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Original Research

Study on Remediation of Cd Contamination in Riverbed Soils Around Outfalls by Six Typical Plants

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Abstract

To study the phytoremediation effect of Cd pollution in the riverbed soil around the sewage, the effects of six typical plants, namely *Solanum nigrum L (SNL), Phytolacca acinosa roxb (PAR), Nephrolepis auriculata (L.) (NAL), Pogonatherum crinitum (Thunb.) kunth (PCK), Pteris vittata L (PVL),* and *Sedum lineare Thunb (SLT),* on the Cd concentration in the soil with different pollution levels (3, 5, and 8 mg/kg) and the Cd concentration in different parts of the plant (root, stem, and leaf) after planting were studied to explore the remediation effects of different plants on different Cd polluted soils. The research results show that when the concentration of Cd in the soil was 3 mg/kg, the Cd enrichment coefficient of *SNL* and *SLT* was the largest. At the same time, the Cd concentrations in the stem and leaf of *SNL* and the root and stem of *SLT* are 26.18, 40.26, 34.38, and 49.45 mg/kg, which can be recycled by composting. Therefore, it is recommended to plant *SNL* or *SLT* to repair the Cd pollution in the urban residential area. At 5 mg/kg, the Cd enrichment coefficient of *SLT* was the largest. At the same time, the concentration of Cd in roots and stems was 65.79 and 108.11 mg/kg, which could be reused by composting and hydrothermal transformation. Therefore, it is recommended to plant *SLT* to repair the Cd pollution in the light industry zone. At 8 mg/kg, the Cd enrichment coefficients of *NAL* and *SNL* were the largest. At the same time, the stem and leaf of *SNL* and the leaf of *NAL* could be reused by composting and hydrothermal transformation. Therefore, it is recommended to plant *NAL* to repair the Cd pollution in the heavy industry zone and mix *NAL* and *SNL* to repair the Cd pollution in the chemical industry concentration zone.

Keywords: riverbed around the sewage outlet, heavy metal cadmium, phytoremediation, resource reuse, soil

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Introduction

With the acceleration of industrialization, more than 63% of China's urban rivers are polluted by heavy metals to varying degrees, with Cd pollution taking the brunt of the problem [1]. As a window for heavy metals and other pollutants to enter the river, the outfall is badly polluted by Cd in the riverbed around it, and it is very easy to be absorbed by plants and transferred to the food chain, causing great harm to human survival, so it needs to be treated urgently [2-4]. At present, the commonly used technologies for remediation of soil heavy metal pollution mainly include solidification and stabilization technology, bioremediation technology, electrokinetic remediation technology, and drenching remediation technology. Compared with other technologies, bioremediation is currently at the forefront of research because it combines a low cost/efficiency ratio, low secondary pollution, and a wide range of applications [5]. In terms of phytomediation of Cd and other heavy metal pollution in river basins, most of the previous studies have focused on remediation of Cd pollution from sedimentary sludge at the bottom of the river, while relatively few studies have been conducted on the remediation of Cd pollution in the riverbed around the outfalls [6].

In addition, if the plants after the remediation of soil Cd pollution are not used for resource utilization and left to wither on the riverbed, most of the heavy metals will still be returned to the river, resulting in twice the result with half the effort [7]. However, there is a lack of relevant studies in China at present, and only a few of them, such as MIN T. et al. [8], were retrieved for the energy utilization of *Nicotiana tabacum L*., *Ocimum basilicum L*., and *Sedum alfredii Hance* after remediation of Cd pollution, respectively [9].

Therefore, concerning the average Cd concentration of riverbed soils around four typical regional outfalls in Mianyang City, Cd-contaminated soils were collected from forest park soils in Mianyang City to prepare Cd-contaminated soils by exogenous addition. Through the experiment of planting six typical plants in pots（*SNL*, *PAR*, *NAL*, *PCK, PVL,* and *SLT*）, the Cd concentrations of the soil and the roots, stems, and leaves of each plant were determined. The remediation effects of different plants on soil in different typical areas were studied to provide a guiding program for the phytoremediation of Cd-contaminated soils in the riverbed of the outfalls in each typical area.

Material and Methods

Test Soil

Since a large amount of soil extraction around the river is prone to cause riverbed collapse and violates the relevant laws, the non-polluted shallow (0-20 cm) natural soil of Forest Park in Mianyang City was selected as the test soil in this study. The pH of the test soil was 6.7, the cation exchange capacity (CEC) was 35.2 cmol(+)/kg, the Cd concentration was 0.09 mg/kg, and the dry basis water content was 140%. The soil properties of the riverbed within 1 m of the periphery were measured at three randomly selected outfalls in four typical areas, namely, residential living areas (hereinafter referred to as living area), light industrial areas, heavy industrial areas, and chemical industry areas in the industrial area of the FuJiang River Basin in Mianyang City. The Cd concentration, pH, CEC, and soil dry basis water content for each regional outfall can be obtained as shown in Table 1.

From the analysis in Table 1, the average alkaline pH value of the soil at the outfall is 7.2, the mean CEC value is 34.5 cmol(+)/kg, and the average dry basis moisture content is 178.75%. These three means were used as targets to adjust the soil indicators for testing before the experiment. The soil Cd concentration in the living area, light industry area, heavy industry area, and chemical industry area corresponded to concentrate at 3, 5, 7, and 9 mg/kg, respectively, so it was proposed to set the exogenously added Cd concentration at 3, 5, and 8 mg/kg, respectively, in this experiment.

