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# Accumulation of Cd, Pb and Zn by 19 wetland plant species in constructed wetland

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**Abstract**

Uptake and distribution of Cd, Pb and Zn by 19 wetland plant species were investigated with experiments in small-scale plot constructed wetlands, into which artificial wastewater dosed with Cd, Pb and Zn at concentrations of 0.5, 2.0 and 5.0 mg $l^{-1}$ was irrigated. The results showed that the removal efficiency of Cd, Pb and Zn from the wastewater were more than 90%. Generally, there were tens differences among the 19 plant species in the concentrations and quantity accumulations of the heavy metals in aboveground part, underground part and whole plants. The distribution ratios into aboveground parts for the metals absorbed by plants varied also largely from about 30% to about 90%. All the plants accumulated, in one harvest, 19.85% of Cd, 22.55% of Pb and 23.75% of Zn that were added into the wastewater. Four plant species, e.g. *Alternanthera philoxeroides*, *Zizania latifolia*, *Echinochloa crus-galli* and *Polygonum hydropiper*, accumulated high amounts of Cd, Pb and Zn. *Monochoria vaginalis* was capable for accumulating Cd and Pb, *Isachne globosa* for Cd and Zn, and *Digitaria sanguinalis* and *Fimbristylis miliacea* for Zn. The results indicated that the plants, in constructed wetland for the treatment of wastewater polluted by heavy metals, can play important roles for removal of heavy metals through phytoextraction. Selection of plant species for use in constructed wetland will influence considerably removal efficiency and the function duration of the wetland.
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*Keywords:* Cadmium (Cd); Lead (Pb); Zinc (Zn); Wetland plant; Accumulation

## 1. Introduction

Owing to industrial development and population expansion, heavy metal pollution in water environment is becoming increasingly serious in China [1,2]. Of all the heavy metals, Zn is an essential element for plant growth and easily taken up by roots [3], but it is regarded as poisonous at tissue concentration of 150–200 $\mu g\,g^{-1}$ in plant [4]. Zn contents of plants from some contaminated sites have reached the magnitude of 0.X% (DW) and may create an important environmental problem [5]. Cd is a toxic element and exists along with Zn in nature. It is one of the most important pollutants to consider in terms of food-chain contamination, because it is readily taken up by plant and translocated to different parts of plant [6]. The most important sources that cause Cd pollution are metal industry, plastics, mailed home tools, fossil fuels of vehicles and sewers [7]. Pb is not essential for plant growth and considered as toxic at the concentration of 30–300 $\mu g\,g^{-1}$ in plant tissues [8]. It has recently received much attention as a hazardous pollutant to human and animals. Pb is found in accumulator industry sludge, toy production, printing, petroleum industry, waste water and exhaust gases [7].

Constructed wetlands have been used for a variety of purposes, from rehabilitating areas where wetlands were previously located, to serving very specific functions such as wastewater treatment [9]. Much interest has been focused on constructed wetlands for removing toxic metals from wastewater in recent years [10]. In constructed wetlands, substrate interactions remove most metals from contaminated water [11]. The permanent or temporarily anoxic condition in wetland soil helps to create an environment for immobilization of heavy metals in the highly reduced sulfite or metallic form [12]. But plants may play an important role in metal removal through filtration, adsorption, cation

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exchange, and root-induced chemical changes in the rhizosphere [13,14].

Plant species have variety of capacity in removing and accumulating heavy metals, and some plant species can take much more heavy metals than others, such as duckweed (*Lemna minor*) [15], salix [16], cattail (*Typha latifolia*) and common reed (*Phragmites australis*) [17]. There are also literatures indicating that some species can accumulate specific heavy metals, such as the *Spirodela polyrhiza* for Zn [18]. So the plant species planted in a constructed wetland may affect the function of the wetland for the removal of heavy metals from wastewater.

The following issues were addressed in this article:

1. Variations among 19 wetland plant species in Cd, Pb and Zn uptake and accumulations.
2. The differences among the wetland plant species in Cd, Pb and Zn distribution between underground and aboveground parts.
3. To discuss the potential functions of wetland plant and the selection of plant species for metal removal in constructed wetlands.

The results could be referred for selection of appropriate wetland plant species in constructed wetland to exploit the removal potential of heavy metals by wetland plants.

