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ScienceDirect

Journal of Hazardous Materials 151 (2008) 261–267

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Growth responses of three ornamental plants to Cd and Cd–Pb stress and their metal accumulation characteristics

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Received 15 March 2007; received in revised form 6 August 2007; accepted 8 August 2007
Available online 12 August 2007

Abstract

Up to now, there was no document on ornamental plants that had been applied to phytoremediation, which can remedy contaminated environment and beautify it at the same time. Thus, the growth responses and possible phytoremediation ability of three ornamental plants selected from the previous preliminary experiments were further examined under single Cd or combined Cd–Pb stress. The results showed that these tested plants had higher tolerance to Cd and Pb contamination and could effectively accumulate the metals, especially for *Calendula officinalis* and *Althaea rosea*. For *C. officinalis*, it grew normally in soils containing 100 mg kg^{-1} Cd without suffering phytotoxicity, and the Cd concentration in the roots was up to 1084 mg kg^{-1} while the Cd concentration in the shoots was 284 mg kg^{-1}. For *A. rosea*, the Cd accumulation in the shoots was higher than that in the roots when the Cd concentration in soils was <100 mg kg^{-1}, and reached 100 mg kg^{-1} as the criteria of a Cd hyperaccumulator when the Cd concentration in soils was 100 mg kg^{-1}. Their accumulation and tolerance to Cd and Pb were further demonstrated through the hydroponic-culture method. And *A. rosea* had a great potential as a possible Cd hyperaccumulator under favorable or induced conditions. Furthermore, the interactive effects of Cd and Pb in the three ornamentals were complicated, not only additive, antagonistic or synergistic, but also related to many factors including concentration combinations of heavy metals, plant species and various parts of plants. Thus, it can be forecasted that this work will provide a new way for phytoremediation of contaminated soils.

Keywords: Hyperaccumulator; Ornamental plant; Phytoremediation; Cd; Cd–Pb interaction

1. Introduction

Large areas of soils have been contaminated by heavy metals, which are deleterious to the existence, reproduction and development of living organisms including plants, animals and microorganisms. This phenomenon has even threatened the health of ecosystems and human beings themselves [1,2]. Because soils contaminated by toxic heavy metals have important characteristics such as concealment, delay, accumulation, regionalism, and irreversibility [3–5], soil remediation has not only received more attention in environmental science and engineering, but also becomes global problems to be solved urgently [6,7].

Phytoextraction, which makes use of the harvestable parts of plants to remove pollutants, represents a green and environmental-friendly tool for cleaning metal-polluted soils and waters compared with conventional chemical and physical remediation technologies, which are generally costly and often harmful to soil ecosystems [8–10]. In phytoremediation, screening out effective hyperaccumulators has become important, however, limited hyperaccumulators have been reported [11–13]. Thus, it is necessary to search for more hyperaccumulators to remedy contaminated soils effectively [3].

Ornamental plants are an important type of higher plants apart from those in the food chain, and are quite crucial if they have hyperaccumulation properties and can be applied to

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doi:10.1016/j.jhazmat.2007.08.016

remediation of contaminated soils [14]. It can be inferred from available data that if we can find hyperaccumulative ornamentals which can be used to remedy contaminated soils from abundant plant species and types, they may bring economic benefits because they can beautify the environment at the same time. This is the special advantage that ornamental plants are different from other hyperaccumulators. Up to now, there is no systematic identification of ornamental plants applicable to remediation of contaminated soils. In fact, in populous urban areas, ornamentals have many practical applications in indication and prevention of pollution produced by atmospheric precipitation and sewage discharge while ornamentals can beautify environment [15,16]. Thus, using ornamentals for remediation of contaminated environment has a significant and realistic purpose [17]. According to an elementary screen from herbaceous ornamental plants [18], *Impatiens Balsamina*, *Calendula officinalis* and *Althaea rosea* had higher tolerance and accumulation ability to cadmium (Cd) and lead (Pb). Therefore, this work investigated the growing responses and possible hyperaccumulation ability of the three ornamentals under single Cd or combined Cd–Pb contamination by the further experiment. Both the soil-culture and hydroponic-culture methods were employed. The results can provide scientific methods for generating a new way of phytoremediation.

