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ARTICLE

Organic Materials Could Improve the Phytoremediation Efficiency of Soil Potentially Hazardous Metal by *Sedum alfredii* Hance

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ABSTRACT

Soil potentially hazardous metal (PHM) is continually attracting public attention worldwide, due to its highly toxic properties and potentially huge damage to human being through food chain. Phytoremediation is an effective and eco-friendly way in remediation technology. A pot experiment was carried out to investigate the effect of different organic materials (biogas residue (BR), mushroom residue (MR), and bamboo-shoot shell (BS)) application on phytoremediation of two PHM-contaminated soils (Fuyang soil as 'heavily-polluted soil' and Wenzhou soil as 'moderately-polluted soil', respectively) by *Sedum alfrecdii* Hance. The results indicated: 1) for moderately-polluted soil, the 5% BR treatment had the strongest activation to Cu and Zn, for heavily-polluted soil, 1% BS treatment had the highest activation effect for Cu, Zn, Pb and Cd. 2) the above-ground biomass of *Sedum alfredii* Hance increased with the addition rate of organic materials. 3) for Cd uptake of *Sedum alfredii* Hance in moderately-polluted soil, only 1% BS treatment had a better accumulation effect, compared to the control, for Zn element, MR treatments were weaker than the control, while other treatments were better than the control, of which 5% BR, 1% BS and 5% BS accumulated more Zn element by 39.6%, 32.6% and 23.8%, respectively; in heavily-polluted soil, the treatments of 5% BS, 1% BR and 5% BR accumulated more Cd than the control by 12.9%, 12.8% and 6.2%, respectively, the treatments with organic materials addition promoted Zn accumulation in shoots of *Sedum alfredii* Hance, and the best treatment was 5% BS. Therefore, an appropriate application rate of BS and BR could improve the remediation efficiency for Zn/Cd contaminated soils by *Sedum alfredii* Hance.

KEYWORDS

Organic material; *Sedum alfredii* Hance; potentially hazardous metal polluted soil; phytoremediation efficiency

1 Introduction

Potentially hazardous metal (PHM) pollution of arable soils is attracting more and more attention worldwide due to the high toxicity, persistence and easy-bioaccumulation characteristics of PHMs [1]. It is urgent to find economic, efficient and feasible remediation technology for soil PHM pollution [2]. The general remediation methods of soil PHM pollution refer to physicochemical measures such as soil washing, surface capping and electro-kinetic extraction, bioremediation and phytoremediation [3,4].

However, the physicochemical methods cannot deal with large-scale soil pollution, which also can further lead to soil structure damage, biological activity decrease and soil quality degradation [5,6]. Compared with physicochemical remediation methods, phytoremediation has the advantage of *in-situ* treatment, low cost, simplicity of practice and compatibility with environmental aesthetics [7,8]. Because of its obvious advantages, phytoremediation has been received increasing attention and becomes one of the hot-spots in the environmental research field [9–11]. But the phytoremediation also has deficiencies such as lower remediation efficiency in highly polluted soil, slow remediation process, longer remediation cycle and is limited by practically environmental factors [12,13]. Therefore, it is important to take necessary measures to improve the efficiency of phytoremediation [14–19].

Applying organic fertilizer or organic material into soils is a practicable method, which could improve soil fertility and activate soil PHMs by dissolved organic matter (DOM) such as small molecule organic acids, leading to the availability change of PHMs for plants uptake [20]. Pan et al. found that organic fertilizer was beneficial to increase the content of exchangeable Cu and Cd in topsoils, which further promoted the uptake and accumulation of Cu and Cd by wheat [21]. In addition, Wei et al. [22] reported the remediation efficiency of hyperaccumulator (*Rorippa globose*) on Cd in contaminated soil was significantly improved, with the application of chicken manure. However, Wu et al. [23] reported that 2% humus combined with 2% lime application could immobilize the potentially hazardous metal in Cd- and Cu-polluted soil. While phytostabilized plant restrict the root uptake and translocation of toxic metals, resulting in a phytostailization effect [24]. Therefore, the organic material application has different effects on phytoremediation efficiency in different situations and how to apply organic materials for the remediation of PHMs-contaminated soils needs further study. Meanwhile, there is little research related to agricultural wastes application for the remediation efficiency of PHMs-contaminated soil by hyperaccumulators.

In China, a large number of organic wastes are produced in the process of agricultural production, including biogas residue (BR), mushroom residue (MS), bamboo shell (BS) and so on. The application of organic wastes as manure not only reduces their pollution to the environment, but also reduces the use of chemical fertilizer [17]. Biogas residue is a high-quality organic fertilizer which contains a large amount of organic matter and nutrients (e.g., N, P and K) for plant growth [23]. Mushroom residue is rich in cellulose, vitamins, mineral elements and other bioactive substances. It can be used as organic fertilizer or soil amendment in agricultural production [25]. As the processing waste of bamboo shoots, the bamboo-shoot shell also contains a large amount of amino acids, proteins, coarse fibers and other nutrients. High-quality compost can be obtained from bamboo shells [26,27].

Sedum alfredii (*S. alfredii*) Hance is a kind of Zn/Cd hyperaccumulators, which is found in a mine area in Southeast China [28]. It is one of the ideal remediation plants which can be applied to remove Cd and other PHMs from the contaminated soils [29]. In this study, a pot experiment was conducted to investigate the effects of three organic materials (biogas residue (BR), mushroom residue (MS) and bamboo shell (BS)) on phytoremediation by *S. alfredii* Hance. The objectives of our study were: (1) to investigate the effect of different organic materials on phytoremediation efficiency by *S. alfredii* Hance; (2) to select suitable ways of organic materials application on different polluted soils; and (3) to provide important information for practical field remediation of PHMs-contaminated soils.

2 Materials and Methods

2.1 Experimental Materials

2.1.1 Soils

The Cd-contaminated farmland soils were collected in two places (Wenzhou and Fuyang cities). Based on GB 15618-2018 in China [30] and single factor pollution index [31,32], Wenzhou soil was classified as "moderately-polluted soil", which was collected from an experimental base in Wenzhou academy of agricultural science, Wenzhou City, Zhejiang Province; while Fuyang soil was named as 'heavily-polluted soil', which was taken from the surrounding area of a smelting plant in Huanshan Town, Fuyang City, Zhejiang Province. The basic physico-chemical properties are shown in Table 1. Soil samples were air-dried and sieved to pass a 5 mm nylon mesh.

