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Effects of Soil pH on the Growth and Cadmium Accumulation in *Polygonum hydropiper* (L.) in Low and Moderately Cadmium-Contaminated Paddy Soil

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Abstract: Wetland macrophytes have advantages when used in the remediation of cadmium (Cd)-contaminated paddy fields because they can adapt to overly wet soil environments; however, only a few studies have tested the efficiency of macrophytes in Cd phytoremediation. In this study, we investigated the effect of soil pH (pHs of 5, 6, and 7) on the accumulation and translocation of Cd by *Polygonum hydropiper* (L.) in low and moderately Cd-contaminated paddy soil (0.56 and 0.92 mg/kg, respectively). Our results indicated that Cd accumulation in stems and roots, as well as subcellular distribution in *P. hydropiper*, was affected by soil pH, with significant interactions between the soil pH and Cd level. At low soil Cd levels, stem and root Cd contents were higher at a soil pH value of 6. In addition, with higher soil pH values, the proportion of Cd distributed in the cell wall increased, whereas that distributed in the organelles decreased. The Cd content in the roots and stems of *P. hydropiper* significantly decreased with the increase in soil pH in the moderate Cd-contaminated soil. In addition, with higher soil pH values, the proportion of Cd distributed in the cell wall decreased, whereas that distributed in the organelles increased. The translocation factor (TF) of *P. hydropiper* was higher than one in all treatments, indicating that it can effectively transport root-absorbed Cd to the aboveground shoots. Based on the relatively high bioconcentration factor and TF, *P. hydropiper* has the potential to remediate Cd-polluted paddy soil. Furthermore, the remediation efficiency of *P. hydropiper* can be enhanced by adjusting the pH as per the soil-Cd pollution.

Keywords: phytoremediation; heavy metal pollution; paddy field; wetland macrophyte; *Polygonum hydropiper* (L.)

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1. Introduction

Heavy metal pollution in soil and water has aroused global concern because of its toxicity, minimal degradation, and biomagnification [1]. In China, 19.4% of the arable land is polluted by heavy metals, such as cadmium (Cd), nickel (Ni), copper (Cu), and arsenic (As) [2]. Among them, Cd-contaminated sites are common, posing a serious threat to organisms in food chains and webs [3]. Rice (*Oryza sativa* L.) is a staple food crop and has a high capacity to absorb and accumulate Cd from polluted soils. It was estimated that 10.6% of the brown rice samples exceeded the Cd limit according to Chinese standard (GB2762-2012, 0.2 mg/kg) [4]. Therefore, it is of great significance to remediate Cd-contaminated paddy soils to protect ecosystems and human health.

Among the various ways to remediate Cd-contaminated soil, phytoremediation is recommended as an effective, economical, and eco-friendly method [5,6]. Previous studies

have shown that several terrestrial plants, such as *Solanum nigrum*, *Sedum alfredii*, *Miscanthus floridulus*, *Gossypium* spp, and *Amaranthus Hypochondriacus* (L.), can be used in soil remediation because of their ability to absorb heavy metals from the soil. [7–12]. However, paddy fields, as a type of artificial wetland, periodically alternate between shallow surface water and drainage [13]. Most plants used in phytoremediation are mesophytes or xerophytes, which are difficult to apply in paddy soils [14] because of the fluctuating cultivation conditions.

Wetland macrophytes have morphological and physiological traits, such as adventitious roots and well-developed aerenchyma tissues, which allow them to adapt to shallow water or overly wet soil conditions [15,16]; thus, macrophytes can potentially remediate contaminated paddy fields. Recent studies have found that some wetland plants have tolerance and accumulation ability to Cd, such as *Typha latifolia* and *Polygonum hydropiper* (L.), *Phragmites australis*, *Eichhornia*, *Lemna*, *Azolla*, and *Typha angustifolia* [17–22]. However, only a few macrophyte species have a high Cd accumulation ability, which has great potential for application in phytoremediation.

Furthermore, the efficiency of phytoremediation is affected by soil physical and chemical properties such as soil pH, moisture, and nutrient content [23–25]. Under certain acidic conditions, immobile Cd can be transformed into a more active form, which is conducive to absorption by plants [26–28]. Several studies have shown that plants have the highest remediation potential in acidic environments [29–31]. In addition, the effects of phytoremediation are influenced by the degree of soil contamination [32,33]. Generally, macrophytes accumulate more Cd in soils with higher Cd content, but a high Cd content may also constrain the performance of the macrophytes in remediation [34,35]. However, the synergistic effects of soil pH and Cd contamination degree on efficiency of phytoremediation by wetland macrophytes have rarely been examined.

Previous studies have shown that *Polygonum hydropiper* (L.), a widely distributed wetland macrophyte, has a large biomass and a high capacity to accumulate cadmium [19,36]. Under a 30-day 1 mg/kg-Cd hydroponic solution treatment, the bioconcentration factor (BCF) of shoots and roots of *P. hydropiper* were 45.6 and 111.7, respectively [19]. In 100 mg/kg-Cd soil, the Cd content of aboveground shoots and roots of *P. hydropiper* was 68 and 200 mg/kg, respectively [37]. The above studies demonstrated that *P. hydropiper* is tolerant to Cd stress and has the potential to be used in remediation of Cd-polluted paddy soil.

