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Effect of amendments on growth and metal uptake of giant reed (*Arundo donax* L.) grown on soil contaminated by arsenic, cadmium and lead

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Abstract: The effects of five amendments such as acetic acid(AA), citric acid (CA), ethylenediamine tetraacetic acid (EDTA), sepiolite and phosphogypsum on growth and metal uptake of giant reed (*Arundo donax* L.) grown on soil contaminated by arsenic (As), cadmium (Cd) and lead (Pb) were studied. The results showed that the shoot biomass of giant reed was enhanced by 24.8% and 15.0%, while superoxide mutase and catalase activities slightly varied when adding 5.0 mmol/kg CA and 2.5 mol/kg EDTA to soil as compared to the control, respectively. The concentrations of As, Cd and Pb in shoots were remarkably increased by the addition of 2.5 mmol/kg AA and CA, 5.0 mmol/kg EDTA, and 4.0 g/kg sepiolite as compared to the control. The accumulations of As and Cd were also significantly enhanced in the above condition, while the shoot Pb accumulation was noticeably enhanced by amending with 4.0 g/kg sepiolite and 8.0 g/kg phosphogysum, respectively. The results suggested that AA, CA and sepiolite could be used as optimum soil amendments for giant reed remediation system.

Key words: phytoremediation; giant reed; soil amendments; heavy metal contaminated soil; metal uptake

1 Introduction

Soil contaminated by metal elements, such as As, Cd, Cu, Pb and Zn, which mainly originate from nonferrous mineral processing and smelting activities, has become one of the major environmental concerns around the world [1,2]. Conventional remediation technologies for heavy metal contaminated soils include excavation and landfill, thermal treatment, acid leaching and electro-reclamation [3]. These techniques, however, are limited for large-scale remediation engineering due to expensive cost and destruction of soil biota and fertility. Alternatively, phytoremediation, an emerging solution which refers to the use of green plants for the removal of contaminants or rendering them harmless, is cost-effective, environmental-friendly and can be applied to large-scale soils [4]. Usually, it is a determining factor for phytoremediation that the plant has the ability to cultivate a large biomass with high contents of toxic metals in its shoots [5,6]. However, low biomass, low bioavailability and limited translocation of some metals to the shoots are major obstacles in the phytoextraction process experienced by most of plant species. A combination of high biomass-producing plant species and chemically assisted phytoextraction would be available [7].

Suitable soil amendments play an important role in enhancing phytoremediation efficiency by stimulating plant growth, or/and enhancing metal accumulation in shoots [8]. Synthetic chelators, such as ethylenediamine tetraacetic acid (EDTA), ethylene diamine disuccinate (EDDS), nitrilo acetic acid (NTA), and glycoletherdiamine tetra acetic acid (EDGA), are mostly used chelating agents [8,9]. Organic amendments, in particular low relative molecular mass organic acids such as citric acid and oxalic acid, have also been extensively studied because of their good biodegradability after amending contaminated soils [10]. In addition, sepiolite, a feasible soil additive for the adsorption of Cd and Zn [11], which can significantly enhance the shoot dry biomass of *Juncus effuses* grown on soils polluted by Pb/Zn mine tailings were also used [12]. The potential of phosphogypsum (industrial by-product) for increasing heavy metal sorption capacity in contaminated soils was also studied [13].

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Giant reed (*Arundo donax* L.), a perennial plant, which is widely used as energy material and paper pulping, has received considerable attention for remediating soils polluted by multi-metals due to its capacity of thriving in various range of adverse conditions with rapid growth and high yields [14]. Furthermore, giant reed can grow well in soils contaminated by Cd and Ni [15,16] or by As, Cd and Pb [17] and wastewater contaminated with As [18]. Our previous long-term field experiment also exhibited that giant reed is useful for ecoremediating soil contaminated by As, Cd, Pb and Zn [19]. Based on the preliminary research, the objectives of this work are: 1) to study the effect of amendments, such as AA, CA, EDTA, sepiolite and phosphogysum, on growth and physiological characteristics of giant reed grown on soil contaminated by As, Cd and Pb, 2) to elucidate their effect on metal concentrations and accumulations in plant shoots, and then 3) to optimize soil amendments as well as the optimum application concentrations.

