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RESEARCH ARTICLE

Cadmium tolerance and accumulation in fifteen wetland plant species from cadmium-polluted water in constructed wetlands

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Abstract Variations in cadmium (Cd) tolerances and accumulations among fifteen wetland plant species in moderately ($0.5\,\mathrm{mg\cdot L^{-1}}$) and heavily ($1.0\,\mathrm{mg\cdot L^{-1}}$) Cd-polluted wastewaters were investigated in constructed wetlands. Cd removal efficiencies from the wastewaters were more than 90%, and 23.5% and 16.8% of the Cd in the water accumulated in wetland plants for 0.5 and 1.0 $\mathrm{mg\cdot L^{-1}}$ Cd treatments, respectively. The variations among the plant species were 29.4-fold to 48.7-fold in plant biomasses, 5.4-fold to 21.9-fold in Cd concentrations, and 13.8-fold to 29.6-fold in Cd accumulations. The plant species were also largely diversified in terms of Cd tolerance. Some species were tolerant of heavy Cd stress, and some others were sensitive to moderate Cd level. Four wetland plant species were selected for the treatment of Cd-polluted wastewater for their high Cd accumulating abilities and relative Cd tolerances. Plant Cd quantity accumulations are correlated positively and significantly ($P < 0.05$) with plant biomasses and correlated positively but insignificantly ($P > 0.05$) with plant Cd concentrations. The results indicate that the Cd accumulation abilities of wetland plant species are determined mainly by their biomasses and Cd tolerances in growth, which should be the first criteria in selecting wetland plant species for the treating Cd-polluted wastewaters. Cd concentration in the plants may be the second consideration.

Keywords cadmium (Cd), wastewater treatment, wetland plant, selection, index

1 Introduction

Cadmium (Cd) is one of the most toxic metals in aquatic systems. The release of Cd from anthropogenic activities, such as waste disposal, mining, fertilization, metal smelting and electroplating is 10 times higher than that of natural sources [1]. Cd cannot be removed from water by self-purification. Moreover, it is readily taken up by plants and translocated into different parts of plants. Thus, it could seriously threaten the health of human body if it accumulates through the food chain [2,3].

Current widely used sewage treatment technologies in China, for example the active sludge system, have several shortcomings, such as high construction costs and complex operation, especially for small towns [4,5]. Constructed wetlands are an appropriate treatment system for developing countries. They require low investment, have low energy dissipation, are easy to operate, and produce high-quality effluent [6–8]. As a low-cost treatment measure, constructed wetlands have been successfully used in some countries [9–11].

Wetland plants are the main biological component of a wetland. They absorb pollutants into their tissues directly and change the environment in the rhizosphere, which can enhance pollutant purification by promoting various chemical and biochemical reactions [12,13]. Some plants are highly tolerant of heavy metal stress and can accumulate high levels of metals in their tissues. Thus, these plants have the potential for phytoremediation [14]. Examples of such plants include *Salix phylicifolia*, *Typha latifolia*, *Phragmites australis* and *Juncus effuses* [15–17]. Previous studies showed that uptake, transport and accumulation of heavy metals by plants were strongly governed by plant factors, and they differed significantly with plant species [18,19]. Thus, the plants with certain characteristics, such as tolerance and high accumulation of target metals, fast growth and high biomass, are important for phytoremediation of metal-polluted environments.

This paper aims to investigate the following: 1) the differences among 15 wetland plant species in terms of

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tolerance to different levels of Cd-polluted wastewaters; 2) variations among wetland plant species in terms of Cd accumulation from wastewater; 3) some rules of Cd accumulation in the plants. Our findings can be useful for selecting plant species that can remove Cd from wastewaters.

2 Materials and methods

2.1 Design of constructed wetland

Wetlands were constructed under open air in Changzhou, China, as described in our previous publications [20,21]. The plots consisted of six chambers, each with a surface area of 2 m^2 (1 m × 2 m). Each chamber was filled with soil to 25 cm depth. The soil was obtained from an uncontaminated wetland and sieved through a 5 mm sieve. This soil has a pH 6.82, organic matter 2.39%, cation exchange capacity 13.2 $cmol \cdot kg^{-1}$, and nitrogen content 0.15%. Atomic Absorption Spectrophotometry was performed to determine the total Cd concentration in the soil after the soil was digested by using H_2O_2 - HF- HNO_3 - $HClO_4$ [22]. Cd concentration of the soil was 0.13 $mg \cdot kg^{-1}$ (DW). Before the wetland plant seedlings were transplanted, the soil was submerged with water for a month (approximately 5 cm above the soil surface).

2.2 Collection of wetland plant species and experimental design

Seedlings of 15 wetland plant species (7 families in total) were obtained from the wetlands in the suburb of Changzhou (Table 1). Among them, six species belong to the Gramineae family. These species are often significant components of the plant community that thrives in metal-polluted sites [13]. For each plant species, three seedlings of similar size (15±5 cm in height) were selected and transplanted into each chamber. The plants were arranged in an even and randomized order.

