

Article

Soil pH Modulates Cadmium Uptake and Translocation in *Amaranthus hypochondriacus* L. Under Divergent Phosphorus Fertilization Strategies

Feng Li, Shuai Li, Jingxiong Liu, Bin Deng * and Haifeng Xiao *

Hunan Provincial Key Laboratory of Xiangnan Rare-Precious Metals Compounds Research and Application, School of Chemistry and Environmental Science, Xiangnan University, Chenzhou 423000, China; lifeng214@xnu.edu.cn (F.L.); lishuai1218@xnu.edu.cn (S.L.); l511024135@126.com (J.L.)

* Correspondence: dengbinxnu@163.com (B.D.); hfxiao@xnu.edu.cn (H.X.)

Abstract

Soil pH is a key regulator of cadmium (Cd) mobility, uptake, and translocation under phosphorus (P) fertilization. We hypothesized that P fertilization would enhance Cd phytoextraction by improving photosynthesis and biomass, that foliar KH_2PO_4 would better maintain Cd availability than soil-applied P, and that $\text{NH}_4\text{H}_2\text{PO}_4$ would promote Cd uptake through acidification, whereas CaHPO_4 would reduce Cd availability by increasing soil pH. A greenhouse pot experiment compared soil-applied KH_2PO_4 , CaHPO_4 , and $\text{NH}_4\text{H}_2\text{PO}_4$ with foliar KH_2PO_4 at 0.2%, 0.4%, and 0.8% in grain amaranth grown in Cd-contaminated acidic soil, with four replicates. Soil-applied P increased P availability, photosynthesis, biomass, and plant Cd accumulation by 69.8–139.5%, primarily through biomass promotion rather than greater soil Cd availability; foliar P was less effective. CaHPO_4 increased soil pH, whereas $\text{NH}_4\text{H}_2\text{PO}_4$ decreased it. Pot-level analyses showed negative relationships between soil pH and CaCl_2 -extractable Cd and Cd concentrations in roots, stems, and leaves. $\text{NH}_4\text{H}_2\text{PO}_4$ produced the highest tissue Cd concentrations, translocation factor, and total Cd accumulation, likely because acidification promoted Cd uptake and root-to-shoot translocation. Overall, the biomass-promoting and acidification hypotheses were supported, whereas the advantage of foliar P was not. However, repeated $\text{NH}_4\text{H}_2\text{PO}_4$ application may intensify soil acidification and increase heavy-metal mobility, posing ecological risks.

Keywords: phytoextraction; heavy-metal bioavailability; rhizosphere acidification; BCR fractionation; foliar application



Received: 29 June 2026

Revised: 26 July 2026

Accepted: 27 July 2026

Published: 30 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Phytoextraction of heavy metals refers to the use of accumulator plants to absorb heavy metals from contaminated soils through their root systems, translocate them to above-ground tissues, and subsequently remove the contaminants by harvesting the aboveground biomass. Compared with conventional engineering-based remediation technologies, phytoremediation has several advantages, including low cost, minimal soil disturbance, and the absence of secondary pollution [1]. It is particularly suitable for the remediation of large areas of agricultural land with mild-to-moderate heavy-metal contamination [2]. The efficiency of phytoremediation is generally determined by two key factors: above-ground biomass production and heavy-metal accumulation capacity. Although many hyperaccumulator species exhibit strong abilities to accumulate heavy metals, their field

application is often limited by slow growth, low biomass, poor environmental adaptability, and limited agronomic performance and management feasibility [3]. These limitations result in low remediation efficiency, thereby restricting the large-scale application of phytoremediation technology.

To enhance phytoremediation efficiency, increasing attention has been paid to accumulator plants that combine high biomass production with strong heavy-metal accumulation capacity, as well as to the optimization of agronomic practices that promote plant growth and heavy-metal uptake [4,5]. Grain amaranth (*Amaranthus hypochondriacus* L.) is characterized by relatively high biomass, rapid growth, strong adaptability, and ease of cultivation and management, indicating its potential for the remediation of Cd-contaminated soils [6].

Fertilization, which is an important agronomic practice for regulating plant growth, is a key factor influencing the chemical forms of heavy metals in soil. Appropriate fertilization can improve nutrient availability in contaminated soils, promote root development, and increase aboveground biomass accumulation. In addition, fertilizers may alter soil physico-chemical properties, such as pH and redox potential, thereby affecting the speciation and bioavailability of heavy metals in soil [7].

Phosphorus is an essential macronutrient for plant growth; however, the role of phosphorus fertilization in phytoremediation is complex. On the one hand, soil application of phosphorus can improve plant phosphorus nutrition and promote the growth of accumulator plants. On the other hand, phosphate ions introduced into soil may react with heavy-metal ions to form insoluble phosphate precipitates or reduce heavy-metal bioavailability through competitive adsorption and changes in soil pH, thereby inhibiting heavy-metal uptake by accumulator plants. Previous studies have shown that some phosphorus sources can immobilize heavy metals by forming poorly soluble metal phosphates or altering soil pH, consequently decreasing the concentration of bioavailable heavy metals in soil and limiting plant uptake [8]. Therefore, inappropriate phosphorus fertilization may reduce the effectiveness of phytoremediation.

Compared with soil phosphorus application, foliar phosphorus fertilization can provide P directly through leaf uptake while minimizing fertilizer contact with soil, thereby avoiding phosphate-induced immobilization reactions that may occur in contaminated soils, such as the formation of poorly soluble metal phosphates and reduced plant availability of metals [8]. Thus, foliar phosphorus application may promote plant growth while minimizing its negative effects on soil heavy-metal bioavailability. Moreover, foliar fertilization has the advantages of high specificity, low fertilizer input, and rapid response, and may therefore serve as an effective strategy for improving phytoremediation efficiency [9,10]. However, research remains limited regarding the effects of foliar phosphorus application on Cd uptake by grain amaranth.

Accordingly, this study aimed to determine how phosphorus application method and phosphorus source regulate soil P status and Cd fractions, plant growth and photosynthetic performance, Cd uptake and translocation, and ultimately the Cd phytoextraction efficiency of grain amaranth. Because different P sources may exert contrasting effects on soil pH and Cd mobility, their effects on plant Cd accumulation were also expected to differ.

We hypothesized that P fertilization would enhance Cd phytoextraction by grain amaranth primarily through improved photosynthetic performance and increased biomass production. Specifically, we predicted that: (1) P fertilization would increase plant biomass and total Cd accumulation compared with the non-P control; (2) foliar-applied KH_2PO_4 would have less influence on soil Cd immobilization than soil-applied P and would therefore maintain higher Cd bioavailability and Cd accumulation efficiency; and (3) among the soil-applied P sources, $\text{NH}_4\text{H}_2\text{PO}_4$ would promote Cd uptake and root-to-shoot translocat-

tion more strongly than KH_2PO_4 and CaHPO_4 because of its soil-acidifying effect, whereas CaHPO_4 would tend to reduce Cd availability by increasing soil pH.

2. Materials and Methods

2.1. Soil Preparation and Characteristics

The soil used in this experiment was collected from the experimental field of the South China Botanical Garden, Chinese Academy of Sciences. The soil is a typical alluvial soil from the Pearl River Delta region, which was classified as Anthrosol under WRB 2022. According to the international particle size classification system, the soil texture is silty loam, with sand, silt and clay fractions accounting for 23.6%, 52.3% and 24.1%, respectively. The soil has been intensively cultivated with vegetables for decades with annual organic manure application. Several hundred kilograms of surface soil at a depth of 0–20 cm were collected, air-dried outdoors, ground, thoroughly mixed, and passed through a 5 mm sieve. Soil contamination was artificially induced in square concrete tanks with a side length of 1 m by adding an aqueous CdCl_2 solution. The soil was thoroughly mixed to ensure uniform Cd distribution and then subjected to wetting–drying cycles for approximately 6 months to further equilibrate the contamination level. After equilibration, the soil was air-dried again, ground, homogenized, and passed through a 5 mm sieve before use. After contamination and equilibration, the basic physicochemical properties of the soil were as follows: pH, 4.63; total Cd, 8.40 mg kg^{-1} ; available Cd, 2.51 mg kg^{-1} ; total carbon, 68.2 g kg^{-1} ; total nitrogen, 2.51 g kg^{-1} ; total phosphorus, 0.48 g kg^{-1} ; and available phosphorus, 25.1 mg kg^{-1} .

2.2. Pot Experiments

A pot experiment was conducted in a greenhouse using plastic pots with an inner diameter of 29 cm and a height of 24 cm. Each pot was filled with 4 kg of dry soil. Basal fertilizers were applied to each pot at rates of $200 \text{ mg kg}^{-1} \text{ N}$ and $200 \text{ mg kg}^{-1} \text{ K}_2\text{O}$ in the form of aqueous urea and KCl solutions, respectively. A total of seven treatments were established: a control without phosphorus fertilizer application (CK); three soil phosphorus application treatments with KH_2PO_4 (K), CaHPO_4 (Ca), and $\text{NH}_4\text{H}_2\text{PO}_4$ (NH_4); and three foliar phosphorus application treatments with KH_2PO_4 at concentrations (w/v) of 0.2% (FP1), 0.4% (FP2), and 0.8% (FP3). Each treatment was replicated four times, resulting in a total of 28 pots. Grain amaranth (*Amaranthus hypochondriacus* cv. 'K112') seeds were germinated in seedling trays. When the seedlings reached 10–15 cm in height, three seedlings with similar growth status were selected and transplanted into each plastic pot. During seedling growth, soil moisture was maintained at 70–80% of field capacity. Phosphorus treatments were initiated 25 days after transplanting. For the soil phosphorus application treatments, phosphorus fertilizer was applied at a rate of 25 mg kg^{-1} per application and evenly added to the soil as an aqueous solution, whereas the other treatments received an equal volume of deionized water. For the foliar phosphorus application treatments, KH_2PO_4 solution was sprayed until droplets began to run off from the leaf surface, whereas plants in the other treatments were sprayed with deionized water to the same extent. All treatments were conducted once every 7 days for four consecutive applications. Plants were harvested and soil samples were collected two weeks after the final treatment.