2 Experimental

2.1 Test soil and plant

Surface soil (0−20 cm) was collected from arable land in the vicinity of typical smelting district of Zhuzhou City, Hunan Province, China, which belongs to allitic udic ferriols and develops from the typical quaternary red clay. Soil samples were air dried and then ground to pass through a 2 mm sieve. The basic physiochemical properties of soil are listed in Table 1.

Table 1 Basic physiochemical properties of soil

Item	Value
pH	6.48
Organic matter content/($g·kg^{-1}$)	45.8
Total N/($g·kg^{-1}$)	2.04
Total P/($g·kg^{-1}$)	0.77
Total K/($g·kg^{-1}$)	4.13
Available N/($mg·kg^{-1}$)	76.8
Available P/($mg·kg^{-1}$)	14.6
Available K/($mg·kg^{-1}$)	48.4
Total As/($mg·kg^{-1}$)	13.7
Total Cd/($mg·kg^{-1}$)	1.07
Total Pb/($mg·kg^{-1}$)	52.4

The air dried soils of 5 kg were put into container with diameter of 20 cm and height of 17 cm. Test soil in each pot was homogeneously sprayed with aqueous solutions containing 80 mg As, 10 mg Cd and 500 mg Pb per kg soil, which were prepared by dissolving salts of $Na_3AsO_4·12H_2O$, $CdCl_2·2.5H_2O$ and $Pb(CH_3COO)_2·3H_2O$ into deionized water, respectively. The fertilizers were applied to each pot with 0.27 g $CO(NH_2)_2$, 0.05 g KH_2PO_4 and 0.10 g KNO_3 per kg soil, respectively.

Root systems (roots and rhizomes) of giant reed, which had begun to sprout, were also collected from Zhuzhou district in Hunan Province, China. Concentrations of As, Cd and Pb in rhizome cuttings were 0.03, 0.01 and 0.07 mg/kg, respectively. Uniform size root systems cutting per pot were cultivated under laboratory condition in modified Hoagland solution for pre-culture.

2.2 Amendment

Five soil amendments including acetic acid (AA), citric acid (CA), EDTA, sepiolite and phosphogypsum were serviced. AA, CA and EDTA were pure salts. Sepiolite was obtained from a sepiolite plant in Hunan Province, China. Phosphogypsum, an industrial by-product, was collected from a phosphour fertilizer plant in Guizhou Province, China. Both samples of sepiolite and phosphogypsum were milled and then sieved through a 0.084 mm sieve before use. The concentrations of As, Cd, Pb in sepiolite and phosphogypsum are detailed in Table 2.

Table 2 Concentrations of heavy metals in sepiolite and phosphogypsum

Amendment	pH	Heavy metal concentration/($mg·kg^{-1}$)		
		As	Cd	Pb
Sepiolite	7.87	3.51	−	11.1
Phosphogysum	5.46	1.91	0.89	1.51

2.3 Experimental design and plant cultivation

Sepiolite and phosphogypsum were added to each pot with concentrations of 0, 4.0, 20 and 40 g per kg soil, and 0, 2.0, 4.0 and 8.0 g per kg soil, respectively, then mixed thoroughly with heavy metal contaminated soils (Table 3). The pot soil maintained 70% of the total water-holding field capacity for 15 days equilibration. Then, three uniform size root systems of giant reed were transplanted into each pot and cultivated in a greenhouse with a daily 14 h photoperiod and 10 h dark period, with day/night temperature of 30 °C/20 °C, and relative humidity of 60%. Two weeks before harvesting, AA, CA and EDTA at the concentrations of 0, 1.25, 2.5 and 5.0 mmol/kg soil were added to the remaining pots, respectively (Table 3). Each treatment was four replicates.