The artificial wastewater was spiked with Cd at concentrations of 0.5 and 1.0 $mg \cdot L^{-1}$ to mimic moderately and heavily Cd-polluted wastewater, respectively [23]. The Cd-polluted water was prepared by using $CdCl_2 \cdot 2.5H_2O$. Each level of Cd-treated water was fed into two of the six chambers three times (160 L for each chamber at each time), i.e., the 15th, 22nd and 29th day after the plant seedlings were transplanted. The two chambers that received water untreated with Cd (tap water) served as controls. All the chambers were submerged with approximately 5 cm water above the soil surface during the experiment.

2.3 Sample preparation and analytical methods

The wetland plants were harvested at 50 days after seedlings transplanting, washed thoroughly with tap water, and then rinsed with deionized water. The plants were divided into belowground and aboveground parts, and the plant parts were oven-dried at 70°C to a constant weight. The dry weights of the samples were measured. The samples were ground with a stainless steel grinder (FW-100, Shanghai Ziyi Reagent Factory, China) to pass through a 100-mesh sieve. The Cd concentrations of the samples were tested by Atomic Absorption Spectrophotometer following a digestion procedure using HNO_3-$HClO_4$ (4:1) [24]. Certified standard plant reference materials of China (GBW07604, GBW08508) were run simultaneously as quality control.

Table 1 Family and species of the wetland plants used in this experiments

code name	family	species
A	Gramineae	*Echinochloa crus-galli* (L.) Beauv
B	Gramineae	*Echinochloa oryzicola* (Ard.) Fritsch
C	Gramineae	*Zizania latifolia* (Griseb.) Stapf
D	Gramineae	*Digitaria sanguinalis* (L.) Scop
E	Gramineae	*Phragmites communis* Trin.
F	Gramineae	*Isachne globosa* (Thunb.) Kuntze
G	Polygonaceae	*Polygonum lapathifolium* L.
H	Polygonaceae	*Polygonum hydropiper* L.
I	Compositae	*Eclipta prostrata* L.
J	Compositae	*Aster subulatus* Michx
K	Cyperaceae	*Cyperus iria* L.
L	Cyperaceae	*Fimbristylis miliacea* (L.) Vahl
M	Leguminosae	*Aeschynomene indica* L.
N	Pontederiaceae	*Monochoria vaginalis* (Burm. f.) Presl
O	Amaranthaceae	*Alternanthera philoxeroides* (Mart.) Griseb

2.4 Data analysis

Data were analyzed by using the statistical package SPSS 13.0 and Excel 2003 for Windows. Differences between the control and the Cd treatments in plant biomasses were tested by a paired *t*-test. Pearson correlations were used to test the relationships between different parameters. Two significant levels of $P < 0.05$ and 0.01 were used to present the results.

3 Results

3.1 Variations among wetland plant species in biomasses and Cd tolerances

Significant differences were observed among the 15 wetland plant species in the biomasses of aboveground, belowground, and whole plants. The magnitudes of the differences increased as Cd levels in the water rose (Table 2). With regard to the biomasses of aboveground parts, the plant species ranged from 16.31 g·chamber^{-1} to 479.83 g·chamber^{-1} (29.4-fold variation) for the control, from 14.90 to 478.00 g·chamber^{-1} (32.1-fold variation) for the 0.5 mg·L^{-1} Cd treatment and from 13.10 to 473.40 g·chamber^{-1} (36.1-fold variation) for the 1.0 mg·L^{-1} Cd treatment. With regard to the biomasses of belowground parts, the species ranged from 6.72 to 272.82 g·chamber^{-1} (40.6-fold variation), from 5.69 to 265.60 g·chamber^{-1} (46.7-fold variation), and from 5.48 to 251.13 g·chamber^{-1} (45.8-fold variation) for the control, 0.5 mg·L^{-1} and 1.0 mg·L^{-1} Cd treatments, respectively. With regard to the biomasses of whole plants, the species ranged from 23.03 to 752.65 g·chamber^{-1} (32.7-fold variation), from 20.59 to 743.60 g·chamber^{-1} (36.1-fold variation), and from 18.58 to 724.53 g·chamber^{-1} (39.0-fold variation) for the control, 0.5 mg·L^{-1}, and 1.0 mg·L^{-1} Cd treatments, respectively.

The tolerance of the plant species to water Cd stress varied largely according to plant species and water Cd levels. On average, the biomasses of the 15 species under 0.5 mg·L^{-1} Cd treatment changed little and insignificantly ($P > 0.05$) compared with the control. However, the biomass of 1.0 mg·L^{-1} Cd treatment decreased significantly ($P < 0.05$) whether the plants were aboveground or belowground.