2.3. Measurement of Leaf Gas-Exchange Parameters and Photosynthetic Pigments

Three days before plant harvest, mature leaves were selected from plants in each pot, with three plants per pot, and leaf gas-exchange parameters were measured using an LI-6400P portable photosynthesis system, LI-COR Biosciences, Lincoln, NE, USA. Three mature leaves were randomly collected from each pot, and leaf disks were excised using a

hole punch. Photosynthetic pigments were extracted with 80% acetone, and the contents of chlorophyll a, chlorophyll b, and carotenoids were determined using a multifunctional microplate reader (SpectraMax iD5), Molecular Devices, San Jose, CA, USA [11,12].

2.4. Soil and Plant Samples Analyses

After harvest, the plants were separated into roots, stems, and leaves, and rinsed with deionized water to remove surface contaminants. The plant samples were then oven-dried at 75 °C to constant weight. After dry biomass was recorded, the samples were ground, passed through a 0.149 mm sieve, sealed, and stored for subsequent analysis. A subsample of the ground plant tissue was digested with a mixed solution of guaranteed-reagent-grade HNO_3 and HClO_4 at a volume ratio of 4:1. The digested solution was diluted to 50 mL with ultrapure water and filtered through a membrane filter. The Cd concentration was then determined using a flame atomic absorption spectrophotometer (Z-2300), Hitachi High-Tech Corporation, Tokyo, Japan. The certified reference material GBW10015 (spinach) was used for quality control to ensure the reliability of the digestion and analytical procedures. Plant total P was determined using the molybdenum blue colorimetric method. Plant total N was determined by the semi-micro Kjeldahl method after digestion with H_2SO_4 – H_2O_2 mixture. Plant samples were digested with HNO_3 – HClO_4 mixture, and K concentration was then determined by a flame atomic absorption spectrophotometer (Z-2300), Hitachi High-Tech Corporation, Tokyo, Japan.

Soil samples collected from the pot experiment were air-dried, ground, and passed through a 2 mm sieve for the analysis of soil physicochemical properties. Soil pH was measured using a glass electrode (Mettler-Toledo International Inc., Greifensee, Switzerland) at a soil-to-deionized water ratio of 1:2.5 (*w/v*). Soil total phosphorus was determined using the molybdenum blue colorimetric method. Soil-available phosphorus was extracted with an acid ammonium fluoride–hydrochloric acid solution (0.03 M NH_4F + 0.025 M HCl) at a soil-to-extractant ratio of 1:5 (*w/v*) and then determined using the molybdenum antimony colorimetric method. Soil-available Cd was extracted with 0.1 M CaCl_2 . The fractions of Cd in soil were analyzed using a modified BCR three-step sequential extraction procedure [13].

2.5. Data Analysis

Pearson correlation analysis was conducted using pot-level paired observations. Each pot was regarded as an independent experimental unit because it was independently treated, cultivated, sampled, and analyzed. Soil pH, CaCl_2 -extractable Cd, and plant tissue Cd concentrations measured in the same pot were paired before analysis, resulting in 28 independent observations across the seven treatments.

The bioconcentration factor (BCF) was defined as the ratio of heavy metal concentration in plant tissues to that in contaminated soil. In this study, the BCF of plant shoot was calculated as follows: $\text{BCF}_{\text{shoot}} = \text{C}_{\text{shoot}}/\text{C}_{\text{soil}}$. The translocation factor (TF) was defined as the ratio of Cd concentration in the plant shoot to that in the roots.

All statistical analyses were performed using SPSS 20.0 package. Mean comparisons among treatments were conducted using Tukey's honest significant difference (HSD) test to determine significant differences at $p < 0.05$. The correlation analysis was conducted using a Pearson's correlation test with a significance level of $p < 0.05$ (two-tailed). Figures were produced using Origin 8.5 software.

3. Results

3.1. Soil Properties and Cd Fractions

Soil chemical properties in different treatments after the pot experiment are displayed in Table 1. Compared with the control, soil application of phosphorus fertilizers signifi-

cantly increased soil total phosphorus (TP), with TP increasing from $0.50 \text{ g} \cdot \text{kg}^{-1}$ in the CK treatment to $0.69\text{--}0.72 \text{ g} \cdot \text{kg}^{-1}$, whereas foliar application of KH_2PO_4 had no significant effect on soil TP. A similar trend was observed for soil-available phosphorus (AP). Soil phosphorus application significantly increased AP, among which the $\text{NH}_4\text{H}_2\text{PO}_4$ treatment showed the greatest effect, with an increase of 175% compared with CK. In contrast, AP contents in the foliar phosphorus treatments did not differ significantly from that in CK. No significant difference in soil-available Cd was observed among all the treatments, indicating that phosphorus application did not significantly affect the CaCl_2 -extractable Cd content in soil. Soil pH was significantly increased with the addition of CaHPO_4 compared with CK, whereas it was significantly decreased by 0.24 units in the soil with the addition of $\text{NH}_4\text{H}_2\text{PO}_4$, which may be attributed to soil acidification associated with NH_4^+ hydrolysis. Overall, soil phosphorus application significantly increased soil TP and AP contents, while foliar phosphorus application had no obvious effect on soil phosphorus status or pH. Among the measured soil properties, soil pH showed the clearest treatment-dependent response to P source, particularly between the CaH_2PO_4 and $\text{NH}_4\text{H}_2\text{PO}_4$ treatments.

Table 1. Soil chemical properties in different treatments after the pot experiment.

Treatments	TP g/kg	AP mg/kg	CaCl_2 -Cd mg/kg	pH
CK	0.50 ± 0.01 b	23.7 ± 2.27 c	2.86 ± 0.07 a	4.54 ± 0.09 ab
K	0.69 ± 0.02 a	57.6 ± 0.99 ab	2.69 ± 0.06 a	4.59 ± 0.09 ab
Ca	0.72 ± 0.03 a	51.0 ± 7.28 b	2.68 ± 0.07 a	4.70 ± 0.05 a
NH_4	0.72 ± 0.02 a	65.2 ± 1.43 ab	2.82 ± 0.13 a	4.30 ± 0.05 c
FP1	0.50 ± 0.01 b	27.5 ± 1.37 c	2.86 ± 0.17 a	4.43 ± 0.08 bc
FP2	0.49 ± 0.01 b	23.0 ± 1.71 c	2.79 ± 0.1 a	4.44 ± 0.04 bc
FP3	0.53 ± 0.02 b	26.5 ± 0.12 c	2.6 ± 0.11 a	4.41 ± 0.04 bc

Data are means $\pm$ SE ($n = 4$). Different letters of the same vertical forms indicate significant differences among different treatments ($p < 0.05$). CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaHPO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 ; TP, soil total phosphorus; AP, soil-available phosphorus; CaCl_2 -Cd, soil CaCl_2 -extractable Cd.

In the case of the speciation characteristics of Cd, the results from BCR sequential extraction elucidated the changes in different extractable fractions of Cd in soil resulting from the application of phosphorus (Table 2). Compared with the control, soil application of phosphorus fertilizers tended to decrease the exchangeable Cd (F1), whereas foliar phosphorus application increased this Cd fraction. For example, the exchangeable Cd was significantly decreased by 7.8% with the addition of KH_2PO_4 , while it was increased by 2.9% with the foliar spraying of 0.4% KH_2PO_4 . Except for the addition of KH_2PO_4 , which significantly increased the reducible Cd (F2), the other phosphorus treatments had no significant effect on reducible Cd. Compared with the control, all phosphorus treatments decreased the oxidizable Cd (F3), with reductions ranging from 11.8% to 29.4%, but increased the residual Cd (F4) by 75% to 150% ($p < 0.05$). These results indicate that phosphorus application promoted the transformation of Cd into the more stable residual fraction.

Table 2. Soil Cd fractions distribution by BCR sequential extraction after phosphorus addition.

Treatments	F1 (%)	F2 (%)	F3 (%)	F4 (%)
CK	51.5 ± 1.42 ab	44.7 ± 1.16 bc	3.40 ± 0.21 a	0.80 ± 0.16 b
K	47.5 ± 0.50 c	47.8 ± 0.78 a	3.00 ± 0.17 ab	1.70 ± 0.24 a
Ca	49.7 ± 0.56 bc	46.0 ± 0.46 ab	2.90 ± 0.17 abc	1.50 ± 0.16 a
NH_4	51.2 ± 1.39 ab	44.0 ± 1.27 bc	2.50 ± 0.17 bc	2.00 ± 0.33 a

Table 2. Cont.

