Effects of soil properties on accumulation characteristics of copper, manganese, zinc, and cadmium in Chinese turnip

Boqun Li a, b, Di Chen c, Yongping Yang a, b, Xiong Li a, b, *

a Key Laboratory for Plant Diversity and Biogeography of East Asia, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China
b Germplasm Bank of Wild Species, Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, China
c School of Life Sciences, Yunnan University, Kunming 650091, China

A R T I C L E   I N F O

Article history:
Received 27 February 2019
Received in revised form 10 June 2019
Accepted 12 June 2019
Available online 27 June 2019

Keywords:
Phytoremediation
Bioconcentration
Soil composition

A B S T R A C T

Clarifying the mechanisms of heavy metal (HM) accumulation and translocation from soil-root-leaf is crucial to coping with soil HM pollution. In this study, we analysed copper (Cu), manganese (Mn), zinc (Zn) and cadmium (Cd) accumulation characteristics in Chinese turnips and the effect of soil physico-chemical properties on both HM accumulation and translocation. Our results indicate that Chinese turnips absorb and translocate Mn, Zn, and Cd at much higher levels than they do Cu. When we measured bioconcentration factors in Chinese turnips for different HMs in the same soil, we found Chinese turnip capacities for HM accumulation decrease from Zn > Mn > Cd > Cu. In addition, the translocation factor for these HMs decreases from Mn > Cd > Zn > Cu. Correlation analysis indicates that soil pH and various soil components are either negatively or positively correlated with Mn, Zn, and Cd accumulation; also, soil properties are correlated with Mn translocation from root to leaf. These findings may help evaluate HM accumulation and translocation mechanisms as well as artificially regulate HM uptake levels from soils to turnips.

1. Introduction

The existence of heavy metals (HMs) in soil is of great concern because of their potential toxicity (Khan et al., 2015, 2016). Even at low concentrations, HMs may be toxic to plants, animals, and humans (Di Salvatore et al., 2008; Khan et al., 2016). Reducing the risk of HM toxicity to humans requires minimizing HM concentrations in crops and vegetables. Hence, research on soil HMs has focused on reducing the bioavailability of HMs in soils or weakening the HM absorption capacity of plants (Arshad et al., 2016; Che et al., 2016). Conversely, numerous methods have been employed for remediating contaminated soils (Buendia-Gonzalez et al., 2010). Phytoremediation, which is economic and eco-friendly, is considered a promising method for soil remediation (Ehsan et al., 2014; Sarwar et al., 2017). Phytoremediation mainly depends on the HM absorption and translocation capacities of plants; thus, high-HM accumulation species, especially hyperaccumulators, are good contributors in phytoremediation (Gerhardt et al., 2017). However, plant biomass is also an important factor of phytoremediation efficiency. Phytoremediation is generally a slow process because few plants possess a large biomass and also have the capacity to accumulate high levels of HMs. Additionally, single phytoremediation may produce limited effects on contaminated soils with multiple HMs because plants often have distinct HM accumulation capacities (Xie et al., 2016; Zhou et al., 2016). Therefore, in addition to understanding the mechanisms of HM accumulation in plants, it is critical to screen for more efficient high-HM-accumulating plants.

Several recent studies have investigated the soil—root—leaf transfer mechanism of HMs (Yin et al., 2011; Khan et al., 2016). Environmental factors, such as soil properties, have been shown to regulate accumulation levels of HMs in plants (Gustin et al., 2009; Benis et al., 2015; Huang et al., 2016; Velickovic et al., 2016). Specifically, the physicochemical properties of soil, including pH, electrical conductivity (EC), organic matter content, and cation...
exchange capacity (CEC), have been found to affect the absorption of HMs in plants (Yu et al., 2014). However, the same soil property can have differential effects on different HM-plant systems (Yu et al., 2014). For example, a study reported that the soil CEC and exchangeable calcium (Ca) are important indexes for predicting the critical value of nickel (Ni) to barley and tomato (Rooney et al., 2007), whereas two other reports found that soil pH rather than soil CEC significantly affects the critical value of Ni toxicity in barley or tomato (Zhang et al., 2009; Li et al., 2011). Therefore, analyzing the effect of soil properties on the HM accumulation characteristics of plants for specific HM-plant systems is of great importance in assessing the safety risks of crop and vegetable foodstuffs or phytoremediation efficiency.