After three months of cultivation, the aboveground of giant reed was harvested and thoroughly washed with tap water, then rinsed with deionized water. Parts of fresh leaves were selected for the determination of chlorophyll content and enzyme activities. The remaining samples were oven dried at 105 °C for 30 min and dried at 60 °C until constant mass. Then the dried samples were milled with mortar and pestle, passed through a 0.25 mm sieve and stored for analysis.

Table 3 Amount of amendments applied to soils

Treatment	Addition level/ ($mmol\cdot kg^{-1}$)			Addition level/ ($g\cdot kg^{-1}$)	
	AA	CA	EDTA	Sepiolite	Phosphogypsum
Control	0	0	0	0	0
Low level	1.25	1.25	1.25	4.0	2.0
Middle level	2.5	2.5	2.5	20	4.0
High level	5.0	5.0	5.0	40	8.0

2.4 Sample analysis

The physicochemical properties of the soil were analyzed according to the methods described by LU [20]. Using a pH meter, the pH value of soil samples was determined by suspending them in distilled water at the soil to water ratio of 1:2.5 (w/v). Soil organic matter was oxidized with $K_2Cr_2O_7$. Available N was extracted with 1 mol/L NaOH and titrated with 0.01 mol/L H_2SO_4, and total N was determined by the Kjeldahl method. Available P (Olsen-P) was extracted using 0.5 mol/L $NaHCO_3$ with pH 8.5 and total P was determined by the Williams and Stewart method. Available K was extracted with 1.0 mol/L NH_4OAc of pH 7.0. Total K and availble K were determined with atomic absorption spectrometry (AA−6800, Shimadzu, Japan). Soil sample and amendments including sepiolite and phosphogypsum were digested with a mixture of HNO_3−H_2O_2 [21], and plant samples were digested with a mixture of HNO_3−$HClO_4$ [20]. Concentrations of As, Cd and Pb in solutions were determined using an inductively coupled plasma optical emission spectrometer (ICP−OES, IRIS Intrepid II XSP, USA). Blank and standard reference materials for plant (GBW—08513) and soil (GBW—08303) obtained from China National Center for Standard Reference Materials were included for QA/QC program.

Chlorophyll content in fresh leaves of giant reed was determined according to PORRA [22] and was expressed in mg of chlorophyll per g of fresh mass (FM). Activities of superoxide mutase (SOD) and catalase (CAT) were determined as described by RAO et al [23].

2.5 Statistical analysis

Statistical analyses were performed using Microsoft Excel 2003 and SPSS 13.0. Analysis of variance (ANOVA) was used to examine statistical significant differences among addition levels of soil amendments. A probability level of P<0.05 was considered significant.

3 Results

3.1 Effect of amendments on biomass of giant reed

The shoot biomass of giant reed grown on soil contaminated with As, Cd and Pb amending with soil amendments was presented in Fig. 1. Shoot biomass with respect to low level (1.25 mmol/kg) and middle level (2.5 mmol/kg) of AA varied slightly as compared to that for the control (12.6 g/pot), while that from the treatment with high level (5.0 mmol/kg) of AA was significantly decreased by 34.2% (P < 0.05). Plant shoot biomass increased with the increasing level of CA addition, which was enhanced by 14.2% and 24.8% in middle and high level treatment as much as the control, respectively, while a significant decrease of 28.7% was observed at low level treatment (P<0.05). For treatments of EDTA, the dry biomass obtained in middle level treatment was significantly higher than that in low level treatment (P<0.05), but showed slight difference from the control. The biomass of giant reed was slightly decreased with the increasing sepiolite addition. A reduction of 45.1% in shoot biomass was observed at the middle level treatment of phosphogypsum (P<0.05), but those obtained from low and high level treatments changed slightly as compared to the control.