The differences of the plant species in Cd tolerances were highly diversified. Under 0.5 mg·L^{-1} water Cd treatment, the biomasses of whole plants increased for seven species compared with the control: the increases were significant ($P < 0.05$) in three species. The most tolerant species was *Alternanthera philoxeroides*, which increased its biomass by 8.0%. The biomasses decreased for eight species: the decreases were significant ($P < 0.01$) in two species. The most sensitive species was *Eclipta prostrata*, which exhibited a 12.1% decrease in its biomass.

Under 1.0 mg·L^{-1} water Cd treatment, all the plant species decreased in biomass, and the decreases were significant ($P < 0.05$, or 0.01) in 10 species. The most tolerant species was *Digitaria sanguinalis*, with only 0.1% and insignificant ($P > 0.05$) decrease in its biomass. The most sensitive species was *Aster subulatus*, with a 19.3% decrease in its biomass.

3.2 Variations among wetland plant species in Cd accumulations

Table 3 shows the Cd concentrations and quantity accumulations of the 15 wetland plant species under water Cd treatments. The plants accumulated 38.32 and 53.07 mg of Cd in their aboveground parts, and 18.12 and 27.53 mg of Cd in their belowground parts for the 0.5 and 1.0 mg·L^{-1} Cd treatments, respectively. In terms of the whole plants (above- and belowground), the plants accumulated 56.44 and 80.60 mg of Cd for 0.5 and

Table 2 The biomasses of the wetland plants in different water Cd levels/(g·chamber^{-1}, DW)

plant species	belowground					aboveground				
	control	0.5 mg·L^{-1} Cd treatment	±% a)	1.0 mg·L^{-1} Cd treatment	±%	control	0.5 mg·L^{-1} Cd treatment	±%	1.0 mg·L^{-1} Cd treatment	±%
A	91.42	89.23	−2.39	78.78	−13.82**	418.59	420.83	0.53	404.94	−3.26
B	26.25	28.18	7.36*	22.61	−13.86**	110.96	114.62	3.30	102.99	−7.18*
C	272.82	265.60	−2.65	251.13	−7.95*	479.83	478.00	−0.38	473.40	−1.34
D	43.78	43.47	−0.70	42.40	−3.14	125.81	133.89	6.42*	126.95	0.91
E	99.59	105.36	5.79*	92.19	−7.43*	377.88	388.75	2.88	370.54	−1.94
F	32.84	35.82	9.09*	31.72	−3.40	133.44	141.94	6.37*	122.85	−7.94*
G	18.95	19.37	2.22	15.85	−16.36**	97.39	92.63	−4.89*	85.05	−12.68**
H	26.35	23.84	−9.51**	24.29	−7.81*	225.18	219.91	−2.34	217.17	−3.56
I	12.82	11.58	−9.65*	9.56	−25.41**	54.93	47.99	−12.62**	45.27	−17.59**
J	6.72	5.69	−15.27**	5.48	−18.39**	16.31	14.90	−8.62*	13.10	−19.69**
K	27.73	26.70	−3.71	23.21	−16.29**	106.88	110.49	3.37	99.02	−7.36*
L	32.33	32.72	1.21	29.52	−8.69*	146.25	141.31	−3.38	136.06	−6.97*
M	37.01	34.65	−6.38*	29.44	−20.46**	198.98	193.07	−2.97	178.54	−10.27**
N	16.99	17.71	4.25	16.37	−3.64	128.51	125.19	−2.58	121.44	−5.50*
O	35.43	38.04	7.37*	34.53	−2.54	319.55	345.23	8.04*	311.26	−2.59
average	52.07	51.86	−0.39	47.14	−9.47*	196.03	197.92	0.96	187.24	−4.49*

Notes: a) Relative change of water Cd treatment compared to the control.±% = ((weight of Cd treatment − weight of control)/weight of control) × 100
*, ** Significant difference between the control and water Cd treatment at the $P_{0.05}$, $P_{0.01}$ level, respectively

Table 3 Cd concentrations and accumulations of the wetland plants in different water Cd levels