Table 1: Basic physicochemical properties of materials used in the experiment

Experimental materials	Moderately-polluted soil	Heavily-polluted soil	Biogas residue	Mushroom residue	Bamboo shell
pH	5.32	5.64	6.50	7.80	6.80
OM (%)	4.05	2.86	52.72	75.11	56.22
CEC (cmol kg^{-1})	20.60	9.19	–	–	–
TN (%)	–	–	1.72	1.14	2.24
TP (%)	–	–	0.20	0.10	0.44
TK (%)	–	–	0.91	0.60	1.35
AN (mg kg^{-1})	246.96	197.72	–	–	–
AP (mg kg^{-1})	74.86	9.19	–	–	–
AK (mg kg^{-1})	365.50	88.50	–	–	–
TCu (mg kg^{-1})	84.64	1183.48	25.50	10.00	8.43
TZn (mg kg^{-1})	228.15	2403.15	256.25	85.40	7.59
TPb (mg kg^{-1})	77.35	817.75	1.75	3.30	0.23
TCd (mg kg^{-1})	2.65	13.15	0.25	nd[1)]	nd
ACu (mg kg^{-1})	8.14	768.73	–	–	–
AZn (mg kg^{-1})	54.20	1140.36	–	–	–
APb (mg kg^{-1})	11.71	515.01	–	–	–
ACd (mg kg^{-1})	0.49	2.61	–	–	–

Note: "nd" means the content was undetected; OM: organic matter; CEC: cation exchange capacity; TN: total nitrogen; TP: total phosphorus; TK: total potassium; AN: available nitrogen; AP: available phosphorus; AK: available potassium; TCu: total copper; TZn: total zinc; TPb: total lead; TCd: total cadmium; ACu: available copper; AZn: available zinc; APb: available lead; ACd: available cadmium.

2.1.2 Experimental Plant

The PHM hyperaccumulator *S. alfredii* Hance was taken from an ancient Pb/Zn mine in Quzhou City, Zhejiang Province, which could reproduce asexually. After artificial propagation through cuttage, all the homogeneous plants with a length of about 5 cm, uniform size, leaves and no terminal bud were selected as tested materials.

2.1.3 Experimental Organic Materials

The biogas residue (BR) was collected from a pig manure digester in an organic farm of Yuhang County, Hangzhou City, Zhejiang Province. The mushroom residue was collected in a farm of Jiaxing City, Zhejiang Province, where the black fungus cultivation was carried out. The main raw material of fungus-stick was mulberry sawdust (about 80%). The auxiliary materials were wheat bran, cotton seed hull and lime. The bamboo-shoot shell was collected from an agricultural product processing factory in Lin'an County, Hangzhou City, Zhejiang Province. After mushroom residue (MR) and bamboo-shoot shell (BS) were fermented, three organic materials were air-dried and were ground for sieving through 2 mm nylon mesh. The basic properties are shown in Table 1.

2.2 Pot Experiment

Each organic material (BR, MR, BS) was mixed with the soil according to the organic material-soil ratio of 1% and 5%, respectively. Therefore, a total of 7 treatments were set up including a control (no organic material application) (Table 2). Each treatment had three replications. The size of the plastic pot was 305 mm × 210 mm × 110 mm (length × width × height) and 5 kg soil was filled in each pot. The *S. alfredii* Hance seedlings were transplanted into pots (row space: 5 cm, 35 plants per pot). When *S. alfredii* Hance was at the plant sealing line stage (average 45 days after planting), all the plants were harvested and soil samples were collected.

Table 2: Available potentially hazardous metal contents in different treatments soil

Treatments	Moderately-polluted soil (mg kg^{-1})				Heavily-polluted soil			
	ACu	AZn	APb	ACd	ACu mg g^{-1}	AZn mg g^{-1}	APb mg g^{-1}	ACd mg kg^{-1}
CK	7.6 ± 0.8 b	46.96 ± 4.1b	11.05 ± 1.5a	0.47 ± 0.03a	0.8 ± 0.06bc	0.99 ± 0.12c	0.49 ± 0.04d	1.8 ± 0.13b
1% BR	7.0 ± 0.7b	44.22 ± 3.4b	9.35 ± 1.4bcd	0.35 ± 0.05d	0.84 ± 0.07ab	1.00 ± 0.1b	0.53 ± 0.05ab	1.8 ± 0.20b
5% BR	8.4 ± 1.1a	68.51 ± 7.1a	10.93 ± 1.3a	0.37 ± 0.04cd	0.70 ± 0.05d	0.87 ± 0.05d	0.41 ± 0.03e	1.5 ± 0.08c
1% MR	7.1 ± 0.5b	45.26 ± 5.0b	9.70 ± 0.7bc	0.41 ± 0.03b	0.81 ± 0.1b	1.03 ± 0.08bc	0.52 ± 0.05bc	1.9 ± 0.12 b
5% MR	5.3 ± 0.6c	44.23 ± 3.6b	8.05 ± 0.9d	0.39 ± 0.06bc	0.77 ± 0.07c	1.00 ± 0.08bc	0.47 ± 0.05d	1.7 ± 0.46b
1% BS	6.9 ± 0.7b	40.38 ± 5.1b	8.85 ± 1.0cd	0.31 ± 0.05e	0.86 ± 0.09a	1.11 ± 0.09a	0.56 ± 0.04a	2.3 ± 0.12a
5% BS	7.2 ± 1.2b	43.63 ± 3.5b	10.62 ± 1.3ab	0.40 ± 0.04bc	0.76 ± 0.06c	1.03 ± 0.07bc	0.49 ± 0.04cd	1.9 ± 0.11b

Note: ACu: available copper; AZn: available zinc; APb: available lead; ACd: available cadmium. Different lower cases on the same column indicated significant differences between treatments ($P < 0.05$).

2.3 Analytical Method

Plant samples were washed with deionized water and were measured their fresh weight. Then *S. alfredii* Hance samples were dried to a constant weight at 70°C and measured again. The dry samples were ground in an agate grinder for further analyses. The plant samples were digested with HNO_3-H_2O_2, then the PHMs were determined by ICP-OES (Optima 7000 DV, PerkinElmer).

Soil samples were air-dried and sieved to pass a 5 mm nylon mesh. Soil pH was directly determined using a pH meter at a soil to water ratio of 1:2.5. (*w/v*) [33]. Soil organic matter was determined by concentrated sulphuric acid (H_2SO_4) and potassium dichromate ($K_2Cr_2O_7$), and titration with ammonium sulfate iron ($Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$) solution [34]. Cation exchange capacity was determined by Ammonium acetate method [34]. Available nitrogen was determined by Alkali hydrolysis diffusion method; available phosphorus was determined by sodium bicarbonate-molybdenum-antimony resistance colorimetric method; available potassium was determined by Ammonium acetate extraction-flame photometer method [34].

The available PHMs of soil samples were extracted by HCl (0.1 mol L^{-1}) and determined by ICP-OES (Optima 7000 DV, PerkinElmer) [34]. Total soil PHM contents were extracted using HNO_3-HF-$HClO_4$. Soil sample (0.1g) after passing through 0.149 mm nylon sieve, was taken in a 30 mL PTFE crucible, moistened the soil with deionized water, then added HF solution (7 ml) and concentrated HNO_3 solution (1 ml), boiled and evaporated it on the hot plate and removed the crucible from the electric heating plate when it is nearly dry. After cooling, add $HClO_4$ (2 ml), continue to boil until no white smoke and the residue in the crucible appears with light color. Then 1:1 HNO_3 (1 ml), is added and heated until the solution is completely clear.

