

Article

Effect of Phosphate Amendment on Cadmium Accumulation in Pepper (*Capsicum annuum* L.) Grown in Geogenic Cd-Rich Soil from the Karst Region

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Abstract: Soil in the karst region usually features high geogenic cadmium (Cd) and limited available phosphorus (P). Appropriate phosphate amendment is crucial for alleviating Cd accumulation in food crops and reducing health risks. However, the interaction of Cd and P in geogenic Cd-rich soil-plant systems is poorly understood. In this study, a pot experiment was conducted to investigate the translocation of Cd in the soil-pepper system under different amendment rates of $\text{Ca}(\text{H}_2\text{PO}_4)_2$. The results showed that the biomass of pepper was not affected by the application rates of $\text{Ca}(\text{H}_2\text{PO}_4)_2$, even up to 0.45 g/kg, but was affected by the application of nitrogen and potassium fertilizers. High contents of total Cd (6.19 mg/kg) and bioavailable Cd (2.72 mg/kg, 44%) in the studied soils resulted in elevated Cd content in pepper, and it decreased in the order of root (8.18 mg/kg) > stem (4.89 mg/kg) > fruit (3.88 mg/kg). This indicates that pepper planted in the studied soils may present potential health risks. Furthermore, phosphate amendment neither influences the bioavailable Cd in rhizosphere soil nor Cd uptake and transport in pepper plants. The findings of this study highlight that monocalcium phosphate is not a suitable choice for reducing the accumulation of Cd in pepper fruits in the studied soil and that other remediation strategies are needed.

Keywords: soil pollution; heavy metal; Cd accumulation; phosphorus; food crops



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1. Introduction

Cadmium (Cd) is a ubiquitous contaminant in global agricultural soils [1,2] and is known to be a potential carcinogen [3]. Cd in soils can be easily translocated into food crops due to its high mobility [4]. Elevated Cd content in plants can interfere with photosynthesis and cell membrane structure [5], affect nutrient uptake, and reduce crop yield and quality [6]. Moreover, Cd in food crops threatens human health via the food chain [7,8]. Therefore, it is imperative to unravel the factors that influence the translocation of Cd from soil to food crops and, thus, control the potential health risks of Cd.

Numerous studies have reported Cd pollution in food crops grown in anthropogenic Cd-contaminated soils [9,10], whereas little attention has been paid to Cd accumulation in crops in geogenic Cd-rich soil. Soils developed on carbonate rocks in Asia and Europe have been widely reported to enrich Cd [11–13]. For example, in southwestern China, it is

estimated that approximately 68.9×10^3 km² of area has high Cd content (>1.5 mg/kg) and is mainly related to carbonates [14]. The anomalously high Cd content in the carbonate-derived soils in the Swiss Jura Mountains even up to 16.3 mg/kg [15]. Under high Cd stress, plants grown in these soils may accumulate Cd and thus present potential health risks [14,16,17]. Meanwhile, carbonate-derived soils may also be featured by low available phosphorus (P) because P is typically fixed in less soluble primary minerals, such as combined with Ca²⁺ and Mg²⁺ to form carbonate minerals [18,19]. Hence, the growth of plants is sometimes restricted by low levels of available P in carbonate regions [20,21]. Given this, the amendment of phosphate fertilizer is crucial for crop growth in carbonate regions [22]. However, it remains unclear whether and how P addition influences the translocation of Cd in soil-plant systems in carbonate regions with a high Cd baseline.