Turnip (Brassica rapa var. rapa Lin.) is a cruciferous biennial species that is widely cultivated in Europe, Asia, and America as a local vegetable or fodder. To date, several studies have investigated the turnip accumulation characteristics for various HMs, including cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), and manganese (Mn) (Parveen et al., 2015; Li et al., 2016). However, these studies have produced inconsistent conclusions about the HM accumulation capacity of turnips with different HM concentrations at specific HM-plant systems. To understand the absorption and translocation characteristics of four HMs (Cu, Mn, Zn, and Cd) in the Chinese turnip, we studied whether physicochemical soil properties affect HM accumulation or translocation in Chinese turnip. The results can help us to further assess the risk of HM toxicities to animals and humans via turnip foodstuffs or the potential values of turnip for phytoremediation.

2. Materials and methods

2.1. Soil preparation

To investigate the effects of soil properties on HM accumulation in turnip, we prepared four different HM-contaminated soils and measured their physicochemical properties (Table 1). A total of 15 kg of dried soil of each soil type filled uniform watertight boxes (length: 64 cm; width: 44 cm; height: 26 cm).

2.2. Plant culture and harvest

Turnip seeds (Landrace KTRG-B54) were germinated in the greenhouse and grown for five weeks. Then, seedlings that showed consistent growth were transplanted into prepared boxes, three seedlings to a box. The boxes were placed under natural light and temperature, and watered appropriately. After growing for one month, the root and leaf parts of the plants were collected, and the roots were cleaned with ultrapure water. The samples were dried at 80 °C for 48 h before being weighed. The root and leaf parts of plants growing in different soil types were then used to measure Cu, Mn, Zn and Cd concentrations.

2.3. Detection of HM concentrations

The four HM concentrations were determined according Li et al. (2016). Briefly, approximately 0.5—1.0 g of dried samples were added to the polytetrafluoroethylene digestion tanks. Then, 5 mL of HNO3 was injected, and the tanks were left to stand. After the digestion tanks were treated using the same method. The sample solutions were detected using an inductively coupled plasma mass spectrometer (ICP-MS, Thermo Fisher Scientific, USA), and the HM contents were calculated according to the standard curve.

The standard curve, the content of the respective standard solutions (1 mg mL⁻¹) of Cu, Mn, Zn, and Cd diluted with 5% HNO3 to a 20-mg L⁻¹ stock solution. The stock solution was then prepared into 0, 8, 16, 24, 32, 48, and 64 μg L⁻¹ standard solutions for detection. The standard curve was drawn only when the linear correlation coefficient was greater than 0.99.

2.4. Parameter calculation

To understand the absorption and translocation characteristics of turnip of different HMs, two parameters, namely bioconcentration factor (BCF) and translocation factor (TF), were introduced (He, 2013). BCF represents the ratio of plant HM concentration to the soil HM concentration, while TF is the ratio of HM concentration in the leaf to that in the root.

2.5. Statistical analysis

One-way ANOVA was used to analyse the significant differences among multiple samples. Linear regression and Pearson correlation analyses were performed to identify the correlations. These statistical analyses were performed using SPSS version 18.0.

