EFFECTIVENESS OF SOIL AMENDMENT AND DIFFERENT FOLIAR FERTILIZERS IN REDUCING CADMIUM ACCUMULATION AND TRANSPORT IN WINTER WHEAT (*TRITICUM AESTIVUM* L.)

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Abstract. The area of Cd-contaminated wheat farmland is large worldwide, to achieve safe wheat production in Cd-contaminated farmland, it is necessary to take cost-effective measures to mitigate the Cd accumulation in wheat plants. A pot experiment was conducted in this study to evaluate the effectiveness of sepiolite and potassium dihydrogen phosphate (KDP) as soil amendment, in combination with different leaf barriers, for mitigating Cd translocation and accumulation in wheat plants grown in farmland soil contaminated with Cd. The application of soil amendment either alone or in conjunction with foliage supplementation of Si, Ca or Zn significantly reduced soil DTPA-extractable Cd by 27.97%-34.58% and grain Cd concentration by 18.69%-43.61% respectively. Exogenous Si/Ca/Zn spray had an additive effect in reducing Cd in wheat grain grown on sepiolite + KDP treated soil, with increased dosages of foliar barriers resulting in decreased grain Cd concentrations. The lowest concentration of Cd (0.60 $mg \cdot kg^{-1}$) in wheat grain was observed with foliar spraying a higher dosage of Si and soil application of sepiolite + KDP treatment (ASi-H). These results suggest that soil application of sepiolite + KDP combined with foliar application of Si/Ca/Zn, especially Si, could be an efficient and low-cost method for remediating Cd-contaminated alkaline soils.

Keywords: *soil conditioner, foliar barrier agents, availability, wheat grains, alkaline arable soils*

Introduction

Cadmium (Cd) is a highly biotoxic metal with strong activity and mobility in the water-soil-plant system (Liu et al., 2018). When Cd is released into the environmental media, it is easily absorbed by plants and moved through food chains, having negative impacts on both the environment and human health (Rizwan et al., 2016, 2017a).

Wheat (*Triticum aestivum* L.) is one of the most important staple food worldwide and is particularly important in the daily diet of the people of northern China (Zhang et al., 2018). However, owing to increasing anthropogenic activities, including wastewater irrigation (Ochoa et al., 2020), metal mining, manufacturing, and metallurgy (Du et al., 2020), farmland Cd contamination is widespread (Galdames et al., 2017; Li et al., 2016; Rehman et al., 2017). Xinxiang City in Henan Province is an important light industrial city in northern China, with more than 200 battery enterprises. During the process of battery production, heavy metals (e.g. Cd, Ni, Zn and As) are released into the environment through wastewater discharge and atmospheric deposition. Heavy metal pollution in the vicinity of battery enterprises has led to increased concentrations of Cd, Zn and Ni in cereal grains, with Cd pollution being the most severe, negatively affecting the local population's health (Jiang et al., 2020). Therefore, to guarantee the food security of wheat and preserve human health, it is crucial to decrease the Cd contamination in the soil-wheat system.

Cd accumulation in wheat plants is highly correlated with the soil bioavailable Cd fractions, therefore, applying immobilizing agents in Cd-polluted soils is a commonly used remediation technique to reduce soil Cd bioavailability and thus decrease plant uptake and accumulation at present (Hamid et al., 2020, 2019; Xu et al., 2017). Many amendments such as clay minerals (Yin et al., 2017), biochar (Mohan et al., 2014), lime (Duan et al., 2018), and phosphate minerals (Sun et al., 2016) have been explored to immobilize Cd in contaminated acidic paddy soils through pH regulation or high binding capacity to heavy metal ions. However, most farmland soils in Henan Province are alkaline calcareous, making it difficult to reduce Cd availability in soil by increasing the pH of the soil, so the effect of single passivation technology is often unsatisfactory in these alkaline calcareous soils (Guo et al., 2017), and it needs to be combined with other methods to reduce heavy metal accumulation in crops (Li and Zhou, 2019).