2. Materials and methods

2.1. Soil-culture experiment

The Cd treatments (TS_0–TS_4) were designed according to the National Soil-Environmental Quality Standard of China (NSEQSC, GB15618, 1995) [19] and the results of the preliminary screening experiment by the soil-culture method. There were five treatments with Cd concentrations of 0, 10, 30, 50 and 100 mg kg^{-1}, respectively, as $CdCl_2{\cdot}2.5H_2O$. In April of 2005, surface (0–20 cm) soil samples were collected from the Shenyang Station of Experimental Ecology of the Chinese Academy of Sciences. The tested soil is meadow burozem which is not contaminated by heavy metals according to the NSEQSC. The soil samples were sieved through a 4.0 mm sieve and filled into plastic pots, then mixed with $CdCl_2{\cdot}2.5H_2O$ and equilibrated completely for 1 month. After that, seedlings of three ornamentals with 1 month old and similar biomass were transplanted into the pots. There were 3–4 seedlings in each pot based on the plant size. The number of seedlings for each treatment was kept equal, and all treatments were replicated trebly to minimize experimental errors. The experiment was carried out in the outdoor lab of Shenyang Institute of Applied Ecology of the Chinese Academy of Sciences, there was no contamination in the surrounding area, the annual average temperature was >10 °C and the frostless duration was 127–164 days a year. Loss of water was made up using tap water (no Cd detected) to sustain 75–85% of soil water-holding capacity. The plants were harvested at the seed-maturity stage except *A. rosea*, because *A. rosea* did not bloom out during the whole growing period.

2.2. Hydroponic-culture experiment

Healthy seedlings with the similar age of the three ornamentals were selected, and their roots were soaked in 0.1% $KMnO_4$ for 10 min. This process sterilized and accelerated root growth. The seedlings were then cultivated in 300 mL conical flasks. The medium containing aerated 20× diluted Hoagland nutrient solution (pH 6.7) was used during this experiment. After 10 days of cultivation when the seedlings had adapted to the condition of diluted Hoagland nutrient solution, Cd as $CdCl_2{\cdot}2.5H_2O$ and Pb as $Pb(NO_3)_2$ were added to the solution (Cd + Pb, mg L^{-1}). There were nine treatments (TP_0–TP_8) and the Cd and Pb concentrations for each treatment were 0 + 0, 1 + 50, 3 + 50, 5 + 50, 10 + 50, 1 + 100, 3 + 100, 5 + 100 and 10 + 100 mg L^{-1}, respectively. There was one plant in each flask, and all treatments were replicated trebly to minimize experimental errors. The solution was changed every 5 days, the growth responses of plants were observed, and the plants were harvested after they had grown in contaminated solutions by Cd and Pb for 20 days.

2.3. Metal determination and data processing

Harvested plant samples were divided into roots and shoots for the hydroponic culture experiment, and roots, stems, leaves and inflorescences for the soil culture experiment. They were then carefully washed with deionized water after rinsing with tap water, dried at 105 °C for 20 min and then at 70 °C in an oven until completely dried. The dried plant samples were ground to powder after their dry weights were weighed. Soil samples were air-dried and ground using a mortar and pestle, and then were sieved through a 0.149 mm sieve [20]. The plant and soil samples were digested in a solution containing 3:1 HNO_3:$HClO_4$ solution [21]. The concentrations of heavy metals were determined using an atomic absorption spectrophotometer (AAS, Hitachi 180–80 type) with certified reference materials (bought from an authoritative company in Shijiazhuang, China) for quality assurance purposes. The recovery rates for Cd and Pb in all samples were within $92.01 \pm 8.63\%$. Reagent blanks and internal standards were used to ensure accuracy and precision in Cd and Pb analysis. Data were statistically processed on a computer using the Excel XP, SPSS 13.0, DPS 3.01. The values are expressed as mean ± standard deviation (S.D.) of the three replicates. Data were analyzed by one-way ANOVAs with the Duncan's multiple range tests to separate means.