plant species	Cd concentrations/($\mu g\cdot g^{-1}$, DW)				Cd accumulations/($mg\cdot chamber^{-1}$)					
	0.5 $mg\cdot L^{-1}$ Cd treatment		1.0 $mg\cdot L^{-1}$ Cd treatment		0.5 $mg\cdot L^{-1}$ Cd treatment			1.0 $mg\cdot L^{-1}$ Cd treatment		
	belowground	aboveground	belowground	aboveground	belowground	aboveground	whole plant	belowground	aboveground	whole plant
A	18.93	7.75	29.84	11.40	1.69	3.26	4.95	2.35	4.62	6.97
B	22.26	7.03	32.35	11.18	0.63	0.81	1.44	0.73	1.15	1.88
C	10.47	6.46	16.86	8.30	2.78	3.09	5.87	4.23	3.93	8.16
D	24.97	14.80	44.02	23.65	1.09	1.98	3.07	1.87	3.00	4.87
E	6.65	7.30	17.18	11.54	0.70	2.84	3.54	1.58	4.28	5.86
F	26.25	34.61	49.55	53.15	0.94	4.91	5.85	1.57	6.53	8.10
G	43.45	10.99	74.87	16.08	0.84	1.02	1.86	1.19	1.37	2.56
H	50.27	14.58	80.91	21.75	1.20	3.21	4.41	1.97	4.72	6.69
I	24.34	11.23	34.12	16.90	0.28	0.54	0.82	0.33	0.76	1.09
J	39.89	17.33	71.09	22.33	0.23	0.26	0.49	0.39	0.29	0.68
K	19.94	23.57	43.54	37.71	0.53	2.60	3.13	1.01	3.73	4.74
L	22.49	14.84	35.83	21.62	0.74	2.10	2.84	1.06	2.94	4.00
M	13.83	8.05	25.43	12.20	0.48	1.55	2.03	0.75	2.18	2.93
N	145.57	26.41	241.68	41.06	2.58	3.31	5.89	3.96	4.99	8.95
O	89.77	19.83	131.41	27.54	3.41	6.85	10.26	4.54	8.57	13.11
total					18.12	38.32	56.44	27.53	53.07	80.60

Table 4 Cd removal efficiencies from the wastewaters by the constructed wetland

Cd concentrations of the inflow wastewaters/($mg\cdot L^{-1}$)	Cd concentrations of the outflow waters after experiment/($mg\cdot L^{-1}$)	Cd removal efficiencies/%
0.500	0.034	93.2
1.000	0.039	96.1

1.0 $mg\cdot L^{-1}$ Cd treatments, respectively, which account for 23.5% and 16.8% of the Cd added to the water. Cd concentrations for some samples of the control were below the testing limit. Thus, the data of the control are not shown.

In general, great differences in Cd concentrations and accumulations were found among the plant species.

For the plant species, Cd concentrations in the aboveground parts ranged from 6.46 to 34.61 $\mu g\cdot g^{-1}$ (5.4-fold variation) for 0.5 $mg\cdot L^{-1}$ Cd treatment and from 8.30 to 53.15 $\mu g\cdot g^{-1}$ (6.4-fold variation) for 1.0 $mg\cdot L^{-1}$ Cd treatment. Cd concentrations in the belowground parts ranged from 6.65 to 145.57 $\mu g\cdot g^{-1}$ (21.9-fold variation) for 0.5 $mg\cdot L^{-1}$ Cd treatment, and from 16.86 to 241.68 $\mu g\cdot g^{-1}$ (14.3-fold variation) for 1.0 $mg\cdot L^{-1}$ Cd treatment. In terms of the mean, for the Cd concentrations in whole plants (Cd accumulation of whole plants/biomass of whole plant), the plant species ranged from 7.16 to 41.18 $\mu g\cdot g^{-1}$ (5.8-fold variation) for 0.5 $mg\cdot L^{-1}$ Cd treatment and from 11.27 to 64.89 $\mu g\cdot g^{-1}$ (5.8-fold variation) for 1.0 $mg\cdot L^{-1}$ Cd treatment.

Cd accumulations in aboveground parts of the plant species ranged from 0.26 to 6.85 $mg\cdot chamber^{-1}$ (26.3-fold variation) and from 0.29 to 8.57 $mg\cdot chamber^{-1}$ (29.6-fold variation) for 0.5 $mg\cdot L^{-1}$ and 1.0 $mg\cdot L^{-1}$ Cd treatments, respectively. Cd accumulations in the belowground parts ranged from 0.23 to 3.41 $mg\cdot chamber^{-1}$ (14.8-fold variation) and from 0.33 to 4.54 $mg\cdot chamber^{-1}$ (13.8-fold variation) for the 0.5 and 1.0 $mg\cdot L^{-1}$ Cd treatments, respectively. Cd accumulations in the whole plants of the species ranged from 0.49 to 10.26 $mg\cdot chamber^{-1}$ (20.9-fold variation) for 0.5 $mg\cdot L^{-1}$ Cd treatment, and from 0.68 to 13.11 $mg\cdot chamber^{-1}$ (19.3-fold variation) for 1.0 $mg\cdot L^{-1}$ Cd treatment. The four species that had the highest Cd accumulations were *Alternanthera philoxeroides*, *Isachne globosa*, *Monochoria vaginalis* and *Zizania latifolia*. They accounted for 49.4% and 47.5% of the total Cd accumulation in the 15 plant species, for 0.5 and 1.0 $mg\cdot L^{-1}$ Cd treatments, respectively.

The Cd removal efficiencies of the constructed wetland were 93.2% and 96.1% for 0.5 and 1.0 $\mathrm{mg \cdot L^{-1}}$ Cd treatments, respectively by the end of this experiment (Table 4).