3. Results

3.1. HM accumulation in turnip plants under different soil types

The concentrations of four HMs in leaves and roots of different samples were measured. The Cu concentrations in turnip roots ranged from 4.90 (Soil C) to 7.70 mg kg⁻¹ DW (Soil D) and 4.22—6.64 mg kg⁻¹ DW in leaves (Fig. 1A). However, no significant

| Parameter | Unit | Soil types |
|-----------|------|------------|
| pH        |      | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| Cu        | g kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| Mn        | g kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| Zn        | g kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| Cd        | g kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| Fe        | g kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| Mg        | cmol kg⁻¹ | Soil A   |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| Ca        | cmol kg⁻¹ | Soil A   |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| K         | mg kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| P         | g kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |
| N         | g kg⁻¹ | Soil A     |
|           |      | Soil B     |
|           |      | Soil C     |
|           |      | Soil D     |

Table 1

Soil compositions of different soil types.
differences among the different plants cultivated in four soil types were observed (Fig. 1A). The root Mn concentrations were 36.23, 25.84, 18.23 and 115.75 mg kg\(^{-1}\) DW in turnip plants in Soils A, B, C and D, respectively (Fig. 1B), while the leaf Mn concentrations were 42.04, 83.55, 54.48 and 570.30 mg kg\(^{-1}\) DW, respectively (Fig. 1B). Both the root and leaf Mn concentrations in turnip plants in Soil D were markedly higher than in those cultivated in the other three soil types (P < 0.05; Fig. 2A). The root Zn concentrations were 47.52, 52.16, 50.26 and 126.00 mg kg\(^{-1}\) DW in turnip plants in Soils A, B, C and D, respectively (Fig. 1B), while the leaf Zn concentrations were 62.39, 91.41, 73.31 and 227.75 mg kg\(^{-1}\) DW, respectively (Fig. 1C). Both the root and leaf Zn concentrations in turnip plants in Soil D were obviously higher than in those cultivated in the other three soil types (Fig. 1C). The root Cd concentrations were 4.94, 1.91, 2.09 and 6.45 mg kg\(^{-1}\) DW in turnip plants in Soils A, B, C and D, respectively (Fig. 1D), while the leaf Cd concentrations were 6.82, 3.76, 5.63 and 18.01 mg kg\(^{-1}\) DW, respectively (Fig. 1D). The leaf Cd concentration in turnip plants in Soil D was significantly higher than in those cultivated in the other three soil types (P < 0.05; Fig. 1D).

3.2. BCFs and TFs of different HMs in turnip plants under different soil types

In order to reflect HM absorption and distribution characteristics in turnips under different soil types, BCF and TF parameters were calculated for each sample. The changes in the BCFs of the four HMs under different soil types are shown in Fig. 2A. The Cu BCFs in turnip leaves ranged from 0.40 (Soil A) to 0.65 (Soil D) (Fig. 2A), without significant differences among different plants cultivated in the four soil types (Fig. 2A). The Mn BCFs in turnip leaves were 0.87, 1.57, 1.13 and 13.58 in Soils A, B, C and D, respectively, and the Mn BCF in turnip leaf in Soil D was significantly higher than in those cultivated in the other three soil types (P < 0.05; Fig. 2A). The Zn BCFs in turnip leaves were 3.53, 6.56, 5.75 and 19.45 in Soils A, B, C and D, respectively, and the Zn BCF in turnip leaf in Soil D was significantly higher than in those cultivated in the other three soil types (P < 0.05; Fig. 2A). The Cd BCFs in turnip leaves were 1.27, 0.71, 1.07 and 3.35 in Soils A, B, C, and D, respectively, and the Cd BCF in the turnip leaf in Soil D was significantly higher than in those cultivated in the other three soil types (P < 0.05; Fig. 2A).

The changes in the TFs of the four HMs under different soil types are shown in Fig. 2B. The Cu TFs in turnip plants ranged from 0.86 (Soil D) to 1.25 (Soil B) (Fig. 2B), without significant differences among the different plants cultivated in the four soil types (Fig. 2B). Similar results were observed in the Zn and Cd TFs in turnip plants, which ranged from 1.45 (Soil C) to 1.81 (Soil B) and from 1.91 (Soil A) to 2.73 (Soil D), respectively (Fig. 2B). The Mn TFs in turnip plants were 1.59, 3.32, 2.98 and 4.94 in Soils A, B, C and D, respectively, and the Mn TF in turnip in Soil D was significantly higher than that cultivated in Soil A (P < 0.05; Fig. 2B).