Test Plant

The current study generally recognizes that four herbaceous plants, namely *SNL*, *PAR*, *NAL*, and *PCK*, are Cd hyper-enriched plants [10-12], and *PAR*, *NAL*, and *PCK* were found in the riverbed around the outfalls of the Fuling River Basin in the city of Mianyang after the field study. At the same time and after field investigation, *PVL* and *SLT* also grow in large quantities around the outfalls in Mianyang City. Therefore, six typical herbaceous plants, namely *SNL*, *PAR*, *NAL*, *PCK*, *PVL,* and *SLT,* were finally selected as the restoration plants for the experimental study.

Since no age-appropriate seedlings of *SNL* were found in Mianyang City, the seeds of *SNL* with full grains and basically the same size were selected in this study and sown in the spring for potting experiments. There are a large number of ageable seedlings of *PAR, NAL, PCK, PVL,* and *SLT* growing in the Forest Park of Mianyang City, so in this study, we chose wild seedlings of *PAR, NAL, PCK, PVL,* and *SLT* to be transplanted for potting experiments.

A General Description of Experimental Methods

The test soil taken from the forest park was removed from stones and other impurities, crushed, mixed, and commissioned according to the criteria in Test Soil, and placed in plastic cultivation pots at 4 kg per pot at the Mianyang Polytechnic research site. Seedlings of six plants were then transplanted into cultivation pots; 12 pots of each plant were cultivated and divided into four groups numbered 0, 3, 5, and 8. After being cultivated in pots for 30 d [13], 24.6, 40.0, and 65.6 mg

Table 1. Physical and chemical properties of river beds around typical regional outfalls.

Area	Cd concentration (mg/kg)	Ph	Cec (cmol(+)/kg)	Moisture content (%)
Living area	2.58±0.01	6.9±0.2	34±1	175±7
Light industrial area	4.91±0.03	7.0±0.1	35±1.4	180±4
Heavy industrial area	7.18±0.05	7.3±0.2	34±2.2	183±3
Chemical industrial area	9.04±0.04	7.5±0.2	35±1.7	177±7

of $CdCl_2 \cdot 2.5H_2O$ were added to treatment groups numbered 3, 5, and 8, respectively, concerning the Cd concentration of the soil in the riverbed of the outfall, so that the soil Cd concentrations were 3, 5, and 8 mg/kg, respectively. The group numbered 0 was used as a control (CK), and each treatment group was replicated three times. Spraying the appropriate amount of water from time to time in accordance with the growth habit of the plants and the environment surrounding the outfall to maintain a soil moisture content of 178.5% on a dry basis to maintain the vital characteristics of the plants [14]. It also simulated soil moisture in the riverbed, and parameters were measured on soil and plant samples after 2 months of incubation [15].

Methods for Determining Soil Cd Concentration

After mixing the soil in the cultivation pots, 500 g of soil samples were taken and dried in an oven at 75ºC until a constant weight was reached [16]. Then 1 g of soil sample was ground and added to the HNO_3: HCl: $HClO_4$ mixture (v:v:v = 3:1:1) and put into the graphite digestion furnace according to the national standard method of digestion and volume. Total soil Cd was determined using inductively coupled plasma emission spectrometry-mass spectrometry (ICP-MS) [17].

Methods of Determining the Dry Weight and Water Content of Plants

The plants removed from each pot were rinsed with distilled water and dried with residual water before measurement, and then divided into three parts: roots, stems, and leaves, which were then weighed with an electronic balance and recorded as fresh weight [18]. Then the samples were sorted into an electric blast drying oven at 105ºC for 45 min, and then dried at 70ºC until a constant weight was reached, and the quality was measured and recorded [19].

The dry basis water content of each plant is calculated as in Eq. 1

$$\omega = \frac{m_1 - m_2}{m_2} \times 100\% \tag{1}$$

In Eq. (1): m_1 = Wet weight of the roots, stems, and leaves of each potted plant, m_2 = Dry weight of the roots, stems, and leaves of each potted plant.

Determination of Cd Concentration in the Roots, Stems, and Leaves of Plants

The dry samples of each plant were crushed in a crusher and passed through a 100-mesh nylon sieve [20]. Then 1 g was added to the HNO_3: HCl: $HClO_4$ mixture (v:v:v = 3:1:1), put into the graphite digestion furnace according to the national standard method of digestion, and the volume adjusted to 25 mL, using ICP-MS to determine the total amount of Cd in the roots, stems, and leaves of each plant, respectively [21].

Combined with the dry weight of the roots, stems, and leaves of each plant, the concentration of Cd in the roots, stems, and leaves can be converted to the concentration of Cd within the whole plant, as shown in Eq. 2 [22]:

$$c_q = \frac{c_r m_r + c_s m_s + c_l m_l}{m_r + m_s + m_l} \times 100\% \tag{2}$$

In Eq. (2): c = Cd concentration, m = mass, the subscripts r, s, and l correspondingly represent roots, stems, and leaves, respectively.

Calculation of Cd Enrichment and Transport Coefficients

The enrichment capacity of plants for Cd is characterized by the bioconcentration factor BCF, calculated as in Eq. (3) [23]. The transport pattern of Cd in plant roots, stems, and leaves was characterized by the transport coefficient TF, calculated as in Eq. 4 [24].

$$BCF = \frac{c_q}{c_t} \tag{3}$$

$$TF = \frac{c_o}{c_u} \tag{4}$$

In Eqs 3 and 4: c_q = Cd concentration in plants; c_t = Cd concentration in soil; c_o = Cd concentration in aboveground parts of plants; c_u = Cd concentration in underground parts of plants.

Methods of Data Analysis

The data were statistically analyzed using multifactor ANOVA in SPSS 26.0. The data were tested for significance using the Ducan method, and all data were expressed as "mean±standard error". Then use Origin 2020 for mapping.