Treatments	F1 (%)	F2 (%)	F3 (%)	F4 (%)
FP1	52.3 ± 1.14 ab	44.0 ± 0.82 bc	2.40 ± 0.35 c	1.50 ± 0.19 a
FP2	53.0 ± 0.75 a	42.6 ± 0.64 c	2.40 ± 0.12 c	1.70 ± 0.24 a
FP3	51.6 ± 0.51 ab	44.6 ± 0.71 bc	2.50 ± 0.17 bc	1.40 ± 0.27 a

Data are means ± SE ($n = 4$). Different letters of the same vertical forms indicate significant differences among different treatments ($p < 0.05$). CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaHPO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 ; F1, exchangeable Cd; F2, reducible Cd; F3, oxidizable Cd; F4, residual Cd.

3.2. Plant Growth

Dry biomass of grain amaranth under different treatments can be seen in Figure 1. Overall, phosphorus fertilizer treatments promoted plant biomass accumulation. Soil phosphorus application and the foliar spraying of 0.8% KH_2PO_4 treatment significantly increased plant biomass, with increases ranging from 87.25% to 149.5% compared with the control, among which the soil addition of KH_2PO_4 and CaHPO_4 showed the greatest effects. Compared with soil phosphorus application, the foliar spraying of 0.2% and 0.4% KH_2PO_4 resulted in significantly lower biomass, indicating that foliar phosphorus application was less effective than soil phosphorus application in promoting plant growth. In addition, the growth-promoting effects of foliar phosphorus application varied with concentration. Foliar spraying of 0.8% KH_2PO_4 enhanced plant biomass accumulation more effectively than the foliar spraying of 0.2% and 0.4% KH_2PO_4 , suggesting that the higher concentration of foliar phosphorus fertilizer had the strongest positive effect on plant growth.

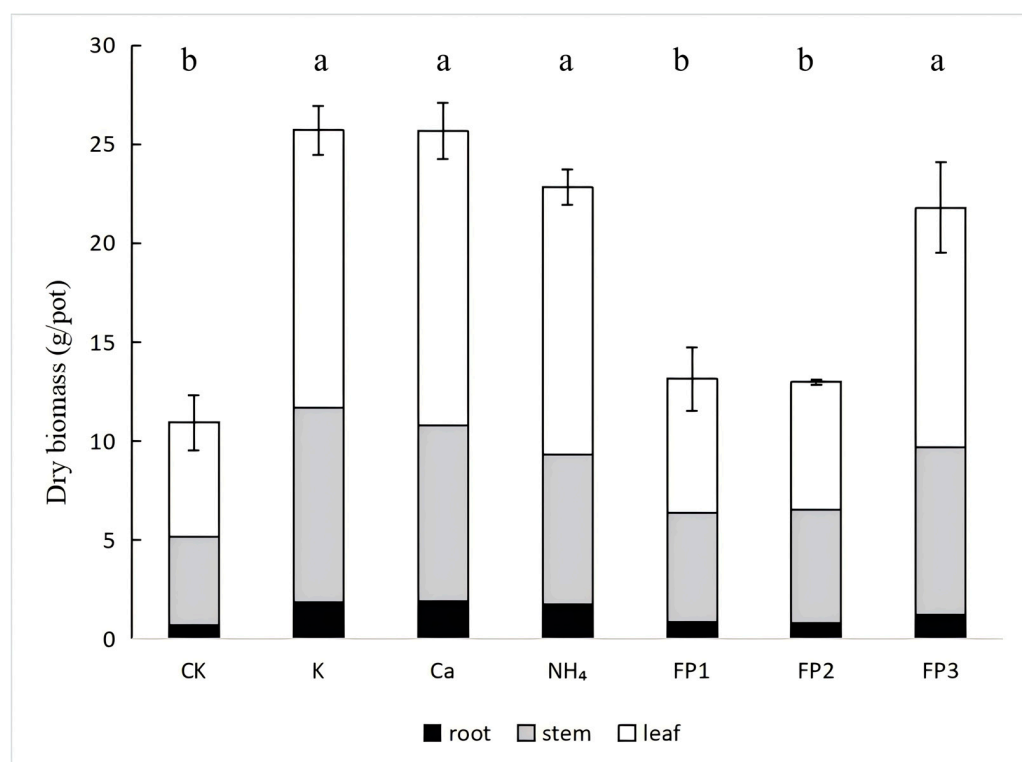


Figure 1. Dry biomass of grain amaranth under different treatments. Data are means ± SE ($n = 4$). Means followed by the same lowercase letters are not significantly different at $p \leq 0.05$. CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaHPO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 .

Except for foliar spraying of 0.2% KH_2PO_4 treatment, all other treatments significantly enhanced plant photosynthesis, with increases ranging from 25.9% to 66.3% (Table 3). However, compared with soil P application, foliar P application showed a relatively weaker stimulatory effect on plant photosynthesis. For example, photosynthetic rates under the foliar spraying of 0.2% and 0.4% KH_2PO_4 treatments were significantly lower than those under soil P application, whereas the effect of foliar spraying of 0.8% KH_2PO_4 was comparable to that of soil P application. With increasing foliar P concentration, plant photosynthesis was significantly enhanced, indicating a concentration-dependent response of photosynthesis to foliar P application. The effects of P fertilization on stomatal conductance and transpiration rate showed a pattern similar to that observed for photosynthesis. Low-concentration foliar P application had no significant effect on stomatal conductance or transpiration rate, whereas high-concentration foliar P application, similar to soil P application, significantly increased both parameters. Among all treatments, the soil addition of KH_2PO_4 treatment exhibited the strongest effect, increasing stomatal conductance and transpiration rates by 150% and 93.7%, respectively ($p < 0.05$). Only the foliar spraying of 0.2% KH_2PO_4 treatment significantly increased plant water use efficiency, while the other treatments had no significant effect.

Table 3. Plant gas-exchange parameters of different treatments in leaves.

Treatments	Pr ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	Gs ($\text{mmol m}^{-2}\text{s}^{-1}$)	E ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	WUE
CK	16.0 $\pm$ 0.93 c	0.12 $\pm$ 0.01 c	3.66 $\pm$ 0.2 d	4.37 $\pm$ 0.03 bc
K	26.6 $\pm$ 0.52 a	0.30 $\pm$ 0.02 a	7.09 $\pm$ 0.33 a	3.77 $\pm$ 0.13 c
Ca	25.8 $\pm$ 1.05 a	0.22 $\pm$ 0.02 b	5.69 $\pm$ 0.45 b	4.59 $\pm$ 0.26 ab
NH_4	26.0 $\pm$ 1.26 a	0.25 $\pm$ 0.02 b	6.31 $\pm$ 0.3 ab	4.13 $\pm$ 0.14 bc
FP1	15.4 $\pm$ 0.87 c	0.12 $\pm$ 0.01 c	2.97 $\pm$ 0.31 d	5.34 $\pm$ 0.54 a
FP2	20.15 $\pm$ 0.37 b	0.16 $\pm$ 0.00 c	4.66 $\pm$ 0.22 c	4.35 $\pm$ 0.24 bc
FP3	26.18 $\pm$ 0.60 a	0.27 $\pm$ 0.03 ab	6.41 $\pm$ 0.29 ab	4.10 $\pm$ 0.18 bc

Data are means $\pm$ SE ($n = 4$). Different letters of the same vertical forms indicate significant differences among different treatments ($p < 0.05$). CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaH_2PO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 ; Pr, photosynthetic rate; Gs, stomatal conductance; E, transpiration rate; WUE, water use efficiency, defined as the ratio of photosynthetic rate to transpiration rate.

Photosynthetic pigment contents expressed as chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids concentrations in grain amaranth leaves are illustrated in Table 4. Compared with the control, P application had no significant effect on chlorophyll a content. Compared with soil p addition, foliar P spraying tended to decrease chlorophyll a content. In particular, foliar spraying of 0.4% KH_2PO_4 significantly reduced chlorophyll a content by approximately 26.5% ($p < 0.05$). P application, except for the foliar spraying of 0.4% KH_2PO_4 , increased the contents of chlorophyll b and chlorophyll a + b, with the soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$ showing increases of 43.5% and 23.0%, respectively. Overall, soil P addition exerted a stronger positive effect on photosynthetic pigment synthesis than foliar P spraying, with soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$ showing the greatest promotion effect, whereas foliar spraying of 0.4% KH_2PO_4 exhibited a certain inhibitory effect.

Table 4. Effect of different treatments on photosynthetic pigment contents in amaranth leaves.

Treatments	Chl a (mg/g)	Chl b (mg/g)	Car (mg/g)	Chl a + b (mg/g)
CK	0.99 $\pm$ 0.03 ab	0.23 $\pm$ 0.01 d	0.24 $\pm$ 0.03 a	1.22 $\pm$ 0.03 bc
K	1.11 $\pm$ 0.07 a	0.28 $\pm$ 0.02 bc	0.23 $\pm$ 0.02 a	1.40 $\pm$ 0.07 ab
Ca	1.12 $\pm$ 0.09 a	0.30 $\pm$ 0.02 ab	0.22 $\pm$ 0.02 a	1.42 $\pm$ 0.11 ab
NH_4	1.17 $\pm$ 0.02 a	0.33 $\pm$ 0.01 a	0.25 $\pm$ 0.01 a	1.50 $\pm$ 0.02 a

Table 4. Cont.

Treatments	Chl a (mg/g)	Chl b (mg/g)	Car (mg/g)	Chl a + b (mg/g)
FP1	1.08 ± 0.09 a	0.25 ± 0.01 cd	0.20 ± 0.02 a	1.33 ± 0.10 ab
FP2	0.83 ± 0.08 b	0.20 ± 0.02 d	0.19 ± 0.03 a	1.03 ± 0.09 c
FP3	1.04 ± 0.06 a	0.29 ± 0.01 abc	0.20 ± 0.04 a	1.33 ± 0.07 ab

Data are means ± SE ($n = 4$). Different letters of the same vertical forms indicate significant differences among different treatments ($p < 0.05$). CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaH_2PO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 ; Chl a, chlorophyll a concentration; Chl b, chlorophyll b concentration; Car, carotenoids concentration; Chl a + b, total chlorophyll concentration.