Leaf barrier technology is a new application in recent years to block the heavy metals uptake by crops (Liu et al., 2019). As a non-essential element for plant growth, Cd is transported in plants mainly by transporters of essential elements with similar chemical properties, such as Zn, Fe, Mn, Si, and Ca. Foliar spraying these elements which may compete for transporters with Cd has been proposed as an effective technology to reduce Cd concentration in grains by affecting the translocation and redistribution of Cd in crops. For example, with a foliar application of Si (20 $mg \cdot L^{-1}$), the Cd accumulation in rice grains was significantly reduced by 37% (Hussain et al., 2020). Foliar application of an appropriate amount of Zn in the booting stage effectively enhanced wheat growth and reduced Cd accumulation in wheat grains (Saifullah et al., 2016; Sarwar et al., 2015). Supplementing exogenous Ca could reduce Cd accumulation in plants, regulate plant physiological and biochemical metabolism, thereby relieving the Cd toxicity to plants (Huang et al., 2017).

We hypothesized that the application of soil amendment and foliar barrier technologies in combination, i.e. spraying foliar blockers to decrease the Cd transfer from wheat roots to grains after applying soil passivation agents, could further reduce the risk of excessive heavy metal content in crops. Nevertheless, there is limited research in this area.

Hence, the objective of this study was to investigate the effects of soil amendment combined with foliar spraying of Si/Zn/Ca on Cd translocation and accumulation in wheat plants grown in an alkaline farmland soil contaminated with Cd, the result will provide technical guidance for the safe wheat production in Cd-contaminated farmlands.

Materials and methods

Contaminated soil, winter wheat, soil passivation agents, and leaf barrier agents

The Cd-contaminated soil was collected from the top 20 cm layer of the agricultural fields in Xinxiang, China. The soil type is classified as alluvial soil. Historical sewage irrigation caused soil Cd contaminated in this area. The collected soil samples were air-dried and homogenized thoroughly. They were then sifted through 20- and 100-mesh sieves. The basic soil physicochemical properties were as follows: pH (8.58 ± 0.04), Total N (0.54 ± 0.04 $g \cdot kg^{-1}$), Total P (0.68 ± 0.03 $g \cdot kg^{-1}$), Organic matter (10.30 ± 0.04 $g \cdot kg^{-1}$), Total Cd (1.75 ± 0.06 $mg \cdot kg^{-1}$). The total Cd concentration was 1.75 $mg \cdot kg^{-1}$, which was much higher than the Environmental Risk Screening Value of 0.6 $mg \cdot kg^{-1}$ for soil pollution on agricultural land in China (GB 15618–2018, pH > 7.5).

A winter wheat cultivar Bainong-207 was employed as the representative plant, it is a main cultivar widely planted in the local area.

A mixture of natural sepiolite and potassium dihydrogen phosphate (KDP) was chosen as the soil amendment in this study because of its common application and better performance in our previous study (Sun et al., 2020). Natural sepiolite was purchased from commercial sources in China, which contains 55.4% SiO_2, 15.0% MgO, 3.7% Al_2O_3, pH 8.62. KDP was an analytical grade reagent.

Three commercially available foliar fertilizers were supplied as leaf barrier agents because they were low-cost, easy to apply, and safe for crop production. The three foliar fertilizers, including chelated sugar alcohol silicon fertilizer (SiO ≥ 26%), chelated sugar alcohol calcium fertilizer (Ca ≥ 180 $g \cdot L^{-1}$), and chelated sugar alcohol zinc fertilizer (Zn ≥ 150 $g \cdot L^{-1}$), were all purchased from Lulong Biotechnology Co. Ltd, Shandong, China.

Pot experiment design

The pot experiment was carried out in the rain shelter under open field at Henan Institute of Technology (113.9°E, 35.3°N) in Xinxiang City, Henan province, China, during October 2020 to June 2021. The annual mean temperature is 14°C, and average annual sunshine duration is 2400 h. Eight treatments were set in this work as shown in *Table 1*. Treatments were randomly arranged and 3 replications per treatment. According to our previous study (Sun et al., 2020), the application rate of immobilization material was 1% sepiolite composited with 0.04% KDP (w/w). The high (H) and low (L) foliar barrier application rates were set based on the recommended levels of different foliar fertilizers for wheat.