Results and Discussion

Analysis of Soil Cd Concentration after Phytoremediation

Cd concentration in the soil after potting phytoremediation is a key indicator for characterizing the phytoremediation capacity of Cd-contaminated plants [25]. Exogenously added Cd concentrations were analyzed by the significance test for differences in Cd concentrations remaining in the soil after remediation of the plant, and the results are shown in Fig. 1.

It can be analyzed from Fig. 1: Since the Cd content in the test soil was lower than the risk screening value of 0.3 mg/kg for soil Cd pollution on agricultural land in GB15618-2018, there was no significant difference in soil Cd concentration after remediation of each plant. When the concentration of exogenously added Cd was 3 mg/kg, the soil Cd concentration after *PVL* remediation was 2.55 mg/kg, which was close to the risk control value of 3 mg/kg, so it was not suitable for remediation of Cd pollution. However, the soil Cd concentrations of 0.43 and 0.51 mg/kg after the restoration of *PCK* and *PAR,* respectively, were less than the risk control value and 83.14% and 80% lower than that of *PVL* after restoration, so the soil of the restored streambed could be used as a landscape site. Meanwhile, the soil Cd concentrations of *NAL*, *SNL*, and *SLT* after restoration were 0.21, 0.25, and 0.29 mg/kg, respectively, which were 91.67%, 90.20%, and 88.67% lower than that of *PVL* after restoration, respectively, and were all smaller than the risk screening value, so the restored riverbed soil can be directly used for agricultural production. When the concentration of exogenously added Cd is 5 mg/kg, the Cd concentration of soil after remediation *PVL* is 4.36 mg/kg, which is greater than the risk control value. The soil Cd concentrations after remediation of *NAL*, *SNL, PAR*, and *PCK* were 0.55, 0.82, 0.89, and 1.34 mg/kg, respectively, which were 87.39, 81.19, 79.59%, and 69.27% lower than those after remediation of *PVL*, respectively. All of them are less than the risk control value, and the restored riverbed soil can be used as landscape land. The soil Cd concentration after remediation of *SLT* is 0.29 mg/kg, which is 93.12% lower than the soil Cd concentration after remediation of *PVL*. It is smaller than the risk screening value, and the soil of the remediated riverbed can be directly used for agricultural production. The exogenously added Cd concentration of 8 mg/kg resulted in soil Cd concentrations of 7.36 and 7.25 mg/kg for remediated *PVL* and *SLT*, respectively. The soil Cd concentrations after remediation in *PCK*, *PAR*, *SNL and NAL* corresponded to 4.65, 3.98, 3.23, and 3.08 mg/kg, respectively, compared to the corresponding reductions of 36.82%, 45.92%, 56.11%, and 58.15% in soil Cd concentrations after *PVL* remediation.

Analysis of Plant Growth after Remediation of Cd Pollution

Biomass (dry weight) characterizes the promotion or inhibition of plant growth by each soil Cd concentration. The growth of each plant at different exogenously added Cd concentrations was analyzed by the test of significance of differences based on the classification of plant species, and the results are shown in Fig. 2.

From the analysis of Fig. 2: *PAR* growth was not affected at all by exogenously added Cd concentrations compared to CK. *PVL* growth was inhibited at all exogenously added Cd concentrations, and the inhibition increased significantly with increasing exogenously added Cd concentrations. The growth of *PCK* and *SNL* was not affected by exogenous addition of Cd at concentrations of 3 and 8 mg/kg, and the growth was significantly promoted by exogenous addition of Cd at a concentration of 5 mg/kg, which resulted in an increase in dry weight of 119.71% and 81.69%, respectively, compared with that of CK. The growth of

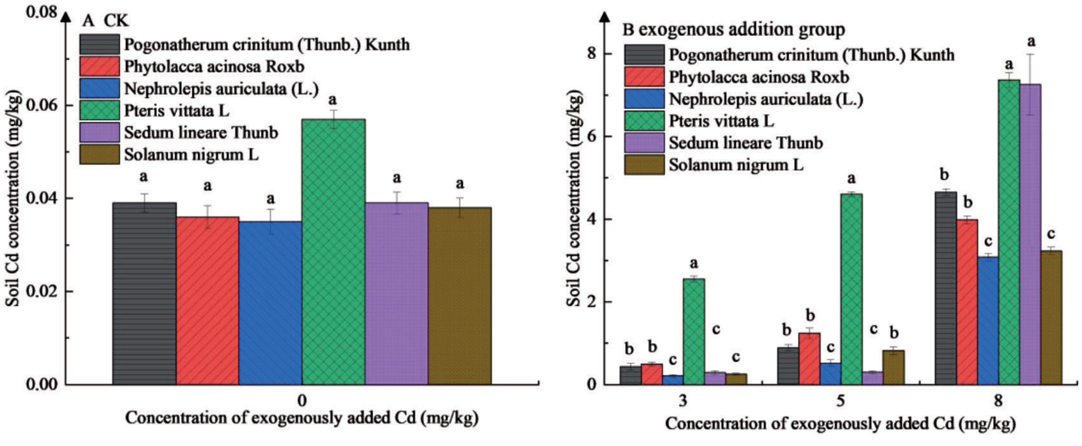

Fig. 1. Soil Cd concentration after phytoremediation.
Differences in soil Cd concentration after different plant treatments at the same Cd concentration ($P<0.05$).