3.3. Cadmium Concentration in the Plant

In this Cd-contaminated soil, amaranth could accumulate a rather high concentration of Cd in the tissues, with 61.0 mg kg^{-1} in roots (Figure 2), 52.1 mg kg^{-1} in stems (Figure 3), and 105.8 mg kg^{-1} in leaves (Figure 4). Soil P application decreased Cd concentration in roots, and the greatest reduction was observed in the treatment with the soil addition of KH_2PO_4 , which decreased root Cd concentration by 29.2% compared with the control ($p < 0.05$). In contrast, foliar P spraying increased root Cd concentration, except for the spraying of 0.2% KH_2PO_4 , and the remarkable effect was observed in the treatment spraying 0.8% KH_2PO_4 , which increased root Cd concentration by 37.5% ($p < 0.05$). P application had no significant effect on the stem Cd concentration, although the soil addition of KH_2PO_4 and CaH_2PO_4 treatments showed a slight decrease. Leaves had the highest Cd concentration among the plant tissues. Except for the soil addition of KH_2PO_4 treatment, leaf Cd concentrations in all treatments exceeded 100 mg kg^{-1} , reaching the threshold commonly used for Cd hyperaccumulator plants. Although a slight decrease was observed in the treatment with the soil addition of KH_2PO_4 , the other treatments promoted Cd accumulation in leaves, with the addition of $\text{NH}_4\text{H}_2\text{PO}_4$ showing the strongest effect and increasing leaf Cd concentration by 38.1% compared with the control ($p < 0.05$). The addition of $\text{NH}_4\text{H}_2\text{PO}_4$ resulted in the highest Cd concentrations in all plant tissues, indicating that $\text{NH}_4\text{H}_2\text{PO}_4$ application was more favorable for Cd accumulation by grain amaranth.

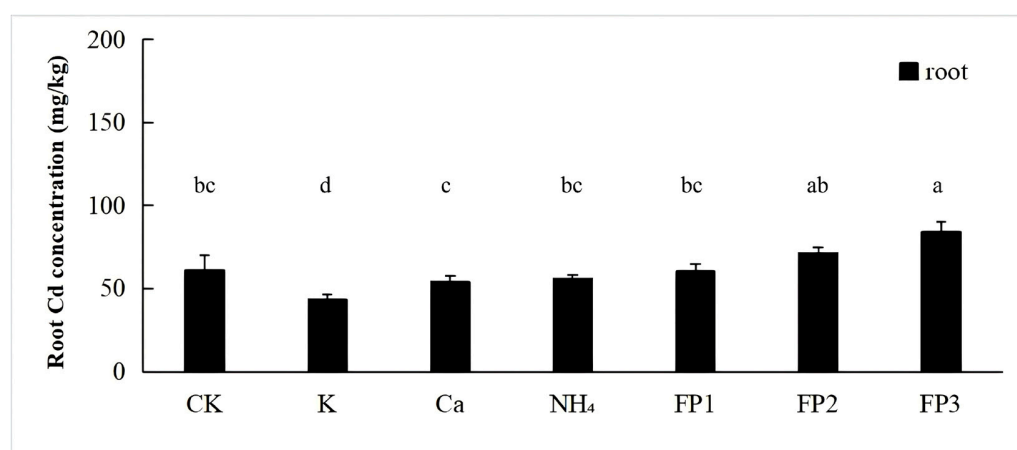


Figure 2. Cadmium concentrations in plant root under different treatments. Data are means ± SE ($n = 4$). Means followed by same lowercase letters are not significantly different at $p \leq 0.05$. CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaH_2PO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 .

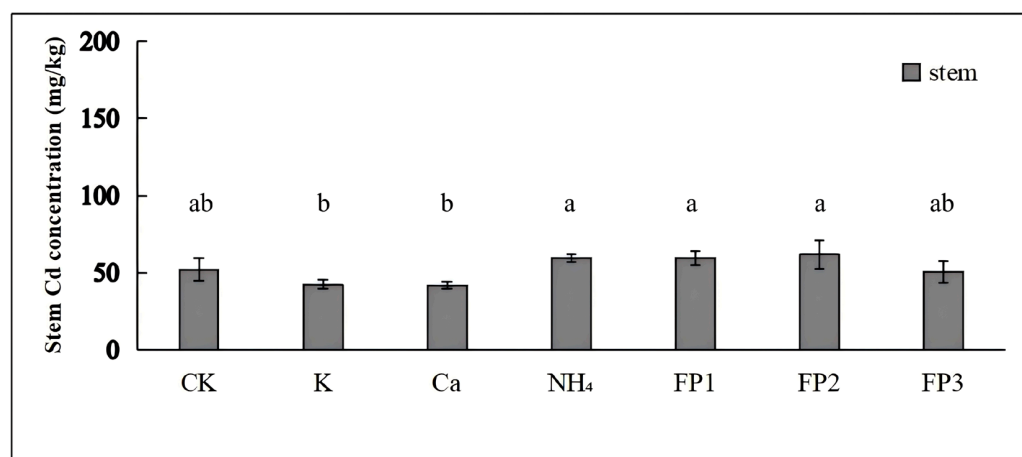


Figure 3. Cadmium concentrations in plant stem under different treatments. Data are means $\pm$ SE ($n = 4$). Means followed by the same lowercase letters are not significantly different at $p \leq 0.05$. CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaH_2PO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 .

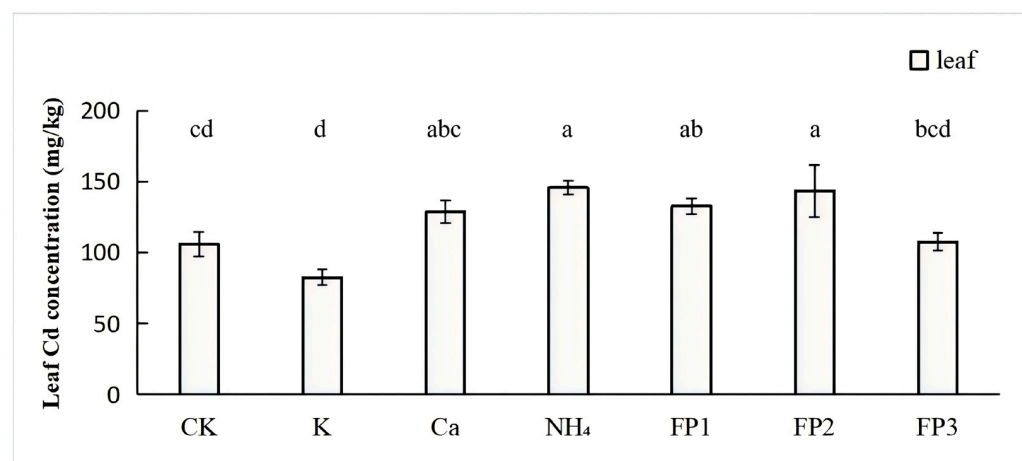


Figure 4. Cadmium concentrations in plant leaf under different treatments. Data are means $\pm$ SE ($n = 4$). Means followed by the same lowercase letters are not significantly different at $p \leq 0.05$. CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaH_2PO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 .

3.4. Cadmium Uptake, TF and BCF of the Plant

Total Cd quantity in plant tissues is calculated in Figure 5. Cd accumulation in different tissues of grain amaranth followed the order of leaves > stems > roots. Soil P application significantly increased Cd accumulation in plant tissues, thereby markedly enhancing total Cd accumulation in the whole plant ($p < 0.05$). Compared with the control, total plant Cd accumulation increased by 69.8%, 105.6%, and 139.5% with the soil addition of KH_2PO_4 , CaH_2PO_4 and $\text{NH}_4\text{H}_2\text{PO}_4$, respectively. The promoting effect of foliar P spraying on plant Cd accumulation was weaker than that of soil P application, with increases ranging from 24.2% to 64.8%. Among the foliar P spraying treatments, only foliar spraying of 0.8% KH_2PO_4 significantly increased total Cd accumulation ($p < 0.05$). Contrary to expectations, soil P application showed a stronger effect than foliar P application in enhancing Cd phytoextraction, mainly because of a higher plant biomass.