The differences in the BCFs of the four HMs under the same soil type are shown in Fig. 2C. For plants grown in each soil type, the Zn BCF was the highest followed by the Mn BCF (P < 0.05; Fig. 2C). The BCFs of Cu and Cd were similar in Soils B, C and D, whereas the Cd BCF was significantly higher than that of Cu (P < 0.05; Fig. 2C). The differences in the TFs of the four HMs under the same soil type are shown in Fig. 2D. In Soil A, the TFs of the four HMs were similar (Fig. 2D). The Mn TFs were the highest, and the Cu TFs were the lowest in Soils B, C and D (P < 0.05; Fig. 2D). The TFs of Zn and Cd were similar in Soil B, whereas the Cd TFs were much higher than those of Zn in Soils C and D (P < 0.05; Fig. 2D).

3.3. Correlation analysis between the BCFs and the soil properties

In order to understand the effects of soil factors on HM accumulation in turnip, we performed correlation analysis between soil factors and the BCFs of four HMs. The Cu BCF in turnip leaf was negatively correlated with soil pH (P < 0.05) (Table 2). However, the Mn, Zn and Cd BCFs in the turnip leaves were significantly affected by various soil properties (P < 0.05) (Table 2): they were significantly negatively correlated with soil pH, the contents of total N, total P, available K, Cu, Mn and Zn (excluding Cd BCF) and exchangeable Ca, whereas they had significantly positive correlations with the contents of organic matter, humus and available Fe (P < 0.05 or P < 0.01) (Table 2).
3.4. Correlation analysis between the TFs and the soil properties

We also performed correlation analysis between soil factors and the TFs of four HMs to understand the effects of soil factors on HM translocation from roots to leaves in turnip. The TFs of Cu, Zn and Cd in the turnip plants had no significant correlations with the soil properties (Table 3). However, the TF of Mn in turnip was significantly negatively correlated with soil pH, the contents of total N, available K, Cu and Zn and exchangeable Ca, whereas it showed significantly positive correlations with the contents of organic matter, humus and available Fe ($P < 0.05$ or $P < 0.01$) (Table 3).

Table 2
Results of correlation analysis between the bioconcentration factors and the principal soil properties.

|                      | Cu bioconcentration factor | Mn bioconcentration factor | Zn bioconcentration factor | Cd bioconcentration factor |
|----------------------|---------------------------|----------------------------|---------------------------|----------------------------|
| pH                   | Pearson Correlation       |                            | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.653^c$                 | $0.795^c$                 | $-0.596^e$                 |
| Organic matter       | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $0.021$                    |                           | $0.003$                    |
| Humus                | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $0.313$                    |                           | $0.322$                    |
| Total N              | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.465$                   |                           | $-0.963^c$                 |
| Total P              | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.172$                   |                           | $-0.009$                   |
| Available K          | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.463$                   |                           | $-0.854^c$                 |
| Exchangeable Ca      | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.422$                   |                           | $-0.816^c$                 |
| Exchangeable Mg      | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.037$                   |                           | $-0.512$                   |
| Available Fe         | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $0.569$                    |                           | $0.944^c$                  |
| Available Cu         | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.293$                   |                           | $-0.690^c$                 |
| Available Mn         | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.285$                   |                           | $-0.829^c$                 |
| Available Zn         | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $-0.420$                   |                           | $-0.612^c$                 |
| Available Cd         | Pearson Correlation       |                           | Pearson Correlation       |                            |
| Sig. (2-tailed)       |                           | $0.229$                    |                           | $0.378$                    |

The bold data imply significant correlation.