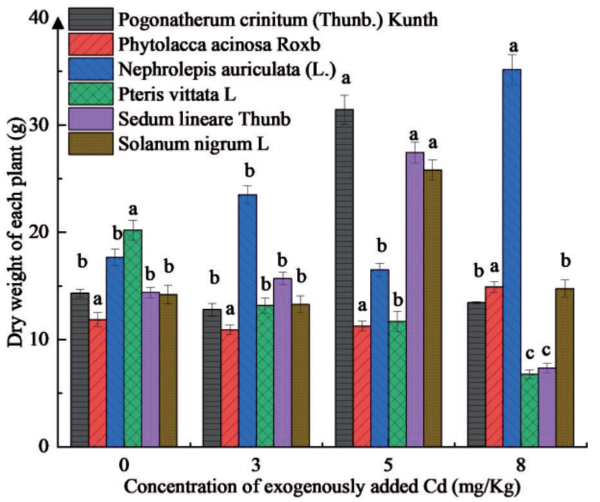

Fig. 2. Dry weight of each plant.
Different letters indicate significant differences in dry weight of the same plants at different exogenously added Cd concentrations (P<0.05).

NAL was not affected by the exogenous addition of Cd at concentrations of 3 and 5 mg/kg; dry weight increased by 99.15% over CK with the exogenous addition of Cd at a concentration of 8 mg/kg, and growth was significantly promoted. The growth of *SLT* was not affected by the exogenous addition of Cd at a concentration of 3 mg/kg; the dry weight increased by 141.12% compared with that of CK, and the growth was significantly promoted by the exogenous addition of Cd at a concentration of 5 mg/kg; the growth was inhibited by the exogenous addition of Cd at a concentration of 8 mg/kg, and the dry weight decreased by 35.59% compared with CK.

The physiological response mechanisms of *SNL*, *PAR*, and *NAL* under Cd stress were investigated by the previous researchers, and it was found that all three plants have strong tolerance to Cd. Due to the stress response of plant cells, most plants show a "low promotion and high inhibition" effect pattern, but there are still a few plants that show a parabolic pattern of significant growth enhancement at specific Cd concentrations [26, 27].

Dry-basis moisture content can also characterize plant health. The results of the significance test of the difference in dry basis water content of each plant at different exogenously added Cd concentrations were analyzed based on plants, and the results are shown in Fig. 3.

From the analysis in Fig. 3, it can be seen that dry basis water content was not affected in all treatments *PAR*, *NAL*, *PVL,* and *SNL* with exogenously added Cd concentrations compared to CK. The water content of *PCK* and *SLT* was not affected when exogenously added Cd concentrations were between 3 and 5 mg/kg. Exogenously added Cd at a concentration of 8 mg/kg increased the water content of *PCK* by 71.99% and decreased the water content of *SLT* by 71.71% compared to the CK. Belgian scholars LADISLAS S. et al. [28] studied the growth response of five aquatic plants to Cd, Cr, Cu, Ni, Pb, and Zn and found that heavy metal ions, after entering the plant's cells, can change the stem cell water content and activity by changing the osmotic pressure difference between inside and outside of the cell and by reacting with the plant's cellular organelles to cause cellular damage, which will in turn affect the plant's growth and health status [29].

In summary, from the perspective of plant growth, combined with the effects of different exogenously added Cd concentrations on the growth and health status of each plant, it can be concluded that exogenously added Cd of 3 mg/kg inhibited the growth of *PVL* and did not affect the growth of the rest of the plants. Adding 5 mg/kg of Cd significantly promoted the growth of *PCK, SLT* and *SNL*, inhibited the growth of *PVL*, and did not affect the growth of *PAR* and *NAL*. Adding 8 mg/kg of Cd significantly promoted the growth of *NAL*, inhibited the growth of *PVL* and *SLT,* and had no effect on *SNL, PCK,* or *PAR*.

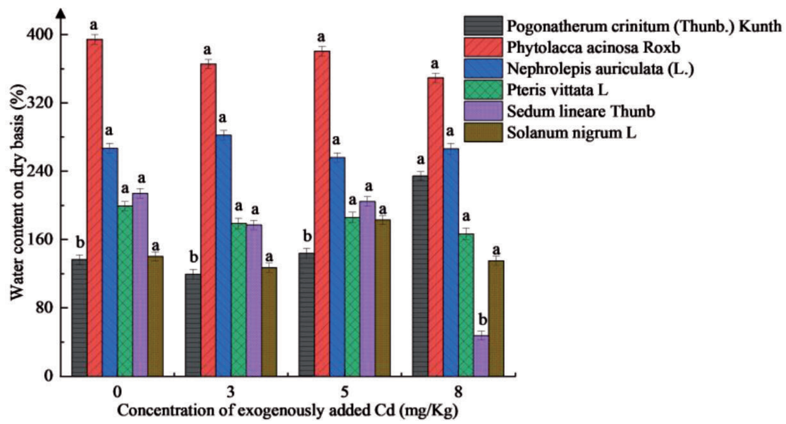

Fig. 3. Dry basis water content of each plant.
Different letters indicate significant differences in water content of the same plants at different exogenously added Cd concentrations (P<0.05).

Cd Enrichment Capacity of Individual Plants

To conduct a comparative study on the enrichment ability of six plants for Cd, the significance test of difference was analyzed for the Cd concentration in the roots, stems, and leaves of the plants, and the results are shown in Fig. 4.