## 2. Materials and methods

### 2.1. Design of constructed wetland

Small-scale plot (SSP) constructed wetland was used for this study. The SSP was established under open-air condition in Changzhou, China (30°41′N, 119°50′E). The plot consists of two chambers, each having 2 $m^2$ surface area (1 m × 2 m). Both chambers were filled with soil to a depth of 25 cm. The soil was obtained from the top 20 cm of an uncontaminated paddy field and sieved through a 5 mm sieve. It was a sandy loam with a higher portion of sand (56.8%) and a neutral pH (6.73). It also contained moderate level of organic matter (2.47%), cation exchange capacity (12.4 cmol $kg^{-1}$) and nitrogen content (0.14%). The total Cd, Pb and Zn concentrations in the soil were tested with AAS following $H_2O_2$–HF–$HNO_3$–$HClO_4$ digestion [19], and these were 0.18, 32.36 and 109.68 mg $kg^{-1}$ (DW) for Cd, Pb and Zn, respectively. The chamber soil was submerged in water (about 5 cm above the soil surface) for a month before the plant seedlings were transplanted into them.

### 2.2. Collection wetland plant species and experimental design

The seedlings of 19 wetland plant species were collected from the suburb of Changzhou. The species consisted of seven families, of which nine species belonged to Gramineae (Table 1). Because the species in Gramineae often formed dominant component of the plants thriving in metal-polluted sites [20] and can be easily found in Changzhou. The seedlings of the species in similar size (10–20 cm in height or length) were transplanted into the chambers, two plants for each species in a chamber. The seedlings were arranged in an even and randomized order in the chambers.

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

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

Artificial wastewater was fed into one of the two chambers thrice, i.e. the 15th, 22nd and 29th day after seedling transplant. One hundred and sixty litres of artificial wastewater was applied to the chamber on each occasion. The artificial wastewater was dosed with Cd, Pb and Zn at concentrations of 0.5, 2.0 and 5.0 mg $l^{-1}$, respectively. This imitates a wastewater polluted heavily by these heavy metals [7]. Heavy metal solutions were prepared as $CdCl_2$, $PbCl_2$ and $ZnCl_2$. Another chamber receiving no metals served as control. The chambers were maintained under flooded conditions (with 5–8 cm of water above soil surface) during the experiment.

### 2.3. Sample preparation and analytical methods

At 60th day after seedling transplant, all plants (whole plant) were harvested and washed thoroughly with tap water and then with deionized water. The plants were divided into aboveground part and underground part. The samples were oven-dried at 70 °C to constant weight for dry weights. Then the oven-dried samples were ground with a stainless steel grinder (FW-100, China) to pass through a 100 mesh sieve. The Cd, Pb and Zn concentrations of the samples were determined with AAS following $HNO_3$–$HClO_4$ (4:1) digestion procedures [21]. Three replicates of all the samples were run to ensure precision of the determinations.

The data on metal concentrations and accumulations of the samples were presented as mean ± standard deviation of three replicative tests, and the data were analyzed with EXCEL 2000 for Win.

Table 2
Cd concentrations and quantity accumulations in the plants of different wetland plant species