The above solution is transferred to volumetric flask (25 ml) and determined by ICP-OES (Optima 7000 DV, PerkinElmer) [35]. Soil standard sample (GSS-4) was used for quality control.

2.4 Data Analyses

The one-way analysis of variance (ANOVA) was used to determine the significant differences among different treatments at the significant level of 0.05. The ANOVA was carried out using SPSS 20.0. All the plots were produced by origin software.

3 Results and Discussion

3.1 Effects of Organic Materials on Soil Physicochemical Properties

3.1.1 pH

Compared with CK, pH values of most treatments decreased, except 5% MR treatment (Fig. 1). For example, the pH values of 5% BR and 1% BS treatments decreased by 0.3 unit in moderately-polluted soil (P < 0.05). The reason for such phenomenon was related to different compositions of organic materials, which were further decomposed into different soluble ions or small organic acids, leading to the pH variation in the soils [36]. In addition, pH values were also be affected by metabolic activities of *S. Alfredii* Hance roots such as root exudates, soil microorganisms and so on. The components of root exudates of the studied plant included some organic acid compounds (oxhydryl, carboxyl andamidogen), which could greatly decrease soil pH [37].

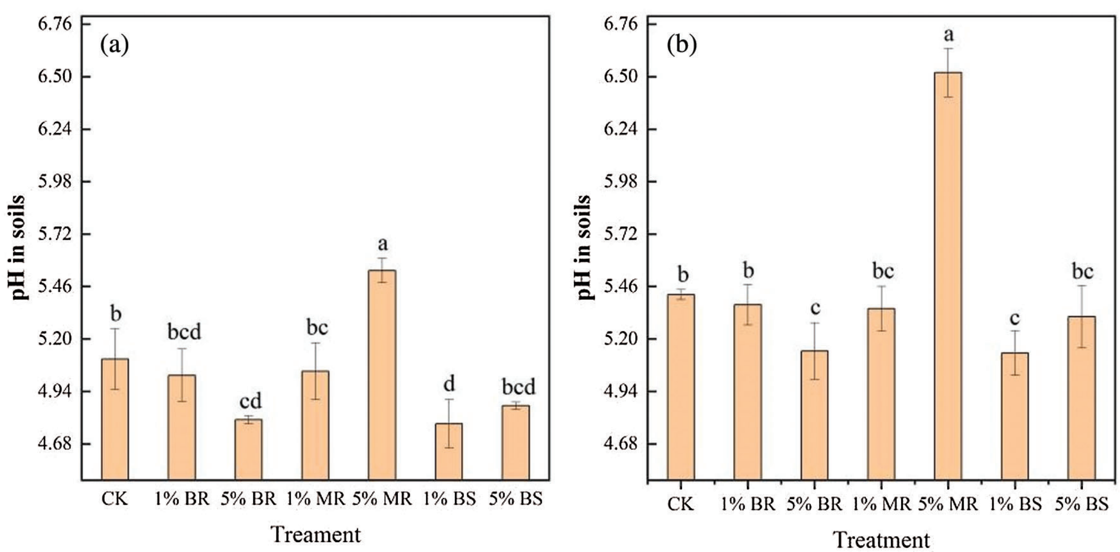

Figure 1: Effects of different treatments on pH in two soils (Different lowercases indicated significant differences between treatments (P < 0.05)). (a) Moderately-polluted soil. (b) Heavily-polluted soil

3.1.2 Soil Organic Matter

Adding 5% organic material had a marked increase in soil organic matter (SOM). However, adding 1% organic materials had no significant effect on SOM (P > 0.05), compared with the control (Fig. 2). This indicated that a higher concentration of organic materials had a better effect on the increase of soil organic matter. In moderately-polluted soil, the SOM contents of 5% BR, 5% MR and 5% BS treatments were 9.5%, 10.3% and 12.8% higher than control, respectively. In heavily-polluted soil, the SOM contents of 5% BR, 5% MR and 5% BS were 23.3%, 40.0% and 26.3% higher than the control, respectively (P < 0.05). The effects of organic material addition on SOM content were much obvious in heavily-polluted soil than that in moderately-polluted soil. The reasons might be as follows: (1) The organic matter content in Heavily-polluted soil was lower than Moderately-polluted soil. When the same dosage of organic material was applied, the increase of SOM in Heavily-polluted soil was obvious; (2) It was also possibly related to the heavy PHM pollution in Heavily-polluted soil, which inhibited the mineralization and decomposition of organic matter by soil microorganisms.

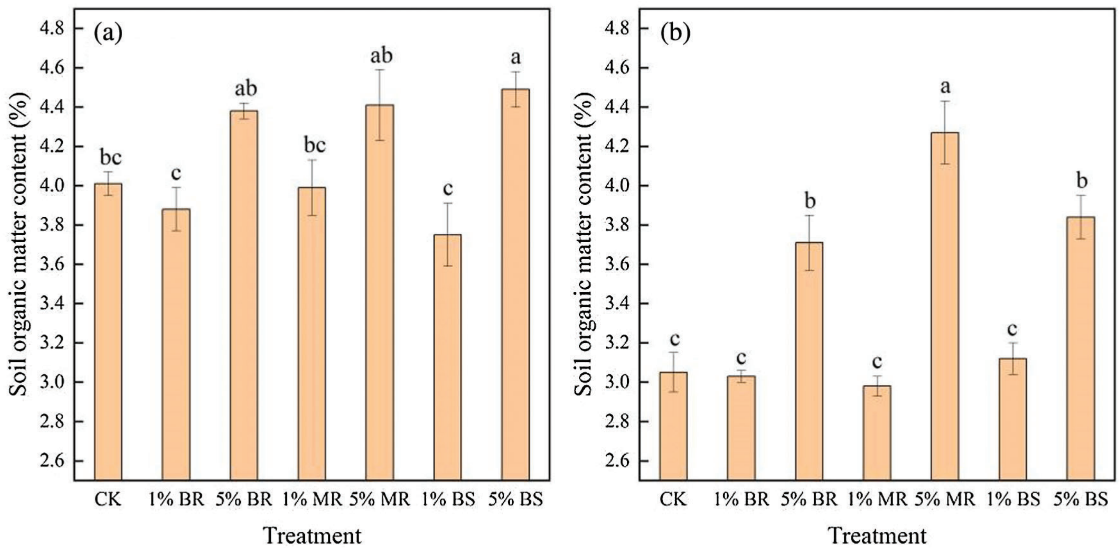

Figure 2: Soil organic matter content affected by different treatments (Different lower cases indicated significant differences between treatments ($P < 0.05$)). (a) Moderately-polluted soil. (b) Heavily-polluted soil

3.2 Effects of Organic Materials on the Concentration of Soil Available PHMs and Their Availability

For Moderately-polluted soil, compared to the control, most treatments (except the Cu and Zn in 5% BR treatment) decreased the available Cu, Zn, Pb and Cd concentration in the soil (Table 2), so did the availability of PHMs (Table 3).