From the analysis of Fig. 4, the Cd concentrations in the roots, stems, and leaves of *PVL* were 13.34, 3.22, and 1.58 mg/kg, respectively, when the soil Cd concentration was 3 mg/kg. The average Cd concentration of the whole plant was 6.04 mg/kg, which had the lowest enrichment capacity for Cd. The mean Cd concentrations within *SLT*, *SNL*, *NAL*, *PAR,* and *PCK* were 58.65, 47.37, 50.03, 48.61, and 44.22 mg/kg, respectively, which were 9.71, 7.84, 8.28, 8.05, and 7.32 times higher than *PVL*. When the soil Cd concentration was 5 mg/kg, the Cd concentrations in *PVL* roots, stems, and leaves were 10.57, 2.98, and 1.38 mg/kg, respectively, and the mean Cd concentration of the whole plant was 4.97 mg/kg,

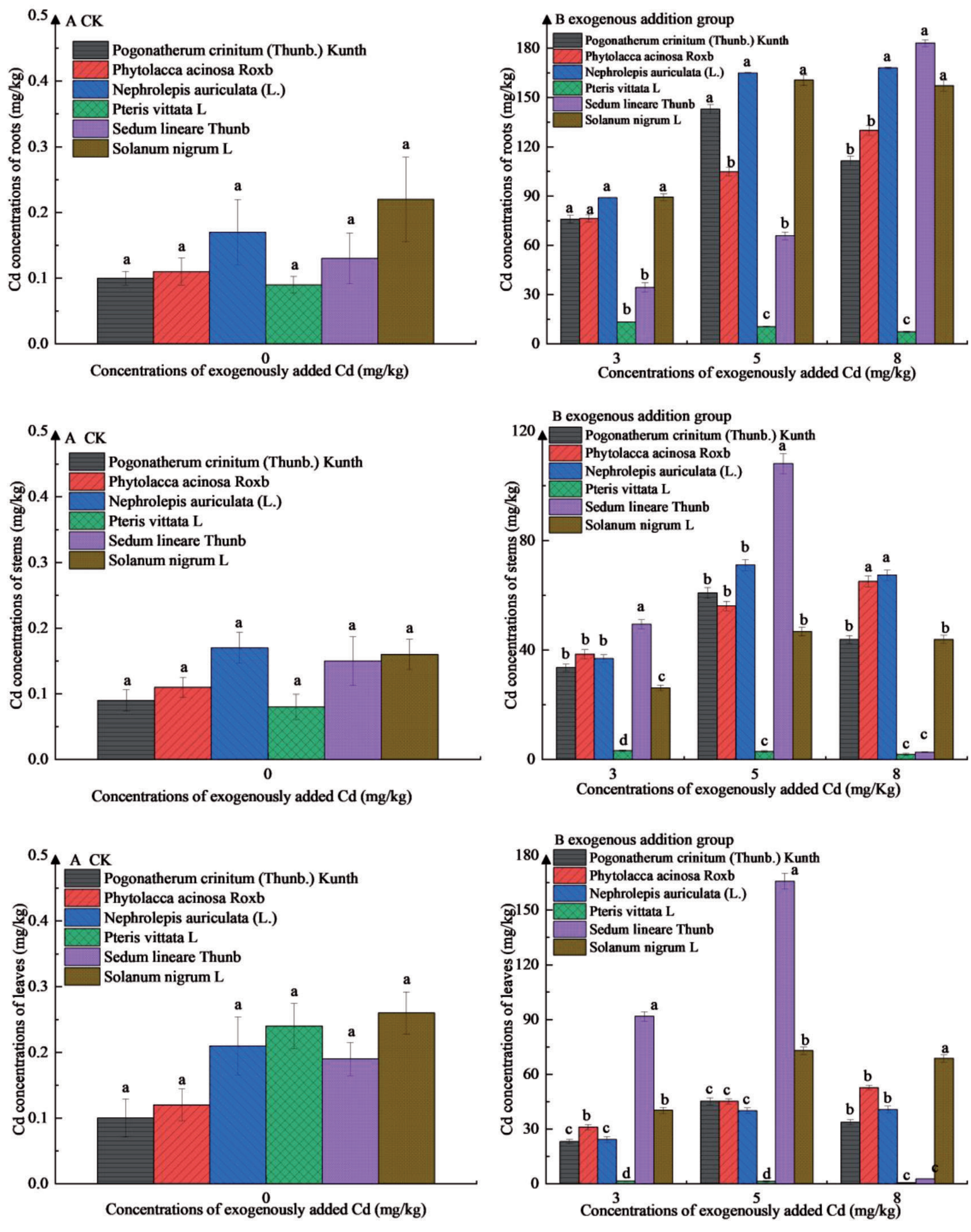

Fig. 4. Cd concentration in roots, stems and leaves of each plant.
Different letters indicate significant differences between Cd concentrations in roots, stems or leaves of different plants at the same exogenously added Cd concentration ($P<0.05$).

which had the lowest Cd enrichment capacity; the mean values of Cd concentration in *SLT*, *SNL*, *NAL*, *Pogonatherum crinitum (Thunb.)* and *Kunthand PAR* were 113.22, 93.45, 92.01, 71.90, and 68.67 mg/kg, respectively. That is 22.78, 18.80, 18.51, 14.47, and 13.82 times that of *PVL*. When the soil Cd concentration was 8 mg/kg, the Cd concentrations in PVL roots, stems, and leaves were 7.31, 1.91, and 0.61 mg/kg, respectively, and the mean Cd concentration of the whole plant was 3.28 mg/kg, which had the lowest Cd enrichment capacity; The mean values of Cd concentration in *NAL*, *SNL*, *PAR*, *Pogonatherum crinitum (Thunb.)* and *Kunthand SLT* were 92.01, 89.95, 82.46, 63.01, and 62.81 mg/kg, respectively.

The Cd concentration in the roots and leaves of each plant was converted to the Cd concentration (c_q) within the whole plant according to Eq. (2), and then the BCF of plants in the three Cd concentration soils was calculated according to Eq. (3), and the results are shown in Table 2.