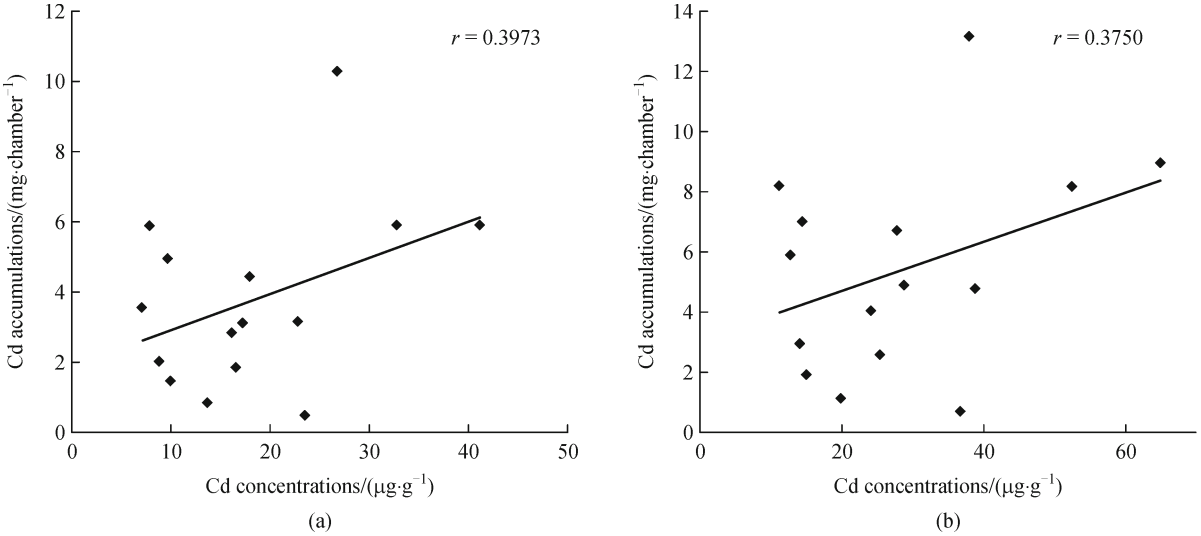
3.3 Relationship between plant Cd accumulations and Cd concentrations and biomasses

Cd quantity accumulations in plants are the result of plant biomasses multiplying Cd concentrations in the plants. Correlation analysis indicated that plant Cd accumulations of the water Cd treatments correlated positively with plant Cd concentrations as well as with the biomasses of the control and Cd treatments (Fig. 1–3). The correlation coefficients were high and significant ($P < 0.05$) for the biomasses of the control and water Cd treatments, but low and insignificant ($P > 0.05$) for plant Cd concentrations.

4 Discussion

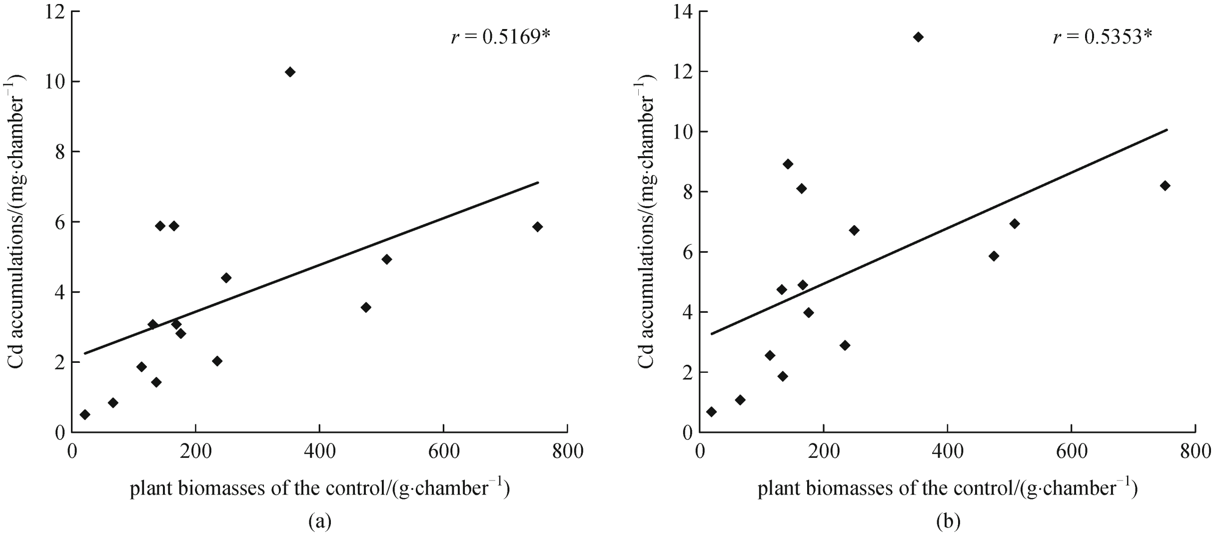
Water pollution has become a major environmental issue in China because of the rapid economic development and urbanization. Thus, developing effective sewage treatment facilities is crucial [25].