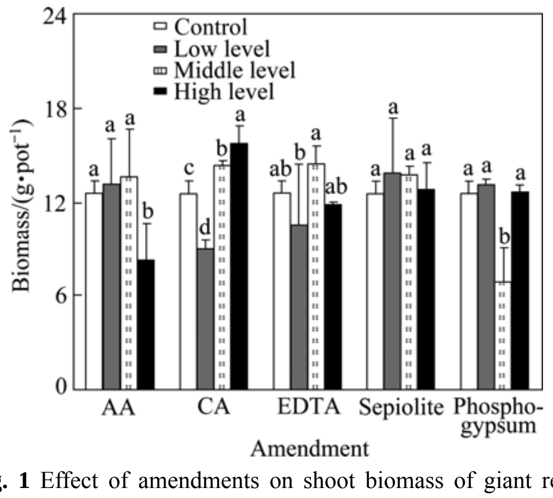

Fig. 1 Effect of amendments on shoot biomass of giant reed grown on soils contaminated with As, Cd and Pb (Values are presented as means ± SD. Different letters statistically stand for significant differences at P<0.05 level)

3.2 Effect of amendments on physiological characteristics of giant reed

3.2.1 Chlorophyll content

Chlorophyll contents in leaves of giant reed grown on soil amended with low and middle level of AA were 1.25 and 1.41 mg/g, which were increased by 58.2% and 78.5%, respectively, while sharply decreased by 68.4% for high level treatment in comparison to the control (Table 4). Treatments of CA at low and middle level exhibited negative influence on the chlorophyll synthesis of giant reed, and chlorophyll content of giant reed for the treatment of CA at low and middle levels was less than that of the control. With respect to EDTA, chlorophyll content in leaves was significantly increased by 119% for low level treatment (P<0.05), while sharply decreased by 39.2% and 25.3% for middle and high level treatments as compared with the control. The results showed that high level of EDTA in contaminated soil detrimentally affected the physiological response characteristics of giant reed. Chlorophyll contents in leaves with high level treatments of both sepiolite and phosphogypsum, however, significantly increased by 87.3% and 72.2% as compared to the control (P<0.05).

3.2.2 Activities of superoxide mutase and catalase

As shown in Table 5, SOD activity in leaves of giant reed was slightly increased with the increasing addition level of AA. The SOD activity obtained at high level treatment (0.123 U/mg) was slightly higher than that of the control, but significantly higher than that at low level treatment (P<0.05). SOD activity observed for treatment of CA varied slightly in comparison with that of the control. SOD activity changed slightly at low level treatment of sepiolite addition, while significant inhibition of 41.2% and 38.2% in SOD activity were found at middle level and high level treatments as compared to the control (P<0.05), respectively. Similar to CA addition treatment, SOD activity of giant reed for the treatment of phosphogypsum was slightly changed with respect to the control.

The activity of CAT in giant reed leaves was less sensitive to soil amendments but still stimulated as compared to the control (Table 6). CAT activity was prompted with AA addition, especially at high level treatment, which was up to 2.11 mg(H_2O_2)/(g·min) and significantly increased by 80.3% in comparison with the control (P<0.05). A slight increase in CAT activity in leaves was detected with increasing CA addition, but no significant difference in CAT activity at treatments between CA addition and the control was found. CAT activities were slightly affected by EDTA and sepiolite amendments, and that in leaves treated by middle level of phosphogypsum was higher than those from other level of phosphogypsum treatments and the control.

Table 4 Contents of chlorophyll in giant reed treated with amendments

Treatment	Chlorophyll content/(mg·g^{-1})				
	AA	CA	EDTA	Sepiolite	Phosphogypsum
Control	0.79±0.47 (ab)	0.79±0.47 (ab)	0.79±0.47 (b)	0.79±0.47 (b)	0.79±0.47 (b)
Low level	1.25±0.30 (a)	0.47±0.02 (b)	1.73±0.53 (a)	0.86±0.83 (b)	0.97±0.74 (b)
Middle level	1.41±0.80 (a)	0.54±0.09 (b)	0.48±0.11 (c)	0.33±0.03 (c)	0.63±0.39 (b)
High level	0.25±0.02 (b)	1.36±1.01 (a)	0.59±0.04 (bc)	1.48±0.02 (a)	1.36±0.24 (a)

Values are presented as means ± SD. Different letters statistically stand for significant differences at P < 0.05 level.

