under pressure and found that an increase in the pyrolysis temperature and rice straw were effective in reducing Cr (VI) to Cr (III) [92]. Moreover, Wang et al. investigated the immobilization mechanism of Cr (VI) by pyrite particles using XPS and found that the reduction resulted in 66.0 % of Cr being immobilized on the particle surface [93].

Effects of Soil Amendments on Physical, Chemical and Biological Properties of Soils

Effects of soil amendments on soil physical properties: Amendment application have a significant impact on the strength and structure of polluted soils. For example, Oprckal et al. found that after 3 and 56 day curing, the combined application of paper ash and red mud increased the unconfined compressive strength of the treated soil by 2 and 4 times, respectively, which was mainly due to the formation of new hydration reaction products during the extended curing time [94]. Li et al. added organic and inorganic soil amendments to Cd polluted soil and showed that the functional groups and large specific surface of amendments could promote the integration of small agglomerates and the formation of large agglomerates in soils [94]. Yang et al. (2020) evaluated the feasibility of Cd remediation in polluted soils using straw ash (SA), coal fly ash (CFA), blast furnace slag (BFS), and ferronickel slag (FNS) and found that the looseness degree of the amended soils was in the order of SA>FNS>CFA>BFS, among which the structure of SA and FNS amended soils were loosened, while that of CFA and BFS amended soils were slightly hardened [76]. Furthermore, Zou et al. found that sludge amendment increased the proportion of soil water-stable agglomerates greater than 0.25 and between 0.106 and 0.25 mm, while soil bulk density decreased by 1.6%, 4.9%, 14.1%, and 18.8%, respectively, when the application rates of sludge were 25, 50, 125, and 250 t /ha [95].

Effect of soil amendments on soil chemical properties: The results obtained from many recent studies have indicated that soil amendments could not only increase soil pH and EC, but also significantly increase soil nutrient content. For example, Hmid et al. prepared biochar from olive waste for soil remediation, and found that increase in soil pH and EC was due to the liming effect of biochar, while the increase in cation exchange was attributed to the large specific surface area and porous structure of biochar [96]. Hamid et al. showed that the hydrolysis of $CaCO_3$ in lime and sepiolite to hydroxide ions increased soil pH [97]. Fan et al. (2020) showed that after 28 days, the addition of biochar and thiol-modified biochar to Cd and Pb contaminated soil increased the total organic carbon (TOC) content by 28.0-115.0% and 33-130%, respectively [87]. The results could be explained by the fact that the biochar had significant high carbon content. Chen et al. prepared two types of biochars by pyrolyzing pig carcass and wood to remediate Cd contaminated soil, and the results showed that both biochars were effective in improving soil physicochemical properties. This is because biochar application increased the available P and K contents in soils and also promoted the uptake of P and K by cabbage [98]. Luo et al. studied the remediation effects of biochar prepared from corn cobs under high-temperature pyrolysis for Cd and As contaminated soil and found that the application of biochars significantly increased the content of organic matter and total nitrogen (TN) in soils [99]. The finding was during immobilization treatment, N and C were released from biochar into the contaminated soil, thus increasing soil TOC and TN contents .