Phosphorus (P) is an essential nutrient for plant growth because it can promote the synthesis of carbohydrates and participate in plant photosynthesis, nucleic acid synthesis, and growth regulation [23,24]. Under nutrient-limited conditions, plants can alter their rhizosphere environment to obtain essential nutrients [25]. When the available P content in soils is less than that required for plant growth, plants employ a range of adaptations to cope with low P stress. These actions include modification of root morphology, increased secretion of root exudates (such as organic acids and acid phosphatases), and the formation of plant-microbial symbioses [26–30]. Nevertheless, the activation of P from soil particles may also mobilize Cd and thus augment Cd uptake by plants (Kirkham, 2006). Phosphate materials are commonly applied to immobilize Cd in contaminated soils [31]. Phosphates in the soil can form complexes with Cd²⁺, such as CdHPO₄ and CdH₂PO₄⁺, or precipitate as Cd₃(PO₄)₂, thereby reducing the availability of Cd [32,33]. Therefore, the amendment of phosphate fertilizer is proposed not only to influence the growth of plants but also to reduce Cd bioavailability. For example, in a 90-day soil incubation experiment, Liu [34] found that the content of DTPA-extractable Cd increased with an increasing rate of P addition. However, the effect and mechanisms of phosphate on the translocation of Cd in soil-crop systems in carbonate regions need to be further studied.

Pepper is an important crop in China, where the cultivation area is over 2×10^6 hm², and the production is approximately 1.7×10^7 t [35]. However, it is a crop that is prone to accumulating Cd [34]. Currently, there is a paucity of studies on the selection and mechanism of Cd-tolerant pepper varieties, particularly on the impact of improved fertilization on Cd absorption and enrichment in pepper [36]. In this study, we conducted pot experiments to investigate the influence of phosphate amendment on the translocation of Cd from natural Cd-rich soil to pepper plants (*Capsicum annuum* L.). The main objective of this study was to reveal the effects of available phosphate on the accumulation and transport of Cd in pepper plants and the underlying mechanisms. These results are expected to provide guidelines for agricultural production and inform optimal fertilization strategies to mitigate Cd accumulation in crops.

2. Materials and Methods

2.1. Soil Collection and Characterization

The soil used for the pot experiment was collected from the Luodian County of Guizhou Province, southwestern China (25°39′57″ N, 106°41′26″ E). It is a rural area without industrial and mining activities, and the limestone-derived soil is naturally enriched in Cd (4.75–13.2 mg/kg) due to the weathering of Cd-rich limestones [11]. The soil type of the experimental soil is classified as Alfisols. Five subsamples (0–20 cm) were collected to form a composite soil sample. The soil was air-dried in the greenhouse, and the litter and rock debris were manually removed and passed through a 5 mm sieve.

The soil was first ground to <1.7 mm and then to <100 µm. Soil pH was determined using a pH meter (METTLER TOLEDO SevenDirect SD20, Shanghai, China), and the solid-water ratio was 1:2.5. The total nitrogen was determined by the element analyzer (vario MACRO cube, Elementar, Langenselbold, Germany). The available P was extracted with 0.5 mol/L sodium bicarbonate for 0.5 h (solid-liquid ratio of 1:20). The extracts were filtered through a 0.45-µm, and the P was quantified using the sodium hydrogen carbonate solution-Mo-Sb anti spectrophotometric method [37]. The available K was extracted by CH₃COONH₄ for 1 h at a solid-liquid ratio of 1:10, and K in extracts was determined by Flame Atomic Absorption Spectrophotometry (AAS, PinAAcle 900F, PerkinElmer, Waltham, MA, USA). The bioavailable Cd was extracted by DTPA (0.005 mol/L DTPA-0.1 mol/L TEA-0.01 mol/L CaCl₂) for 2 h at a solid-liquid ratio of 1:5 [38], and Cd in extracts was determined by AAS. The basic soil properties are listed in Table 1.

Table 1. Physicochemical parameters of the soil.

Parameter	Ave ± SD ^a
pH	7.08 ± 0.01
EC (µS/cm)	140 ± 5.01
Organic matter (g/kg)	34.3 ± 2.97
ECEC ^b (cmol ⁺ /kg)	12.8 ± 0.88
Total nitrogen (g/kg)	2.5 ± 0.02
Available K (g/kg)	0.17 ± 0.01
Total P (g/kg)	0.89 ± 0.13
Available P (mg/kg)	23.2 ± 0.43
Total Cd (mg/kg)	6.19 ± 0.13
Bioavailable Cd (mg/kg)	2.72 ± 0.02

^a average ± standard deviation. ^b effective cation exchange capacity.