3. Results and discussion

3.1. Cd tolerance under soil-culture conditions

After growing in pots for 4 months, the intuitionistic Cd tolerance of the tested plants was in sequence *C. officinalis* > *A. rosea* > *I. Balsamina* (Table 1). For *I. Balsamina*, its height decreased with the increasing Cd concentration, indicating that Cd restrained its growth to some extent, especially for TS_3 and TS_4 (Cd = 50 and 100 mg kg^{-1}, respectively) where the part of the leaves turned brown. For *C. officinalis*, the plant height under TS_4 was higher than that under the control (TS_0). It seemed

Table 1
Growth responses of the three ornamentals under soil-culture conditions[a]

Ornamental	Treatment	Height (cm)	Growth responses
Impatiens Balsamina	TS_0	44.1 ± 2.35a	Plants grew well in TS_1 and TS_2, some leaves turned brown in TS_3 and TS_4.
	TS_1	43.9 ± 1.21a	
	TS_2	42.0 ± 1.08a	
	TS_3	38.8 ± 0.70b	
	TS_4	38.1 ± 0.90b	
Calendula officinalis	TS_0	57.3 ± 1.08ab	No significant difference between various treatments, all plants grew well and showed longer florescence.
	TS_1	57.8 ± 0.78ab	
	TS_2	56.0 ± 0.90bc	
	TS_3	55.1 ± 0.85c	
	TS_4	58.2 ± 0.82a	
Althaea rosea	TS_0	26.1 ± 0.92a	Plant height for each treatment was slightly shorter than TS_0, but the differences between various treatments were not obvious and all plants grew well.
	TS_1	25.0 ± 1.04ab	
	TS_2	25.2 ± 0.96ab	
	TS_3	24.7 ± 0.85ab	
	TS_4	24.0 ± 1.08b	

[a] The values in the same column followed by the same letters are not significantly different, whereas by the different letters are significantly different at $P < 0.05$.

that *C. officinalis* had higher tolerance to Cd. Similar to *C. officinalis*, the growth responses of *A. rosea* did not differ significantly among treatments although the plant height under TS_4 was slightly shorter than that under the control.

Plant dry weight or dry biomass can also be used to assess plant tolerance to Cd. For *I. Balsamina*, its dry weight decreased compared with that under the control (TS_0) except for TS_2. For *C. officinalis,* its dry weight under different treatments increased to different extent, especially under TS1 and TS2, the dry weight of the plant tissues was 1.27 and 1.26 times as much as that under the control, respectively. For *A. rosea*, its dry weight increased under different Cd treatments except for TS1, and the dry weight decreased with the increasing soil Cd concentration from TS2 treatment. The results of plant dry weight showed that not only the three ornamentals had higher tolerance to Cd contaminated soils but also Cd with proper concentration could facilitate the plant growth, indicating tolerance characteristics of an ornamental plant as a hyperaccumulator [22,23].

3.2. Cd accumulation under soil-culture conditions

The Cd concentrations in different parts of the three ornamental plants were shown in Table 2. For *I. Balsamina*, the Cd concentration in the roots was higher than that in other parts, reaching 325 mg kg^{-1} under TS_4 treatment. The Cd concentration in the stems and leaves reached 106 and 103 mg kg^{-1}

Table 2
Cd concentration (mg kg^{-1}) in different parts/tissues, EF, and TF of the three ornamentals under soil-culture conditions[a]