Constructed wetland is an engineered system that takes advantage of natural processes, such as vegetative, soil, and microbial activities, in wastewater treatment. It has been used since the 1990s to treat wastewater from acid



(a) (b)

Fig. 1 Correlations between plant Cd accumulations and concentrations of different wetland plant species. (a) 0.5 $\mathrm{mg \cdot L^{-1}}$ water Cd treatment, (b) 1.0 $\mathrm{mg \cdot L^{-1}}$ water Cd treatment



(a) (b)

Fig. 2 Correlations between plant Cd accumulations and biomasses of the control for different wetland plant species. (a) 0.5 $\mathrm{mg \cdot L^{-1}}$ water Cd treatment, (b) 1.0 $\mathrm{mg \cdot L^{-1}}$ water Cd treatment. * Significant at the $P_{0.05}$ level

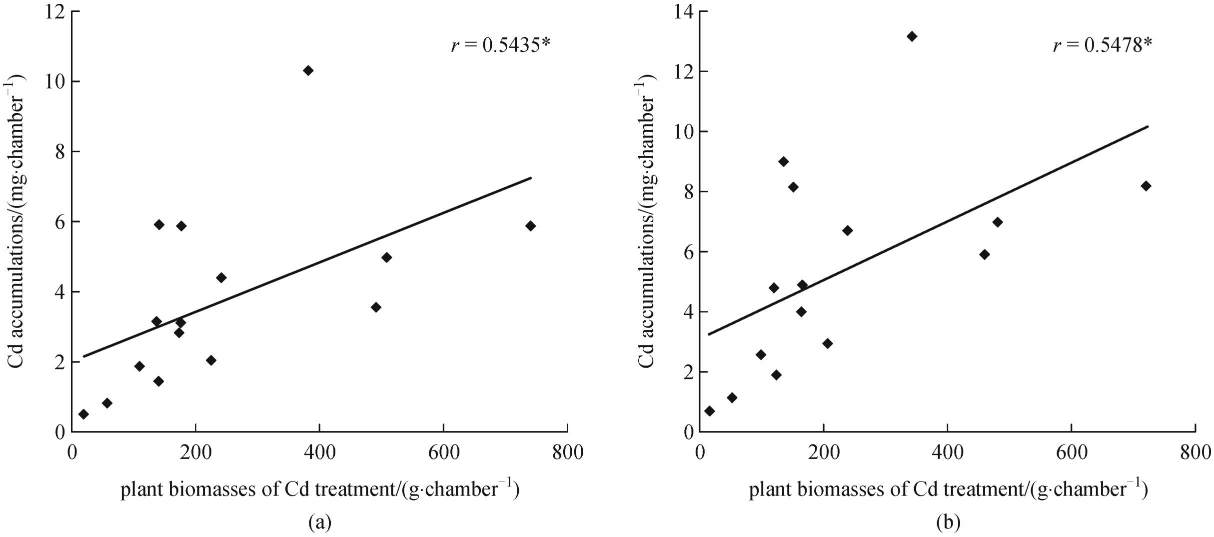


Fig. 3 Correlations between plant Cd accumulations and biomasses of water Cd treatments for different wetland plant species. (a) 0.5 $\mathrm{mg\cdot L^{-1}}$ water Cd treatment, (b) 1.0 $\mathrm{mg\cdot L^{-1}}$ water Cd treatment. * Significant at the $P_{0.05}$ level

mine drainage, industrial and agricultural production, urban and highway runoff, food processing, and sludge dewatering [26]. A constructed wetland removed 81%, 66%, and 59% of incoming Cr, Ni, and Zn, respectively, from the incoming wastewater of a metallurgic factory [27]. It also reduced metal content, removing 87%, 49%, 95%, 85%, and 92% of Mn, Co, Cu, As, and Pb, respectively, from sewage water [9].

Our present research showed that the Cd removal efficiencies from the wastewaters by using the constructed wetland were more than 90% (93.2% and 96.1% for 0.5 and 1.0 $\mathrm{mg\cdot L^{-1}}$Cd treatments, respectively) by the end of this experiment. The results indicate that constructed wetland is an effective and economic system for removing Cd from wastewater and can be used to protect the water environment from Cd pollution.

Sedimentation is the main process for removing heavy metals from wastewater, accounting for 60% to 90% of metal reduction from wastewater [28]. However, some wetland plants can be used to remediate waters or soils contaminated by heavy metal. In densely planted wetlands, plants accumulate considerable amounts of heavy metals, which can be removed by frequently harvesting the plants [20,29]. Wetland plants could account for 27% to 46% of metal removal in wetlands [13]. In our present research, wetland plants accumulated 56.44 and 80.60 mg of Cd for 0.5 and 1.0 $\mathrm{mg\cdot L^{-1}}$ Cd treatments, respectively, which accounts for 23.5% and 16.8% of the Cd added to the water. The Cd restrained in the soil accounted for 69.7% and 79.3% of the added Cd, respectively.