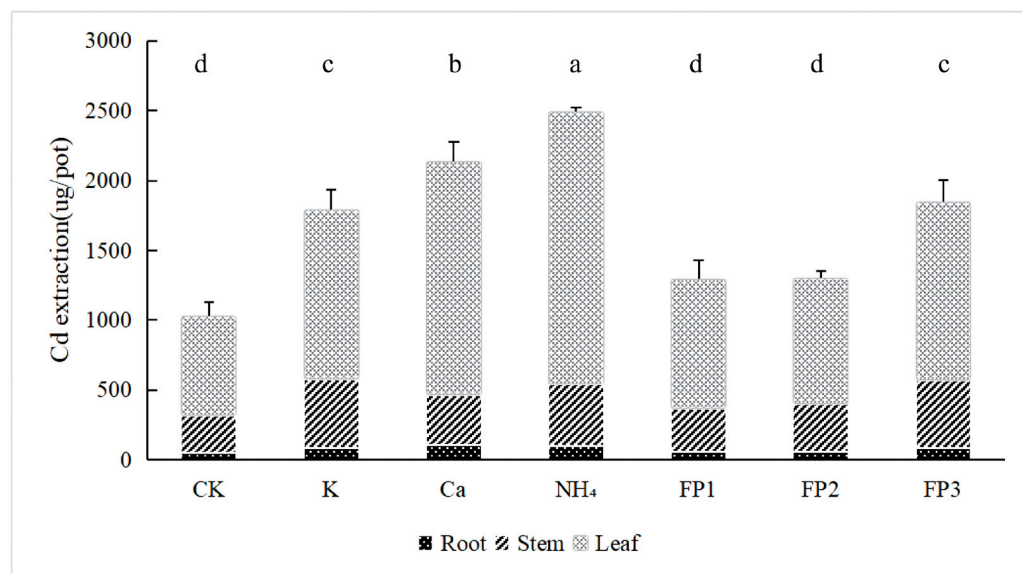


Figure 5. Cd extraction amount in the plant. Data are means $\pm$ SE ($n = 4$). Means followed by same lowercase letters are not significantly different at $p \leq 0.05$.

As shown in Table 5, both the translocation factor (TF) and the bioconcentration factor (BCF) of plant shoot were greater than 1, indicating that this species met the criteria for a Cd hyperaccumulator. Except for the foliar spraying of 0.8% KH_2PO_4 treatment, P application significantly increased the TF of grain amaranth ($p < 0.05$). Soil P application increased the TF by 20.6–42.1%, with the highest TF observed in the treatment with the addition of $\text{NH}_4\text{H}_2\text{PO}_4$, reaching 2.10. Among the foliar P treatments, foliar spraying of 0.2% KH_2PO_4 showed the highest TF, with a value of 1.56. The value of shoot BCF in the control treatment was 10.4. Compared with the control, the soil addition of KH_2PO_4 significantly decreased the BCF by 24.2%, whereas the addition of $\text{NH}_4\text{H}_2\text{PO}_4$ increased the BCF by 31.7%. Among the foliar P treatments, foliar spraying of 0.2% and 0.4% KH_2PO_4 significantly increased the BCF, with increases of 15.4% and 12.5%, respectively.

Table 5. The TFshoot and BCFshoot of plant in different treatments.

Treatments	TFshoot	BCFshoot
CK	1.26 $\pm$ 0.10 d	10.4 $\pm$ 0.45 cd
K	1.52 $\pm$ 0.06 c	7.88 $\pm$ 0.31 e
Ca	1.79 $\pm$ 0.11 b	11.4 $\pm$ 0.48 bc
NH ₄	2.10 $\pm$ 0.07 a	13.7 $\pm$ 0.29 a
FP1	1.56 $\pm$ 0.04 bc	12.0 $\pm$ 0.30 b
FP2	1.51 $\pm$ 0.06 c	11.7 $\pm$ 0.39 b
FP3	1.14 $\pm$ 0.07 d	10.0 $\pm$ 0.45 d

Data are means $\pm$ SE ($n = 4$). Different letters of the same vertical forms indicate significant differences among different treatments ($p < 0.05$). CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaH_2PO_4 ; NH₄, soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 .

3.5. N, P and K in Plant Shoot

Compared with the control, soil P application decreased the N, P, and K contents in the grain amaranth stems and leaves (Table 6). For example, soil P addition significantly reduced P content in stems and leaves by 33.3–67.3% and 25.6–38.8%, respectively ($p < 0.05$). Among the treatments with foliar P application, leaf N, P, and K contents followed the order: foliar spraying of 0.4% KH_2PO_4 > foliar spraying of 0.2% KH_2PO_4 > foliar spraying of 0.8% KH_2PO_4 , indicating that leaf N, P, K concentrations first increased and then decreased

with the elevation of foliar P application concentration. Compared with the control, foliar spraying of 0.8% KH_2PO_4 resulted in certain reductions in leaf N and K concentrations, with decrements of 9.4% ($p < 0.05$) and 6.4% ($p > 0.05$), respectively, while leaf P content exhibited only a slight increase with 4.7% ($p > 0.05$).

Table 6. Plant shoot N, P and K concentration in the different treatments.

Treatments	Stem			Leaf		
	N	P	K	N	P	K
CK	24.4 ± 0.18 a	1.47 ± 0.23 bc	116.7 ± 1.77 a	43.8 ± 1.43 a	3.63 ± 0.35 b	57.9 ± 2.82 a
K	20.6 ± 1.08 bc	0.51 ± 0.10 d	93.7 ± 2.81 c	41.9 ± 0.82 ab	2.70 ± 0.22 c	52.8 ± 2.61 a
Ca	18.3 ± 0.58 d	0.98 ± 0.05 d	63.8 ± 1.32 e	42.6 ± 1.05 ab	2.63 ± 0.19 c	41.0 ± 2.12 b
NH_4	20.7 ± 0.49 bc	0.48 ± 0.05 d	80.7 ± 3.92 d	42.1 ± 0.81 ab	2.22 ± 0.09 c	40.2 ± 1.75 b
FP1	22.8 ± 0.98 a	2.16 ± 0.37 ab	113.3 ± 3.51 ab	41.6 ± 0.93 ab	4.42 ± 0.70 ab	61.9 ± 5.53 a
FP2	22.6 ± 0.46 ab	2.72 ± 0.42 a	120.3 ± 4.42 a	42.9 ± 1.50 a	5.31 ± 0.34 a	62.8 ± 3.58 a
FP3	20.0 ± 0.76 cd	1.42 ± 0.20 c	104.9 ± 4.58 b	39.7 ± 0.77 b	3.80 ± 0.22 b	54.2 ± 6.48 a

Data are means ± SE ($n = 4$). Different letters of the same vertical forms indicate significant differences among different treatments ($p < 0.05$). CK, control; K, soil addition of KH_2PO_4 ; Ca, soil addition of CaH_2PO_4 ; NH_4 , soil addition of $\text{NH}_4\text{H}_2\text{PO}_4$; FP1, foliar application of 0.2% KH_2PO_4 ; FP2, foliar application of 0.4% KH_2PO_4 ; FP3, foliar application of 0.8% KH_2PO_4 .

3.6. Correlation Between the Soil pH and Soil CaCl_2 -Cd and Plant Cd Concentrations

The relationships of soil pH with soil CaCl_2 -extractable Cd and Cd concentrations in different plant tissues are shown in Figure 6. The correlation and linear regression analyses were conducted using individual pot-level replicate values rather than treatment means. Each point in Figure 6 represents one independently treated pot, and the soil and plant measurements were paired within the same pot. Because each of the seven treatments included four independent pot replicates, a total of 28 paired observations were included in each analysis ($n = 28$).

Linear regression analysis showed that soil pH was significantly and negatively correlated with CaCl_2 -extractable Cd in soil (Figure 6d), indicating that pots with higher soil pH generally contained lower concentrations of labile Cd. Significant negative relationships were also observed between soil pH and Cd concentrations in leaves, stems, and roots (Figure 6a–c). Thus, lower soil pH was consistently associated with greater Cd accumulation in all measured plant tissues. Similar response patterns observed for soil CaCl_2 -extractable Cd and plant tissue Cd concentrations suggest that soil acidity influenced both Cd lability in soil and subsequent plant uptake. Overall, pot-level relationships indicate that soil pH was closely associated with Cd availability and Cd accumulation in grain amaranth under the acidic soil conditions of this experiment. However, these correlations describe statistical associations and do not independently demonstrate a causal effect of soil pH.

Moreover, using individual values from independent pot replicates preserves the biological variation within treatments and more comprehensively reflects the continuous relationships of soil pH with Cd lability and plant uptake. The lower soil pH and higher plant Cd concentrations observed under the $\text{NH}_4\text{H}_2\text{PO}_4$ treatment further supported this overall trend.