| Code name | Cd concentration ($mg\,kg^{-1}$) | | | Cd accumulation (mg) | | |
|---|---|---|---|---|---|---|
| | Underground | Aboveground | Whole plant | Underground | Aboveground | Whole plant |
| A | 40.57 ± 4.87[a] | 8.85 ± 1.14 | 13.60 ± 1.74 | 0.539 ± 0.032 | 0.665 ± 0.096 | 1.204 ± 0.154 |
| B | 92.51 ± 4.86 | 11.55 ± 1.28 | 19.65 ± 1.88 | 1.832 ± 0.098 | 2.058 ± 0.240 | 3.890 ± 0.371 |
| C | 9.13 ± 0.23 | 9.04 ± 0.04 | 9.06 ± 0.06 | 0.094 ± 0.008 | 0.373 ± 0.021 | 0.467 ± 0.023 |
| D | 41.81 ± 1.11 | 14.00 ± 3.07 | 22.34 ± 2.61 | 0.163 ± 0.014 | 0.127 ± 0.028 | 0.290 ± 0.034 |
| E | 12.38 ± 1.16 | 18.97 ± 1.95 | 17.65 ± 1.34 | 0.267 ± 0.018 | 1.639 ± 0.125 | 1.906 ± 0.107 |
| F | 10.67 ± 0.67 | 14.24 ± 1.29 | 13.52 ± 0.90 | 0.224 ± 0.014 | 1.196 ± 0.108 | 1.420 ± 0.094 |
| G | 21.20 ± 1.98 | 11.95 ± 1.37 | 13.80 ± 0.46 | 0.657 ± 0.052 | 1.481 ± 0.160 | 2.139 ± 0.125 |
| H | 9.07 ± 1.02 | 6.48 ± 0.55 | 6.87 ± 0.34 | 0.256 ± 0.029 | 1.036 ± 0.088 | 1.291 ± 0.064 |
| I | 171.21 ± 2.65 | 21.26 ± 1.91 | 36.25 ± 1.58 | 1.918 ± 0.130 | 2.143 ± 0.192 | 4.060 ± 0.277 |
| J | 96.66 ± 10.82 | 20.56 ± 1.17 | 28.17 ± 1.56 | 3.219 ± 0.252 | 6.163 ± 0.346 | 9.382 ± 0.664 |
| K | 29.46 ± 5.77 | 6.06 ± 0.08 | 10.74 ± 1.21 | 2.711 ± 0.531 | 2.229 ± 0.128 | 4.939 ± 0.558 |
| L | 39.17 ± 3.39 | 4.74 ± 0.67 | 11.63 ± 0.49 | 1.058 ± 0.084 | 0.512 ± 0.029 | 1.570 ± 0.087 |
| M | 20.97 ± 1.55 | 5.93 ± 0.23 | 8.94 ± 0.29 | 0.491 ± 0.036 | 0.556 ± 0.021 | 1.046 ± 0.134 |
| N | 9.85 ± 0.65 | 4.67 ± 0.32 | 6.74 ± 0.37 | 2.705 ± 0.154 | 1.925 ± 0.114 | 4.630 ± 0.219 |
| O | 25.56 ± 1.02 | 12.56 ± 0.70 | 15.81 ± 0.74 | 0.952 ± 0.080 | 1.403 ± 0.097 | 2.355 ± 0.136 |
| P | 9.08 ± 1.11 | 3.37 ± 0.75 | 5.08 ± 0.80 | 0.225 ± 0.014 | 0.194 ± 0.022 | 0.419 ± 0.034 |
| Q | 2.52 ± 0.26 | 5.60 ± 4.26 | 4.98 ± 3.40 | 0.193 ± 0.010 | 1.711 ± 0.621 | 1.903 ± 0.219 |
| R | 16.48 ± 0.77 | 27.86 ± 0.56 | 26.15 ± 0.35 | 0.342 ± 0.017 | 3.280 ± 0.144 | 3.622 ± 0.231 |
| S | 11.59 ± 0.95 | 9.32 ± 0.85 | 9.78 ± 0.55 | 0.261 ± 0.022 | 0.839 ± 0.043 | 1.100 ± 0.084 |
| Average | 35.26 ± 2.57 | 11.42 ± 1.08 | 14.78 ± 1.16 | 0.953 ± 0.068 | 1.554 ± 0.123 | 2.507 ± 0.189 |

[a] Mean ± standard deviation.

## 3. Results

### 3.1. Variations among wetland plant species in Cd concentrations and accumulations

Table 2 demonstrated that great variations existed among the wetland plant species in plant Cd concentrations and quantity accumulations.

With regard to Cd concentrations, there were 67 times, 8 times and 6 times differences among the species (between the highest and the lowest) for it in underground part, aboveground part and whole plant, respectively. The species with the highest Cd concentration in underground part, aboveground part and whole plant were I (*Monochoria vaginalis*), R (*Isachne globosa*) and I, respectively.

On Cd quantity accumulations, the differences among the species (between the highest and the lowest) were more than 33 times, 47 times and 31 times for it in underground part, aboveground part and whole plant, respectively. The species with the highest Cd accumulation in underground part, aboveground part and whole plant was the same one, i.e. J (*Alternanthera philoxeroides*).

Averagely, Cd concentration of underground part was two times higher than that in aboveground part, but Cd quantity accumulation in underground part was only 61.3% of that in aboveground part.