Table 1. *The experimental treatments*

Treatment abbreviations	Amendment	Leaf barriers
CK	-	-
A	1% sepiolite and 0.04% KDP	-
ASi-H	1% sepiolite and 0.04% KDP	500 times diluted sugar alcohol silicon fluid fertilizer (SiO ≥ 26%)
ASi-L	1% sepiolite and 0.04% KDP	1000 times diluted sugar alcohol silicon fluid fertilizer (SiO ≥ 26%)
ACa-H	1% sepiolite and 0.04% KDP	750 times diluted sugar alcohol calcium fluid fertilizer (Ca ≥ 180 $g \cdot L^{-1}$)
ACa-L	1% sepiolite and 0.04% KDP	1500 times diluted sugar alcohol calcium fluid fertilizer (Ca ≥ 180 $g \cdot L^{-1}$)
AZn-H	1% sepiolite and 0.04% KDP	750 times diluted sugar alcohol zinc fluid fertilizer (Zn ≥ 150 $g \cdot L^{-1}$)
AZn-L	1% sepiolite and 0.04% KDP	1500 times diluted sugar alcohol zinc fluid fertilizer (Zn ≥ 150 $g \cdot L^{-1}$)

The indicators are quality fraction

The collected soils were air-dried, thoroughly mixed, ground, and passed through a 2 mm nylon sieve. The immobilization material was added evenly to the soils to achieve the objective dose. About 3 kg of treated soil was placed in a plastic pot, in parallel, a control experiment without the addition of immobilization material was also performed. Each pot was irrigated with tap water to the maximum water capacity (MWC), and the soils were then aged for 15 days before wheat sowing.

A 2% (v/v) H_2O_2 solution was used to sterilize wheat seeds for 15 min, following which the seeds were rinsed four times in distilled water, then soaked for 24 h in distilled water. Ten soaked wheat seeds were initially sown in each pot. After they had emerged, six seedlings per pot were kept by thinning. During the whole growth period of winter wheat, the moisture content of each pot of soil was controlled to about 40% of the MWC by adding tap water every three days.

Foliar fertilizers were applied three times during the booting and heading stages, the first foliar application was made at the booting stage (5th April), followed by seven-day intervals, the third application was made at the heading stage (19th April). Foliar fertilizers were carried out with hand-operated sprayers late afternoon or evening. To avoid influence between adjacent treatments, each treatment was separated by a plastic board during the spraying process. The foliar dressing was sprayed evenly on the leaves, wetting all the leaves without dripping, and the treatments without foliar barrier spraying were replaced with equal amounts of distilled water.

Sample analysis

After the wheat harvest, the wheat ears were removed from each pot using a sharp scissor. The soil and plant were then removed from each pot, the above-ground parts of the plant were carefully cut using the scissor, the plant roots were manually separated from the soil and carefully washed with tap water to eliminate soil residues attached to them. Subsequently, all plant samples were thoroughly washed with tap water and distilled water several times, the water on the sample surface was carefully absorbed with absorbent paper. After that, the plant samples were divided into four parts, namely root, straw, husk, and grain, and then oven-dried at 70°C till constant weight. Finally, the dried plant samples were weighed and ground into powders using an electric high-speed stainless steel mill for further analysis. Soil samples near the wheat roots were collected, air-dried, milled and passed through 20-mesh and 100-mesh nylon sieves before analysis.

Soil pH was measured in a 1:2.5 soil/water (w/v) suspension using a pH meter (FE28-Meter).

The Cd concentration in plant materials was determined after digesting the samples in HNO_3-$HClO_4$ (4:1, v:v) acids. The soil total Cd concentration was digested with HCl-HNO_3-HF-$HClO_4$. The soil available Cd was evaluated using the extraction solution comprised 0.005 $mol \cdot L^{-1}$ diethylenetriaminepentaacetic acid (DTPA), 0.1 $mol \cdot L^{-1}$ triethanolamine (TEA) and 0.01 $mol \cdot L^{-1}$ calcium chloride dihydrate ($CaCl_2$), and incubated for 120 min with continuous shaking. The Cd concentration in the digested or extracted solution was determined by an atomic absorption spectrophotometer (Agilent 240FS).