Table 5 Superoxide dismutase activity in giant reed treated with amendments

Treatment	SOD activity/(U·mg^{-1})				
	AA	CA	EDTA	Sepiolite	Phosphogypsum
Control	0.102±0.014 (ab)	0.102±0.014 (a)	0.102±0.014 (b)	0.102±0.014 (a)	0.102±0.014 (a)
Low level	0.082±0.003 (b)	0.097±0.003 (a)	0.100±0.006 (b)	0.102±0.004 (a)	0.100±0.007 (a)
Middle level	0.118±0.014 (ab)	0.088±0.003 (a)	0.099±0.008 (b)	0.060±0.028 (b)	0.102±0.006 (a)
High level	0.123±0.007 (a)	0.106±0.002 (a)	0.142±0.021 (a)	0.063±0.001 (b)	0.087±0.009 (a)

Values are presented as means ± SD. Different letters statistically stand for significant differences at P < 0.05 level.

Table 6 Catalase activity in leaves of giant reed treated with amendments

Treatment	CAT activity/(mg(H_2O_2)·g^{-1}·min^{-1})				
	AA	CA	EDTA	Sepiolite	Phosphogypsum
Control	1.17±0.51 (b)	1.17±0.51 (a)	1.17±0.51 (a)	1.17±0.51 (a)	1.17±0.51 (ab)
Low level	1.41±0.35 (b)	1.45±0.58 (a)	1.37±0.30 (a)	1.38±0.37 (a)	0.97±0.48 (b)
Middle level	1.85±0.46 (b)	1.36±0.20 (a)	1.32±0.03 (a)	1.04±0.19 (a)	1.83±0.66 (a)
High level	2.11±0.31 (a)	1.29±0.31 (a)	1.74±0.79 (a)	1.29±0.26 (a)	1.15±0.09 (ab)

Values are presented as means ± SD. Different letters statistically stand for significant differences at P<0.05 level.

3.3 Effect of amendments on heavy metal uptake by giant reed

3.3.1 Effect of amendments on concentrations of As, Cd and Pb in giant reed

The concentrations of heavy metals in shoots of giant reed grown on contaminated soil were significantly enhanced by addition of soil amendments (Fig. 2). Arsenic concentration in giant reed was 4.68 times as much as that in the control when amending with middle level of AA (P<0.05). Arsenic concentration in giant reed was obviously decreased with increasing the amount of CA addition, while increased progressively with EDTA addition, showing that it was useful to enhance As concentration in giant reed by addition of low level CA and high level of EDTA (P<0.05), respectively.