Ornamental	Treatment	Cd concentration (mg kg^{-1})					EF	TF
		Root	Stem	Leaf	Inflorescence	Shoot		
Impatiens Balsamina	TS_0	4.38 ± 0.86b	5.27 ± 0.42a	3.87 ± 0.26b	1.87 ± 0.10c	4.38 ± 0.41b	7.29 ± 0.08	1.00 ± 0.05
	TS_1	61.2 ± 5.11a	57.5 ± 6.37a	54.5 ± 4.47ab	20.3 ± 4.76c	48.0 ± 5.17b	4.90 ± 0.06	0.78 ± 0.04
	TS_2	157 ± 8.28a	106 ± 5.95b	103 ± 1.78b	70.9 ± 2.92c	94.9 ± 5.22b	3.22 ± 0.10	0.60 ± 0.03
	TS_3	174 ± 0.73a	138 ± 1.42b	110 ± 1.10d	57.8 ± 0.82e	114 ± 1.70c	2.32 ± 0.04	0.66 ± 0.03
	TS_4	325 ± 2.90a	191 ± 2.95b	121 ± 4.84d	62.0 ± 5.60e	148 ± 8.71c	1.49 ± 0.02	0.46 ± 0.02
Calendula officinalis	TS_0	4.13 ± 0.81a	3.78 ± 0.68a	4.13 ± 1.10a	1.97 ± 0.30b	3.67 ± 0.44a	6.11 ± 0.11	0.89 ± 0.06
	TS_1	114 ± 3.74a	17.0 ± 3.07c	28.1 ± 0.83b	7.21 ± 1.08d	21.1 ± 5.93c	2.22 ± 0.06	0.19 ± 0.02
	TS_2	344 ± 6.61a	32.0 ± 2.07d	80.1 ± 7.80b	13.7 ± 5.45e	51.9 ± 3.65c	1.77 ± 0.02	0.15 ± 0.01
	TS_3	552 ± 8.85a	83.2 ± 6.88d	146 ± 7.62b	43.7 ± 9.54e	117 ± 2.14c	2.36 ± 0.04	0.21 ± 0.02
	TS_4	1084 ± 1.40a	201 ± 7.22d	383 ± 0.81b	67.5 ± 4.27e	284 ± 1.82c	2.49 ± 0.08	0.26 ± 0.04
Althaea rosea	TS_0	3.56 ± 0.66a	2.20 ± 0.32b	2.12 ± 0.36b	/	2.09 ± 0.15b	3.48 ± 0.11	0.59 ± 0.06
	TS_1	24.8 ± 1.68c	41.7 ± 1.75a	23.6 ± 1.45c	/	30.5 ± 1.17b	3.21 ± 0.08	1.23 ± 0.08
	TS_2	30.5 ± 3.36c	65.3 ± 1.98a	31.0 ± 1.28c	/	43.9 ± 3.23b	1.49 ± 0.06	1.44 ± 0.06
	TS_3	55.9 ± 2.57b	83.7 ± 1.40a	39.3 ± 3.03c	/	58.0 ± 2.30b	1.17 ± 0.05	1.04 ± 0.03
	TS_4	136 ± 0.99a	126 ± 1.32b	78.2 ± 2.46d	/	100 ± 1.65c	1.00 ± 0.03	0.74 ± 0.05

[a] The values in the same row followed by the same letters are not significantly different, whereas by the different letters are significantly different at $P < 0.05$. EF: Cd concentration ratio of shoots to soils; TF: Cd concentration ratio of shoots to roots.