Data analysis

The experimental data were calculated with Microsoft Excel 2019 and analyzed by IBM SPSS Statistics 19 software. The means among different treatments were statistically analyzed using one-way analysis of variance (ANOVA) followed by multiple comparisons with Duncan’s multiple range test. The graphical presentations were completed by Origin 2021.

The translocation factor (TF) of Cd from roots - straws - husks - grains was calculated with the formula described previously (Hamid et al., 2019):

$$TF_{root-straw}(\%TF) = \frac{Cd\ content\ in\ straws}{Cd\ content\ in\ roots} \times 100 \qquad \text{(Eq.1)}$$

$$TF_{straw-husk}(\%TF) = \frac{Cd\ content\ in\ husks}{Cd\ content\ in\ straws} \times 100 \qquad \text{(Eq.2)}$$

$$TF_{husk-grain}(\%TF) = \frac{Cd\ content\ in\ grains}{Cd\ content\ in\ husks} \times 100 \quad \text{(Eq.3)}$$

Results

Soil pH and soil available Cd

As shown in *Figures 1* and *2*, compared to the control, all treatments that included soil amendment (alone or in combination with foliar application of Si, Ca or Zn) significantly decreased soil pH by 0.10-0.16 units and soil available Cd by 27.97%-34.58%, and there were no notable differences among different treatments. This indicated that the decreases in soil pH and soil available Cd under different treatments were mainly caused by the application of soil amendment rather than foliar spraying of different barrier agents.

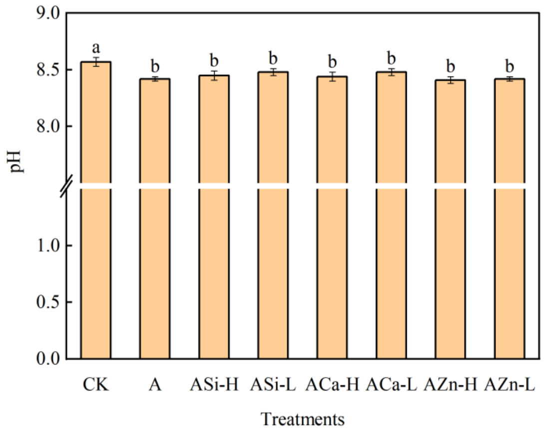

Figure 1. *Soil pH values under different treatments. Note: Bars represent standard error of three replicates, different letters represent significant differences between different treatments at the P <0.05 level*

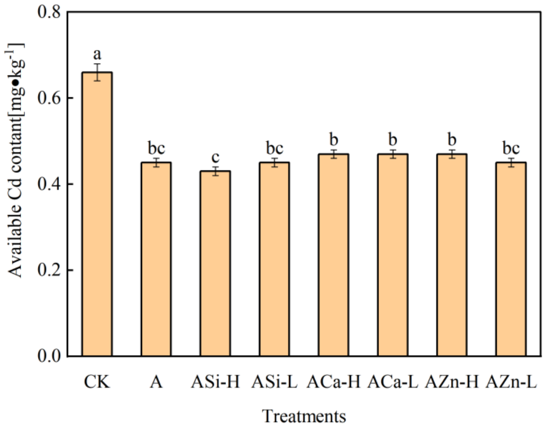

Figure 2. *Soil available Cd contents under different treatments. Note: Bars represent standard error of three replicates, different letters represent significant differences between different treatments at the P <0.05 level*

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Cd concentration in different wheat plant parts

As shown in *Figure 3,* Cd in the parts of the wheat plant decreased in the following order: root Cd, straw Cd, husk Cd, and grain Cd, respectively. In comparison with the control, the Cd concentrations in all parts of wheat plants were significantly reduced under different treatments, which indicated that soil amendment alone or in combination with foliar barrier could effectively hinder the Cd uptake, translocation, and accumulation in different parts of the wheat.