A seven-step sequential chemical extraction method was employed to ascertain the chemical fractions of Cd in the soil. Briefly, 2.50 g of soil was added into 50 mL centrifuge tubes, the water-soluble Cd (F1) was extracted by 25 mL deionized water for 2 h, exchangeable fraction (F2) was extracted by 25 mL 1 mol/L MgCl₂ for 2 h, carbonate fraction (F3) was extracted by 25 mL 1 mol/L CH₃COONa (pH = 5.0) for 5 h, humic acid bound Cd (F4) was extracted by 50 mL 0.1 mol/L Na₄P₂O₇ (pH = 10.0) for 3 h, Fe-Mn oxides bound Cd (F5) was extracted by 50 mL 0.25 mol/L HONH₃Cl·HCl for 6 h, strong organically bound Cd (F6) was extracted by 3.2 mol/L CH₃COONH₄ + HNO₃ + 30% H₂O₂ (pH = 2.0) at 83 °C for 3 h, and residual fraction (F7) was digested by mixed acid (HNO₃ + 30% H₂O₂). The extracts were filtered, and the Cd in the solution was determined using AAS.

2.2. Pot Experiment

The pot experiment was conducted in a stainless steel box (22 cm × 10 cm × 22 cm) that included a rhizosphere and a non-rhizosphere room separated by 0.3-µm nylon materials. A total of 3.4 kg of soil was placed in the box, and nitrogen fertilizer (0.20 g/kg urea) and potassium fertilizer (0.20 g/kg K₂SO₄) were added to the treatment groups. Based on the results of the previous field experiment conducted by the Guizhou Academy of Agricultural Sciences, different rates of phosphate fertilizers (Ca(H₂PO₄)₂·H₂O), i.e., 0 g/kg (TP0), 0.15 g/kg (TP1), 0.30 g/kg (TP2) and 0.45 g/kg (TP3) were added to the treatment groups. The group without any fertilizer was set as the control group (CK). Triplicates were set for each group, resulting in a total of 15 pots. The specific details of the treatments are shown in Table 2.

Table 2. Design of experimental treatments.

Group	Amended Fertilizer
CK	Soil only
TP0	0 g/kg P ^a + N ^b + K ^c
TP1	0.15 g/kg P + N + K
TP2	0.30 g/kg P + N + K
TP3	0.45 g/kg P + N + K

^a Ca(H₂PO₄)₂·H₂O (Damao Chemical Reagent Co., Ltd., Tianjin, China). ^b 0.20 g/kg urea (Tianjin Kemiou Chemical Reagent Co., Ltd., Tianjin, China). ^c 0.20 g/kg K₂SO₄ (Tianjin Kemiou Chemical Reagent Co., Ltd., Tianjin, China).

This study used Qianjiao No. 8 (line capsicum) for cultivation. The seedling-rearing process adopted the floating seedling-rearing method. Upon entering the period of transplanting, 15 robust pepper seedlings of similar height were selected and transplanted into pots. The pots were regularly irrigated with tap water (pH = 8.02) to meet the growth requirements of the peppers. During the growth period, 0.5 g of urea and 0.5 g of K₂SO₄ were re-added on the 30th day after transplantation. The plants were harvested after 103 days, and the plant height and weight of the root, stem, and fruit were measured. Subsequently, the plant samples were dried in an oven, and the soils were air-dried in a greenhouse for further experiments.