As can be seen from Table 2, *PVL*, with a Cd enrichment factor <1, is not a Cd hyper-enriched plant and is not recommended for soil Cd pollution remediation; the remaining five plants, with a BCF >1, are all Cd hyper-enriched plants. Comparison of the BCF of six plants at three soil Cd concentrations showed that the remediation capacity of each plant at an exogenously added Cd concentration of 3 mg/kg was *SLT>SNL>NAL>PAR>PCK>PVL*; at 5 mg/kg it was *SLT>SNL>NAL>PCK>PAR>PVL*; and at 8 mg/kg it was *NAL>SNL>PAR>PCK>SLT>PVL*.

In summary, with the increase in exogenously added Cd concentration, the Cd concentration in the roots, stems, and leaves of *NAL* showed the change rule of increasing first and then stabilizing. The Cd concentration in the roots, stems, and leaves of *PVL* showed a continuous decrease. The Cd concentration in the roots, stems, and leaves of *PCK* showed a pattern of first increasing and then decreasing. The patterns of Cd concentration in the roots, stems, and leaves of *PAR* and *SNL* were continuously increasing. The Cd concentration in the roots, stems, and leaves of *SLT* showed an increasing pattern when the exogenous Cd concentration was between 3 mg/kg and 5 mg/kg, and the average Cd concentration in the roots, stems, and leaves of *SLT* also took the maximum value in the group with an exogenous Cd concentration of 5 mg/kg. However, at 8 mg/kg, the Cd concentration in the roots was 183.17 mg/kg, which was much higher than that in the stems and leaves (2.68 mg/kg and 2.59 mg/kg). It may be due to the adsorption of Cd by the roots of *SLT,* which adsorbed excessive amounts of Cd at the high soil Cd concentration of 8 mg/kg, resulting in the death of *SLT* root cells. Subsequently, Cd entered the necrotic root cells in large quantities through cell membranes that lost their selective permeability and could not be transported to stems and leaves.

Laws of Cd Transport in Plant Roots, Stems, and Leaves

In order to clarify the transport pattern of Cd in six plant species and to provide a basis for the resourceful reuse of plants after remediation of soil Cd contamination, this paper compared the root, stem, and leaf Cd concentrations of each plant species with the plant species as the variables, respectively. The permutation graphing is performed for Fig. 4, and the results are shown in Fig. 5. The TF between rhizomes, stems, and leaves of each plant was calculated according to Eq. (4) and the results are shown in Table 3.

Combined with the analysis of Table 3 and Fig. 5, it can be seen that the TF≤1 between *PCK*, *PAR*, *NAL,* and PVL roots, stems, and leaves, and the distribution of Cd in all the above four species of plants showed the pattern of roots>stems>leaves; *PCK*, *PAR,* and *NAL* were Cd hyper-enriched plants and had the largest leaf Cd concentrations of 33.72, 52.71, and 40.68 mg/kg in all treatments, respectively; *PVL* is a non-Cd hyper-enriched plant and is generally not used for remediation of soil Cd contamination. The TF between roots and stems of *SNL*≤1, while the TF between stems and leaves>1. The distribution pattern of Cd within *SNL* was roots>leaves>stems. *SLT* at exogenously added Cd concentrations of 3 and 5 mg/kg, TF>1 between rhizomes and stems and leaves, and the distribution pattern of Cd in *SLT* was leaf>stem>root. At an exogenously added Cd concentration of 8 mg/kg, the Cd concentration in SLT roots amounted to 183.17 mg/kg, whereas the Cd concentrations in stems and leaves were 2.68 and 2.59 mg/kg, with minimal TF. It may be due to the enrichment of Cd in *SLT* roots, resulting in the death of root cells and the inability of Cd to be translocated to stems and leaves.

Table 2. BCF of each plant at different soil Cd concentrations.

Cd concentration (mg/kg)	*PCK*	*PAR*	*NAL*	*PVL*	*SLT*	*SNL*
3	14.74±0.57b	16.2±0.68b	16.67±0.76a	0.95±0.12 c	19.51±0.89a	17.27±0.74a
5	16.6±0.76b	13.7±0.71b	18.4±0.82a	0.58±0.10 c	22.87±0.92a	18.93±0.83a
8	7.87±0.69b	10.56±0.70 a	11.5±0.75a	0.31±0.08c	7.85±0.61b	11.24±0.75 a

Note: Different letters in the table indicate significant (P<0.05) differences between plant BCF values in different treatments at the same soil Cd concentration.

Capitalize on Resources

According to CHEN H. et al. [30], research on resourceful reuse after phytoremediation of soil heavy metal pollution showed that common resourceful reuse methods include composting, hydrothermal transformation, pyrolysis, and incineration. Among them, high-temperature incineration of Cd curing ability is poor, and the generation of dioxins and other highly toxic substances is prone to causing serious air pollution, so it is rarely used. ZHONG D. et al. [31], A 13-week composting experiment on a variety of plants containing heavy metals such as Cd, Ni, and Zn, respectively, showed that when the concentration of Cd in the plants was ≤ 68 mg/kg, it promoted the dissolution of more than 90% of the Cd into the leachate. And 20-30% of the remaining Cd in the organic fertilizer has been reduced and is extremely easy to extract, resulting in both highly efficient organic fertilizer and complete non-hazardousness through the solidification of leachate. ZHANG J.W. et al. [32] conducted a hydrothermal conversion of Cd-enriched A and B and found that the calorific value of the bio-oil obtained from the conversion was ≥35.2 MJ/K and that 95±2% of