Table 3: The availability of potentially hazardous metals affected by different treatments

Treatments	Moderately-polluted soil				Heavily-polluted soil			
	ACu	AZn	APb	ACd	ACu	AZn	APb	ACd
Original	9.57%	23.40%	15.13%	18.47%	64.93%	47.38%	62.97%	19.84%
CK	8.93%	20.29%	14.21%	17.72%	67.57%	41.14%	59.92%	13.69%
1% BR	8.23%	18.99%	12.14%	13.20%	70.95%	41.55%	64.81%	13.69%
5% BR	9.87%	29.79%	14.21%	13.95%	58.28%	36.15%	50.13%	11.40%
1% MR	8.35%	19.43%	12.53%	15.46%	68.42%	41.55%	63.59%	14.45%
5% MR	6.23%	18.99%	10.46%	14.70%	65.04%	41.55%	57.47%	12.93%
1% BS	8.11%	17.27%	11.50%	11.69%	72.64%	45.71%	68.48%	17.49%
5% BS	8.46%	18.99%	14.21%	15.08%	64.19%	41.55%	59.92%	14.45%

Note: The availability of PHMs means (available concentration of a metal)/(total concentration of the metal) * 100%.

The available concentration of PHMs varied depending on the types and dosages of organic materials in heavily-polluted soil (Table 2). In heavily-polluted soil, the concentrations of PHMs, significantly increased under 1% BS while significantly decreased under 5% BR, compared to the control ($P < 0.05$). For the available concentration of soil Cu, 5% organic material treatments had a lower concentration than the control, while 1% organic material treatments increased the content of soil available Cu. For available concentration of Zn, 1% BR and 1% BS significantly increased while 5% BR significantly decreased, compared to the control ($P < 0.05$). Low dosage (1%) treatments significantly ($P < 0.05$) increased the available Pb and high dosage (5%) decreased soil available Pb. For available Cd, 1% BS significantly increased while 5% BR significantly decreased, compared to the control ($P < 0.05$). Similar phenomena were found for the availability of PHMs in the heavily-polluted soil (Table 3).

The results from our pot experiment showed that organic material types and their application rates had different effects on the concentrations of available four PHMs in soils and their availability. Obviously, this was related to the complex reaction process in the soil system. The effects of organic materials on the bioavailability of PHMs depend on the properties of organic materials, the internal redox, the soil types and the characteristics of PHM ions [38]. Organic materials would be transformed and decomposed into low-molecular-weight organic acid and high-molecular-weight humic acid, after entering into soils. Lu et al. [39] and Garcia-Mina et al. reported that humic acid had different effects on PHMs under different conditions, which included activation or passivation of PHMs [40]. In this experiment, the properties of three organic materials were different. The BR was from the excretion of animals which was anaerobically fermented in biogas digester. The BS was aerobically fermented by the edible bamboo shoots leftover. And the MR was mainly produced in the fermentation of leftover from the cultivation of black fungus. Biogas residue contains a large amount of organic matter and nutrients (e.g., N, P and K) for plant growth [41]. Mushroom residue is rich in cellulose, vitamins, mineral elements and other bioactive substances. [42]. The bamboo-shoot shell contains a large amount of amino acids, proteins, coarse fibers and other nutrients [27]. Therefore, in terms of organic material compositions, BS had more simple-structure and easier-decomposition organic compositions (such as cellulose ($(C_6H_{10}O_5)n$) and hemicellulose (arabinan, galactan and glucomannan)), compared with BR and MR [27,43]. Thus, BS can promote the available PHM contents in soils. Research indicated that the decreased pH values could improve the efficiency of Zn, Cd accumulation by plants [44]. Due to the high pH value of MR, which could lead to the pH increase in soils, the availability of soil PHMs significantly decreased [45]. The high pH affected the PHM uptake of plants. Therefore, the PHM accumulation in shoots of *S. alfredii* Hance under MR treatments was lower than the others and control. The decrease of soil pH could lead to the dissolution and release of carbonate-bound and hydroxide-bound PHMs. Therefore the acidic condition can increase the PHMs' dissolution and release [46,47].

For Cu and Zn in moderately-polluted soil, 5% BR increased their contents, while 1% BR had no significant effect on their contents. However, the inverse phenomena were found in heavily-polluted soil. Both the nutrient contents and cation exchange capacity in moderately-polluted soil were higher than heavily-polluted soil, while the contents of PHMs were lower than heavily-polluted soil (Table 1). In such case, the activity or metabolic rate of microorganisms in moderately-polluted soil was much higher than that in heavily-polluted soil. The microorganism of rhizosphere is the benefit to plants' uptake of PHMs [48], which might be a reason for the different results in the two soils.

For Cd, almost all treatments in this study restrained the available Cd to some extent. However, only the BS treatments had an activation effect on Cd in Heavily-polluted soil. Previous studies revealed that the root exudates and rhizosphere microorganisms (such as arbuscular mycorrhiza and endophytic mycorrhiza) of *S. alfredii* Hance had activation or inhibition effects on PHMs [49]. Therefore, PHMs would be activated or inhibited in different soil systems. This was influenced by a series of factors, such as the type and dosage of organic materials, root exudates, edaphon and soil organic matter [50]. The interaction between above factors determined the contents of available PHMs. In addition, with *S. alfredii* Hance absorbing PHMs from soil, the soil available PHMs reduced. Therefore, the mechanism of organic materials on the soil available PHMs during the growth of *S. alfredii* Hance was complicated.

3.3 Effects of Organic Materials on S. alfredii Hance

3.3.1 Effects of Organic Materials on the Growth of S. alfredii Hance

Overall, the addition of organic materials enhanced the shoot dry weight of *S. alfredii* Hance. In Moderately-polluted soil, compared to the control, 5% MR, 1% BS and 5% BS treatment significantly ($P < 0.05$) enhanced the biomass production of *S. alfredii* Hance's shoots (Fig. 3). In heavily-polluted soil, all treatments had an increase in biomass of the shoots. The 5% MR treatment had the highest biomass production for both soils. The addition of organic materials could promote the growth of *S. alfredii* Hance and increase the shoots biomass.