2.3. Sample Analysis

The pH, available P, and bioavailable Cd in the soil samples were analyzed according to the methods described in Section 2.2. The pepper samples were ground and passed through a 0.15 mm sieve. A 0.10 g of pepper plant was weighed in a polytetrafluoroethylene digester and subsequently digested in an automatic microwave digester (Auto Digiblock S60 UP, Beijing, China) with HNO₃ + H₂O₂ [39]. The Cd concentration in the digested solution was determined using inductively coupled plasma-mass spectrometry (ICP-MS, Agilent 7700x, Agilent Technologies Inc., Santa Clara, CA, USA). Blank, duplicate, and certified reference materials (GBW10014, cabbage, IGGE, Beijing, China) were used for quality control, and the recovery rate of Cd for the reference samples ranged from 83% to 108%.

2.4. Data Processing

2.4.1. Cd Mass, Bioconcentration and Translocation Factors

The Cd mass was calculated to compare the total Cd quantity in different pepper tissues. It is defined as the product of the Cd concentration and biomass of pepper. The bioconcentration factor (BCF) and translocation factor (TF) were calculated to evaluate the enrichment and migration ability of Cd in the soil-pepper system [40]. The BCF of roots and fruits was calculated as the ratio of Cd content in fruit or root to that in soil, respectively [41]. The TF is defined as the ability of plants to transfer Cd from roots to aboveground parts (stems or fruits) and was employed to assess the transportation of Cd from the root to the ground part of the plant [41]. The TF_{root-stem} and TF_{stem-fruit} were calculated as the ratio of Cd content in stem to root and the ratio of Cd content in fruit to stem, respectively.

2.4.2. Data Analysis

The data were processed using Excel 2021, and the graph was fitted using Origin 2021. One-way ANOVA ($p < 0.05$) was used to analyze the differences among treatments.

3. Results

3.1. Soil pH, Available P and Cd

The pH of the original soil was 7.08 ± 0.01 (Table 1), which was lower than that of soils following pepper cultivation (7.14 to 7.54, Figure 1a). The pH initially declined with increasing P amendment until 0.30 g/kg of P; then, it increased in 0.45 g/kg of P amendment. For the rhizosphere soil, pH in the 0.15 g/kg and 0.30 g/kg P amendment was significantly lower than in the other treatments. For non-rhizosphere soils, there was a significant difference in pH among all treatments, except CK. In all groups, the pH of the rhizosphere soil was generally lower than that of the non-rhizosphere soil.

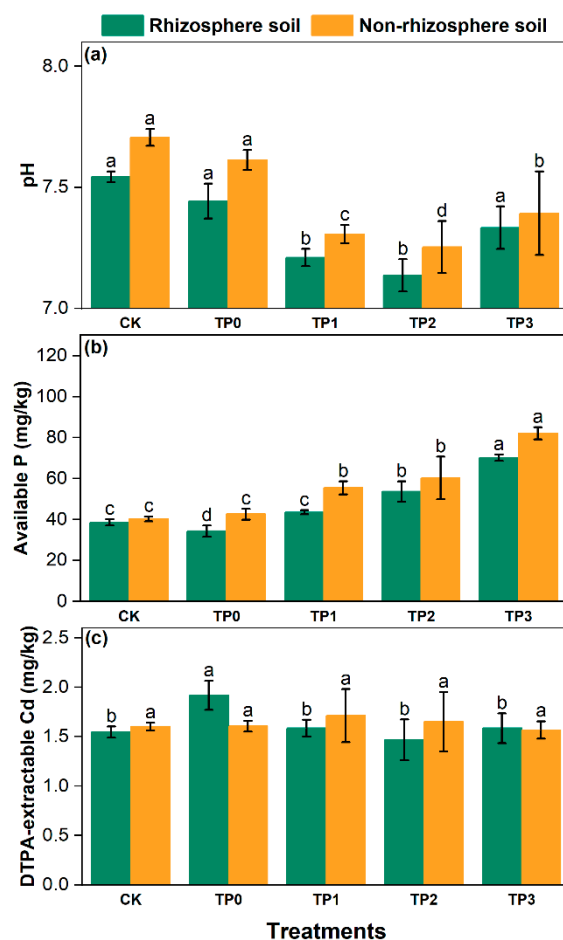


Figure 1. Soil pH (a), content of available P (b), and DTPA-extractable Cd (c) in rhizosphere and non-rhizosphere soils under different treatments. Different letters in columns of the same color indicate significant differences among treatments at the $p < 0.05$.