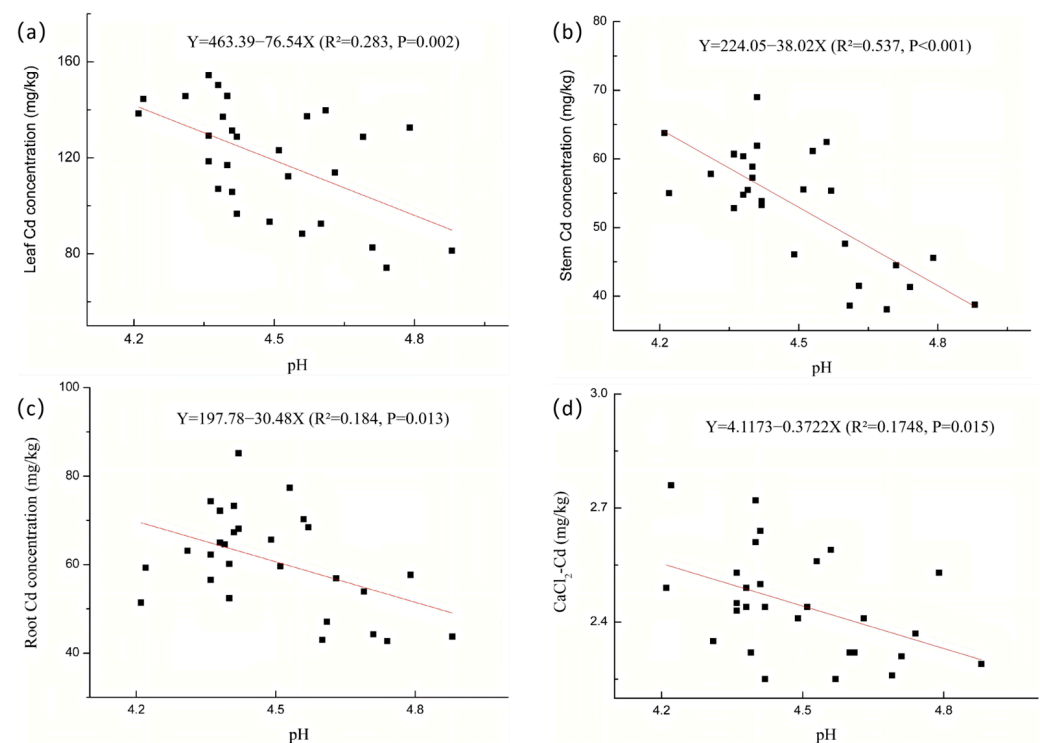


Figure 6. Relationships between soil pH and (a) leaf Cd concentration, (b) stem Cd concentration, (c) root Cd concentration, and (d) soil CaCl_2 -extractable Cd concentration. Each point represents one independently treated pot, and the soil and plant measurements were paired within the same pot. Each treatment contained four independent pot replicates, resulting in 28 pot-level paired observations across the seven treatments ($n = 28$). Pearson's regression equations, coefficients of determination (R^2), and p -values are shown in the corresponding panels. The observations represent independent biological replicates rather than technical replicates or repeated measurements. R^2 (coefficient of determination) reflects the explanatory power of linear relationships and fails to indicate whether the correlation is positive or negative.

4. Discussion

4.1. Effects of Phosphorus Application on Soil Cd Fractions

The initial soil pH of 4.63 indicates that the experimental soil was strongly acidic. Under such conditions, relatively small changes in pH may substantially affect Cd sorption, desorption, and plant availability. Therefore, the contrasting effects of the soil-applied P fertilizers should be interpreted primarily in relation to their effects on soil acidity.

Different P sources affected soil pH. CaHPO_4 significantly increased soil pH, whereas $\text{NH}_4\text{H}_2\text{PO}_4$ decreased it. The pH increase under CaHPO_4 may be attributed to the alkaline nature of calcium phosphate and Ca^{2+} input, while the decrease under $\text{NH}_4\text{H}_2\text{PO}_4$ is likely associated with the acidic nature of monoammonium phosphate and NH_4^+ nitrification accompanied by proton release [14–16]. Because Cd mobility is generally enhanced under acidic conditions, $\text{NH}_4\text{H}_2\text{PO}_4$ -induced acidification may partly explain the higher Cd accumulation observed under this treatment [17].

Phosphorus (P) application also altered soil P status and Cd fraction distribution, and these effects depended on application method and P source. Soil application of P significantly increased soil total P and available P, whereas foliar spraying of KH_2PO_4 did not significantly affect soil P status. This indicates that soil P addition directly entered the soil system and increased the available P pool, while foliar P mainly supplied nutrients through leaf absorption and avoided direct reactions with soil components. Thus, foliar P application may reduce the need for soil-applied P fertilizers, thereby helping to avoid excessive soil P accumulation and minimizing direct phosphate–Cd interactions in soil [18].

The BCR sequential extraction results showed that P application promoted the transformation of soil Cd into more stable forms. Soil P application tended to reduce exchangeable Cd, and KH_2PO_4 significantly decreased this fraction. In contrast, foliar P slightly increased exchangeable Cd, probably because it did not introduce phosphate directly into soil. All P treatments decreased oxidizable Cd and significantly increased residual Cd, indicating Cd stabilization. This immobilization may be related to phosphate-induced precipitation, adsorption, complexation, and the formation of poorly soluble Cd-phosphate compounds [19]. Nevertheless, P addition exhibited no significant effect on CaCl_2 -extractable Cd, suggesting that the immediately available Cd pool was not strongly affected, as CaCl_2 -extractable Cd is commonly used as an indicator of labile or plant-available Cd in soils [20–22]. Thus, BCR fractionation and CaCl_2 extraction reflected different but complementary aspects of Cd availability, with BCR fractionation describing Cd redistribution among operationally defined geochemical fractions and CaCl_2 extraction indicating the labile, immediately available Cd pool [23].

4.2. Effects of Phosphorus Application on Plant Growth

P fertilization significantly promoted the growth of grain amaranth, although the response varied with P source and application method. Previous studies have shown that grain amaranth responds differently to different P sources and application rates, and that foliar KH_2PO_4 application can improve crop biomass, but its effectiveness depends on P concentration and soil P status [24,25]. The stronger response under soil P application may be attributed to the continuous P supply to the root zone, which can improve rhizosphere P availability, promote root development, and enhance whole-plant nutrient acquisition. Foliar-applied P is absorbed mainly through leaf surfaces, and the total amount entering the plant may be lower. Thus, although foliar fertilization provides rapid nutrient supplementation and avoids direct soil reactions, its biomass-promoting effect may be limited when the concentration is insufficient.

Foliar spraying of 0.8% KH_2PO_4 produced the greatest biomass increase, whereas 0.2% and 0.4% KH_2PO_4 had weaker effects, suggesting that low-concentration foliar P did not fully meet plant demand under Cd stress. However, high foliar P may also affect nutrient balance, as leaf N, P, and K contents followed the order of 0.4% $\text{KH}_2\text{PO}_4 > 0.2\%$ $\text{KH}_2\text{PO}_4 > 0.8\%$ KH_2PO_4 . These results suggest a concentration-dependent effect of foliar KH_2PO_4 : insufficient concentrations may fail to satisfy plant P demand under Cd stress, whereas excessive foliar P supply may alter nutrient balance or induce a dilution effect in leaf nutrient concentrations [26].

The increase in biomass was closely related to improved photosynthetic performance. Most P treatments significantly increased photosynthetic rate, stomatal conductance, and transpiration rate, indicating enhanced carbon assimilation and gas exchange. Because P participates in ATP production, sugar phosphate metabolism, membrane formation, and photosynthetic carbon metabolism, improved P nutrition may support photosynthesis and biomass production [27]. Increased stomatal conductance and transpiration may also facilitate the upward movement of Cd through the transpiration stream [28].

Photosynthetic pigments responded differently from gas-exchange parameters. P application had no significant effect on chlorophyll a, but most treatments increased chlorophyll b and chlorophyll a + b. Soil application of $\text{NH}_4\text{H}_2\text{PO}_4$ showed the strongest promotion of chlorophyll b and chlorophyll a + b synthesis, suggesting improved light-harvesting and photoprotective capacity. In contrast, foliar spraying of 0.4% KH_2PO_4 significantly reduced chlorophyll a, indicating that some foliar P concentrations may disturb pigment metabolism. Overall, P fertilization enhanced grain amaranth growth mainly by improving

photosynthesis and biomass accumulation, with soil P application being more effective than foliar P application [25,29].

4.3. Effects of Phosphorus Application on Cd Phytoextraction by Grain Amaranth

Grain amaranth showed strong Cd accumulation and translocation capacity in Cd-contaminated soil. Cd preferentially accumulated in leaves, which is favorable for phytoextraction because Cd can be removed by harvesting aboveground biomass. P application affected Cd concentration differently among plant tissues and treatments. Soil application of KH_2PO_4 decreased root Cd concentration and slightly reduced leaf Cd concentration, probably because phosphate promoted Cd immobilization in soil. This treatment also significantly decreased shoot BCF, suggesting reduced Cd enrichment capacity. In contrast, foliar P generally increased root Cd concentration, especially under 0.8% KH_2PO_4 , indicating that foliar P may enhance root Cd uptake without directly immobilizing Cd in soil.

Among the soil P treatments, $\text{NH}_4\text{H}_2\text{PO}_4$ produced the strongest effect on Cd accumulation. It resulted in the highest Cd concentrations in plant tissues, the highest translocation factor, and the greatest increase in total plant Cd accumulation. This effect may be explained by three mechanisms. Firstly, $\text{NH}_4\text{H}_2\text{PO}_4$ decreased soil pH, which may have increased Cd mobility and bioavailability in soil, thereby enhancing Cd uptake by accumulator plants [30], and accelerated plant biomass production enhances plant heavy metal uptake [31]. Secondly, it improved photosynthetic pigment synthesis and physiological activity, promoting biomass and Cd transport. Thirdly, NH_4^+ may have influenced rhizosphere processes and nutrient uptake, indirectly regulating Cd absorption and translocation [32].

Total Cd accumulation is a more direct indicator of phytoextraction efficiency than tissue Cd concentration because it integrates Cd concentration and plant biomass. Soil P application significantly increased total Cd accumulation in grain amaranth. Compared with the control, total plant Cd accumulation increased by 69.8%, 105.6%, and 139.5% under soil application of KH_2PO_4 , CaH_2PO_4 , and $\text{NH}_4\text{H}_2\text{PO}_4$, respectively. These results indicate that soil P application enhanced Cd phytoextraction mainly by increasing biomass, even when Cd concentration or Cd availability was not consistently increased. Thus, for high-biomass accumulator plants such as grain amaranth, improving biomass production may be as important as increasing tissue Cd concentration [33].

Contrary to the initial expectation, foliar P application was less effective than soil P application in enhancing total Cd phytoextraction. Foliar P avoided significant changes in soil P status and pH, and low-to-moderate foliar KH_2PO_4 increased shoot BCF. However, the limited biomass increase restricted total Cd accumulation. Only 0.8% KH_2PO_4 significantly increased total Cd accumulation, mainly through stronger growth promotion. Therefore, foliar P may be useful when direct soil P addition is undesirable, but its effectiveness depends on whether it sufficiently increases biomass.