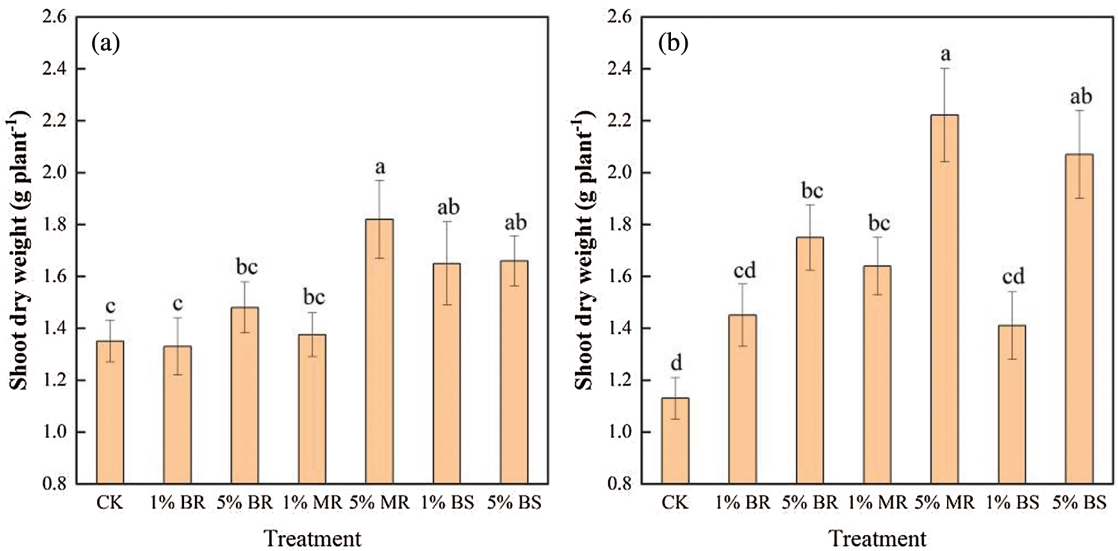

Figure 3: Biomass of *S. alfredii* Hance shoot dry weights affected by different treatments (Different lower cases in the above three tables indicated significant differences between treatments ($P < 0.05$)). (a) Moderately-polluted soil. (b) Heavily-polluted soil

3.3.2 Effects of Organic Materials on PHM Content in Shoots and Remediation Efficiency of S. alfredii Hance

Compared with control, the PHM contents in shoots of *S. alfredii* Hance showed a decreasing trend after organic materials application in two soils (Table 4). However, in moderately-polluted soil, the content of Zn in shoots had an inverse trend. Compared to the control, the treatments of 1% BR, 5% BR and 1% BS significantly ($P < 0.05$) increased the content of Zn in shoots of the plant. Generally speaking, the Zn concentration in plant shoots was high in this study. This was in line with other studies. Ni et al. [51] found that the accumulation of zinc reached more than 10 g kg^{-1}, using *S. alfredii* Hance. In another study [52], the accumulation of zinc in above-ground part of *S. alfredii* Hance was more than 15 g kg^{-1}.

Table 4: Effects of different treatments on potentially hazardous metal concentrations in shoots of *Sedum alfredii* Hance

Treatments	Moderately-polluted soil				Heavily-polluted soil			
	Cu mg kg^{-1}	Zn mg g^{-1}	Pb mg kg^{-1}	Cd mg kg^{-1}	Cu mg kg^{-1}	Zn mg g^{-1}	Pb mg g^{-1}	Cd mg g^{-1}
CK	4.6 ± 0.35bc	4.03 ± 0.30c	1.0 ± 0.06a	36 ± 3.0a	35 ± 3.0a	16.82 ± 1.00a	0.19 ± 0.01a	0.47 ± 0.01 a
1% BR	4.3 ± 0.20c	4.45 ± 0.35a	0.42 ± 0.03d	31 ± 2.0b	30 ± 2.0ab	15.86 ± 0.8b	0.14 ± 0.01b	0.41 ± 0.01ab
5% BR	5.0 ± 0.45ab	4.80 ± 0.32a	0.41 ± 0.05d	29 ± 2.0b	24 ± 1.0c	14.07 ± 0.50c	0.10 ± 0.01c	0.31 ± 0.01cd
1% MR	3.5 ± 0.32d	3.33 ± 0.30d	0.50 ± 0.05d	23 ± 1.0c	24 ± 2.0c	12.70 ± 0.50d	0.11 ± 0.01c	0.32 ± 0.01cd
5% MR	3.0 ± 0.25d	2.72 ± 0.25e	0.43 ± 0.03 d	21 ± 2.0c	11 ± 0.80d	11.92 ± 0.40d	0.05 ± 0.01d	0.20 ± 0.01e
1% BS	4.8 ± 0.40abc	4.40 ± 0.50b	0.75 ± 0.05b	36 ± 3.0a	25 ± 2.0bc	14.74 ± 0.50c	0.13 ± 0.01b	0.36 ± 0.01c
5% BS	5.3 ± 0.68a	3.66 ± 0.25d	0.52 ± 0.04c	24 ± 2.0c	20 ± 2.0c	11.83 ± 0.50d	0.10 ± 0.01c	0.27 ± 0.01d

Note: Different lower cases on the same column in the table indicated significant differences between treatments ($P < 0.05$).

Organic material reduced the content of Cd in plant shoots. The 5% MR treatment decreased by 57.6%, compared to the control. In heavily-polluted soil, Cu, Zn, Pb and Cd contents in shoots of *S. alfredii* Hance decreased after adding three organic materials. The effects of organic materials on PHM contents in shoots of *S. alfredii* Hance decreased more significantly with the increased application rates of organic materials.

To evaluate the efficiency of *S. alfredi*i Hance in remediation of PHM-contaminated soil, not only the improvement of soil structure, fertility, and transport rate [2], but also the total amount of PHMs removed from the soil per unit time should be considered. The total amount of PHMs uptaken by *S. alfredii* Hance was related to two factors. One was the biomass of shoots, the other was the PHM contents in *S. alfredii* Hance. The PHM accumulation was the product of biomass and content, which could directly reflect the effect of organic materials on the PHM remediation efficiency of *S. alfredii* Hance. In this experiment, all three types of organic materials addition enhanced the biomass production in moderately-polluted and heavily-polluted soils, especially for the MR treatments (Fig. 3). The MR application was helpful for the better nutritional condition of *S. alfredii* Hance, which was mainly attributed to the fact that the sticks had much more glucose, amino acids and beneficial microorganisms for the growth of target plants [53]. Unlike biomass production, three organic materials had different effects on the uptake and accumulation of PHMs in shoots of *S. alfredii* Hance. This finding was in line with the results of other studies [54,55], revealing that the effect of organic materials on PHMs removal was also related to soil properties and PHMs. The MR treatments inhibited the accumulation of PHMs in moderately-polluted soil, and the Cu, Pb, Cd accumulation in heavily-polluted soil (Table 5). BR and BS treatments mainly promoted Cu and Zn accumulation but inhibited Pb accumulation in both two soils. For Cd, only 1% BS treatment significantly promoted its accumulation in shoots in Moderately-polluted soil; both 1% BR and 5% BS treatments significantly promoted Cd accumulation in Heavily-polluted soil. The inhibition effect on the PHMs might be due to the increase of soil pH, the complexation and fixation of PHM by macromolecules complex organic matters such as humic substances during the decaying organic materials process, which resulted in the decrease of PHM activity in soil and the restraint of their uptake by plant roots [20]. On the other hand, the promotion effect on the PHMs of the shoots was related to the similar effect of organic materials on the growth of *S. alfredii* Hance, and the activation of soil PHMs by micro-molecular organics, which were generated from organic materials' mineralization and decomposition process [21,34,56]. Therefore, although the same organic material treatment enhanced the biomass product in shoots of *S. alfredii* Hance, it could also reduce the accumulation of PHMs in shoots.