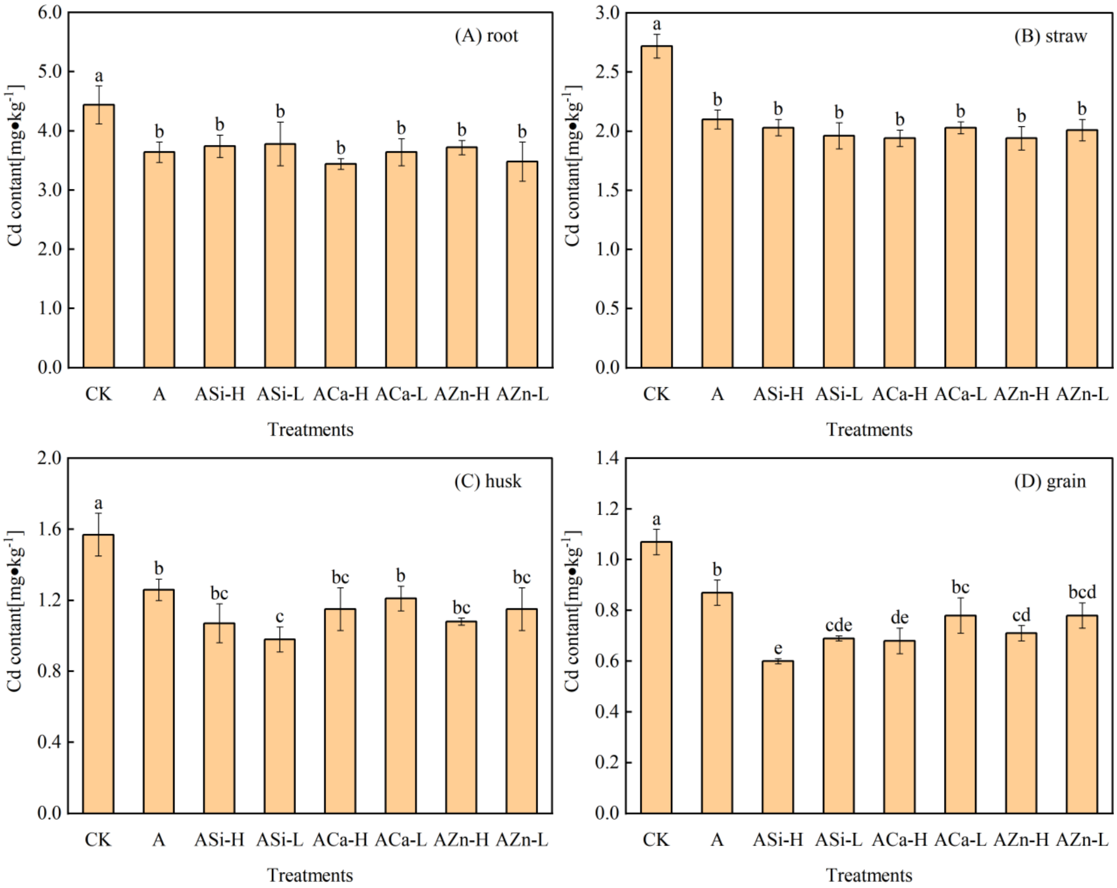

Figure 3. *Cd contents in the root, straw, husk and grain of wheat under different treatments. Note: Bars represent standard error of three replicates, different letters represent significant differences between different treatments at the P <0.05 level*

In comparison to the control, soil amendment alone significantly decreased the Cd concentrations in the wheat root, straw, husk, and grain by 18.11%, 22.58%, 19.75%, and 18.69%, respectively. After treatment with different foliar applications, the combined treatments tended to further reduce Cd concentrations in the husk and grain of wheat. Additionally, the wheat grain Cd concentrations were significantly decreased by 43.61%, 35.20%, 36.45%, and 33.96% in ASi-H, ASi-L, ACa-H, and AZn-H treatments compared to that in the control, and the reduction range of the above treatments was significantly better than that of treatment A.

To show the distribution of Cd in different parts of wheat after different treatments, a heat map was created. As shown in *Figure 4*, compared with the control, soil passivation alone or combined with foliar dressing all reduced the Cd concentration in wheat roots, straws, husks, and grains to different extents, and effectively suppressed Cd uptake and accumulation in wheat. However, there were some differences in the effect of controlling Cd absorption and accumulation by wheat among the different treatments, with the cluster analysis, all remediation measures were divided into three groups with similar characteristics, in contrast to the control, AZn-H, ASi-L, and ASi-H treatments had the best remediation effect, next came AZn-L and ACa-H treatments, ACa-L and A treatments had a relatively weak remediation effect on inhibiting the Cd absorption of wheat plants.