The results generally supported our first hypothesis that P fertilization could enhance Cd phytoextraction by improving plant physiological performance and biomass production. However, this response depended on the treatment, because low- and moderate-concentration foliar KH_2PO_4 treatments did not significantly increase total plant Cd accumulation.

Our second hypothesis was not supported. Although foliar P application caused smaller changes in soil P status and avoided direct phosphate addition to the soil, it was less effective than soil P application in increasing total Cd phytoextraction. The limited biomass response under the low- and moderate-concentration foliar treatments outweighed their potential advantage in maintaining soil Cd availability.

Our third hypothesis was largely supported. Among the soil-applied P treatments, $\text{NH}_4\text{H}_2\text{PO}_4$ resulted in the lowest soil pH, the highest plant Cd concentrations, the highest translocation factor, and the greatest total Cd accumulation. These findings suggest that $\text{NH}_4\text{H}_2\text{PO}_4$ -induced acidification contributed to enhanced Cd uptake and translocation. In contrast, CaHPO_4 increased soil pH and promoted the redistribution of Cd toward more stable fractions, although it did not significantly reduce CaCl_2 -extractable Cd.

4.4. Long-Term Ecological Implications and Field-Scale Feasibility

From an ecological perspective, the short-term enhancement of Cd phytoextraction by $\text{NH}_4\text{H}_2\text{PO}_4$ should be weighed against the consequences of repeated field application. In this study, $\text{NH}_4\text{H}_2\text{PO}_4$ lowered soil pH by 0.24 units, and soil pH was negatively correlated with CaCl_2 -extractable Cd and Cd concentrations in plant tissues, indicating that progressive acidification could increase Cd lability. Long-term application of ammonium-containing P fertilizer may release protons during nitrification, while lower pH reduces negative surface charge and promotes Cd desorption from soil colloids [34]. Under field conditions, rainfall and irrigation may consequently facilitate Cd movement to deeper soil layers, drainage water, or non-target crops. Although phosphate can immobilize Cd through adsorption and precipitation, this effect may be offset by fertilizer-induced acidification and depends on fertilizer source, application rate, soil buffering capacity, and hydrological conditions, as increased irrigation frequency can enhance Cd leaching and downward movement in the soil profile [35]. Therefore, long-term field monitoring of soil pH, Cd fractions, crop uptake, and leaching is required, together with balanced P inputs and liming where necessary.

Because the Pearl River Delta has a long frost-free period (approximately 335–360 d) and is characterized by intensive multi-cropping systems [36,37], assuming only one grain amaranth crop per year would underestimate potential annual Cd removal. Field-grown *A. hypochondriacus* has been harvested within approximately 60–93 d after planting [38,39], indicating a relatively short biomass production cycle. Taken together, the long frost-free period of the Pearl River Delta and the relatively short biomass-production cycle of *A. hypochondriacus* suggest that two cropping cycles per year are agronomically plausible in this region, while three cycles may be possible under favorable planting schedules and field management. Based on the $\text{NH}_4\text{H}_2\text{PO}_4$ treatment in the present study, the area-equivalent shoot dry-matter production was approximately $3.19 \text{ t ha}^{-1} \text{ crop}^{-1}$ and shoot Cd removal was approximately $0.363 \text{ kg ha}^{-1} \text{ crop}^{-1}$. This corresponds to approximately $6.38\text{--}9.57 \text{ t dry matter ha}^{-1} \text{ yr}^{-1}$ and $0.73\text{--}1.09 \text{ kg Cd ha}^{-1} \text{ yr}^{-1}$ under two to three annual cropping cycles. Assuming a 0–20 cm soil layer, a bulk density of 1.3 Mg m^{-3} , and a target Cd concentration of 0.30 mg kg^{-1} , approximately $21.1 \text{ kg Cd ha}^{-1}$ would need to be removed from the initial soil containing $8.40 \text{ mg Cd kg}^{-1}$. Under the simplifying assumption of a constant Cd-removal rate, approximately 19–29 years would therefore be required. This estimate should be considered optimistic because plant Cd uptake would likely decrease as soil Cd concentrations decline. Nevertheless, these calculations should not be interpreted as evidence that phytoextraction alone can rapidly remediate severely Cd-contaminated acidic soils. Rather, they provide a first-order estimate of the potential timescale of Cd removal under intensive cropping conditions and highlight both the potential and limitations of grain amaranth-based phytoextraction.

In conclusion, P fertilization enhanced Cd phytoextraction by grain amaranth through combined effects on plant growth, Cd uptake, and Cd translocation. Soil application of $\text{NH}_4\text{H}_2\text{PO}_4$ was the most effective treatment because it simultaneously promoted biomass, Cd concentration, root-to-shoot translocation, and total Cd accumulation. However, its potential acidification effect should be considered in field applications, because excessive

acidification may increase Cd mobility and environmental risk. Appropriate application rates and field validation are therefore necessary before this strategy is recommended for large-scale remediation.

A limitation of this study is that fertilizer source and soil pH were not manipulated independently. Consequently, the observed differences among KH_2PO_4 , CaH_2PO_4 , and $\text{NH}_4\text{H}_2\text{PO}_4$ cannot be attributed exclusively to either phosphate form or pH. Future experiments should include pH-buffered treatments or pH-adjusted controls to separate fertilizer-specific effects from pH-mediated effects.

5. Conclusions

Overall, P fertilization represents a feasible agronomic strategy for improving Cd phytoextraction by grain amaranth. The hypothesis that P fertilization enhances Cd phytoextraction mainly through biomass promotion was generally supported, whereas the expectation that foliar P application would outperform soil P application was not supported. Under the strongly acidic soil conditions of this study, soil pH appeared to be a key proximal factor explaining the contrasting responses of grain amaranth to different P treatments. Soil-applied P, particularly $\text{NH}_4\text{H}_2\text{PO}_4$, showed greater potential than foliar-applied P because it simultaneously promoted biomass production, Cd uptake, and root-to-shoot translocation. The superior phytoextraction performance under $\text{NH}_4\text{H}_2\text{PO}_4$ was primarily associated with fertilizer-induced soil acidification, enhanced Cd accumulation and translocation, and increased plant biomass. In contrast, CaH_2PO_4 increased soil pH and tended to promote Cd stabilization. These findings indicate that the effects of P source should be interpreted mainly in relation to fertilizer-induced changes in soil pH, whereas the direct role of phosphate chemical form appears to be secondary. Nevertheless, because soil pH and P source were not manipulated independently, their individual contributions could not be fully distinguished. Future studies should therefore employ pH-buffered or pH-adjusted treatments and further evaluate the long-term effects of repeated P application, field-scale performance, rhizosphere processes, and the balance between Cd removal efficiency and potential environmental risks.