Table 5: Effects of different treatments on potentially hazardous metal accumulation in *Sedum alfredii* Hance shoots

Treatments	Moderately-polluted soil				Heavily-polluted soil			
	Cu µg $plant^{-1}$	Zn mg $plant^{-1}$	Pb µg $plant^{-1}$	Cd µg $plant^{-1}$	Cu µg $plant^{-1}$	Zn mg $plant^{-1}$	Pb mg $plant^{-1}$	Cd mg $plant^{-1}$
CK	6.5 ± 0.5 b	5.51 ± 0.40cd	1.40 ± 0.10a	48.96 ± 4bc	39.47 ± 3ab	19.63 ± 1.00cd	0.22 ± 0.02a	0.53 ± 0.05bc
1% BR	6.6 ± 0.60b	5.99 ± 0.50c	0.51 ± 0.05e	41.03 ± 4c	44.33 ± 4a	22.86 ± 1.00bc	0.21 ± 0.02ab	0.60 ± 0.05a
5% BR	8.7 ± 0.70a	7.69 ± 0.60a	0.75 ± 0.06d	43.48 ± 3c	45.44 ± 3a	24.68 ± 1.20ab	0.16 ± 0.01c	0.56 ± 0.06ab
1% MR	4.5 ± 0.37c	4.28 ± 0.40e	0.82 ± 0.07cd	32.32 ± 3d	35.96 ± 2b	20.03 ± 1.00cd	0.18 ± 0.01bc	0.46 ± 0.05de
5% MR	6.0 ± 0.60b	5.13 ± 0.35d	1.10 ± 0.10b	37.80 ± 3d	21.59 ± 1d	24.02 ± 1.10ab	0.10 ± 0.01d	0.40 ± 0.04e
1% BS	8.4 ± 0.70a	7.31 ± 0.60ab	1.20 ± 0.10ab	60.02 ± 5a	35.39 ± 3b	19.96 ± 2cd	0.18 ± 0.01c	0.49 ± 0.05cd
5% BS	9.3 ± 1.0a	6.82 ± 0.50b	1.00 ± 0.10c	47.30 ± 4c	42.16 ± 2a	27.17 ± 1.50a	0.22 ± 0.01a	0.60 ± 0.05a

Note: Different lower cases on the same column in the table indicated significant differences between treatments ($P < 0.05$); TCu: total copper; TZn: total zinc; TPb: total lead; TCd: total cadmium.

The properties of organic materials, as well as their application rates can influence the soil PHMs' availability. Therefore, more attention should be paid to the availability of soil PHMs and the growth of *S. alfredii* Hance. In such a case, the phytoremediation efficiency of *S. alfredii* Hance under the application of the organic material could be effectively evaluated. Among the tested three organic materials, BS and BR applications were better choices for phytoremediation to soil PHMs pollution. If an appropriate rate of BS and BR was added to soil, the remediation efficiency for Zn/Cd contaminated soils by *S. alfredii* Hance could be promoted. While the MR addition inhibited the absorption of Cu, Zn, Pb and Cd by *S. alfredii* Hance, reducing the PHM uptake in shoots of the plant.

4 Conclusions

The BR, MR and BS application could decrease the pH in two soils (moderately-polluted soil and heavily-polluted soil) except the 5% MR treatment. The contents of soil organic matter with 5% organic materials application were significantly higher than that with 1% organic materials. For the available PHM concentrations in soil, 5% BR treatment had the best activation effect on Cu and Zn in moderately-polluted soil, while 1% BS has the best effect on Cu, Zn, Pb and Cd in heavily-polluted soil.

Based on the biomass production and PHM contents in shoots of *S. alfredii* Hance, 1% BS treatment had the best effect on Cd uptake and accumulation in shoots of *S. alfredii* Hance in moderately-polluted soil. In heavily-polluted soil, the remediation effect on Zn was as follows: 5% BS > 5% BR > 5% MR while for Cd, 1% BR and 5% BS treatments were better than the control.

The proper addition of BR and BS could promote the phytoremediation efficiency of soil PHMs by *S. alfredii* Hance. The MR had no significant effect due to its higher pH. The degree of soil pollution and the types of organic materials could both influence the phytoremediation efficiency. These indicated that the application of organic materials to improve phytoremediation efficiency should both consider physico-chemical properties of organic materials and soils.

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References

1. Zhao, K. L., Fu, W. J., Qiu, Q. Z., Ye, Z. Q., Li, Y. F. et al. (2019). Spatial patterns of potentially hazardous metals in paddy soils in a typical electrical waste dismantling area and their pollution characteristics. *Geoderma, 337(2–3),* 453–462. DOI 10.1016/j.geoderma.2018.10.004.
2. Shah, V., Daverey, A. (2020). Phytoremediation: A multidisciplinary approach to clean up heavy metal contaminated soil. *Environmental Technology & Innovation, 18(5),* 100774. DOI 10.1016/j.eti.2020.100774.
3. Liu, L., Li, W., Song, W., Guo, M. (2018). Remediation techniques for heavy metal-contaminated soils: Principles and applicability. *Science of the Total Environment, 633(2),* 206–219. DOI 10.1016/j.scitotenv.2018.03.161.
4. Zhou, K. N., Zhang, Y. Y., Ye, Z. Q., Dou, C. Y., Ye, Z. H. et al. (2021). Fertilizer application could improve the Zn and Cd accumulation of *Sedum alfredii* Hance. *Phyton-International Journal of Experimental Botany, 90(4),* 1217–1232. DOI 10.32604/phyton.2021.014951.
5. Wang, L. W., Rinklebe, J., Tack, F., Hou, D. (2021). A review of green remediation strategies for heavy metal contaminated soil. *Soil Use and Management, 27(4),* 936–963. DOI 10.1111/sum.12717.
6. Fu, W. J., Dong, J. Q., Ding, L. Z., Yang, H. S., Ye, Z. Q. et al. (2022). Spatial correlation of nutrients in a typical soil-hickory system of Southeastern China and its implication for site-specific fertilizer application. *Soil & Tillage Research, 217,* 105265. DOI 10.1016/j.still.2021.105265.
7. Xiao, R., Ali, A., Wang, P., Li, R., Tian, X. et al. (2019). Comparison of the feasibility of different washing solutions for combined soil washing and phytoremediation for the detoxification of cadmium (Cd) and zinc (Zn) in contaminated soil. *Chemosphere, 230,* 510–518. DOI 10.1016/j.chemosphere.2019.05.121.
8. Yu, Z. Y., Dong, J. Q., Fu, W. J., Ye, Z. Q., Li, W. Y. et al. (2019). The transfer characteristics of potentially toxic trace elements in different soil-rice systems and their quantitative models in Southeastern China. *International Journal of Environmental Research and Public Health, 16,* 2503. DOI 10.3390/ijerph16142503.
9. Huang, Z., Xu, L. G., Xu, N. J., Yang, J. S. (2007). Current status and expectation of phytoremediation of heavy metals in soil-crop system. *Journal of Agro-Environment Science, 26,* 58–62. DOI 10a.3321/j.issn:1672-2043.2007.z1.013.
10. Krumins, J. A., Goodey, N. M., Gallagher, F. (2015). Plant-soil interactions in metal contaminated soils. *Soil Biology and Biochemistry, 80,* 224–231. DOI 10.1016/j.soilbio.2014.10.011.
11. Chandra, R., Kumar, V. (2018). Phytoremediation: A green sustainable technology for industrial waste management. In: Chandra, R., Dubey, N. K., Kumar, V. (Eds.), *Phytoremediation of environmental pollutants*, pp. 14–35. Boca Raton: CRC Press.
12. Pulford, I. D., Watson, C. (2003). Phytoremediation of heavy metal contaminated land by trees—A review. *Environment International, 29(4),* 529–540. DOI 10.1016/S0160-4120(02)00152-6.
13. An, J., Gong, X. S., Wei, S. H. (2015). Research progress on technologies of phytoremediation of heavy metal contaminated soils. *Chinese Journal of Ecology, 34(11),* 3261–3270. DOI 10.13292/j.1000-4890.20151023.025.
14. Wang, Y. K., Zhang, H. C., Hao, X. Z., Zhou, D. M. (2010). A review on application of organic materials to the remediation of heavy metal contaminated soils. *Chinese Journal of Soil Science, 41(5),* 1275–1280. DOI 10.19336/j.cnki.trtb.2010.05.050.
15. Dong, J. Q., Zhou, K. N., Jiang, P. K., Wu, J. S., Fu, W. J. (2021). Revealing vertical and horizontal variaiton of soil organic carbon, soil total nitrogen and C:N ratio in subtropical forests of Southeastern China. *Journal of Environmental Management, 289(8),* 112483. DOI 10.1016/j.jenvman.2021.112483.
16. He, C. Q., Zhao, Y. P., Wang, F. F., Oh, K., Zhao, Z. Z. et al. (2020). Phytoremediation of soil heavy metals (Cd and Zn) by castor seedlings: Tolerance, accumulation and subcellular distribution. *Chemosphere, 153(1),* 126471. DOI 10.1016/j.chemosphere.2020.126471.