### 3.2. Variations among wetland plant species in Pb concentrations and accumulations

The differences among the species in plant Pb concentrations and accumulations were even larger than Cd (Table 3). They were more than 73 times, 25 times and 29 times for Pb concentrations, and 34 times, 60 times and 27 times for Pb quantity accumulations, in underground part, aboveground part and whole plant, respectively.

The species with the highest Pb concentration in underground part, aboveground part and whole plant were I (*M. vaginalis*), E (*Cyperus iria*) and I, respectively. The species with the highest Pb accumulation in underground part, aboveground part and whole plant was also J (*Alternanthera philoxeroides*), the same species as for Cd.

Average Pb concentration of underground part was 1.8 times higher than that in aboveground part, but average Pb accumulation in underground part was only 59.5% of that in aboveground part.

### 3.3. Variations among wetland plant species in Zn concentrations and accumulations

Table 4 showed that the differences among the species in plant Zn concentrations were relatively smaller compared to Cd and Pb. They were only 11 times, 8 times and 6 times for it in underground part, aboveground part and whole plant, respectively. Nevertheless the differences for Zn quantity accumulations were also very large, with 31 times, 121 times and 56 times differences in underground part, aboveground part and whole plant, respectively.

The species with the highest Zn concentration in underground part was B (*Polygonum hydropiper*), but the species with the highest Zn concentration in aboveground part and whole plant was R (*I. globosa*). The species with the most Zn accumulation in underground part was N (*Zizania latifolia*), and the species with the most Zn accumulation in

Table 3
Pb concentrations and quantity accumulations in the plants of different wetland plant species

| Code name | Pb concentration (mg kg$^{-1}$) | | | Pb accumulation (mg) | | |
|---|---|---|---|---|---|---|
| | Underground | Aboveground | Whole plant | Underground | Aboveground | Whole plant |
| A | 124.12 ± 7.32[a] | 38.59 ± 4.04 | 51.42 ± 1.31 | 1.648 ± 0.082 | 2.903 ± 0.340 | 4.551 ± 0.216 |
| B | 410.90 ± 56.84 | 54.81 ± 4.46 | 90.42 ± 7.00 | 8.136 ± 0.563 | 9.767 ± 0.839 | 17.903 ± 1.386 |
| C | 112.35 ± 25.50 | 50.44 ± 0.35 | 62.82 ± 5.00 | 1.157 ± 0.263 | 2.078 ± 0.114 | 3.235 ± 0.258 |
| D | 114.68 ± 3.21 | 95.41 ± 16.94 | 101.19 ± 12.82 | 0.447 ± 0.013 | 0.868 ± 0.154 | 1.316 ± 0.167 |
| E | 102.99 ± 1.95 | 98.40 ± 4.19 | 99.31 ± 3.61 | 2.225 ± 0.131 | 8.501 ± 0.368 | 10.726 ± 0.488 |
| F | 59.80 ± 1.93 | 90.10 ± 6.12 | 84.04 ± 5.28 | 1.256 ± 0.041 | 7.568 ± 0.514 | 8.824 ± 0.554 |
| G | 78.27 ± 10.12 | 76.61 ± 7.67 | 76.95 ± 3.45 | 2.427 ± 0.161 | 9.500 ± 0.338 | 11.927 ± 0.790 |
| H | 59.04 ± 14.10 | 36.37 ± 6.41 | 39.77 ± 5.41 | 1.665 ± 0.298 | 5.812 ± 1.025 | 7.477 ± 1.016 |
| I | 710.96 ± 51.74 | 85.98 ± 10.76 | 148.48 ± 8.59 | 7.963 ± 0.579 | 8.667 ± 1.085 | 16.629 ± 0.963 |
| J | 477.94 ± 41.61 | 66.62 ± 5.74 | 107.75 ± 14.21 | 15.915 ± 0.969 | 19.966 ± 1.204 | 35.881 ± 3.310 |
| K | 94.68 ± 7.85 | 50.35 ± 6.42 | 59.22 ± 6.37 | 8.711 ± 0.722 | 18.530 ± 2.362 | 27.241 ± 2.931 |
| L | 138.04 ± 16.75 | 50.73 ± 6.65 | 68.19 ± 11.11 | 3.727 ± 0.167 | 5.478 ± 0.286 | 9.205 ± 0.489 |
| M | 107.60 ± 12.33 | 69.88 ± 5.57 | 77.42 ± 3.43 | 2.518 ± 0.289 | 6.540 ± 0.522 | 9.058 ± 0.401 |
| N | 51.63 ± 4.45 | 35.23 ± 3.54 | 41.79 ± 2.40 | 14.177 ± 1.044 | 14.513 ± 1.246 | 28.690 ± 1.808 |
| O | 160.28 ± 22.28 | 49.27 ± 6.92 | 77.02 ± 5.09 | 5.970 ± 0.218 | 5.506 ± 0.271 | 11.476 ± 0.449 |
| P | 37.27 ± 5.92 | 5.66 ± 2.61 | 15.15 ± 2.81 | 0.923 ± 0.075 | 0.327 ± 0.078 | 1.250 ± 0.119 |
| Q | 9.59 ± 0.27 | 3.71 ± 2.20 | 4.89 ± 1.71 | 0.732 ± 0.040 | 1.134 ± 0.220 | 1.866 ± 0.311 |
| R | 31.93 ± 2.66 | 51.03 ± 4.27 | 48.12 ± 3.70 | 0.663 ± 0.054 | 6.008 ± 0.340 | 6.671 ± 0.328 |
| S | 22.67 ± 1.38 | 22.46 ± 0.67 | 22.51 ± 1.66 | 0.510 ± 0.037 | 2.022 ± 0.134 | 2.532 ± 0.164 |
| Average | 152.88 ± 15.34 | 54.30 ± 5.08 | 67.18 ± 5.23 | 4.251 ± 0.403 | 7.141 ± 0.666 | 11.392 ± 0.956 |