Table 3
Changes in the accumulation of Cd or Pb in the three ornamental plants with Cd and Pb concentrations in solution

Ornamental	Tissue	Regression equation	R^2	*n*	*P*
Impatiens Balsamina	Shoot	$Y_{\text{shoot}} = 17.1 + 6.70X_{\text{Cd}} + 0.17X_{\text{Pb}}$	0.74	26	<0.01
		$Y'_{\text{shoot}} = 37.5–4.74X_{\text{Cd}} + 1.30X_{\text{Pb}}$	0.74	26	<0.01
	Root	$Y_{\text{root}} = 179 + 109X_{\text{Cd}} - 0.95\ X_{\text{Pb}}$	0.89	26	<0.01
		$Y'_{\text{root}} = 126–5.31X_{\text{Cd}} + 3.94\ X_{\text{Pb}}$	0.76	26	<0.01
Calendula officinalis	Shoot	$Y_{\text{shoot}} = 41.0 + 76.2X_{\text{Cd}}\text{-}0.46\ X_{\text{Pb}}$	0.97	26	<0.01
		$Y'_{\text{shoot}} = 18.4–3.94X_{\text{Cd}} + 2.35\ X_{\text{Pb}}$	0.88	26	<0.01
	Root	$Y_{\text{root}} = 134.1 + 151X_{\text{Cd}} - 0.90\ X_{\text{Pb}}$	0.95	26	<0.01
		$Y'_{\text{root}} = 166 + 4.70X_{\text{Cd}} + 5.45\ X_{\text{Pb}}$	0.81	26	<0.01
Althaea rosea	Shoot	$Y_{\text{shoot}} = 28.4 + 45.3X_{\text{Cd}} + 0.19X_{\text{Pb}}$	0.94	26	<0.01
		$Y'_{\text{shoot}} = 65.5–2.93X_{\text{Cd}} + 2.63X_{\text{Pb}}$	0.81	26	<0.01
	Root	$Y_{\text{root}} = 68.5 + 133X_{\text{Cd}}\text{-}0.37X_{\text{Pb}}$	0.96	26	<0.01
		$Y'_{\text{root}} = 190–4.80X_{\text{Cd}} + 6.52X_{\text{Pb}}$	0.77	26	<0.01

respectively, under TS_2 treatment ($\text{Cd} = 30\ \text{mg kg}^{-1}$) and they increased with increasing Cd concentration. The Cd concentration in the shoots reached the maximum when Cd was higher than $100\ \text{mg kg}^{-1}$ (the criteria of Cd hyperaccumulator) but lower than that in the roots. For all the four Cd treatments, the EF values were higher than 1.0 and they decreased with the increasing soil Cd concentration, however, the TF values were lower than 1.0.

For *C. officinalis*, the Cd concentration in the shoots was also lower than that in the roots ($\text{TF} < 1.0$), and the EF values were also all higher than 1.0, furthermore, the Cd accumulation in roots was much higher than that of *I. Balsamina*. The Cd concentration in the roots and shoots under TS_4 treatment was 1084 and $284\ \text{mg kg}^{-1}$, respectively, and increased with increasing Cd concentration in soil. Furthermore, there was no obvious symptom of phytotoxicity, so *C. officinalis* had the potential to accumulate higher Cd concentration. Although *I. Balsamina* and *C. officinalis* cannot be used as hyperaccumulators, Cd concentration in the plants was high, especially for *C. officinalis*. They also can grow normally and fulfill their growth periods, and considerable heavy metals can be extracted when they were harvested [24–26], they can thus remedy contaminated soils to some extent as a manner of phytostabilization and at the same time beautify the environment.

For *A. rosea*, the Cd concentration in the shoots was higher than that in the roots under TS_1, TS_2 and TS_3 treatments, respectively. The Cd concentration in each part increased under TS_4 treatment, and the Cd concentration in the shoots exceeded $100\ \text{mg kg}^{-1}$, the criteria of Cd hyperaccumulators, however, the Cd concentration in the roots was higher than that in the shoots, indicating the limited ability of transferring Cd from roots to shoots. This can be improved by some chemical induced methods, so to increase its accumulation and translocation ability [27–29].