Effect of soil amendments on soil biological properties: Soil amendments can promote plant growth and increase biomass, and meanwhile reduce the accumulation of heavy metals by plants. For example, Liu et al. found that biochar treatment reduced the Zn concentrations in sunflower by 13.8% to 37.2% [1]. Mu et al. studied the metal accumulation in vetiver using CaO-activated silica-based slag as an amendment, which effectively reduced metal uptakes by plants and promoted plant growth. The results was mainly due to an increase in soil pH and available silica extracted from citric acid [100]. Similarly, Wang et al. studied the effects of triple superphosphate on soil remediation, and reported that the biomass of B. microphylla and Sliax sp reduced by 24.9% and 57.4%, respectively [101]. In addition, amendment applications not only significantly reduced the metal toxicity, but also significantly increased crop yields. For instance, Zhao et al. showed that zeolite application in 2017 and 2018 decreased the available Cd content by 26.0% and 28.0%, respectively, while increased the rice yields by 29.8% and 31.7%, respectively [53]. The results could be interpreted by the fact that zeolite addition increased available Si content, and thus promoted rice growth. Wang et al. studied the effects of silicon applications on the growth of brassica chinensis and found that 0.2 to 1.6% silicon fertilizer significantly increased the fresh weight (74.7% to 189.9%), dry weight (38.5% to 84.6%) and leaf (18.3% to 46.1%) of *Brassica chinensis* L., compared to the control [72]. The result was attributed to the fact that silica fertilization promoted the uptake of N, P and K by the plants and plant growth. Similarly, Xiao et al. found that compared with the control, the grain weight of rice was increased by 19.0-27.2% and 45.3-57.1% in soils amended by 5 g/kg and 10 g/kg of biochar, respectively [102]. The finding could be due to the fact that biochar could enhance soil nutrient, and reduce phytotoxicity caused by Cr(VI). Soil amendment applications could increase the activity of biological enzymes and microorganisms in soils. For example, Abad-Valle et al. found that when sepiolite was added at 5.0%, basal respiration as well as dehydrogenase and alkaline phosphatase activities in soils increased to 25.0%, 138.0%, and 42.0%, respectively, because sepiolite application reduced the metal toxicity and increased pH in soils [67]. Meanwhile, soil amendment applications could change the population of animals and microorganisms. For example, Li et al. found that the total number of animals in the three treatment groups decreased by 14.5%, 33.3%, and 46.6%, respectively, after a 9-year biosolids application [103]. Hou et al. added 3% carboxymethylcellulose loaded zero-valent iron to soils and found that bacteria and fungi increased by 175.6% and 188.0%, respectively [91]. Similarly, a biochemical composites material (BCM) was prepared by Ma et al, which also significantly increased the numbers of bacteria and fungi in Cd polluted agricultural soil [104]. In addition, soil amendment could increase the abundance and diversity of bacterial community. For instance, calcium-based magnetic biochar (Ca-MBC) and biochar treatment changed the bacterial abundance and increased soil bacterial α-diversity [105].

Conclusion and Future Perspective

Heavy metal pollution in soils results from various anthropogenic activities. At present, the remediation of heavy metal contaminated soils has received extensive attention on an international scale. During stabilization, soil amendments can not only reduce the bioavailability, mobility, and toxicity of heavy metals in soils through physicochemical reactions such as adsorption, ion exchange, precipitation, complexation and redox, but also improve soil quality and restore soil ecosystem functions. Despite the utilization rate of chemical stabilization technology is significantly high in soil remediation practice in China, its application has some technical challenges. Future work in the following research priorities areas is therefore encouraged:

(1) Heavy metal pollutants poses potential health risks to the soil-crop-human systems and other environmental mediums. Therefore, studies on the migration and transformation behaviors, as well as ecotoxicological effects of heavy metals in multimedia systems are of great significance for the utilization and development of heavy metal contaminated sites.

(2) Soil enzyme activities, and microbial activities, biomass as well as community structure can be regarded as sensitive indicators to reflect the amelioration effects. Therefore, during soil habitat function restoration, the qualitative relationship of heavy metals with soil physicochemical properties and biological indicators need to be studied to provide an insight into the bioremediation strategies.

(3) Because the remediation costs mainly derive from materials, equipment, process operations, on-site stabilization experiments, soil amendments with high treatment costs can not be applied in large-scale remediation projects. In addition, soil amendments with the advantages of environmentally friendly, high efficiency and low costs should be developed for soil remediation. At present, it is difficult to assess the long-term effectiveness of soil amendments in stabilization remediation. Therefore, the quantitative accelerated aging simulation experiments should be conducted to establish the mathematical models, which are used to predict the metal stabilization effect after decades or even centuries.

(4) Chemical stabilization technology with advantages, disadvantages and applicability needs to be explored in depth and combined with other technologies to show the better remediation effects of heavy metal contaminated soil. For example, soil amendments are used to improve the plant habitat environment, and then significantly increase the heavy metal enrichment in hyperaccumulated plants.

(5) The traditional (XRD, SEM-EDS, XPS, FTIR) and modern instrumental analytical techniques [X-ray absorption fine structure (XAFS), X-ray absorption spectroscopy (XAS), and spherical aberration-corrected scanning transmission electron microscopy

(Cs-STEM)] should be combined to in depth investigate the mechanisms of metal stabilization, and predict its long-term effectiveness.

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Conflict of Interest

The authors declare no conflict of interest.

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