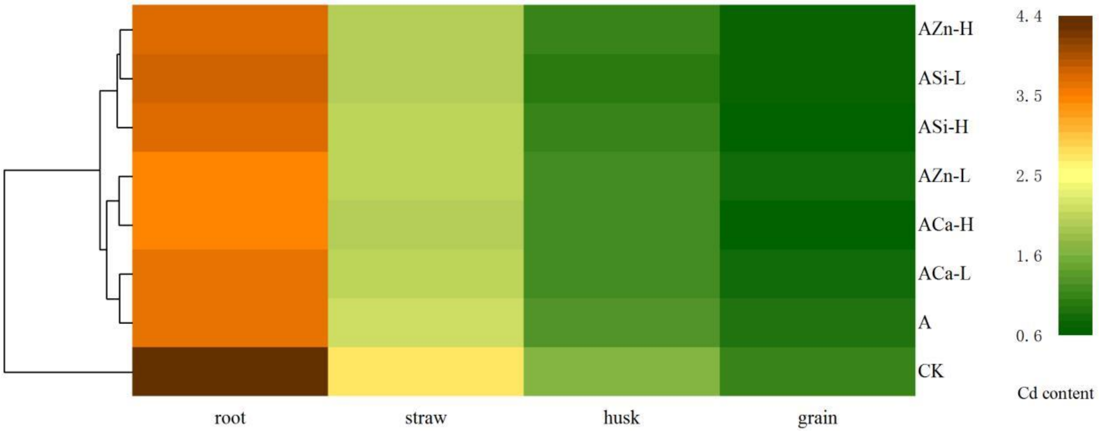

Figure 4. *Heat map displaying the Cd contents in wheat root, straw, husk and grain under different treatments. Note: High and low Cd contents are indicated by the color key*

Translocation factor

The translocation factors of Cd in wheat under different treatments are shown in *Table 2*. As seen in *Table 2*, compared to the control, all treatments reduced the $TF_{root\text{-}straw}$ of Cd in varying degrees, among which soil passivation combined with foliar barrier treatments decreased by 5.60%-15.43%, which was higher than 5.46% of treatment A. As compared to CK, treatment A slightly increased the $TF_{straw\text{-}husk}$ and $TF_{husk\text{-}grain}$ by 3.66% and 1.31%, while the combined treatments decreased the $TF_{straw\text{-}husk}$ and $TF_{husk\text{-}grain}$ by 1.29%-13.33% and 0.19-17.01%, except for the $TF_{straw\text{-}husk}$ of foliar-applied Ca treatments (ACa-H and ACa-L) and the $TF_{husk\text{-}grain}$ of ASi-L treatment.

Table 2. *Transfer factor of Cd in wheat under different treatments*

Items	CK	A	ASi-H	ASi-L	ACa-H	ACa-L	AZn-H	AZn-L
$TF_{root\text{-}straw}$	0.61	0.58	0.54	0.52	0.57	0.56	0.52	0.58
$TF_{straw\text{-}husk}$	0.58	0.60	0.52	0.50	0.59	0.60	0.56	0.57
$TF_{husk\text{-}grain}$	0.68	0.69	0.57	0.71	0.59	0.65	0.65	0.68

Correlations analysis

The correlation between the soil available Cd concentrations and the Cd concentrations in different parts of the wheat plants are given in *Table 3*. Correlation analysis revealed that there were highly significant positive correlation between the soil available Cd concentrations and the Cd concentrations in wheat roots, straws, husks, and grains. In addition, highly significant positive relationships were observed among the Cd concentrations in wheat grains, husks, and straws. There was also a strong positive correlation between Cd concentrations in wheat straws and roots.