[a] Mean ± standard deviation.

aboveground part and whole plant was J (*Alternanthera philoxeroides*).

On the average, Zn concentration of underground part was one time higher than that in aboveground part, but Zn accumulation in underground part was only 46.3% of that in aboveground part.

### 3.4. Variations among wetland plant species in the total amounts of Cd, Pb and Zn accumulations

It can be seen in Fig. 1 that great variations existed among the 19 wetland plant species in total amounts of Cd, Pb and Zn accumulation in aboveground part and whole plant. The species with

Table 4
Zn concentrations and quantity accumulations in the plants of different wetland plant species

| Code name | Zn concentration (mg kg$^{-1}$) | | | Zn accumulation (mg) | | |
|---|---|---|---|---|---|---|
| | Underground | Aboveground | Whole plant | Underground | Aboveground | Whole plant |
| A | 353.28 ± 47.99[a] | 90.30 ± 16.05 | 129.75 ± 9.98 | 4.690 ± 0.262 | 6.793 ± 1.421 | 11.482 ± 0.884 |
| B | 753.10 ± 77.65 | 189.96 ± 26.60 | 246.28 ± 27.51 | 14.911 ± 0.769 | 33.852 ± 5.267 | 48.763 ± 5.447 |
| C | 159.04 ± 22.61 | 179.14 ± 9.91 | 175.12 ± 6.90 | 1.638 ± 0.233 | 7.380 ± 0.510 | 9.019 ± 0.252 |
| D | 254.38 ± 2.24 | 63.51 ± 14.47 | 120.77 ± 10.80 | 0.992 ± 0.009 | 0.578 ± 0.188 | 1.570 ± 0.140 |
| E | 154.83 ± 11.27 | 114.02 ± 5.24 | 122.18 ± 5.94 | 3.344 ± 0.180 | 9.851 ± 0.419 | 13.195 ± 0.355 |
| F | 129.67 ± 8.26 | 159.89 ± 7.86 | 153.85 ± 5.06 | 2.723 ± 0.174 | 13.431 ± 0.826 | 16.154 ± 0.531 |
| G | 426.09 ± 21.99 | 263.90 ± 19.13 | 296.34 ± 12.98 | 13.209 ± 0.242 | 32.723 ± 1.052 | 45.932 ± 1.604 |
| H | 111.40 ± 16.38 | 40.18 ± 8.60 | 50.87 ± 2.55 | 3.141 ± 0.462 | 6.421 ± 1.617 | 9.563 ± 0.479 |
| I | 716.35 ± 4.82 | 211.41 ± 24.36 | 261.90 ± 39.24 | 8.023 ± 0.054 | 21.310 ± 2.728 | 29.333 ± 4.395 |
| J | 597.82 ± 79.27 | 235.39 ± 36.70 | 271.63 ± 45.78 | 19.908 ± 1.847 | 70.547 ± 8.551 | 90.454 ± 9.666 |
| K | 270.72 ± 46.41 | 85.31 ± 6.43 | 122.39 ± 12.84 | 24.907 ± 4.270 | 31.395 ± 2.959 | 56.301 ± 5.906 |
| L | 273.07 ± 34.90 | 73.71 ± 2.13 | 113.58 ± 8.40 | 7.373 ± 0.244 | 7.961 ± 0.175 | 15.334 ± 0.294 |