In the present study, we investigated the effect of soil pH and Cd contamination degree on the efficiency of *P. hydropiper* in remediation of paddy soil. A survey of rice cultivation areas in South China found that the majority of the soil is acidic to neutral, with pH values of 5.26–7.77 [38]. According to the Chinese standard on soil environmental quality (GB 15618-2018), paddy fields are at risk of Cd contamination when soil Cd content exceeds 0.3 mg/kg under acidic conditions (pH $\leq$ 5.5). Paddy fields are defined as lightly polluted when the total Cd concentration is within the range of 0.3–0.6 mg/kg and moderately polluted when it is within the range of 0.9–1.5 mg/kg [39]. Over 90% of polluted paddy fields in China have light to moderate Cd contamination [40]. Therefore, to investigate the effects of soil pH and Cd contamination degree on the efficiency of *P. hydropiper* in the remediation of paddy soil, we manipulated three levels of soil pH (5, 6, and 7) and used two degrees of Cd-contaminated paddy soil (low and moderate) to test their effects on the growth, Cd accumulation, and translocation of *P. hydropiper*. We hypothesized that lower soil pH and higher soil Cd contamination would decrease plant growth but increase the Cd accumulation in *P. hydropiper*. The results of this research may provide a feasible basis for the utilization of *P. hydropiper* in the remediation of Cd-contaminated paddy fields.

2. Materials and Methods

2.1. Plant and Soil Preparation

We conducted the experiments in a greenhouse at the Research Station for Agricultural and Environmental Monitoring, Institute of Subtropical Agriculture, Chinese Academy of

Sciences, Changsha County, Hunan Province, China (28°22′ N, 112°58′ E). We collected contaminated paddy soil within the plow layer (0–20 cm) from two patches of local paddy fields with different levels of contamination. The Cd content of the two paddy soils was 0.52 ± 0.03 mg/kg and 0.92 ± 0.01 mg/kg, respectively; one of which is in the range of light (0.3 mg/kg < total soil concentration < 0.6 mg/kg) and the other in that of moderate pollution (0.9 mg/kg < soil total Cd concentration < 1.5 mg/kg) [39]. Soil samples were air-dried, plant residues and gravel were removed, and the soil was then passed through a 10 mm sieve.

2.2. Plant Culture and Experimental Design

We collected rhizomes of *P. hydropiper* from the Dongting Lake wetland and cultivated them in a nursery bed inside a greenhouse in August 2021. On 18 September 2021, we selected 108 plants with similar growth status and transplanted them into 36 plastic buckets (height: 40 cm, diameter: 30 cm), with three ramets in each bucket. Eighteen buckets contained 8 kg of lightly polluted soil, and eighteen moderately polluted soil. The fresh weight of plants in each bucket was 15 ± 2 g. We punched five small holes with diameters of 3 mm at the bottom of each plastic bucket.

The experiment had a random block design with six treatments (three soil pH levels × two levels of Cd contamination) and was replicated six times. We placed the three buckets with lightly polluted soil and three buckets with moderately polluted soil into one of six large plastic tanks (150 cm × 80 cm × 100 cm), which was then filled with water to maintain a water level of 40 cm (0 cm for the plants). After growing for six weeks, we calculated the amount of citric acid monohydrate and calcium oxide (analytically pure) and applied them evenly into the buckets in two batches, ensuring that the pH of each treatment was approximately 5, 6, and 7. The pH value of the original paddy soil was approximately 6. We added 12 g citric acid to decrease the soil pH to 5 and add 2.4 g calcium oxide to increase the soil pH to 7.

2.3. Sample Collection and Processing

When the leaves were partially wilted, we harvested the plants (17 December 2021). We collected six to eight leaves from top to bottom of the plants and placed them in sealed bags. We stored these samples at 4 °C in a refrigerator for subcellular structure analysis. We harvested all the remaining plants and cleaned them with running water. We divided the plants into roots, stems, and leaves and placed them into brown envelopes. We placed these plant samples in an oven at 105 °C for 30 min to deactivate the enzymes and then dried them at 70 °C to achieve a constant weight for measurements. We ground the plant samples to powder using a stainless-steel grinder (FW-80, Ultralight Medical Equipment Co., Ltd., Beijing, China), passed them through a 1 mm sieve, homogenized them, and then stored them in sealed bags.

We spread the collected soil samples on paper and placed them in a drying room for ventilation and shade drying, after which we removed debris from the samples. We rolled out the soil with a wooden stick, sifted the finely ground soil through a 10- and a 100-mesh sieve, and placed the samples in sealed bags for further analysis.