3.3. Growth responses under hydroponic-culture conditions

Whether the Hoagland solution aerated continuously was used or not, the whole trend of growth responses of the tested ornamental plants to Cd stress or Cd–Pb stress was basically accordant each other under hydroponic-culture conditions. After a 5-day growth, all plants grew normally and new roots could be observed. After a 10-day growth, plant roots were flourishing and all plants grew well. After a 15-day growth, differences of growth responses were visible for the three ornamentals. After a 20-day growth, differences in plant tolerance to Cd and Pb were great. For example, *A. rosea* had higher tolerance compared with other two ornamentals, only plants under TP_4 and TP_8 treatments (Cd and $\text{Pb} = 10 + 50$ and $10 + 100\ \text{mg L}^{-1}$) showed mild phytotoxicity symptoms. This indicates that the growth of the tested ornamental plants was affected when Cd concentration was $10\ \text{mg L}^{-1}$ and Pb concentration was $\geq 50\ \text{mg L}^{-1}$. Unlike *A. rosea*, the growth of *C. officinalis* was further affected, the plants under TP_8 treatment died at the end of the experiment. *I. Balsamina* also showed tolerance to heavy metals, but the nigrescence was apparent for the roots under TP_3, TP_4, TP_7 and TP_8 treatments, respectively [30]. Nearly all plants in TP_4 and TP_8 treatments (the highest Cd and Pb concentrations) withered when they were harvested.

3.4. Cd and Pb accumulation under hydroponic-culture conditions

The hydroponic-culture experiment using the Hoagland solution aerated continuously showed that the Cd accumulation in the three ornamental plants changed obviously with different Cd and Pb concentrations in solution. The changing trends could be expressed using the regression equations listed in Table 3, where Y_{shoot} is the Cd concentration in shoots (mg kg^{-1}), Y_{root} is the Cd concentration in roots ($\text{mg kg}^{\text{-}1}$), X_{Cd} is the Cd concentration in solution (mg L^{-1}), and X_{Pb} is the Pb concentration in solution (mg L^{-1}). In other words, there were significant positive correlations between the Cd concentration in the three ornamental plants and the concentrations of Cd and Pb in solution. This phenomenon implied that the Cd accumulation in the plants was not only dependent on the Cd concentration in solution, but also related to the Pb concentration in solution, thus leading to plant death in TP_8 treatment for *C. officinalis* (Fig. 1).

Analysis of variance showed that the Cd concentrations in the three ornamentals and their different parts/tissues differed significantly ($P < 0.05$) between different treatments under the hydroponic culture conditions using the Hoagland solution

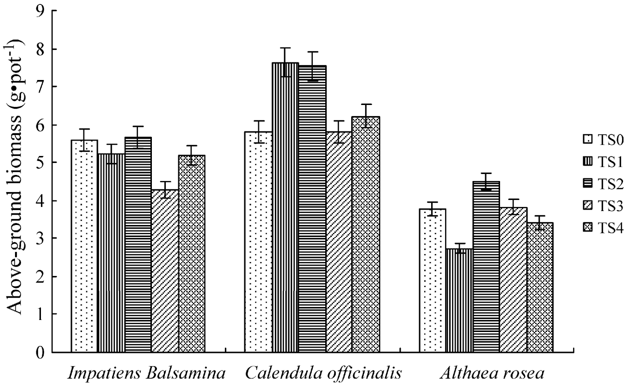

Fig. 1. Comparison of dry biomass in the three ornamentals growing under different soil Cd concentrations.

aerated continuously (Fig. 2). For *I. Balsamina*, the Cd concentration in the shoots was much lower than that in the roots, indicating its ability of transferring Cd from roots to shoots was weak [31]. However, plant Cd concentration in each part increased with the increasing Cd in solution. When Cd was 10 mg L^{-1}, the Cd concentration in the shoots was only 88.3 and 99.2 mg kg^{-1}, while the Cd concentration in the roots was 1280 and 991 mg kg^{-1}, respectively. This indicated that most of the absorbed Cd was deposited in the roots and could not be transferred to the shoots. Among the three ornamentals, *C. officinalis* had the highest ability to accumulate Cd, the Cd concentration in the shoots and roots reached 825 and 1585 mg kg^{-1} in TP_4 treatment, 700 and 1492 mg kg^{-1} in TP_8 treatment, respectively. *A. rosea* also had higher ability to accumulate Cd besides the stronger tolerance, showing the potential to remedy Cd contaminated environment [32,33].