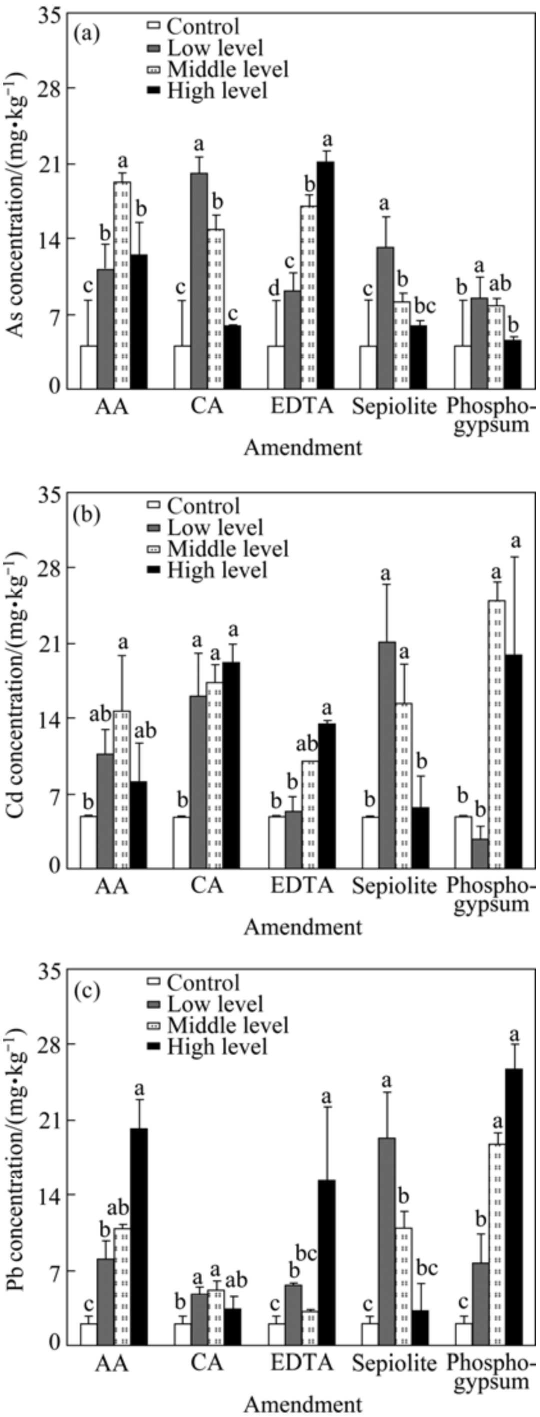

Fig. 2 Concentrations of As (a), Cd (b) and Pb (c) in giant reed grown on soils treated with different amendments

The Cd concentration in shoot of giant reed increased with the increasing of CA and EDTA addition, of which CA was proved to be more effective (Fig. 2). When CA was applied at level of 1.25, 2.5 and 5.0 mmol/kg soil, Cd concentration in giant reed was 3.26, 3.52 and 3.91 times as much as that in the control, respectively (P<0.05). Cadmium concentration in giant reed was significantly increased with the addition level of sepiolite and phosphogypsum, especially for treatment with low level of sepiolite and middle level of phosphogypsum (P<0.05), respectively.

The Pb concentration in shoots of giant reed increased significantly with increasing AA addition level (P<0.05) (Fig. 2). Lead concentration obtained in low and middle level treatment of sepiolite was 9.37 and 5.33 times of that in the control (P<0.05), respectively. The concentration of Pb observed in phosphogypsum treatment was progressively increased with the application level, with 25.8 mg/kg in giant reed shoots recorded at high level treatment (P<0.05). The application of CA and EDTA, however, exhibited less effective in Pb uptake by giant reed.

3.3.2 Effect of amendments on accumulations of As, Cd and Pb in giant reed

In terms of total metal accumulation, which is based on the biomass multiplying by metal concentration, the middle level of AA application could significantly increase As accumulation in giant reed to 4.3-fold of that in control (P<0.05) (Fig. 3). The addition of low and middle level of CA also demonstrated obviously stimulating effect on As accumulation in shoots at low and middle level treatments, which was 4.02 and 4.34 times as much as that in the control, respectively. In addition, As accumulation was significantly increased by 4.42 times and 5.03 times compared to the control when middle and high levels of EDTA were added, respectively.

The accumulation of Cd was increased with the addition level of CA, which in middle and high level treatment was 4.17 and 4.42 times as much as that in the control (P<0.05), respectively (Fig. 3). Sepiolite was found to be more effective to enhance Cd accumulation at low (0.25 mg/pot) and middle level treatment (0.21 mg/pot), which was 4.17 and 3.51 times as much as that in the control, respectively. Cadmium accumulation was significantly increased with increasing the addition level of phosphogypsum, and significantly increased by 2.41 and 3.25 times for middle and high level treated plants as compared to the control (P<0.05), respectively.