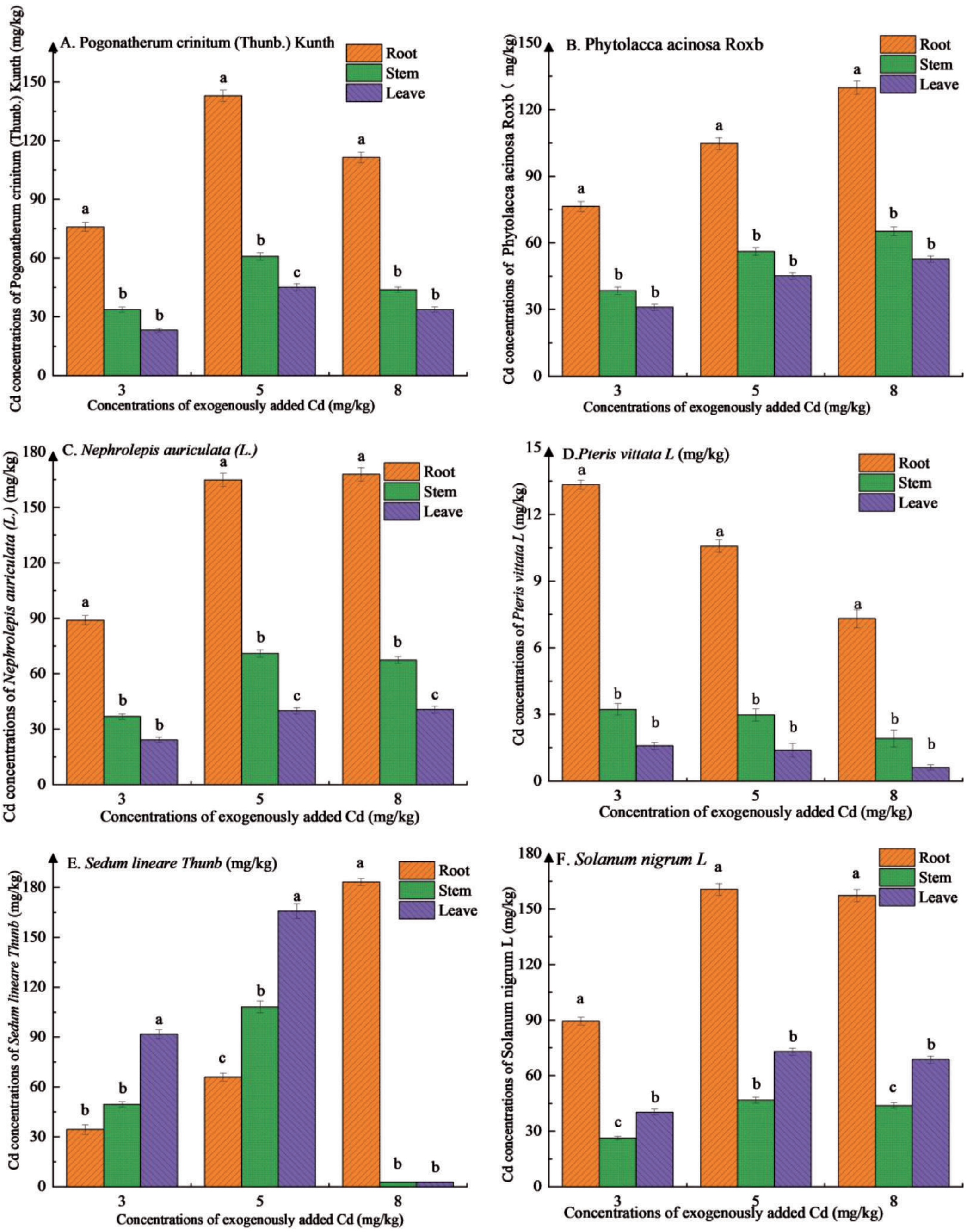

Fig. 5. Distribution of Cd concentration in roots, stems and leaves of various plants.
Different letters indicate significant differences between Cd concentrations in roots, stems, and leaves of the same plant at the same exogenously added Cd concentration ($P<0.05$).

Table 3. TF between roots, stems and leaves of each plant at different soil Cd concentrations.

Cd concentration (mg/kg)		PCK	PAR	NAL	PVL	SLT	SNL
3	root-stem	0.44±0.011 c	0.50±0.011 b	0.41±0.014 b	0.14±0.010 c	1.44±0.021 a	0.29±0.008 c
	stem -leave	0.69±0.020 b	0.81±0.013 b	0.66±0.016 b	0.74±0.012 b	1.86±0.019 a	1.54±0.018 a
5	root-stem	0.43±0.014 b	0.54±0.015 b	0.43±0.014 b	0.15±0.007 c	1.64±0.022 a	0.29±0.010 c
	stem -leave	0.19±0.006 c	0.80±0.010 b	0.56±0.012 b	0.73±0.014 b	1.53±0.019 a	1.56±0.015 a
8	root-stem	0.39±0.011 a	0.50±0.013 a	0.40±0.011 a	0.13±0.008 b	0.01±0.005 c	0.28±0.009 b
	stem -leave	0.77±0.013 b	0.81±0.012 b	0.60±0.013 b	0.74±0.015 b	0.97±0.012 b	1.57±0.017 a

Note: Different letters in the table indicate significant ($P<0.05$) differences between TF values of plants in different treatments at the same soil Cd concentration.