2.4. Analysis of Cd in Plants and Soils

We blended 10 g of air-dried soil with 25 mL of deionized water without CO_2 for 30 s and equilibrated it for 30 min. We determined the soil pH using a pH meter (PHS-3C, Shanghai Dapu Instruments, Shanghai, China). We measured soil organic matter content by dry combustion using a CN auto-analyzer (Vario MAX C/N, Berlin, Germany), and measured soil total phosphorus (TP) and potassium (TK) using the NaOH fusion method. We extracted soil-available phosphorus using 0.03 mol/L NH_4F–0.025 mol/L HCl and measured it using an ultraviolet spectrophotometer (UV-2600, Shimadzu (Hong Kong) Limited, Hong Kong, China) at a wavelength of 7 nm. We extracted available soil potassium

using 1 mol/L NH_4OAc and measured it using the flame photometric method [41]. The basic physical and chemical properties of the soils are listed in Table 1.

Table 1. Basic soil properties used in the experiment.

Soil Parameters	Organic Matter Content	Total Nitrogen Content	Total Potassium Content	Available Potassium Content	Total Phosphorus Content	Available Phosphorus Content	Total Cadmium Content
Low pollution	15.62 (g/kg)	0.18 (g/kg)	18.25 (g/kg)	3.10 (g/kg)	0.431 (g/kg)	0.11 (g/kg)	0.56 (mg/kg)
Moderate pollution	14.23 (g/kg)	0.27 (g/kg)	20.84 (g/kg)	2.48 (g/kg)	0.593 (g/kg)	0.19 (g/kg)	0.92 (mg/kg)

To determine the soil total Cd content, we digested 0.5 g of soil sample with a mixture of concentrated HCl–HNO_3–$HClO_4$ and measured it using inductively coupled plasma-optical emission spectrometry (ICP-OES 720; Varian, Palo Alto, CA, USA). To extract the available cadmium, we weighed 5 g of soil sample, added 25 mL of 0.01 M $CaCl_2$, shook it at 180 rpm for 2 h, filtered it, and analyzed the filtrate using ICP-OES.

We weighed 0.2 g of the plant samples and added them to a polypropylene digestion tube, where they were digested with 8 mL concentrated HNO_3 and 1 mL $HClO_4$, and then diluted to 25 mL with 1% HNO_3. Further, we used 10 mL filtrate to measure the Cd content using ICP-OES [42]. We used blanks and certified reference material, GBW07602 Chinese plant samples, and GBW070011 Chinese soil samples for quality control (Science and Exhibition Biotech Co., Ltd., Beijing, China). The recoveries of the samples were between 96.8% and 102.6%.

2.5. Determination of Cd in Leaf Subcellular

We determined the subcellular distribution of Cd in *P. hydropiper* leaves using the method described by Wang et al. [43] with slight modifications. We homogenized fresh samples (1 g) in a mortar with an appropriate amount of liquid nitrogen and 10 mL extraction buffer, including 250 mmol/L sucrose, 50 mmol/L Tris–HCl (pH 7.5), and 1 mmol/L dithiothreitol, above ice. Afterwards, we obtained the cell wall fraction (F1) by centrifuging the homogenate at 2400 rpm for 30 s in a high-speed refrigerated centrifuge (CR22 GII, Hitachi, JPN). We collected the supernatant and centrifuged at 12,000 rpm for 45 min. We defined the solid residue and supernatant as the organelle and soluble fractions, respectively. We performed all experimental operations at 4 °C. We digested the three fractions using a mixture of concentrated HNO_3 and $HClO_4$. Finally, we determined the Cd content of the three subcellular fractions using inductively coupled plasma-mass spectrometry (ICP-MS 7900; Agilent, Santa Clara, CA, USA).

2.6. Statistical Analysis

Bioconcentration and translocation factors have previously been used to evaluate the capacity of plants to absorb Cd [44]. We calculated the BCF using the Cd content in each plant organ divided by the total Cd content in the soil. We calculated the translocation factor (TF) from Cd content in the aboveground parts of plants divided by the Cd content in the roots.

We assessed the effect of soil pH value and Cd level on plant growth, Cd accumulation, and translocation using a general linear model. We performed multiple comparisons of the means using a Tukey's test at a significance level of 0.05 ($p < 0.05$). The data were square root or log10 transformed, if necessary, to reduce the heterogeneity of variances. We performed all statistical analyses using R (version 3.6.1; R Core Team 2019).

3. Results

3.1. Effects of pH Value and Soil Cd Content on Biomass Accumulation

Shoot mass and total biomass of *P. hydropiper* were significantly affected by soil Cd levels (Table 2; Figure 1A,C). Higher soil Cd levels reduced the shoot mass and the total biomass of *P. hydropiper*. The root mass of *P. hydropiper* was affected by soil Cd levels with significant interactions between soil Cd levels and pH values (Table 2, Figure 1B). Higher soil Cd levels reduced the root mass of *P. hydropiper*. Under low soil Cd levels, root mass was lower at lower pH (5) than at higher pH (Table S1; Figure 1B).