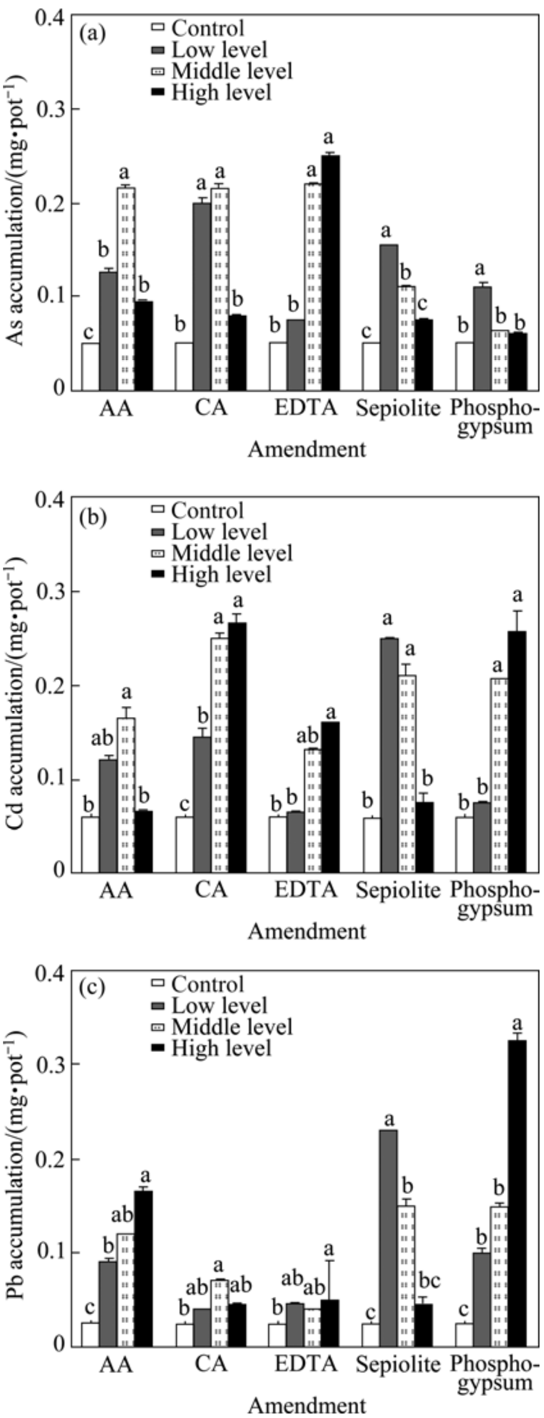

Fig. 3 Accumulations of As (a), Cd (b) and Pb (c) in giant reed grown on soils contaminated with heavy metals treated with different amendments

Amendments of AA and EDTA also could enhance Cd accumulation in giant reed, while show less effect than other amendments.

Lead accumulation in giant reed shoot was sharply increased at treatments with AA, especially for high level treatment, which was 5.6 times higher than that of the control (Fig. 3). The addition of CA and EDTA, however, was less effective than AA addition. Similar to As and Cd accumulation, Pb accumulation was decreased gradually with increasing the level of sepiolite, while substantially increased with increasing doses of phosphogypsum ($P<0.05$). Lead accumulation recorded at low level of sepiolite and high level of phosphogypsum addition significantly reached up to 0.23 mg/pot and 0.33 mg/pot ($P<0.05$), respectively.

4 Discussion

4.1 Effect of amendments on growth of giant reed

In the study, shoot dry biomass was significantly increased by 14.2% and 24.8% for treatments with CA doses of 2.5 and 5.0 mmol/kg, respectively, and a low dosage (1.25 mmol/kg) showed little inhibitory effect (Fig. 1). Similar studies also observed the stimulating effect of CA (5.0 mmol/kg) on ryegrass growth [10] and showed that CA was considered the good option to enhance the growth of giant reed.

Chlorophyll synthesis and enzyme activities in plants are sensitive under adverse condition and can provide precise information on any perturbation occuring in plant [24]. In the present study, chlorophyll contents in leaves of giant reed increased at 1.25 and 2.5 mmol/kg of AA addition, while decreased sharply at 5.0 mmol/kg treatment accompanied with biomass decrease (Table 4). Similarly, chlorophyll content in leaves was increased by 72.2% amended with high level CA in comparison to the control, which was in agreement with the change of biomass, suggesting that CA application did not deteriorate photosynthetic parameters of plant [25]. The activities of SOD and CAT increased resistance to the stress of multi-metals, especially CAT played a role in defying As, Cd, Pb-induced oxidative stress in plant [26].