Table 3. *Correlation analysis between Cd content in different organs of wheat and soil available Cd content*

Influencing factors	**Cd content in different organs of wheat**				**Available Cd content**
	Grain	**Husk**	**Straw**	**Root**	
Grain	1	.929**	.879**	0.706	.843**
Husk		1	.921**	0.706	.883**
Straw			1	.906**	.942**
Root				1	.878**
Available Cd					1

**Significant correlation at 1% level

Discussion

The effects of soil amendment along with leaf barrier on soil pH and soil available Cd

In this research, we found that the application of sepiolite + KDP to soils with or without foliar supplementation obviously reduced the soil pH and available Cd in comparison with the control. Soil pH is an important parameter that directly affects the heavy metal mobility and bioavailability in polluted soils (Chen et al., 2007; Zhu et al., 2016). Previous experiments reported that natural sepiolite transformed metal cations from available fractions to less available fractions by increasing soil pH, which resultantly, inhibited Cd accumulation in plants (Liang et al., 2014; Sun et al., 2014). However, in current alkaline soils, it was not easy to change the available fraction of Cd via the effect of soil pH-regulating (Liang et al., 2019; Wang et al., 2020). Similar findings were reported by Xing et al. (2019), who observed that the addition of soluble phosphate in combination with bentonite could reduce soil pH and improve Cd and Pb immobilization in lead-smelting impacted calcareous soils. The reason accountable for this reduction in soil pH may be associated with the properties of the soil and the passivator used in this study. In the current research, the experimental passivator was the combination of natural sepiolite and KDP, the pH of the natural sepiolite was 8.62, similar to the pH of the experimental soil (8.58), due to the soil's buffering capacity, the addition of sepiolite might not have an obvious effect on soil pH. On the other hand, the addition of KDP in calcareous soils usually lower the pH of the soil (Li et al., 2012). The slight decrease in soil pH may cause a slight increase in Cd solubility in soils, but at higher pHs, Cd was sorbed as an innersphere complex on hydroxylated sites on the edges of layer silicates or on Fe or Al oxides (Loganathan et al., 2012), only a relatively small amount of Cd were desorbed, and the dissolved Cd could react with phosphate radicals to form sparingly soluble Cd-phosphates (Mo et al., 2021). As such, the decrease in DTPA-extractable Cd by sepiolite + KDP in this study could be mainly due to the Cd adsorption on the sepiolite surface (Shirvani et al., 2006) and the formation of metal phosphates (Cao et al., 2013, 2011; Mo et al., 2021), and the slight decrease in soil pH should have limited impact on the Cd availability.

Foliar fertilizers that unintentionally fall into the soil during spraying may cause small changes in soil pH (Tan et al., 2020). In our research, compared with sepiolite + KDP alone, sepiolite + KDP combined with exogenous application of Si, Ca or Zn on wheat plants had no obvious effects on soil pH or soil available Cd. These results correlated with the findings of previous studies where foliar applied Fe and Zn had limited influence on soil pH and soil available Cd (Duan et al., 2018; Feng et al., 2013; Shao et al., 2008). This showed that the variations in soil pH and available Cd in the current study were mainly caused by the application of sepiolite + KDP rather than the foliar spraying of Si, Ca or Zn.

The effects of soil amendment along with leaf barrier on Cd translocation and accumulation in wheat plants

In this work, we found that the addition of sepiolite + KDP (with or without foliar application) obviously decreased available Cd in soil and Cd accumulation in wheat plants. Our findings coordinate with the results of previous research, where the mixture of sepiolite and phosphate fertilizer was effective in reducing Cd and Pb concentrations in *Lactuca sativa L*. (Liang et al., 2011). Moreover, we found a significant positive correlation between the concentration of DTPA-Cd in soil and the concentration of Cd in wheat root, straw, husk, or grain. This indicated that the decreased Cd concentration in wheat plants could be largely attributed to the decrease of soil Cd bioavailability caused by the addition of sepiolite + KDP, which resultantly, inhibited the absorption and translocation of Cd by wheat plants. Previously, literature has reported that the amendments could inhibit the mobility and bioavailability of many metals by adsorbing, complexing or precipitating (Bolan et al., 2014), and thus reduce their translocation from roots to shoots. In the current research, we did find that the application of sepiolite + KDP (with or without foliar application) decreased the $TF_{root\text{-}straw}$ to different extents in comparison to the control, which showed that the addition of sepiolite + KDP not only inhibited Cd uptake by wheat roots but also hindered internal Cd transport from roots to aboveground parts of wheat.