17. Zhou, J., Chen, L. H., Peng, L., Luo, S., Zeng, Q. R. (2020). Phytoremediation of heavy metals under an oil crop rotation and treatment of biochar from contaminated biomass for safe use. *Chemosphere, 247,* 125856. DOI 10.1016/j.chemosphere.2020.125856.
18. Zhao, K. L., Zhang, L. Y., Dong, J. Q., Wu, J. S., Ye, Z. Q. et al. (2020). Risk assessment, spatial patterns and source apportionment of soil heavy metals in a typical Chinese hickory plantation region of Southeastern China. *Geoderma, 360(1–4),* 114011. DOI 10.1016/j.geoderma.2019.114011.
19. Liu, Z. C., Chen, B. C., Wang, L. A., Urbanovich, O., Nagorskaya, L. et al. (2020). A review on phytoremediation of mercury contaminated soils. *Journal of Hazardous Materials, 400(1),* 123138. DOI 10.1016/j.jhazmat.2020.123138.
20. Wang, Y. M., Zhou, L. X., Zhan, X. H., Wong, W. C. J. (2004). Dynamics of dissolved organic matter and its effect on metal availability in paddy soil: Field micro-plot trials. *Acta Scientiae Circumstantiae, 24(5),* 858–864. DOI 10.13671/j.hjkxxb.2004.05.017.
21. Pan, Y., Zhou, L. X. (2007). Influence of applying organic manures on the chemical form of Cu and Cd in the contaminated soil and on wheat uptake: Field micro-plot trials. *Journal of Nanjing Agricultural University, 30(2),* 142–146. DOI 10.7685/j.issn.1000-2030.2007.02.030.
22. Wei, S. H., Zhu, J. G., Zhou, Q. X., Zhan, J. (2011). Fertilizer amendment for improving the phytoextraction of cadmium by a hyperaccumulator *Rorippa globose* (Turca.) Thell. *Journal of Soils and Sediments, 11(6),* 915–922. DOI 10.1007/s11368-011-0389-5.
23. Wu, L. S., Zeng, D. M., Mo, X. R., Lv, H. H., Su, C. C. et al. (2015). Immobilization impact of different fixatives on heavy metals contaminated soil. *Environmental Science, 36(1),* 309–313. DOI 10.13227/j.hjkx.2015.01.041.
24. Shi, G., Xia, S., Liu, C., Zhang, Z. (2016). Cadmium accumulation and growth response to cadmium stress of eighteen plant species. *Environmental Science and Pollution Research, 23(22),* 23071–23080. DOI 10.1007/s11356-016-7545-9.
25. Wen, G. C., Ye, Z. Q., Wang, X. D., Ma, J. W., Zhen, Y. (2012). Effects of edible fungus residue on dynamic changes of soil nutrients in paddy field. *Journal of Soil and Water Conservation, 26(3),* 82–86. DOI 10.13870/j.cnki.stbcxb.2012.03.018.
26. Zhang, Y. Z., Ma, J. W., Yao, F., Hu, G. L., Ye, Z. Q. (2012). Study on utilization of microbial manure from bamboo shoot shell. *World Bamboo and Rattan, 10(1),* 16–19. DOI 10.13640/j.cnki.wbr.2012.01.009.
27. Zhou, Z. X., Tian, J. X., Lai, C. G. (1991). Chemical compositions of bamboo shoot shell. *Journal of Zhejiang Forestry College, 8(1),* 54–59.
28. Yang, X. E., Long, X. X., Ni, W. Z., Fu, C. X. (2002). *Sedum alfredii* H.–A kind of New Zn Hyperaccumulator. *Chinese Science Bulletin, 47(13),* 1003–1006. DOI 10.1007/BF03184113.
29. Lin, Z. W., Dou, C. Y., Li, Y. F., Wang, H. L., Niazi, N. K. et al. (2020). Nitrogen fertilizer enhances zinc and cadmium uptake by hyperaccumulator *Sedum alfredii* Hance. *Journal of Soils and Sediments, 20(1),* 320–329. DOI 10.1007/s11368-019-02405-4.
30. China Ministry of Ecology and Environment (2018). Chinese soil environmental quality: Risk control standard for soil contamination of agricultural land (GB 15618-2018) (in Chinese). Beijing, China: China Environmental Science Press.
31. Shi, A., Shao, Y. F., Zhao, K. L., Fu, W. J. (2020). Long-term effect of E-waste dismantling activities on the heavy metals pollution in paddy soils of Southeastern China. *Science of the Total Environment, 705,* 135971. DOI 10.1016/j.scitotenv.2019.135971.
32. Zhao, K., Fu, W., Liu, X., Zhang, C., Ye, Z. et al. (2014). Spatial variations of concentrations of copper and its speciation in the soil-rice system in Wenling of Southeastern China. *Environmental Science and Pollution Research, 21(11),* 7165–7176. DOI 10.1007/s11356-014-2638-9.
33. Wang, H. B., Jin, J., Fu, W. J., Morrison, L., Lin, H. P. et al. (2020). Converting evergreen broad-leaved forests into tea and Moso bamboo plantations affects labile carbon pools and the chemical composition of soil organic carbon. *Science of the Total Environment, 711(3),* 135225. DOI 10.1016/j.scitotenv.2019.135225.
34. Lu, R. K. (2000). *Analysis method of agricultural chemistry in soil*. Beijing: Chinese Agriculture and Science Press.