| M | 283.24 ± 10.14 | 144.21 ± 3.60 | 172.01 ± 14.74 | 6.628 ± 0.237 | 13.498 ± 0.422 | 20.126 ± 0.555 |
| N | 116.74 ± 5.05 | 71.34 ± 3.19 | 89.50 ± 5.87 | 32.057 ± 1.185 | 29.386 ± 2.873 | 61.442 ± 0.811 |
| O | 515.95 ± 19.71 | 240.93 ± 15.00 | 309.68 ± 8.32 | 19.219 ± 0.893 | 26.924 ± 0.735 | 46.143 ± 1.408 |
| P | 197.83 ± 16.30 | 75.42 ± 3.85 | 112.14 ± 7.10 | 4.896 ± 0.208 | 4.355 ± 0.164 | 9.252 ± 0.302 |
| Q | 62.95 ± 0.68 | 43.40 ± 2.55 | 47.31 ± 1.91 | 4.810 ± 0.025 | 13.262 ± 0.465 | 18.072 ± 0.348 |
| R | 216.12 ± 45.62 | 373.29 ± 6.12 | 349.72 ± 9.56 | 4.490 ± 0.404 | 43.946 ± 1.542 | 48.436 ± 1.581 |
| S | 155.51 ± 33.00 | 176.79 ± 25.63 | 172.53 ± 11.41 | 3.499 ± 0.412 | 15.911 ± 1.602 | 19.410 ± 0.713 |
| Average | 302.53 ± 26.62 | 149.06 ± 12.38 | 174.61 ± 12.55 | 9.498 ± 0.652 | 20.501 ± 1.636 | 29.999 ± 1.723 |

[a] Mean ± standard deviation.

Table 5
Distribution of Cd, Pb and Zn in different species of wetland plants

| Code name | Underground/aboveground ratios in metal concentrations | | | Percentages of the metals translocated into aboveground (%) | | |
|---|---|---|---|---|---|---|
| | Cd | Pb | Zn | Cd | Pb | Zn |
| A | 4.55 | 3.23 | 3.85 | 55.26 | 63.80 | 59.16 |
| B | 8.33 | 7.69 | 4.00 | 52.91 | 54.56 | 69.42 |
| C | 1.01 | 2.22 | 0.88 | 79.85 | 64.23 | 81.84 |
| D | 3.03 | 1.20 | 4.00 | 43.87 | 66.00 | 36.81 |
| E | 0.65 | 1.04 | 1.35 | 85.97 | 79.26 | 74.65 |
| F | 0.75 | 0.66 | 0.81 | 84.22 | 85.77 | 83.14 |
| G | 1.79 | 1.02 | 1.61 | 69.27 | 79.65 | 71.24 |
| H | 1.41 | 1.61 | 2.78 | 80.19 | 77.73 | 67.15 |
| I | 8.23 | 8.30 | 3.33 | 52.78 | 52.12 | 72.65 |
| J | 4.76 | 7.14 | 2.56 | 65.69 | 55.64 | 77.99 |
| K | 4.76 | 1.89 | 3.13 | 45.12 | 68.02 | 55.76 |
| L | 8.26 | 2.70 | 3.70 | 32.62 | 59.51 | 51.92 |
| M | 3.57 | 1.54 | 1.96 | 53.10 | 72.20 | 67.07 |
| N | 2.13 | 1.47 | 1.64 | 41.58 | 50.59 | 47.83 |
| O | 2.04 | 3.23 | 2.13 | 59.58 | 47.98 | 58.35 |
| P | 2.70 | 6.67 | 2.63 | 46.40 | 26.17 | 47.08 |
| Q | 0.45 | 2.56 | 1.45 | 89.88 | 60.76 | 73.39 |
| R | 0.59 | 0.63 | 0.58 | 90.55 | 90.06 | 90.73 |
| S | 1.25 | 1.01 | 0.88 | 76.29 | 79.85 | 81.97 |
| Average | 3.18 | 2.94 | 2.28 | 61.99 | 62.69 | 68.34 |