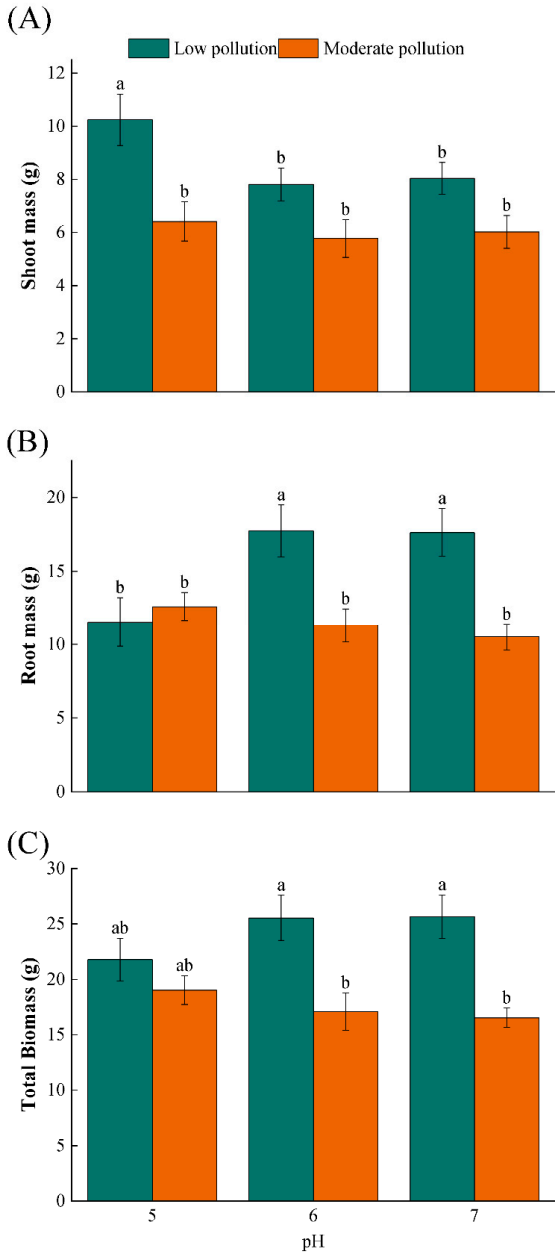

Figure 1. The shoot mass (**A**), root mass (**B**), and total biomass (**C**) of *Polygonum hydropiper* growing under three soil pH values at two cadmium (Cd) contamination levels. Different lowercase letters (a, b) indicate significant differences among the three pH treatments.

Table 2. Summary of the influence of each term (F-value) in a general linear model (GLM) testing the interacting influence of soil pH and cadmium (Cd) levels on biomass accumulation of *Polygonum hydropiper*.

Targets	Biomass	Aboveground Biomass	Root Mass
pH value	0.159 ^{ns}	2.652 ^{ns}	1.757 ^{ns}
Cd content	24.491 ***	20.009 ***	13.451 **
pH × Cd interaction	2.17 ^{ns}	1.05 ^{ns}	5.342 *

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ^{ns} $p > 0.05$.

3.2. Effects of Soil pH and Cd Content on Cd Accumulation in Plant Organs

The Cd content in the leaves of *P. hydropiper* was significantly affected by soil pH (Table 3, Figure 2A). At moderate soil Cd levels, high soil pH values reduced the leaf Cd content (Table S2). Cd content in the stems of *P. hydropiper* was significantly affected by soil pH and Cd levels, with significant interactions between soil Cd levels and pH values (Table 3, Figure 2B). Higher soil Cd levels increased the stem Cd content in *P. hydropiper*. At low soil Cd levels, the stem Cd content was higher when the soil pH was 6. At moderate soil Cd levels, higher soil pH values reduced Cd content in the stems (Table S2).

Table 3. Summary of the influence of each term (F−value) in a general linear model (GLM) testing the interacting influence of soil pH and cadmium (Cd) levels on Cd accumulation by *Polygonum hydropiper*.

Targets	pH Value	Cd Content	pH × Cd
Leaf Cd content	4.842 *	0.16 ^{ns}	2.707 ^{ns}
Stem Cd content	22.161 ***	17.789 ***	31.061 ***
Root Cd content	6.495 **	3.957 ^{ns}	6.199 **
Cd content in cell wall	7.484 **	1.323 ^{ns}	62.032 ***
Cd content in organelles	6.916 **	8.385 *	54.60 ***
Cd content in soluble fractions	0.167 ^{ns}	11.706 **	2.33 ^{ns}
Leaf bioconcentration factor	3.138 ^{ns}	9.778 **	4.602 *
Stem bioconcentration factor	16.38 ***	1.965 ^{ns}	31.265 ***
Root bioconcentration factor	2.046 ^{ns}	8.66 **	3.332 *
Translocation factor	1.473 ^{ns}	0.025 ^{ns}	3.645 *
Soil available Cd content	78.971 ***	40.931 ***	5.284 *

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, ^{ns} $p > 0.05$.

Cd content in the roots of *P. hydropiper* was affected by soil pH, with a significant interaction between soil pH and Cd levels (Table 3, Figure 2C). At low soil Cd levels, the root Cd content was higher when the soil pH was 6. At moderate soil Cd levels, higher soil pH values reduced Cd content in the roots (Table S2).