The available P content of the experimental soil was 23.2 ± 0.43 mg/kg, representing approximately 2.6% of the total P (Table 1). Available P contents in rhizosphere soils increased with increasing rate of P amendment and decreased in the order of TP3 (70.2 ± 1.53 mg/kg) > TP2 (53.6 ± 5.08 mg/kg) > TP1 (43.5 ± 1.07 mg/kg) > TP0 (34.4 ± 2.75 mg/kg) (Figure 1b). The rhizosphere soil in the CK group presented a higher available P (38.6 ± 1.63 mg/kg) than the TP0. In addition, available P contents in non-rhizosphere soils were generally higher than those in rhizosphere soils.

The Cd content in the original soil (6.19 ± 0.13 mg/kg, Table 1) was considerably higher than the risk screening value for Cd in Chinese agricultural soil (0.6 mg/kg, $6.5 < \text{pH} \leq 7.5$) [42]. The DTPA-extractable Cd content of the soil was 2.72 ± 0.02 mg/kg (Table 1), which accounted for ~44% of the total Cd. Sequential chemical extraction showed that the Cd chemical fractions

in the original soils decreased in the order of exchangeable fraction (46.1%) > bound to Fe-Mn oxides (18.6%) > carbonate fraction (15.8%) > bound to humic acid (11.6%) > residual fraction (6.0%) > strong organically bound fraction (1.8%) > water-soluble fraction (0.1%) (Figure 2). This result is consistent with the high DTPA-extractability of Cd in soils. The DTPA-extractable Cd content of the original soil was higher than that of treated soil. In addition, all treatment groups with phosphate amendment present similar values ($p > 0.05$) (Figure 1c). For the rhizosphere soil, TP0 has the highest content of DTPA-extractable Cd (1.92 ± 0.15 mg/kg) in soils, while other phosphate amendment treatments present similar contents (1.25–1.82 mg/kg). No significant differences were observed in the contents of DTPA-extractable Cd in the non-rhizosphere soils. The DTPA-extractable Cd of the rhizosphere soil was significantly higher than that of the non-rhizosphere soil for TP0, and this phenomenon was not observed in the other groups.

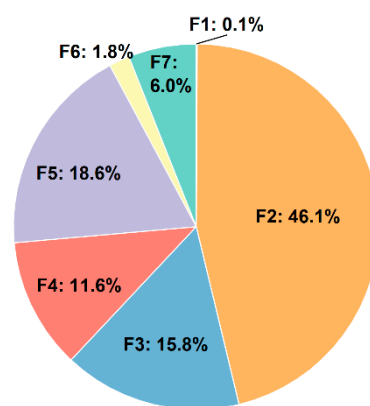


Figure 2. Chemical fractions of Cd in the experimental soil. F1: water-soluble fraction, F2: exchangeable fraction, F3: carbonate fraction, F4: humic acid bound fraction, F5: Fe-Mn oxides bound fraction, F6: strong organically bound fraction, and F7: residual fraction.

3.2. Biomass of Pepper in Different Treatments

In comparison to the control group, the addition of phosphate fertilizer and basic fertilizer resulted in a significant increase (22%) in the plant height of pepper (Table 3). The ANOVA test showed no significant difference in plant height between treatments with basic fertilizer (Table 3). Similarly, the dry weights of the roots, stems, and fruits in the CK treatment were lower than those in the fertilized treatments. In addition, fruits had the highest biomass (9.24 to 16.65 g) among the pepper tissues, and the biomass of fruits from TP3 was lower than that in the other phosphate amendment treatments.