$^a$ Correlation is significant at the 0.05 level.
$^b$ Correlation is significant at the 0.01 level.
Evidence that the accumulation and transport of different HMs are affected by diverse soil factors has been demonstrated in three ways. First, soil pH was negatively correlated with accumulation of all four HMs (Zn, Mn, Cd, Cu) examined in turnips leaves. These results, which are similar to previous studies (Zhang et al., 2009; Li et al., 2011; Liao et al., 2013; Yu et al., 2014), might be explained by the fact that (1) these metal ions, including Zn and Cd, are more mobile in acidic soil (Velickovic et al., 2016), and (2) the bioavailability of some HMs, such as Cd, decreases as the pH value increases under environments with pH > 6 (Liao et al., 1999).

Second, we found that other soil components showed either positive (e.g. organic matter, humus or available Fe) or negative (e.g. total N or P, available K and exchangeable Ca) correlations with accumulation of Mn, Zn and Cd, but not Cu, in turnip leaves. For example, we found that several exchangeable or available metals can disturb the accumulation of Mn, Zn, and Cd from root to leaf. Both the strong ability of turnips to accumulate and transport HMs is consistent with previous studies on Cd accumulation in turnips (Li et al., 2016, 2017).

These results suggest that Chinese turnips may act as hyperaccumulators. Hyperaccumulators, which are plants suitable for use in phytoremediation, are defined as plants with BCF and TF values higher than one (He, 2013). Previous studies have shown that some Chinese turnip landraces are Cd hyperaccumulators (Li et al., 2016). Our BCF and TF values for Mn and Zn in Chinese turnips leaves still meet the criteria for hyperaccumulators. However, the maximum concentrations of Mn and Zn in turnips are still unknown, and it remains unclear whether turnips can serve as Mn or Zn hyperaccumulators.

Our findings also suggest that in addition to being a candidate plant for phytoremediation of either single or multiple HM pollution, Chinese turnips may be able to play a role in the intake of mineral nutrition, including Cu, Mn, and Zn (see Ma et al., 2016). Functional studies on the regulatory genes of the various HM accumulation characteristics in Chinese turnips are critical, as understanding the molecular mechanisms underlying HM accumulation is a promising method for efficiently dealing with HM pollution and reducing the HM intake risk of crop plants; alternatively, this understanding may increase the efficiency of phytoremediation of HM-contaminated soils through the genetic engineering technology (Liu et al., 2017; Luo et al., 2018).

4. Discussion

In this study, we show that (1) Chinese turnips have a strong ability to accumulate and transport various HMs, and that (2) the accumulation and transport of different HMs are affected by diverse soil factors. The ability of Chinese turnips to accumulate and transport HMs was shown by our calculation of bio-concentration factors and translocation factors. The BCF values show that Chinese turnips accumulate Mn, Zn, and Cd at much higher levels than when they accumulate Cu. When we calculated translocation factors, we found that Chinese turnips have a strong ability to transfer Mn, Zn, and Cd from root to leaf. Both the strong ability of turnips to accumulate and transport HMs is consistent with previous studies on Cd accumulation in turnips (Li et al., 2016, 2017).