the Cd could be concentrated in the solid-phase residue when the concentration of plant Cd enrichment was ≤100 mg/kg, which resulted in complete harmlessness and a significant effect of resource utilization. Subsequent studies by the team on five species of plants, including *Sedum alfredii Hance*, *PVL*, and *SNL,* found that all five species showed that more than 85% of the Cd could be concentrated in the solid-phase residue when the Cd enrichment concentration was ≤110 mg/kg; A phenomenon occurs when the proportion of Cd enrichment decreases sharply to less than 50% when the Cd enrichment concentration is ≥127 mg/kg. The above study showed that the limiting concentration of Cd enrichment by plants after hydrothermal conversion treatment for remediation of Cd pollution was 110 mg/kg, independent of plant species. Plants with a Cd enrichment concentration ≥110 mg/kg can be treated by high-temperature pyrolysis (temperature ≥600ºC) at a high cost, which can not only obtain pyrolysis bio-oil, but also immobilize Cd into ash and realize harmless treatment with the process of "solidification + safe landfill". Based on the amount of Cd partitioning in plant roots, stems, and leaves, the highest Cd concentrations in leaves and stems of *PCK* and *PAR* after remediation of Cd-contaminated soil were 60.88 and 65.11 mg/kg, respectively. The maximum Cd concentrations of 65.79, 43.86, and 40.68 mg/kg for *SLT* roots, *SNL* stems, and *NAL* leaves, respectively, were less than the extreme value of 68 mg/kg for the composting method, which can be utilized for resource reuse by the composting method. The highest Cd concentrations in the stems of *NAL* and *SLT* after remediation of Cd-contaminated soil were 71.08 and 108.11 mg/kg, respectively, and the highest Cd concentration in the leaves of *SNL* was 72.92 mg/kg, which was less than the extreme value of 110 mg/kg for hydrothermal transformation and could be utilized for resource reuse by hydrothermal transformation. After remediation of Cd-contaminated soil, the roots of *PCK*, *PAR*, *NAL,* and *SNL* and the leaves of *SLT* can be disposed of harmlessly by the process of "high-temperature pyrolysis + solidification + safe landfill".

Conclusions

(1) An analysis of the remaining Cd concentration in the soil after remediation of each plant can be obtained: *Pteris vittata L* is not suitable for remediation of Cd pollution. When the Cd concentration ≤3 mg/kg, the Cd pollution in the riverbed around the outfall can be used as agricultural land after remediation by *Nephrolepis auriculata (L.)*, *Solanum nigrum L,* and *Sedum lineare Thunb* and can only be used as landscaping land after remediation by *Pogonatherum crinitum (Thunb.) Kunth* and *Phytolacca acinosa Roxb.* When 3 mg/kg≤Cd concentration ≤5 mg/kg, the riverbed Cd pollution around the outfall can be used as agricultural land after remediation by *Sedum lineare Thunb*, and can only be used as landscape land after remediation by *Nephrolepis auriculata (L.), Solanum nigrum L, Pogonatherum crinitum (Thunb.) Kunth,* and *Phytolacca acinosa Roxb.* When 5 mg/kg<Cd concentration <8 mg/kg, the Cd pollution in the riverbed around the outfall could only be used as landscape land after remediation by all five plants individually. When the Cd concentration was ≥8 mg/kg, the Cd pollution in the riverbed around the outfall could not meet the requirements of the risk control value after remediation of the five plants alone, and further treatment was needed.

(2) At a soil Cd concentration of 3 mg/kg, the growth of the other five plant species was not significantly affected, except for *Pteris vittata L*, whose growth was inhibited to a lesser extent; at a Cd concentration of 5 mg/kg, the growth of *Pogonatherum crinitum (Thunb.) Kunth, Sedum lineare Thunb* and *Solanum nigrum L* was significantly promoted, the growth of *Pteris vittata L* was significantly inhibited, and the growth of *Phytolacca acinosa Roxband* and *Nephrolepis auriculata (L.)* was unaffected; Cd concentration of 8 mg/kg significantly inhibited the growth of *Sedum lineare Thunb* and *Pteris vittata L*, promoted the growth of *Nephrolepis auriculata (L.)*, and did not affect the growth of *Pogonatherum crinitum (Thunb.) Kunth*, *Phytolacca acinosa Roxb* and *Solanum nigrum L*. Although the growth of *Phytolacca acinosa Roxb* was almost unaffected by soil Cd concentration

in the experiment, in combination with the shade-loving and flood-intolerant growth habit of *Phytolacca acinosa Roxb* and the fact that the potting experiment could not simulate the unshaded and flood-prone environment of the riverbed around the outfall, planting *Phytolacca acinosa Roxb* is not recommended to remediate the Cd pollution in the riverbed around the outfall.

(3) Ranking the ability of each plant to enrich Cd from the dimension of BCF: The soil Cd concentration of 3 mg/kg was *Sedum lineare Thunb>Solanum nigrum L>Nephrolepis auriculata (L.)>Phytolacca acinosa Roxb>Pogonatherum crinitum (Thunb.) Kunth>Pteris vittata L;* at 5 mg/kg, it was *Sedum lineare Thunb> Solanum nigrum L>Nephrolepis auriculata (L.)> Pogonatherum crinitum (Thunb.) Kunth>Phytolacca acinosa Roxb>Pteris vittata L*; at 8 mg/kg, it *was Nephrolepis auriculata (L.)>Solanum nigrum L> Phytolacca acinosa Roxb>Pogonatherum crinitum (Thunb.) Kunth>Sedum lineare Thunb>Pteris vittata L*. Planting *Solanum nigrum L* or *Sedum lineare Thunb* is recommended for streambeds around domestic outfalls with soil Cd concentrations ≤3 mg/kg. 3 mg/kg≤Cd concentration ≤5 mg/kg Light industrial areas are recommended to plant *Sedum lineare Thunb*. 5 mg/kg≤Cd concentration ≤8 mg/kg Heavy industrial areas are recommended to plant *Nephrolepis auriculata (L.)*. Mixed planting of *Solanum nigrum L* and *Nephrolepis auriculata (L.)* is recommended for soil Cd pollution remediation in chemically industrialized areas with Cd concentration ≥8 mg/kg. *Pogonatherum crinitum (Thunb.) Kunth* is recommended to be planted as an auxiliary remediation plant pair for a Cd pollution remediation at outfalls in all of the above areas.

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Conflict of Interest

The authors declare no conflict of interest.

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