Table 3. Biomass (dry weight) of pepper under different P treatments.

Group	Plant Height (cm)	Biomass (g/plant)		
		Root	Stem	Fruit
CK	59.87 ± 4.71 b	2.19 ± 0.15 b	6.87 ± 0.29 b	9.24 ± 0.85 c
TP0	68.90 ± 3.49 a	2.80 ± 0.24 a	10.36 ± 0.79 a	16.42 ± 1.05 a
TP1	73.37 ± 9.32 a	2.48 ± 0.12 a	10.75 ± 0.91 a	15.18 ± 1.32 a
TP2	76.03 ± 3.81 a	2.75 ± 0.34 a	11.06 ± 1.02 a	16.65 ± 2.84 a
TP3	76.13 ± 4.08 a	2.39 ± 0.26 a	10.23 ± 1.53 a	12.30 ± 1.03 b

Different lowercase letters after data in the same column represent significant differences among treatments at 0.05 level. Data are presented as (mean ± standard deviation).

3.3. Cd in Peppers

The Cd content in the major tissues of pepper is shown in Figure 3a. The Cd content in different tissues of the pepper ranged from 3.13 to 11.17 mg/kg. In general, the content of Cd decreased in the order of root (8.18 ± 0.89 mg/kg) > stem (4.89 ± 0.87 mg/kg) > fruit

(3.88 ± 0.30 mg/kg). There was no significant difference in Cd content in the roots and fruits in all groups. However, the Cd content of the stems in TP3 (3.43 mg/kg) was lower than that in the other groups (4.87–6.87 mg/kg). When the biomass of the pepper tissues was considered, it was found that the fruit accumulated the greatest quantity of Cd (30.59–65.97 μ g, Figure 3b). No significant difference was observed in the Cd mass in the roots across all treatments. The Cd mass in stems and fruits initially increased and then decreased with increasing P addition, and the Cd mass in stems and fruits in the CK and TP3 treatments was significantly lower than that in the other three treatments.

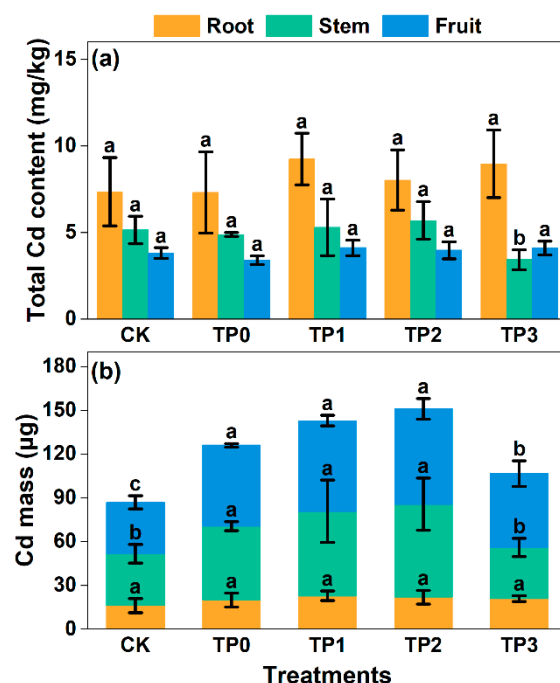


Figure 3. The content of Cd (a) and Cd mass (b) in the roots, stems, and fruits of pepper plants under different P treatments. Different letters in the same column indicate significant differences in the same parts of the pepper at the $p < 0.05$ level.

The BCF_{root} (1.18–1.49) and BCF_{fruit} (0.55–0.67) of Cd in pepper are similar in different groups (Table 4), and the TP0 presented relatively low BCF (1.18) as the CK (1.19). The $TF_{\text{root-stem}}$ (0.40 to 0.75) was lower than the $TF_{\text{stem-fruit}}$ (0.70 to 1.22). The TP3 presents the lowest $TF_{\text{root-stem}}$ and highest $TF_{\text{stem-fruit}}$. There were no significant differences in BCFs and $TF_{\text{root-stem}}$ values across all treatments.