| Table 3 | Results of correlation analysis between the translocation factors and the principal soil properties. |
|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
|                             | Cu translocation factor       | Mn translocation factor       | Zn translocation factor       | Cd translocation factor       |
| pH                            | Pearson Correlation –0.139    | –0.684 *                      | –0.366                      | –0.093                      |
|                              | Sig. (2-tailed)               | 0.667                         | 0.014                       | 0.242                       | 0.773                       |
| Organic matter                | Pearson Correlation –0.330    | 0.710 *                      | 0.020                       | 0.457                       |
|                              | Sig. (2-tailed)               | 0.295                         | 0.010                       | 0.950                       | 0.135                       |
| Humus                         | Pearson Correlation –0.331    | 0.708 *                      | 0.019                       | 0.457                       |
|                              | Sig. (2-tailed)               | 0.293                         | 0.010                       | 0.954                       | 0.135                       |
| Total N                      | Pearson Correlation 0.347     | –0.672 *                     | –0.133                      | –0.265                      |
|                              | Sig. (2-tailed)               | 0.269                         | 0.017                       | 0.679                       | 0.405                       |
| Total P                      | Pearson Correlation 0.521     | –0.358                       | 0.053                       | 0.217                       |
|                              | Sig. (2-tailed)               | 0.082                         | 0.253                       | 0.870                       | 0.499                       |
| Available K                  | Pearson Correlation 0.276     | –0.817 *                     | –0.118                      | –0.425                      |
|                              | Sig. (2-tailed)               | 0.385                         | 0.001                       | 0.714                       | 0.168                       |
| Exchangeable Ca              | Pearson Correlation 0.301     | –0.790 *                     | –0.089                      | –0.436                      |
|                              | Sig. (2-tailed)               | 0.342                         | 0.002                       | 0.782                       | 0.157                       |
| Exchangeable Mg              | Pearson Correlation 0.539     | –0.343                       | 0.150                       | –0.333                      |
|                              | Sig. (2-tailed)               | 0.071                         | 0.275                       | 0.641                       | 0.290                       |
| Available Fe                 | Pearson Correlation –0.197    | 0.860 *                      | 0.203                       | 0.366                       |
|                              | Sig. (2-tailed)               | 0.539                         | 0.000                       | 0.527                       | 0.241                       |
| Available Cu                 | Pearson Correlation 0.367     | –0.683 *                     | –0.003                      | –0.448                      |
|                              | Sig. (2-tailed)               | 0.240                         | 0.014                       | 0.992                       | 0.144                       |
| Available Mn                 | Pearson Correlation 0.470     | –0.475                       | –0.017                      | –0.230                      |
|                              | Sig. (2-tailed)               | 0.123                         | 0.119                       | 0.959                       | 0.471                       |
| Available Zn                 | Pearson Correlation 0.099     | –0.801 *                     | –0.128                      | –0.450                      |
|                              | Sig. (2-tailed)               | 0.799                         | 0.002                       | 0.693                       | 0.143                       |
| Available Cd                 | Pearson Correlation 0.014     | –0.034                       | 0.173                       | –0.263                      |
|                              | Sig. (2-tailed)               | 0.966                         | 0.917                       | 0.591                       | 0.410                       |

The bold data imply significant correlation.

*Correlation is significant at the 0.05 level.

*Correlation is significant at the 0.01 level.
reported that soil environment can affect the transport of metal ions in plants (Huang et al., 2012), the underlying reasons for this effect are unclear. One potential explanation for our findings is that a special Mn transport mechanism exists in turnip.

In summary, the present study indicates that Chinese turnips have a relatively strong ability to absorb various HMs and transport them to leaves, and that soil conditions affect the accumulation and transport of these HMs. These findings have several potential applications, including the use of turnips in phytoremediation, intake of mineral nutrition, and food safety. Furthermore, understanding the molecular mechanisms underlying the HM accumulation characteristics of these plants may be useful for genetic engineering technology. Importantly, the assessment of these practical applications should be conducted with a full knowledge of plant—soil parameters. Although the effect of each soil factor on HM accumulation requires further verification, some agricultural measures may be used to regulate the HM accumulation in turnips. For example, N, P, K and Ca fertilizers may help reduce HM accumulation in turnips, whereas organic matter and Fe fertilizer may have the opposite effects.

Author contributions
X. Li designed the experiments; B.Q. Li, D. Chen, and X. Li performed the experiments; X. Li analyzed the data and wrote the manuscript; Y. P. Yang revised the manuscript.

Conflict of interest
The authors declare no potential conflict of interest.