Similarly, analysis of variance showed that the Pb concentrations in the three ornamentals and their different parts/tissues differed significantly ($P < 0.05$) between different treatments under the hydroponic culture conditions using the Hoagland solution aerated continuously (Fig. 3). Among the three ornamentals, the Pb concentration in the shoots was lower than that in the roots, and increased with the Pb concentration in solution. The corresponding regression equations can be expressed in Table 3, where Y'_{shoot} is the Pb concentration in shoots (mg kg^{-1}), and Y'_{root} is the Pb concentration in roots (mg kg^{-1}). The results of regression analysis about the Pb concentration in the plants showed that there were significant positive correlations between the Pb concentration in the three ornamental plants and the Pb concentration in solution. Furthermore, the Cd in solution had an important influence on the Pb accumulation in the plants. In other words, addition of Cd affected Pb accumulation by plants.

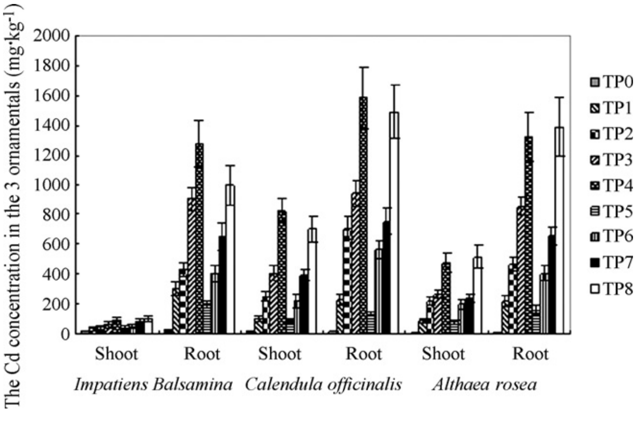

Fig. 2. Cd accumulation in the three ornamentals growing under different Cd and Pb concentrations for 20 days.

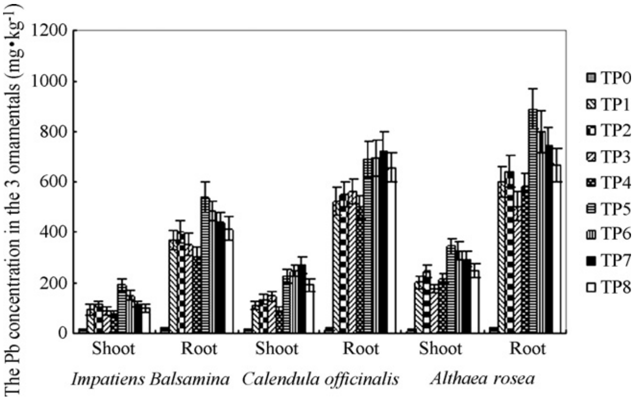

Fig. 3. Pb accumulation in the three ornamentals growing under different Cd and Pb concentrations for 20 days.

Compared with Cd, plant Pb accumulation was weaker for the three ornamentals. *A. rosea* had the highest ability to accumulate Pb, the maximal Pb concentration in the shoots and roots was 24 and 640 mg kg^{-1} in TP_2 treatment (Pb = 50 mg L^{-1} and Cd = 3 mg L^{-1}), and 344 and 890 mg kg^{-1} in TP_5 treatment (Cd = 1 mg L^{-1} and Pb = 100 mg L^{-1}), respectively, when the Cd concentration in solution was lower, suggesting plant metal accumulation was related to not only metal concentrations in solution [34,35] but also plant types and their parts/tissues.