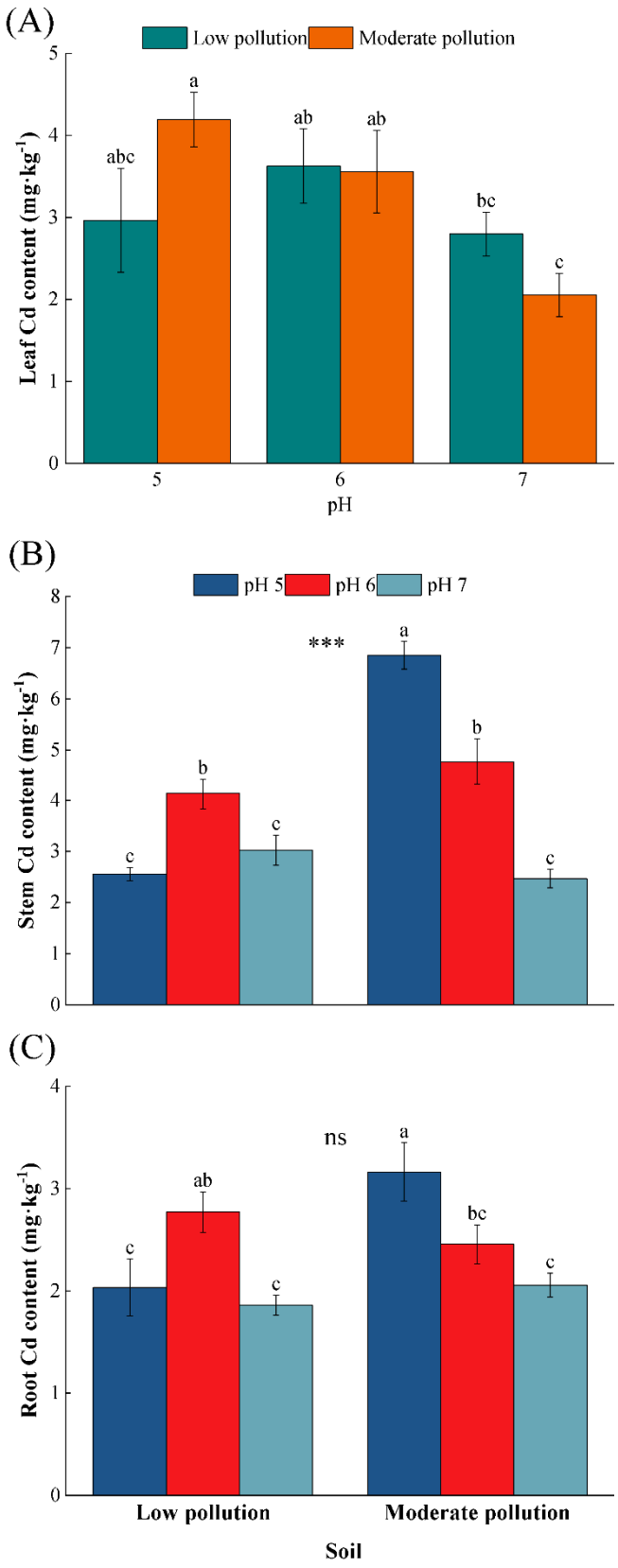

Figure 2. Cadmium (Cd) contents in leaves (**A**), stems (**B**), and roots (**C**) of *Polygonum hydropiper* growing under three soil pH values at two Cd pollution levels. Different lowercase letters (a, b, c) indicate significant differences among different treatments. The ns symbols indicate differences between two soil Cd levels (*** $p < 0.001$, ^{ns} $p > 0.05$).

3.3. Effect of Soil pH and Cd Level on Cd Distribution in Subcellular Structure

At the subcellular level, Cd was primarily distributed in the cell walls and organelles (Figure 3). At low soil Cd levels, the proportion of Cd distributed in the cell wall increased with higher soil pH values, whereas that distributed in the organelles decreased. At moderate soil Cd levels, the proportion of Cd distributed in the cell wall decreased with higher soil pH values, whereas that distributed in the organelles increased (Figure 3A).