Acknowledgments
This work was financially supported by the Western Youth Project B of the “Light of West China” Program of Chinese Academy of Sciences (Y7260411W1) and the Yunnan Applied Basic Research Projects (2018FB068).

Appendix A. Supplementary data
Supplementary data to this article can be found online at https://doi.org/10.1016/j.pld.2019.06.006.

References
Arshad, M., Ali, S., Noaman, A., Ali, Q., Rizwan, M., Farid, M., Irshad, M.K., 2016. Phosphorus amendment decreased cadmium (Cd) uptake and ameliorates chlorophyll contents, gas exchange attributes, antioxidants, and mineral nutrients in wheat (Triticum aestivum L.) under Cd stress. Arch. Agron Soil Sci. 62, 533—546.
Arthur, E., Crews, H., Morgan, C., 2000. Optimizing plant genetic strategies for minimizing environmental contamination in the food chain. Int. J. Phytoremediation 2, 1—21.
Benis, M.R.S., Hassani, A.H., Nouri, J., Mehregan, I., Moattar, F., 2015. The effect of soil amendments and root plant species on the absorption of heavy metals in industrial sewage contaminated soil: a case study of Eshtehrad Industrial Park. Bulg. Chem. Commun. 47, 211—219.
Bingham, F.T., Page, A.L., Mahler, R.J., Ganje, T.J. 1975. Growth and cadmium accumulation of plants grown on a soil treated with a cadmium-enriched sewage sludge. J. Environ. Qual. 4, 207—211.
Brown, G.E., Foster, A.L., Ostergren, J.D., 1999. Mineral surfaces and bioavailability of heavy metals: a molecular-scale perspective. Proc. Natl. Acad. Sci. U.S.A. 96, 3388—3395.
Bueno-Gonzalez, L., Orozco-Villafuerte, J., Cruz-Sosa, F., Barrera-Diaz, C.E., Vernon-Carter, E.J., 2010. Prosopis laevigata has a potential chromium (VI) and cadmium (II) hyperaccumulator desert plant. Bioreourc. Technol. 101, 5862—5867.
Che, J., Yanaji, N., Shao, J.F., Ma, J.F., Shen, R.F., 2016. Silicon decreases both uptake and root-to-shoot translocation of manganese in rice. J. Exp. Bot. 67, 1535—1544.
Wei, S.H., Zhou, Q.X., Koval, P.V., 2006. Flowering stage characteristics of cadmium hyperaccumulator Solanum nigrum L. and their significance to phytoremediation. Sci. Total Environ. 369, 441–446.

Xie, W.J., Che, L., Zhou, G.Y., Yang, L.N., Hu, M.Y., 2016. The bioconcentration ability of heavy metal research for 50 kinds of rice under the same test conditions. Environ. Monit. Assess. 188, 675.

Yin, L.Y., Cheng, Y.W., Espinasse, B., Colman, B.P., Auffan, M., Wiesner, M., Rose, J., Liu, J., Bernhardt, E.S., 2011. More than the ions: the effects of silver nanoparticles on Lolium multiflorum. Environ. Sci. Technol. 45, 2360–2367.

Yu, S.J., Gao, S.F., Qu, Y.M., Chen, Y.H., Wang, G., 2014. Toxicity and its threshold of cadmium to tomato roots in different soils. J. Agro-Environ. Sci. 33, 640–646.

Zhang, H.T., Li, B., Liu, J.F., Ma, Y.B., Wei, D.P., 2009. Major soil factors controlling nickel toxicity to tomato in a wide range of Chinese soils and the predictable models. Asian J. Ecotoxicol. 4, 569–576.

Zhou, H., Yang, W.T., Zhou, X., Liu, L., Gu, J.F., Wang, W.L., Zou, J.L., Tian, T., Peng, P.Q., Liao, B.H., 2016. Accumulation of heavy metals in vegetable species planted in contaminated soils and the health risk assessment. J. Environ. Res. Public Health 13, 289.