Table 4. Bioconcentration factor (BCF) and translocation factor (TF) of different treatments.

Group	BCF_{root}	BCF_{fruit}	$TF_{\text{root-stem}}$	$TF_{\text{stem-fruit}}$
CK	1.19 ± 0.32 a	0.62 ± 0.05 a	0.72 ± 0.10 a	0.76 ± 0.15 a
TP0	1.18 ± 0.38 a	0.55 ± 0.04 a	0.72 ± 0.24 a	0.70 ± 0.07 a
TP1	1.49 ± 0.24 a	0.67 ± 0.07 a	0.57 ± 0.14 a	0.82 ± 0.22 a
TP2	1.30 ± 0.28 a	0.64 ± 0.08 a	0.75 ± 0.29 a	0.71 ± 0.13 a
TP3	1.45 ± 0.31 a	0.66 ± 0.06 a	0.40 ± 0.12 a	1.22 ± 0.26 b

Different letters in the same column indicate significant differences in the same parts of the pepper at the $p < 0.05$ level.

4. Discussion

4.1. Effects of Phosphate Amendment on Pepper Growth

The ability of plants to absorb and accumulate heavy metals is closely related to their biomass [43]. In this study, the available P content of the original soil was 23.2 mg/kg

(Table 1), higher than the average content in the study area (11.5 ± 11.6 mg/kg, National Agro-Tech Extension and Service Center [44]). However, this value is significantly lower than the average content of available P (48.25 mg/kg) in a karst region in southwest China [45]. The different rates of P amendment did not change the biomass or plant height of pepper in the treatment groups (Table 3). In addition, the Pearson's correlation analysis showed that the biomass of pepper was only weakly correlated with the amount of added phosphate ($r = 0.218$). These results suggested that the growth of pepper was not limited by available P in the studied soil. Similar results were obtained in a 2-year field experiment conducted in southwestern China, in which the soil with 33.5 mg/kg of available P was amended with different rates of P_2O_5 [46]. Alternatively, the lower biomass and plant height observed in CK and the low content of available K and N in the soils indicated that pepper biomass may be affected by insufficient N and K. This is consistent with the report that nitrogen fertilization increased the growth of habanero pepper, whereas potassium fertilization had no positive effects [47].

4.2. Decrease in pH of Rhizosphere Soil

Soil pH is a principal factor influencing the bioavailability and mobility of heavy metals in the soil [48,49]. Lower pH in the rhizosphere soil than in the non-rhizosphere soil indicated that the acidification effect resulted from the roots (Figure 1a). First, the secretion of organic acids such as citric acid, malic acid, and tartaric acid by pepper roots can result in a reduction in the pH of the rhizosphere soil [50]. Plants, such as peppers, can secrete organic acids to facilitate the dissolution of minerals in the soil and the activation of insoluble phosphates [51,52]. For example, Hu [53] demonstrated that when the available P was less than 45 mg/kg, the organic acid content in the rhizosphere soil of pepper increased significantly with a decrease in the P concentration, and there was no significant change after the concentration of P exceeded 45 mg/kg. This is probably the case in our study due to the low available P in the soil (23.2 mg/kg, Table 1). Second, the uptake of cations by plants can lead to the release of H^+ from the root via cation exchange and thus result in acidification [54]. Third, the soil pH tends to decrease with increasing rates of phosphate amendment (Figure 1). The addition of $Ca(H_2PO_4)_2 \cdot H_2O$ increased PO_4^{3-} and HPO_4^{2-} in the soil, which can form precipitation with Ca^{2+} and thus decrease soil pH [55].