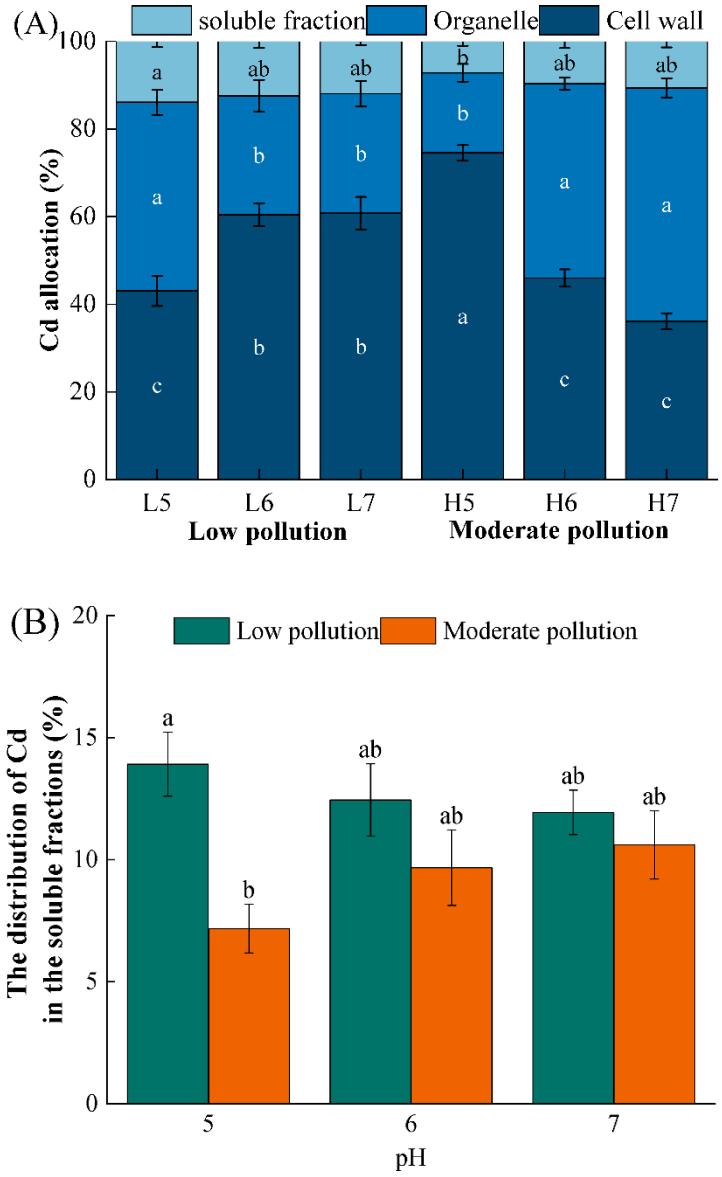

Figure 3. Subcellular cadmium (Cd) distribution (**A**) and the distribution of Cd in the soluble fractions (**B**) under three soil pH values at two Cd levels. Different lowercase letters indicate significant differences between different pH treatments.

Higher soil Cd levels significantly reduced the distribution of Cd in the soluble fraction at a soil pH of 5 (Figure 3B).

3.4. Effect of pH and Soil Cd Content on the BCF and TF

The leaf BCF of *P. hydropiper* was noticeably affected by soil Cd levels, with a significant interaction between the soil pH and Cd levels (Table 3, Figure 4A). Higher soil Cd levels

reduced the leaf BCF of *P. hydropiper*. At moderate soil Cd levels, higher soil pH values reduced the leaf BCF (Table S3).