the highest metals accumulation was J (*Alternanthera philoxeroides*), and the species with the lowest metals accumulation was D (*Aster subulatus*). The differences between them were 60 times and 41 times for that in aboveground part and whole plant, respectively.

On total amounts of Cd, Pb and Zn accumulation in the 19 plant species, 66.5% of that was accumulated in aboveground part.

### 3.5. *Variations among wetland plant species in distribution of Cd, Pb and Zn*

Table 5 showed that the metal concentrations in underground parts were generally higher than that in aboveground parts. But

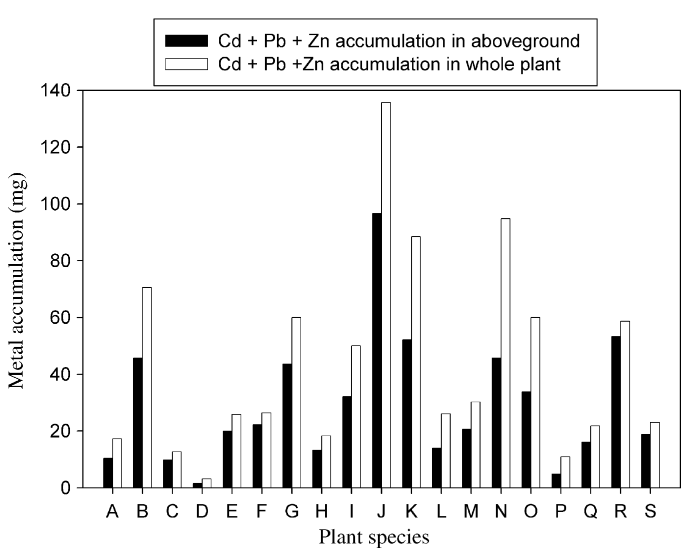


Fig. 1. Total amounts of metals (Cd + Pb + Zn) accumulation in aboveground parts and whole plants of 19 wetland plant species.

it also varied considerably with plant species and the kind of metals. On the average ratios of underground to aboveground in metal concentrations, they were about 3 times for Cd and Pb, and about 2 times for Zn. For some species, the metal concentrations in underground parts were much higher than that in aboveground parts, such as B (*Polygonum hydropiper*) and I (*M. vaginalis*) (the ratios of underground to aboveground were about 8 for Cd and Pb, 3 to 4 for Zn). But for other species, the metal concentrations in underground parts were lower than that in aboveground parts, such as F (*Cyperus difformis*) and R (*I. globosa*).

On the distribution of metal quantity accumulation, averagely more than 60% of the metals absorbed by plant were transferred to aboveground part, and the portion was higher for Zn than for Cd and Pb. The distribution percentages of the metals to aboveground part varied greatly with plant species, and they ranged from 32.62% to 90.55% for Cd, from 26.17% to 90.06% for Pb and from 36.81% to 90.73% for Zn. For some species, a large portion of the metals (more than 80%) was transferred to aboveground part, such as R (*I. globosa*) and F (*C. difformis*). But for other species, most of the metals was restricted in underground part, such as P (*Eleusine indica*) and N (*Z. latifolia*).

## 4. Discussion and conclusions

Heavy metal contamination in water environment is a serious problem that threatens not only the aquatic ecosystems but also human health. Unlike organic pollutants, heavy metals cannot be removed for water environment through degradation by biological processes. Phytoremediation using vegetation to remove, detoxify, or stabilize heavy metal pollutants is an accepted tool for cleaning polluted soil and water [22].

Constructed wetlands are inexpensive systems for wastewater treatment, and have been used for all kinds of wastewater since

1990s. They are used not only in the degrading of organic substances and nutrients, but also for the removing of heavy metals from municipal sewage, landfill leachate, storm runoff, agricultural runoff, mining effluent and special industrial wastewater [23,24].