Compared to soil application of sepiolite + KDP alone, foliar spraying Si, Zn or Ca on wheat plants grown in sepiolite + KDP treatments further lowered Cd concentrations in husks and grains of wheat, but had no obvious effects on Cd concentrations in roots and straw. It can be seen that foliar application of Si, Zn or Ca may limit and/or reduce Cd translocation to above-ground parts of wheat, especially wheat spikes. Previously, many studies have reported that the exogenous addition of beneficial elements, such as Si, Zn and Ca, could effectively reduce heavy metal accumulation in plants via alleviating oxidative stresses (Zhou et al., 2021), regulating nutrient balance (Duan et al., 2018) and strengthening photosynthesis (Gao et al., 2018; Liu et al., 2015). A similar finding was reported by Duan et al. (2018), who found that the combined soil application of liming and foliar application of Zn was more effective than the soil liming application alone in decreasing rice grain Cd accumulation. Nevertheless, some studies reported a limited effect of foliar mineral applications on wheat grain Cd concentrations (Guo et al., 2017; Xing et al., 2018). These observed changes after foliar treatments may be due to the experimental spraying stage and spraying dose (Khaliq et al., 2019). Earlier studies have shown that the optimal foliar applications of Si and Zn would be during the elongating and heading stages (Zhou et al., 2021), furthermore, foliar spraying Zn showed more effectiveness in the booting stage than in other stages on the reduction of grain Cd (Saifullah et al., 2016). In the current study, the foliar fertilizers of Si, Zn and Ca were applied 3 times during the booting and heading stages, which were considered to be the optimum foliar application stages. Liao et al. (2016) and Zong et al. (2017) found that the remediation effect was also affected by the foliar spraying concentrations, similar findings were observed in our work, where the higher dose of foliage supplementation treatments resulted in lower grain Cd concentrations under the same condition.

In this experiment, with few exceptions, we found that foliar application of Si, Zn or Ca combined with soil application of sepiolite + KDP further decreased $TF_{root\text{-}straw}$, TF

$_{\text{straw-husk}}$ and TF $_{\text{husk-grain}}$ to some extent compared with sepiolite + KDP, and the lowest translocation of Cd was found in the foliar spray Si treatments. A lower TF indicates lower mobility or availability of heavy metals in the plants (Guo et al., 2017). These results indicate that foliar dressing of Si, Zn or Ca, especially Si, can further prevent the Cd accumulation in wheat grain grown in the sepiolite + KDP treatments by changing the internal uptake and translocation of Cd in wheat plants, and thus reduce the risk to primary consumers. The possible mechanism could be that Zn and Ca are essential micronutrients for plant growth and compete with Cd for the same transport system (Fahad et al., 2015). Although Si is an non-essential element, previous researches showed that exogenous application of Si can promote the uptake of some essential mineral elements (e.g. B, Cu, Zn, Fe and Mn), and thus antagonize Cd translocation (Meng et al., 2018; Rizwan et al., 2017b). In addition, Si application could also improve Cd binding to cell walls by forming Si-hemicellulose-Cd, thus reducing Cd accumulation in plants (Ma et al., 2015).

Conclusions

Soil applied sepiolite + KDP, with or without foliar spraying Si, Zn or Ca, trended to reduce available Cd in alkaline soils and Cd accumulation in wheat. Foliar spraying of Si, Zn or Ca, particularly Si, further reduced Cd concentrations in sepiolite + KDP treated wheat grains by impeding the internal absorption and movement of Cd within wheat plants. The simultaneous use of sepiolite + KDP and foliar spraying Si presents a promising remediation strategy for alkaline soils contaminated with Cd, leading to a substantial reduction in Cd accumulation in wheat grains, with a maximum reduction of 43.61%.

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APPENDIX

Figure A1. *The tested Cd-contaminated soil (a), winter wheat (b) and the soil samples to be analyzed (c)*

Figure A2. *The natural sepiolite (a), KDP (b) and three foliar fertilizers (c) used in the study*