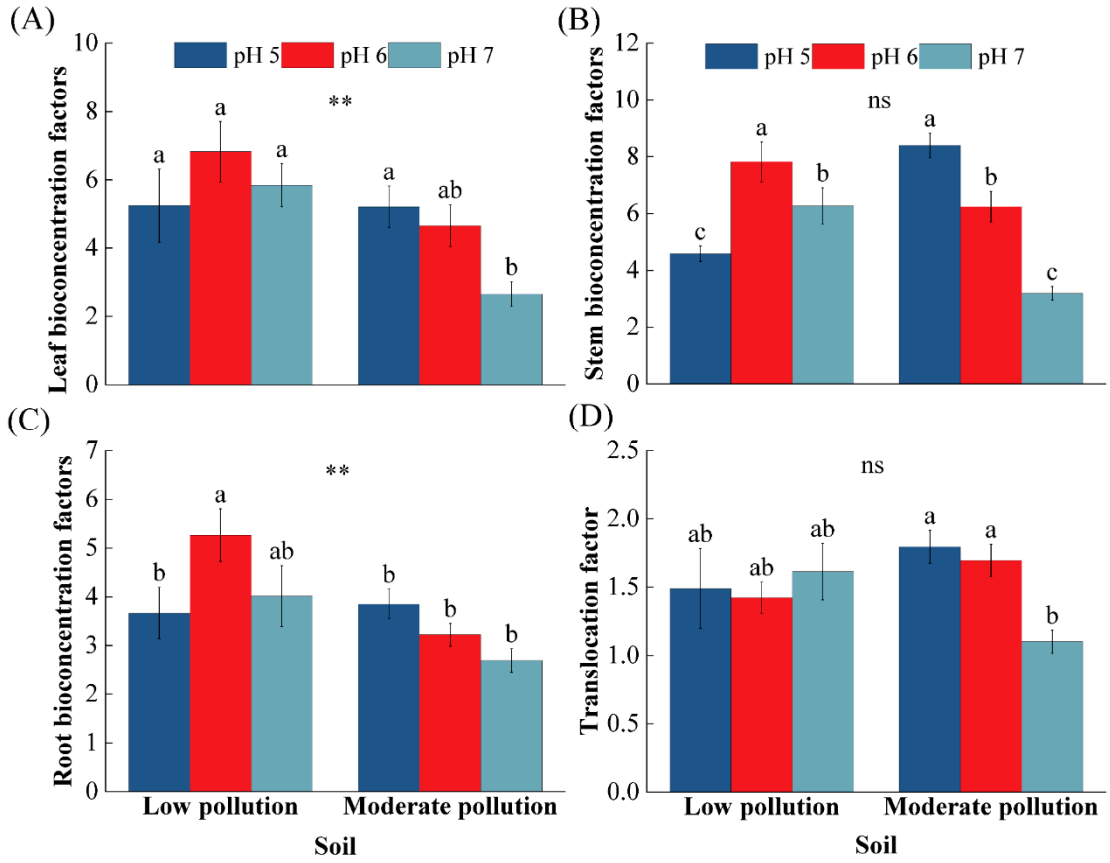

Figure 4. The bioaccumulation factors of leaves (**A**), stems (**B**), roots (**C**), and the translocation factor of *Polygonum hydropiper* (**D**) under three soil pH values at two cadmium (Cd) contamination levels. Different lowercase letters indicate significant differences between different pH treatments. The ** and ns symbols indicate differences between two soil Cd levels (** $p < 0.01$, ^{ns} $p > 0.05$).

The stem BCF of *P. hydropiper* was noticeably affected by soil pH, with a significant interaction between soil pH and Cd level (Table 3, Figure 4B). At low soil Cd levels, stem BCF was higher when the soil pH was 6. At moderate soil Cd levels, the BCF decreased with increasing pH (Tables S3 and 3, Figure 4B).

The root BCF of *P. hydropiper* was noticeably affected by the soil Cd value, with a significant interaction between soil value and Cd level (Table 3, Figure 4C). Higher soil Cd levels reduced the root BCF of *P. hydropiper*. At low soil Cd levels, the BCF was higher when the soil pH was 6 (Table S3).

The TF of *P. hydropiper* was significantly affected by the interaction between the soil pH and Cd levels (Table 3, Figure 4D). At moderate Cd levels, the TF of *P. hydropiper* decreased when the pH increased to 7 (Table S3).

3.5. Effect of Soil pH on Available Soil Cd Content after the Plants Were Grown in the Soil

Both the soil Cd level and pH value affected the soil available Cd content, with significant interactions between soil Cd levels and pH values (Table 3, Figure 5). The available soil Cd content was consistent with the total soil Cd. Higher soil pH values reduced the available Cd content in both low and moderately polluted soils (Table S4).

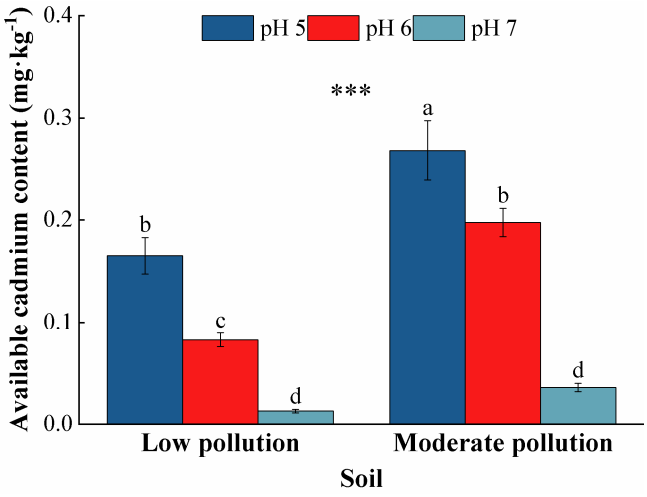

Figure 5. Effects of different treatments on the soil available cadmium (Cd) content after the plants were grown in the soil. Different lowercase letters indicate significant differences between different pH treatments (*** $p < 0.001$).

4. Discussion

4.1. Higher Soil Cd Content Reduced the Growth of P. hydropiper

Some studies have indicated that low Cd concentrations can stimulate plant growth [32,33]. For example, the shoot mass of *Arabis paniculata* slightly increased at low Cd concentrations [32], and the shoot mass of *Picris divaricata* increased by 27% and 23% at Cd concentrations of 5 μM and 10 μM, respectively [33]. In contrast, we found that the biomass of *P. hydropiper* decreased significantly when the soil was moderately polluted by Cd, which indicated that *P. hydropiper* was not tolerant to high levels of soil Cd pollution. Similar phenomena have also been observed in other plant species. For example, plant growth and physiological characteristics of oats (*Avena sativa* L.) decreased significantly when soil Cd concentration increased from low to moderate (0.96 mg/kg) [34]. The reason may be that higher Cd levels will cause the imbalance between the production and removal of reactive oxygen species in plant cells when plants are subjected to high Cd stress. This leads to the structural damage of the membrane system, further aggravating the damage caused by Cd to the plant physiological structure and inhibiting plant growth [45,46].

The acidity and alkalinity of the soil also have prominent effects on plant growth. In this study, we found that, under acidic conditions (pH 5), the development of *P. hydropiper* roots in highly contaminated soils was significantly inhibited. This may be because a low pH increases the activity of Cd, resulting in increased toxicity to plants [47]. In addition, as the soil pH decreases, most H^+ in the soil will exchange with alkaline cations in soil particles, which causes Ca^{2+}, Mg^{2+}, K^+, and Na^+ to dissolve into the soil solution and be lost, reducing soil nutrients and affecting the growth and development of plants [48].