Author Contributions: Conceptualization, F.L. and H.X.; methodology, F.L.; software, F.L. and J.L.; validation, F.L., H.X., S.L. and B.D.; formal analysis, S.L. and J.L.; investigation, F.L. and S.L.; resources, J.L., H.X. and B.D.; data curation, F.L.; writing—original draft preparation, F.L.; writing—review and editing, H.X. and B.D.; visualization, F.L.; supervision, H.X. and B.D.; project administration, F.L.; funding acquisition, F.L., H.X. and B.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Hunan Provincial Natural Science Foundation of China, grant number: 2025JJ70593, 2025JJ70041 and Hunan Provincial Key Laboratory of Xiangnan Rare-Precious Metals Compounds and Applications.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sarwar, N.; Imran, M.; Shaheen, M.R.; Ishaque, W.; Kamran, M.A.; Matloob, A.; Rehim, A.; Hussain, S. Phytoremediation strategies for soils contaminated with heavy metals: Modifications and future perspectives. *Chemosphere* **2017**, *171*, 710–721. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Meers, E.; Van Slycken, S.; Adriaensen, K.; Ruttens, A.; Vangronsveld, J.; Du Laing, G.; Witters, N.; Thewys, T.; Tack, F.M.G. The use of bio-energy crops (*Zea mays*) for ‘phytoattenuation’ of heavy metals on moderately contaminated soils: A field experiment. *Chemosphere* **2010**, *78*, 35–41. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Suman, J.; Uhlik, O.; Viktorova, J.; Macek, T. Phytoextraction of heavy metals: A promising tool for clean-up of polluted environment? *Front. Plant Sci.* **2018**, *9*, 1476. [\[CrossRef\]](#) [\[PubMed\]](#)
4. McGrath, S.P.; Zhao, F. Phytoextraction of metals and metalloids from contaminated soils. *Curr. Opin. Biotechnol.* **2003**, *14*, 277–282. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Huang, R.; Dong, M.; Mao, P.; Zhuang, P.; Paz-Ferreiro, J.; Li, Y.; Li, Y.; Hu, X.; Netherway, P.; Li, Z. Evaluation of phytoremediation potential of five Cd (hyper)accumulators in two Cd contaminated soils. *Sci. Total Environ.* **2020**, *721*, 137581. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Haller, H.; Pronoza, L.; Dyer, M.; Ahlgren, M.; Bergqvist, L.; Flores-Carmenate, G.; Jonsson, A. Phytoremediation of heavy-metal-contaminated soils: Capacity of amaranth plants to extract cadmium from nutrient-poor, acidic substrates. *Challenges* **2023**, *14*, 28. [\[CrossRef\]](#)
7. Huang, R.; Li, Y.; Li, F.; Yin, X.; Li, R.; Wu, Z.; Liang, X.; Li, Z. Phosphate fertilizers facilitated the Cd contaminated soil remediation by sepiolite: Cd mobilization, plant toxicity, and soil microbial community. *Ecotoxicol. Environ. Saf.* **2022**, *234*, 113388. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Cao, X.; Ma, L.Q.; Chen, M.; Singh, S.P.; Harris, W.G. Impacts of phosphate amendments on lead biogeochemistry at a contaminated site. *Environ. Sci. Technol.* **2002**, *36*, 5296–5304. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Niu, J.; Liu, C.; Huang, M.; Liu, K.; Yan, D. Effects of foliar fertilization: A review of current status and future perspectives. *J. Soil Sci. Plant Nutr.* **2020**, *21*, 104–118. [\[CrossRef\]](#)
10. Peng, W.; He, Y.; He, S.; Luo, J.; Zeng, Y.; Zhang, X.; Huo, Y.; Jie, Y.; Xing, H. Exogenous plant growth regulator and foliar fertilizers for phytoextraction of cadmium with *Boehmeria nivea* L. Gaudich from contaminated field soil. *Sci. Rep.* **2023**, *13*, 11019. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Martinez, J.; Damidaux, R. Rapid methods to assess the chlorophyll and carotenoid content of leaves and fruits using a microplate reader. *Ann. Appl. Biol.* **1993**, *123*, 673–684. [\[CrossRef\]](#)
12. Lichtenthaler, H.K.; Buschmann, C. Chlorophylls and Carotenoids: Measurement and Characterization by UV-VIS Spectroscopy. *Curr. Protoc. Food Anal. Chem.* **2001**, *1*, F4.3.1–F4.3.8. [\[CrossRef\]](#)
13. Rauret, G.; López-Sánchez, J.F.; Sahuquillo, A.; Rubio, R.; Davidson, C.; Ure, A.; Quevauviller, P. Improvement of the BCR three step sequential extraction procedure prior to the certification of new sediment and soil reference materials. *J. Environ. Monit.* **1999**, *1*, 57–61. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Liang, H.; Tan, Y.; Yin, J.; Peng, Y.; Wei, M.; Chen, H.; Chen, Q. Phosphate fertilizers’ dual role in cadmium-polluted acidic agricultural soils: Dosage dependency and passivation potential. *Agronomy* **2024**, *14*, 2201. [\[CrossRef\]](#)
15. Tao, J.; Fan, L.; Jiang, T.; Song, X.; Zhao, M.; Zhou, J.; Kuzyakov, Y.; Zamanian, K. In situ visualization of soil profile acidification and processes following nitrogen fertilization and liming. *Geoderma* **2025**, *456*, 117243. [\[CrossRef\]](#)
16. Goulding, K.W.T.; de Varennes, A. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use Manag.* **2016**, *32*, 390–399. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Kicińska, A.; Pomykała, R.; Izquierdo-Díaz, M. Changes in soil pH and mobility of heavy metals in contaminated soils. *Eur. J. Soil Sci.* **2021**, *73*, e13203. [\[CrossRef\]](#)
18. Li, Y.; Liu, M.; Wang, H.; Li, C.; Zhang, Y.; Dong, Z.; Fu, C.; Ye, Y.; Wang, F.; Chen, X.; et al. Effects of different phosphorus fertilizers on cadmium absorption and accumulation in rice under low-phosphorus and rich-cadmium soil. *Environ. Sci. Pollut. Res.* **2024**, *31*, 11898–11911. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Ruangcharus, C.; Kim, S.U.; Hong, C.O. Mechanism of cadmium immobilization in phosphate-amended arable soils. *Appl. Biol. Chem.* **2020**, *63*, 36. [\[CrossRef\]](#)
20. Mar, S.S.; Okazaki, M.; Motobayashi, T. The influence of phosphate fertilizer application levels and cultivars on cadmium uptake by Komatsuna (*Brassica rapa* L. var. *perviridis*). *Soil Sci. Plant Nutr.* **2012**, *58*, 492–502. [\[CrossRef\]](#)
21. Gray, C.W.; McDowell, R.W.; Condron, L.M.; McLenaghan, R.D. Changes in soil cadmium concentrations with time following cessation of phosphorus fertilizer inputs. *J. Environ. Qual.* **2020**, *49*, 1054–1061. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Loganathan, P.; Hedley, M.J. Downward movement of cadmium and phosphorus from phosphatic fertilisers in a pasture soil in New Zealand. *Environ. Pollut.* **1997**, *95*, 319–324. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Sungur, A.; Soylak, M.; Ozcan, H. Investigation of heavy metal mobility and availability by the BCR sequential extraction procedure: Relationship between soil properties and heavy metals availability. *Chem. Speciat. Bioavailab.* **2015**, *26*, 219–230. [\[CrossRef\]](#)

24. Ojo, O.D.; Kintomo, A.A.; Akinrinde, E.A.; Akoroda, M.O. Comparative effect of phosphorus sources for grain amaranth production. *Commun. Soil Sci. Plant Anal.* **2007**, *38*, 35–55. [\[CrossRef\]](#)
25. Rafiullah, R.; Khan, M.J.; Muhammad, D.; Mussarat, M.; Huma; Adnan, M.; Fahad, S.; Wahid, F.; Arif, M.; Amanullah, Jr. Foliar versus soil phosphorus (P) application for improving P use efficiency in wheat and maize in calcareous soils. *J. Plant Nutr.* **2021**, *44*, 1598–1610. [\[CrossRef\]](#)
26. Rafiullah, R.; Khan, M.J.; Muhammad, D. Foliar application of phosphorus to enhance phosphorus utilization and crop growth: A hydroponic study. *Sarhad J. Agric.* **2018**, *34*, 47–53. [\[CrossRef\]](#)
27. Khan, F.; Siddique, A.B.; Shabala, S.; Zhou, M.; Zhao, C. Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants* **2023**, *12*, 2861. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Liu, H.; Wang, H.; Ma, Y.; Wang, H.; Shi, Y. Role of transpiration and metabolism in translocation and accumulation of cadmium in tobacco plants (*Nicotiana tabacum* L.). *Chemosphere* **2016**, *144*, 1960–1965. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Wang, L.; Zheng, J.; You, J.; Li, J.; Qian, C.; Leng, S.; Yang, G.; Zuo, Q. Effects of phosphorus supply on the leaf photosynthesis, and biomass and phosphorus accumulation and partitioning of canola (*Brassica napus* L.) in saline environment. *Agronomy* **2021**, *11*, 1918. [\[CrossRef\]](#)
30. Zhang, J.; Zhu, Y.; Yu, L.; Yang, M.; Zou, X.; Yin, C.; Lin, Y. Research advances in cadmium uptake, transport and resistance in rice (*Oryza sativa* L.). *Cells* **2022**, *11*, 569. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Kama, R.; Li, S.; Nabi, F.; Aidara, M.; Huang, P.; Li, Z.; Diatta, S.; Ma, C.; Li, H. Hyperaccumulators' diversity enhances Cd-contaminated soil restoration and reduces rice Cd uptake under an intercropping system. *ACS Omega* **2024**, *9*, 28784–28790. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Yang, Y.; Xiong, J.; Tao, L.; Cao, Z.; Tang, W.; Zhang, J.; Yu, X.; Fu, G.; Zhang, X.; Lu, Y. Regulatory mechanisms of nitrogen (N) on cadmium (Cd) uptake and accumulation in plants: A review. *Sci. Total Environ.* **2020**, *708*, 135186. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Robinson, B.H.; Brooks, R.R.; Howes, A.W.; Kirkman, J.H.; Gregg, P.E.H. The potential of the high-biomass nickel hyperaccumulator *Berkheya coddii* for phytoremediation and phytomining. *J. Geochem. Explor.* **1997**, *60*, 115–126. [\[CrossRef\]](#)
34. Vidal, A.; Nguyen, C.; Janot, N.; Eon, P.; Coriou, C.; Cornu, J.Y. Effects of sulfur fertilizers applied at agronomic rates on cadmium availability in agricultural soils: Insights from a batch experiment. *Pedosphere* **2025**, *35*, 995–1004. [\[CrossRef\]](#)
35. McDowell, R.W. Assessing the leaching of cadmium in an irrigated and grazed pasture soil. *Environ. Pollut.* **2022**, *292*, 118430. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Li, Y.; Cai, G.; Tan, K.; Zeng, R.; Chen, X.; Wang, X. Emergy-based efficiency and sustainability assessments of diversified multi-cropping systems in South China. *J. Clean. Prod.* **2023**, *414*, 137660. [\[CrossRef\]](#)
37. Cai, G.; Su, X.; Li, Y.; Wang, X. Comparisons between diversified multicropping systems in terms of crop productivity, economic benefits and carbon footprint in the Pearl River Delta region of South China. *Farming Syst.* **2023**, *1*, 100051. [\[CrossRef\]](#)
38. Shadi, H.; Rouzbehan, Y.; Rezaei, J.; Fazaeli, H. Yield, chemical composition, fermentation characteristics, in vitro ruminal variables, and degradability of ensiled amaranth (*Amaranthus hypochondriacus*) cultivars compared with corn (*Zea mays*) silage. *Transl. Anim. Sci.* **2020**, *4*, txaa180. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Abbasi, D.; Rouzbehan, Y.; Rezaei, J. Effect of harvest date and nitrogen fertilization rate on the nutritive value of amaranth forage (*Amaranthus hypochondriacus*). *Anim. Feed Sci. Technol.* **2012**, *171*, 6–13. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.