Uptake and accumulation of heavy metals from wastewater may be species dependent and metal dependent, such as *Hydrilla verticillata* for Cu [30] and *Phragmites communis* for Hg [31]. Our present research showed tens-fold variations in terms of Cd accumulation abilities among 15 wetland plant species. Thus, the composition of plant species in constructed wetlands is important for Cd removal efficiency and maintaining the function of the wetland.

In our present paper, plant biomasses had 29.4-fold to 48.7-fold variations, Cd concentrations had 5.4-fold to 21.9-fold variations, and Cd accumulations had 13.8-fold to 29.6-fold variations, among the plant species. The Cd tolerance of the plant species was also very diverse. The four species that had the highest Cd accumulations were *Alternanthera philoxeroides*, *Isachne globosa*, *Monochoria vaginalis* and *Zizania latifolia*. They accounted for 49.4% and 47.5% of the total Cd accumulation in the 15 plant species, for 0.5 and 1.0 $\mathrm{mg\cdot L^{-1}}$ Cd treatments, respectively. The plants were relatively tolerant to water Cd stress. Thus, these four wetland plant species are suitable for planting in wetland to treat Cd-polluted wastewater.

Correlation analysis showed that plant Cd accumulations correlated positively and significantly ($P < 0.05$) with plant biomasses and correlated positively but insignificantly ($P > 0.05$) with plant Cd concentrations. The results indicate that the Cd accumulation abilities of plant species are determined mainly by plant biomasses, especially the biomasses in Cd-polluted wastewaters. In selecting wetland plant species for treating Cd-polluted wastewaters, the first consideration should be plant biomass and Cd tolerance in growth. The Cd concentrations of the plants may be the second index.

5 Conclusions

In constructed wetlands, the Cd removal efficiencies from wastewaters were more than 90%. A total of 23.5% and

16.8% of the Cd in the waters accumulated into the wetland plants for 0.5 and 1.0 $\mathrm{mg \cdot L^{-1}}$ water Cd treatments, respectively. Plant biomasses had 29.4-fold to 48.7-fold variations, Cd concentrations had 5.4-fold to 21.9-fold variations, and Cd accumulations had 13.8-fold to 29.6-fold variations, among the plant species. The Cd tolerance of the plant species was diverse. Four wetland plant species were selected to treat Cd-polluted wastewaters for their high Cd accumulating abilities and high tolerance of water Cd stress. Plant Cd accumulations correlated positively and significantly ($P < 0.05$) with plant biomasses and correlated positively but insignificantly ($P > 0.05$) with plant Cd concentrations. The results indicate that the Cd accumulation abilities of wetland plant species are determined mainly by plant biomass and Cd tolerance in growth, which should be the first index in selecting wetland plant species to treat Cd-polluted wastewaters.