3.5. *Interactions of Cd and Pb under hydroponic-culture conditions*

For Cd–Pb combined treatments, the interaction between Cd and Pb under hydroponic-culture conditions using the Hoagland solution aerated continuously was demonstrated by the partial correlation coefficient (Fig. 4). The positive correlation indicated

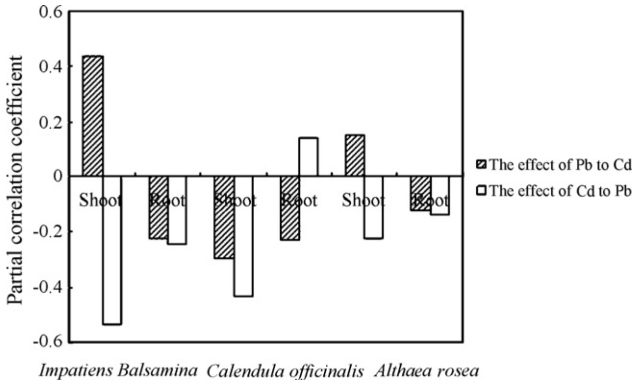

Fig. 4. Interactions between Cd and Pb in the three ornamentals growing under different Cd and Pb concentrations for 20 days.

that one heavy metal could facilitate the accumulation of the other while the negative correlation indicated contrary effects. Whereas some effects were significant ($P < 0.01$ or $P < 0.05$), some were not ($P > 0.05$).

For *I. Balsamina*, the relationship between the Cd concentration accumulated by the shoots and the Pb concentration in solution was significant positive correlation ($P < 0.05$), but not to the roots ($P > 0.05$). The relationship between the Pb concentration accumulated by the shoots and the Cd concentration in solution showed highly significant negative correlation ($P < 0.01$), and the same negative effect to the roots which was not significant ($P > 0.05$). Therefore, it was obvious that Pb could facilitate plant Cd accumulation while Cd could restrain plant Pb accumulation for the shoots of *I. Balsamina*. For *C. officinalis*, the relationship between the Cd concentration accumulated by shoots and the Pb concentration in solution showed negative correlation which was not significant ($P > 0.05$), and the same negative effect to the roots which was also not significant ($P > 0.05$).The relationship between the Pb concentration in the shoots and the Cd concentration in solution showed significant negative correlation ($P < 0.05$), but not to the roots ($P > 0.05$). Thus, only Cd could restrain Pb accumulation in the shoots obviously. For *A. rosea*, there was no significant interaction between Cd and Pb ($P > 0.05$).

4. Conclusions

All the three tested ornamentals showed higher tolerance to Cd and Pb, especially highly accumulated Cd. For *C. officinalis*, it showed great tolerance to Cd, and had stronger ability to accumulate Cd. Although it could not be classified as a Cd hyperaccumulator because the Cd concentration in the roots was greater than that in the shoots, it was tolerant to Cd because it grew well in soils spiked with $100\,\mathrm{mg\,kg^{-1}}$ Cd. Thus this plant has great potential to be used for phytostabilization remediation of contaminated soils by Cd. Similarly, *A. rosea* showed higher tolerance to the heavy metals. It was more effective in not only accumulating Cd and Pb, but also transferring Cd from roots to shoots when soil Cd was $< 100\,\mathrm{mg\,kg^{-1}}$. Thus, this plant may be regarded as a potential hyperaccumulator under favorable or induced conditions. What was more significant was that they were both ornamental plants. This means that they could remedy contaminated soils while beautifying the environment at the same time, especially in urban areas this has an important and practical significance. In addition, for the three ornamentals, the interactive effect of Cd and Pb was observed, including additive, antagonistic or synergistic. They were related to many factors including metal concentrations, plant species and plant tissues.

Acknowledgement

The work was financially supported by the National Natural Science Foundation of China for Overseas Distinguished Young Scholars (No.20427707) and partly as a key project (No.20337010).

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