4.2 Effect of amendments on heavy metal phyto-extraction for giant reed

Based on the results of the study, the concentrations of As, Cd and Pb in shoots of giant reed grown on amended soil were significantly increased. Positive effects of middle level of AA on enhancing concentrations of As and Cd and high level on Pb in giant reed shoots were shown (Fig. 2). CA addition treatment with low and high level could significantly increase As and Cd concentration in giant reed. Similarly, the concentrations of As, Cd and Pb with low level of sepiolite were significantly increased by 2.18, 3.31 and 8.37 times as compared with that in the controls, respectively, while they were not increased with increasing addition level of sepiolite. The reason might be contributed to the large surface area as well as the strong adsorptive capacity of sepiolite [27]. Accumulations of As and Cd were significantly enhanced by 0.60−3.31 times and 1.42−3.42 times when treated with CA, which was in agreement with the other findings [10,28]. Comparing with the control treatment, accumulations of As, Cd and Pb were significantly increased to 0.25, 0.16 and 0.05 mg/pot for high level of EDTA addition, and reached 0.15, 0.25 and 0.23 mg/pot for low level of sepiolite addition ($P<0.05$), respectively. This is consistent with the studies by LIPHADZI and KIRKHAM [29]. Although EDTA played an important role in enhancing the concentrations of As and Cd in giant reed shoots, especially that of Pb at high level treatment (Fig. 2), EDTA is non-biodegradable, and possesses high environmental persistence of soluble chelate-heavy metal complexes in soil as well as toxicity and risk of possible leaching to groundwater [7]. Therefore, AA, CA and sepiolite are better than EDTA in enhancing phytoremediation efficiency of giant greed.

5 Conclusions

1) Soil amendments including AA, CA, EDTA, sepiolite and phosphogypsum can enhance the biomass to some extent. The shoot dry biomass of giant reed for treatments with 5.0 mmol/kg CA and 2.5 mmol/kg EDTA was 1.25 and 1.15 times that of the control, respectively.

2) The concentrations of As, Cd and Pb in giant reed shoots were significantly increased when applying lower levels of AA, CA and sepiolite and high level of EDTA, respectively. Accumulations of As and Cd in plant significantly increased with the addition of 2.5 mmol/kg AA and CA, 5.0 mmol/kg EDTA, and 4.0 g/kg sepiolite, and the shoot Pb accumulation was enhanced obviously by amending with 4.0 mg/kg sepiolite and 8.0 mg/kg phosphogysum, respectively as compared to the control. The results suggested that AA, CA and sepiolite could be considered optimum soil amendments for giant reed remediation system.

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改良剂对 As、Cd、Pb 污染土壤上芦竹生长及重金属吸收的影响

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摘 要：通过室内盆栽试验研究在 As、Cd 和 Pb 复合污染土壤中施用醋酸、柠檬酸、EDTA、海泡石和磷石膏 5 种改良剂对芦竹生长及重金属吸收的影响。结果表明，施加 5.0 mmol/kg 柠檬酸或 2.5 mmol/kg EDTA 时，芦竹地上部生物量较没添加的对照的分别增加了 24.8%和 15.0%，芦竹叶片中过氧化氢酶及过氧化歧化酶活性较对照的无显著变化。与对照相比，添加 2.5 mmol/kg 醋酸、2.5 mmol/kg 柠檬酸、5.0 mmol/kg EDTA 及 4.0 g/kg 海泡石时，地上部中 As、Cd、Pb 的浓度显著增加(P<0.05)。改良剂能明显提高芦竹地上部重金属累积量，地上部中 As、Cd 的累积量在上述条件下均显著增加(P<0.05)，Pb 累积量在添加 4.0 g/kg 海泡石和 8.0 g/kg 磷石膏时显著高于对照(P<0.05)。醋酸、柠檬酸和海泡石可作为合适改良剂促进重金属污染土壤上芦竹对土壤中重金属的累积。

关键词：植物修复；芦竹；土壤改良剂；重金属污染土壤；重金属累积

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