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References

1. DalCorso G, Farinati S, Maistri S, Furini A. How plants cope with cadmium: staking all on metabolism and gene expression. Journal of Integrative Plant Biology, 2008, 50(10): 1268–1280
2. Madejón P, Marañón T, Murillo J M, Robinson B. White poplar (Populus alba) as a biomonitor of trace elements in contaminated riparian forests. Environmental Pollution, 2004, 132(1): 145–155
3. Wang H, Jia Y, Wang S, Zhu H, Wu X. Bioavailability of cadmium adsorbed on various oxides minerals to wetland plant species *Phragmites australis*. Journal of Hazardous Materials, 2009, 167(1–3): 641–646
4. Solano M L, Soriano P, Ciria M P. Constructed wetlands as a sustainable solution for wastewater treatment in small villages. Biosystems Engineering, 2004, 87(1): 109–118
5. Carty A, Scholz M, Heal K, Gouriveau F, Mustafa A. The universal design, operation and maintenance guidelines for farm constructed wetlands (FCW) in temperate climates. Bioresource Technology, 2008, 99(15): 6780–6792
6. Kaseva M E. Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater-a tropical case study. Water Research, 2004, 38(3): 681–687
7. Korkusuz E A, Beklioglu M, Demirer G N. Comparison of the treatment performance of the blast furnace slag-based and gravel-based vertical flow wetlands operated identically for domestic wastewater treatment in Turkey. Ecological Engineering, 2005, 24 (3): 187–200
8. Zhang D Q, Gersberg R M, Hua T, Zhu J, Tuan N A, Tan S K. Pharmaceutical removal in tropical subsurface flow constructed wetlands at varying hydraulic loading rates. Chemosphere, 2012, 87 (3): 273–277
9. Rai U N, Tripathi R D, Singh N K, Upadhyay A K, Dwivedi S, Shukla M K, Mallick S, Singh S N, Nautiyal C S. Constructed wetland as an ecotechnological tool for pollution treatment for conservation of Ganga River. Bioresource Technology, 2013, 148: 535–541
10. Bulc T G. Long term performance of a constructed wetland for landfill leachate treatment. Ecological Engineering, 2006, 26(4): 365–374
11. Justin M Z, Zupančič M. Combined purification and reuse of landfill leachate by constructed wetland and irrigation of grass and willows. Desalination, 2009, 24: 15–16
12. Bobbink R, Whigham D F, Beltman B, Verhoeven J T A. Wetland functioning in relation to biodiversity conservation and restoration. In: Bobbink R, Beltman B, Verhoeven J T A, Whigham D F, eds. Wetlands: functioning, biodiversity conservation, and restoration. Berlin: Springer, 2006, 1–12.
13. Maine M A, Suñe N, Hadad H, Sánchez G, Bonetto C. Removal efficiency of a constructed wetland for wastewater treatment according to vegetation dominance. Chemosphere, 2007, 68(6): 1105–1113
14. Deng H, Ye Z H, Wong M H. Accumulation of lead, zinc, copper and cadmium by 12 wetland plant species thriving in metal-contaminated sites in China. Environmental Pollution, 2004, 132(1): 29–40
15. Ye Z H, Cheung K C, Wong M H. Copper uptake in *Typha latifolia* as affected by iron and manganese plaque on the root surface. Canadian Journal of Botany, 2001, 79(3): 314–320
16. Stoltz E, Greger M. Accumulation properties of As, Cd, Cu, Pb and Zn by four wetland plant species growing on submerged mine tailings. Environmental and Experimental Botany, 2002, 47(3): 271–280
17. Najeeb U, Xu L, Ali S, Jilani G, Gong H J, Shen W Q, Zhou W J. Citric acid enhances the phytoextraction of manganese and plant growth by alleviating the ultrastructural damages in *Juncus effusus* L. Journal of Hazardous Materials, 2009, 170(2–3): 1156–1163
18. Yoon J, Cao X, Zhou Q, Ma L Q. Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. Science of the Total Environment, 2006, 368(2–3): 456–464
19. Qian Y, Gallagher F J, Feng H, Wu M. A geochemical study of toxic metal translocation in an urban brownfield wetland. Environmental Pollution, 2012, 166: 23–30
20. Liu J G, Li G H, Shao W C, Xu J K, Wang D K. Variations in uptake and translocation of copper, chromium, and nickel among nineteen wetland plant species. Pedosphere, 2010, 20(1): 96–103
21. Liu J, Dong Y, Xu H, Wang D, Xu J. Accumulation of Cd, Pb and Zn by 19 wetland plant species in constructed wetland. Journal of Hazardous Materials, 2007, 147(3): 947–953
22. Amacher M C. Nickel, cadmium, and lead. In: Sparks D L, ed. Methods of soil analysis, Part 3— chemical methods. Madison: Soil Science Society of America Inc. and American Society of Agronomy Inc., 1996, 739–768
23. Demirezen D, Aksoy A. Accumulation of heavy metals in *Typha angustifolia* (L.) and *Potamogeton pectinatus* (L.) living in Sultan Marsh (Kayseri, Turkey). Chemosphere, 2004, 56(7): 685–696
24. Allen S E. Analysis of vegetation and other organic materials. In: Allen S E, ed. Chemical Analysis of Ecological Materials. Oxford: Blackwell Scientific Publications, 1989, 46–61
25. Song Z W, Zheng Z P, Li J, Sun X F, Han X Y, Wang W, Xu M. Seasonal and annual performance of a full-scale constructed wetland

system for sewage treatment in China. Ecological Engineering, 2006, 26(3): 272–282

26. Maine M A, Suñe N, Hadad H, Sánchez G, Bonetto C. Nutrient and metal removal in a constructed wetland for wastewater treatment from a metallurgic industry. Ecological Engineering, 2006, 26(4): 341–347
27. Maine M A, Suñe N, Hadad H, Sánchez G, Bonetto C. Phosphate and metal retention in a small-scale constructed wetland for waste-water treatment. In: Golterman, H L, Serrano L, eds. Phosphate in Sediments. Leiden: Backhuys Publishers, 2005, 21–31
28. Cheng S P, Grosse W, Karrenbrock F, Thoennessen M. Efficiency of constructed wetlands in decontamination of water polluted by heavy metals. Ecological Engineering, 2002, 18(3): 317–325
29. Ayaz S C, Akça L. Treatment of wastewater by natural systems. Environment International, 2001, 26(3): 189–195
30. Xue P Y, Li G X, Liu W J, Yan C Z. Copper uptake and translocation in a submerged aquatic plant *Hydrilla verticillata* (L.f.) Royle. Chemosphere, 2010, 81(9): 1098–1103
31. Zhang M Y, Cui L J, Sheng L X, Wang Y F. Distribution and enrichment of heavy metals among sediments, water body and plants in Hengshuihu Wetland of Northern China. Ecological Engineering, 2009, 35(4): 563–569