4.3. Effect of Phosphate Amendment on Cd Accumulation in Pepper

Phosphorus-containing substances can affect the availability of Cd in the soil [56]. It was shown that the amendment of phosphate (KH_2PO_4) (600 mg/kg) in acidic soils stimulates ryegrass growth and increases the extraction of Cd by plants [57]. Tan et al. [58] reported that the addition of P-containing fertilizer (90–500 mg P/kg soil) was a significant factor influencing the bioavailability of Cd. In this study, the bioavailable Cd in the non-rhizosphere soil was similar in all groups, indicating that bioavailable Cd was independent of the application rates of phosphate. The bioavailable Cd in the rhizosphere soil of TP0 was approximately 24% higher than that in CK (Figure 1c). This is likely related to the low biomass and low uptake rate of Cd in CK. As mentioned above, the biomass of pepper in the treatment groups was independent of the phosphate application rate. In addition, the bioavailable Cd in the rhizosphere soil of TP0 was also approximately 20% greater than that of TP1, while the Cd contents in the pepper plant were identical. This probably reflects the absence of phosphate amendment, which results in the activation of Cd in the rhizosphere soil. However, when the P addition rate exceeds 0.15 g/kg, the bioavailable Cd in soil remains unaltered in response to changes in P content. Although an acidification effect was observed in the rhizosphere and bulk soil, it did not result in Cd mobilization. This may be attributed to the neutral-to-alkaline soil environment, in

which Cd may precipitate as insoluble hydroxides, carbonates, and phosphates [59–61]. The similar content of bioavailable Cd in the rhizosphere and non-rhizosphere soils of TP3 may be associated with the precipitation of mobile Cd.

Cd in soils enters the plant through uptake by roots [62], and Cd exhibits high mobility in soil-plant systems [63]. The original soil featured both high Cd content and high Cd bioavailability (Table 1). Therefore, elevated Cd was observed in the peppers and decreased in the order of root > stem > fruit (Figure 3a), which agrees with previous studies on peppers [36,41]. These results suggested that pepper planting in the studied soils may present health risks unless suitable remediation techniques are conducted. The high BCF_{root} (>1) indicated that pepper tends to accumulate Cd from the soil. The majority of plants absorb nutrients from the soil through their roots, which also simultaneously uptake and accumulate heavy metals, such as Cd, in their roots [64–66]. However, the Cd enrichment capacity of pepper roots and fruit was not altered by the amendment of phosphate fertilizer (Table 4). After entering the root, the transportation of Cd primarily dominates Cd accumulation in the stem and fruit. Our results showed that the transportation capacity of Cd from root to stem and from stem to fruit was not influenced by biomass and P addition. The abnormal $TF_{root-stem}$ and $TF_{stem-fruit}$ values of TP3 may be explained by the relatively lower Cd content in the stem (Figure 3). Overall, these results indicate that the uptake, transportation, and accumulation of Cd in pepper plants were not affected by phosphate amendment rates under the experimental conditions of this study. Further studies are needed to investigate the effects of different phosphate-containing materials or organic fertilizers on the accumulation of Cd in peppers.

5. Conclusions

This study investigated the effect of phosphate amendment on the growth and Cd accumulation of pepper cultivated in geogenic Cd-rich soils in a karst region. The results showed that the biomass of pepper was not affected by the application rates of phosphate, but was related to the application of nitrogen and potassium fertilizers. Pepper plants are prone to uptake and accumulate Cd from the soil, and the Cd content in pepper decreases in the order of root > stem > fruit. The amendment of phosphate (0 to 0.45 g/kg, $Ca(H_2PO_4)_2$) neither influences the bioavailable Cd in rhizosphere soil nor the Cd uptake and transportation in pepper plants. The slight acidification effects of rhizosphere soil also did not affect Cd activation. The result of this study suggested that remediation strategies other than monocalcium phosphate are needed when peppers are planted in these geogenic Cd-rich soils in the karst regions. Furthermore, the effect of P on the accumulation mechanism of Cd in soil-plant systems needs to be further investigated.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request.

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