In natural or constructed wetland systems, heavy metals in wastewater were removed by many processes, such as absorption, adsorption, precipitation and plant uptake [25]. Sedimentation has long been recognized as the principal process in the removal of heavy metals. However, Plants can play important roles in constructed wetland for the removal by absorption/adsorption and accumulation of metals [26].

In our present research, the removal efficiency of Cd, Pb and Zn from the wastewater were more than 90% (92.2%, 96.4% and 94.2% for Cd, Pb and Zn, respectively) (Table 6). The results provide evidence that constructed wetland is effective for the decontaminating of heavy metal contaminated wastewater originated from industrial runoff or mining, and it is also an economic system for the protection of water environment from heavy metal pollution for its low-cost in operation and maintenance.

Our experiments also indicate that plants can play an important role in accumulating and removing heavy metals from the wastewater. There were 47.63 mg of Cd, 216.45 mg of Pb and 569.98 mg of Zn accumulated in the plants, respectively, e.g. 19.85% of Cd, 22.55% of Pb and 23.75% of Zn added to the water. Averagely, more than 60% of the heavy metals absorbed by plants were transferred into aboveground part, and the transfer ratios were more than 80% for some species (Table 5). So in dense-planted wetland for wastewater treatment, plants will absorb and accumulate considerable amount of heavy metals which can be removed by harvest of the plants frequently. For most of the plant species, the underground parts can be easily dragged up from soil.

Literatures has shown that some wetland plant species can be used for heavy metal removal from contaminated water and soils [27,28]. Some plant species, such as *Phragmites australis* and *Cyperus* species were normally planted in constructed wetlands [29,30].

In this study, plant species differed greatly in their capacity of heavy metal accumulation. The differences were 31 times, 27 times and 56 times for quantity accumulations of Cd, Pb and Zn in whole plants. The differences on metal accumulations in aboveground part were even larger, and these were 47 times, 60 times and 121 times for Cd, Pb and Zn, respectively.

For Cd, six higher accumulating species accumulated 64.1% of total Cd in 19 species. These species are J (*Alternanthera philoxeroides*), K (*Echinochloa crus-galli*), N (*Z. latifolia*), I (*M. vaginalis*), B (*Polygonum hydropiper*) and R (*I. globosa*). So these six plant species are suitable for the treatment of Cd polluted wastewater.

Table 6
Removal efficiency of Cd, Pb and Zn from wastewater by wetland

| Parameters | Cd | Pb | Zn |
|---|---|---|---|
| Metal concentrations added to water ($mg\,l^{-1}$) | 0.5 | 2.0 | 5.0 |
| Remain metals in water after experiment ($mg\,l^{-1}$) | 0.0392 | 0.0727 | 0.2880 |
| Removal efficiency (%) | 92.2 | 96.4 | 94.2 |

Five higher Pb accumulating species accumulated 58.4% of the Pb in 19 species, and these are J (*Alternanthera philoxeroides*), N (*Z. latifolia*), K (*Echinochloa crus-galli*), B (*Polygonum hydropiper*) and I (*M. vaginalis*). These five plant species are suitable for treatment of the wastewater polluted by Pb.

Zn accumulation in seven higher Zn accumulating species account for 69.7% of total Zn in 19 species. They are J (*Alternanthera philoxeroides*), N (*Z. latifolia*), K (*Echinochloa crus-galli*), B (*Polygonum hydropiper*), R (*I. globosa*), O (*Digitaria sanguinalis*) and G (*Fimbristylis miliacea*). These seven plant species are suitable for the treatment of Zn polluted wastewater.

On the total amount of Cd, Pb and Zn accumulation in plants, seven higher accumulating species were J (*Alternanthera philoxeroides*), N (*Z. latifolia*), K (*Echinochloa crus-galli*), B (*Polygonum hydropiper*), G (*F. miliacea*), O (*D. sanguinalis*) and R (*I. globosa*). They accumulated 68.1% of the heavy metals in 19 plant species.

It can be concluded from this research that sedimentation in constructed wetland was the principal process for the removal of heavy metals from wastewater, but plants were important not only in phytoextraction but also in providing sites for metal precipitation [31]. Selection of plant species for use in constructed wetland will influence removal efficiency of heavy metals from wastewater and the function duration of the wetland.

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