35. Zhao, K. L., Fu, W. J., Ye, Z. Q., Zhang, C. S. (2015). Contamination and spatial variation of heavy metals in the soil-rice system in Nanxun County, Southeastern China. *International Journal of Environmental Research and Public Health, 12(2),* 1577–1594. DOI 10.3390/ijerph120201577.
36. Zhan, S. J., Yv, H., Feng, W. Q., Qin, Y. S., Liao, M. L. et al. (2011). Effects of different organic material and lime on soil pH and available cadmium. *Southwest China Journal of Agricultural Sciences, 24(3),* 999–1003. DOI 10.16213/j.cnki.scjas.2011.03.007.
37. Li, T. Q., Di, Z. Z., Yang, X. E., Sparks, D. L. (2011). Effects of dissolved organic matter from the rhizosphere of the hyperaccumulator Sadum alfredii on sorption of zinc and cadmium by different soils. *Journal of Hazardous Materials, 192(3),* 1616–1622. DOI 10.1016/j.jhazmat.2011.06.086.
38. Yao, G. H., Xu, H. Z., Zhu, L. G., Ma, J. W., Liu, D. et al. (2015). Effects of different kinds of organic materials on soil heavy metal phytoremediation efficiency by *Sedum afredii* Hance. *Environmental Science, 36,* 4268–4276. DOI 10.13227/j.hjkx.2015.11.043.
39. Lu, L. L., Wang, X. D., Wang, H., Liu, S. (2009). Dynamic changes of soluble humus-complexed copper in chicken manure. *Acta Scientiae Circumstantiae, 29(5),* 980–987. DOI 10.13671/j.hjkxxb.2009.05.020.
40. Garcia-Mina, J. M., Antolin, M. C., Sanchez-Diaz, M. (2004). Metal-humic complexes and plant micronutrient uptake: A study based on different plant species cultivated in diverse soil types. *Plant and Soil, 258(1),* 57–68. DOI 10.1023/B:PLSO.0000016509.56780.40.
41. Guo, Q., Niu, G. J., Cheng, H. J., Zhao, Y. C. (2005). Comprehensive utilizing of biogas residue. *China Resources Comprehensive Utilization, 12,* 11–15. DOI 10.3969/j.issn.1674-0912.2005.06.011.
42. Hu, Q. X., Wei, Z. T., Wang, H. Y. (2011). Agaricus bisporus residue compost and its fertilizer efficiency. *Journal of Agro-Environment Science, 30(9),* 1902–1909.
43. Jia, Y. F., Shi, W. Y. (2011). Chemical compositions and natural cellulose fiber characteristics of several bamboo shoot shells. *Journal of Zhejiang University (Agriculture and Life Sciences), 37(3),* 338–342. DOI 10.3785/j.issn.1008-9209.2011.03.016.
44. Lian, M. H., Sun, L. N., Hu, X. M., Tang, J. X. (2014). Effect of soil pH on phytoremediation of *Sedum alfredii* Hance in Cd and Zn contaminated soil. *Chinese Journal of Ecology, 33(11),* 3068–3074. DOI 10.13292/j.1000-4890.2014.0270.
45. Kumpiene, J., Lagerkvist, A., Manrice, C. (2007). Stabilization of Pb and Cu-contaminated soil using coal fly ash and peat. *Environmental Pollution, 145(1),* 365–373. DOI 10.1016/j.envpol.2007.02.001.
46. Kader, M., Lamb, D. T., Megharaj, M., Naidu, R. (2016). Sorption parameter as a predictor of arsenic phytotoxicity in Australian soils. *Geoderma, 265(4),* 103–110. DOI 10.1016/j.geoderma.2015.11.019.
47. Shaheen, S. M., Tsadilas, C. D., Rinklebe, J. (2013). Are view of the distribution coefficients of trace elements in soils: Influence of sorption system, element characteristics, and soil colloidal properties. *Advances in Colloid and Interface Science, 201–202(3),* 43–56. DOI 10.1016/j.cis.2013.10.005.
48. Ma, Y., Prasad, M. N. V., Rajkumar, M., Freitas, H. (2011). Plant growth promoting rhizobacteria and endophytes accelerate phytoremediation of metalliferous soils. *Biotechnology Advances, 29(2),* 248–258. DOI 10.1016/j.biotechadv.2010.12.001.
49. Khan, A. G. (2005). Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. *Journal of Trace Elements in Medicine and Biology, 18(4),* 355–364. DOI 10.1016/j.jtemb.2005.02.006.
50. He, S., He, Z., Yang, X., Stoffella, P. J., Baligar, V. C. (2015). Chapter four-soil biogeochemistry, plant physiology, and phytoremediation of cadmium-contaminated soils. *Advances in Agronomy, 134(5),* 135–225. DOI 10.1016/bs.agron.2015.06.005.
51. Ni, W. Z., Sun, Q., Yang, X. (2004). Growth and zinc accumulation of *Sedum alfredii* Hance–A Zn hyperaccumulator as affected by phosphorus application. *Bulletin of Environmental Contamination and Toxicology, 72(4),* 756–762. DOI 10.1007/s00128-004-0309-0.
52. Chen, Z. Q., Liu, Q. Z., Chen, S. N., Zhang, S. J., Wang, M. et al. (2021). Roles of exogenous plant growth regulators on phytoextraction of Cd/Pb/Zn by *Sedum alfredii* Hance in contaminated soils. *Environmental Pollution, 293(7),* 118510. DOI 10.1016/j.envpol.2021.118510.

53. Sun, J. H., Yuan, L., Zhang, Y. (2008). Research on compost manufacture by use of edible fungus dregs. *Soil and Fertilizer Sciences in China, (1),* 52–55. DOI 10.11838/sfsc.20080114.
54. Cambier, P., Pot, V., Mercier, V., Michaud, A., Benoit, P. et al. (2014). Impact of long-term organic residue recycling in agriculture on soil solution composition and trace metal leaching in soils. *Science of the Total Environment, 499(4),* 560–573. DOI 10.1016/j.scitotenv.2014.06.105.
55. Khan, M. A., Ding, X., Khan, S., Brusseau, M. L., Khan, A. et al. (2018). The influence of various organic amendments on the bioavailability and plant uptake of cadmium present in mine-degraded soil. *Science of the Total Environment, 636(1),* 810–817. DOI 10.1016/j.scitotenv.2018.04.299.
56. Rajkumar, M., Sandhya, S., Prasad, M. N. V., Freitas, H. (2012). Perspectives of plant-associated microbes in heavy metal phytoremediation. *Biotechnology Advances, 30(6),* 1562–1574. DOI 10.1016/j.biotechadv.2012.04.011.