4.2. Higher Soil pH Value Reduced Cd Accumulation by P. hydropiper

Soil pH is a primary parameter affecting the bioavailability of most nutrients and toxic elements [49]. Generally, as the soil pH increases, the available Cd decreases, and insoluble Cd forms, such as residual and oxidation states, increase, which may reduce plant absorption and accumulation [50]. The Cd content in the aboveground parts of *Sedum alfredii* decreased with an increase in soil pH [30], and Cd enrichment in *Brassica juncea* decreased with increasing pH [51]. In this study, we found that the Cd content in the roots and shoots of *P. hydropiper* decreased significantly with increasing soil pH in moderately Cd-polluted soil. However, under low soil Cd pollution the Cd content in the roots and stems of *P. hydropiper* was significantly higher in the near-neutral (pH = 6)

treatment compared to the other two. These results suggest an interactive effect between soil pH and Cd level on Cd accumulation in *P. hydropiper*.

Both acidic soil conditions and Cd contamination may constrain growth and Cd absorption by plants, but their relative roles may differ between slightly and highly Cd-polluted soils [52]. In low Cd-polluted soil where Cd stress is minor, growth and absorption by plant roots may be primarily constrained by soil acidity [53]. In contrast, in highly Cd-polluted soil, Cd stress restricts root growth and Cd absorption, although the pH affects the Cd mobility and phytoavailability [54,55].

4.3. Changes of Subcellular Cd Distribution with Soil pH and Cd Level

As reported in previous studies, absorbed Cd is mainly distributed in the cell walls [56–58]. However, soil pH significantly affected subcellular Cd distribution in the leaves of *P. hydropiper*, with an interaction between soil pH and Cd level. At low soil Cd levels, as the pH increased, the proportion of Cd in the cell wall increased, while that in the organelles decreased. In contrast, at high soil Cd levels, the proportion of Cd in the cell wall decreased, while that in the organelles increased as the pH increased.

The cell wall is the first barrier to Cd toxicity, with a large number of Cd-binding proteins and cation exchange sites [56]. In paddy soils with low Cd pollution, plant subcellular structures, such as chloroplasts and mitochondria, are deformed, owing to the increase in acid stress, resulting in a decreased Cd retention ability of the cell wall [58]. With an increase in pH, Cd translocated to the leaves in large quantities may bind to cation exchange sites on cell walls [59]. Therefore, the proportion of Cd in the cell wall increased, and the proportion of Cd in the organelles decreased. In paddy soils with moderate Cd contamination, the amount of Ca^{2+} (and that of many cations) increases with increasing pH [60,61]. The binding sites of Cd^{2+} on the cell wall compete, resulting in a decreased Cd retention ability of the cell wall [62,63]. Therefore, the proportion of Cd in organelles increased with increasing soil pH value.

4.4. Efficient Cd Accumulation and Translocation by P. hydropiper

The BCF reflects the ability of plants to absorb and accumulate heavy metals from the soil [64]. The stem BCF of *P. hydropiper* was 7.32 at a soil pH of 6 at low pollution, and 6.80 at a soil pH of 5 at moderate pollution, which is much higher than that of plants commonly used in phytoremediation, such as *Sorghum spp.*, *Ricinus communis*, and *Boehmeria nivea* [65,66]. The TF reflects the ability of plants to transfer heavy metals from the roots to the aboveground parts. The TF of *P. hydropiper* in all treatments was >1, which indicates that *P. hydropiper* can efficiently transport root-absorbed Cd to the aboveground shoots. However, under high soil Cd conditions, the TF of *P. hydropiper* decreased with increasing pH, which may reflect the immobilization of soil Cd at higher pH values [67,68]. These results indicate that *P. hydropiper* has a strong ability to absorb and transport Cd to its aboveground parts. Furthermore, the accumulation and translocation efficiency of *P. hydropiper* could be enhanced by adjusting the soil pH according to soil Cd levels.

5. Conclusions

We found that Cd accumulation in stems and roots of *P. hydropiper* as well as its subcellular distribution were affected by the soil pH, with significant interactions between soil pH and the Cd level. *Polygonum hydropiper* (L.) can accumulate and translocate more Cd at a near-neutral pH (pH = 6) in lightly Cd-polluted soil, whereas it accumulates and translocates less Cd at higher soil pH in moderately Cd-polluted soil. Based on the relatively high BCF and TF, *P. hydropiper* has the potential to remediate Cd-polluted paddy soils. Furthermore, the remediation efficiency of *P. hydropiper* could be effectively enhanced by adjusting the pH to an appropriate level based on the soil Cd pollution level.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12030652/s1, Table S1: Shoot mass, root mass, and total biomass of *P. hydropiper* growing under low and moderately Cd-contaminated soil at three pH values (mean ± se); Table S2. Leaf, stem, and root Cd contents of *P. hydropiper* growing under low and moderately Cd-contaminated soil at three pH values (mean ± se); Table S3: Leaf, stem, and root bioconcentration factor (BCF) and translocation factor (TF) under low and moderately Cd-contaminated soil at three pH values; Table S4: Soil available Cd content after the plants were grown in the soil under low and moderately Cd-contaminated soil at three pH values.

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