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Assessment of potential soybean cadmium excluder cultivars at different concentrations of Cd in soils

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ABSTRACT

The selection of cadmium-excluding cultivars has been used to minimize the transfer of cadmium into the human food chain. In this experiment, five Chinese soybean plants were grown in three soils with different concentrations of Cd (0.15, 0.75 and 1.12 mg/kg). Variations in uptake, enrichment, and translocation of Cd among these soybean cultivars were studied. The results indicated that the concentration of Cd in seeds that grew at 1.12 mg/kg Cd in soils exceeded the permitted maximum levels in soybeans. Therefore, our results indicated that even some soybean cultivars grown on soils with permitted levels of Cd might accumulate higher concentrations of Cd in seeds that are hazardous to human health. The seeds of these five cultivars were further assessed for interactions between Cd and other mineral nutrient elements such as Ca, Cu, Fe, Mg, Mn and Zn. High Cd concentration in soil was found to inhibit the uptake of Mn. Furthermore, Fe and Zn accumulations were found to be enhanced in the seeds of all of the five soybean cultivars in response to high Cd concentration. Cultivar Tiefeng 31 was found to fit the criteria for a Cd-excluding cultivar under different concentrations of Cd in soils.

Introduction

With the continuing development of industrial and agricultural production, population expansion, and insufficiency of pollution controls has come a large amount of heavy metals entering soil (Zhou and Song, 2004). Soil pollution by anthropogenic activities such as mining, refining, and use of industrial wastewater for irrigation has lead to polluted soils containing Cd. Cadmium (Cd) is one of the most toxic and mobile of all the heavy metals, impacting on human and environmental health (Murakami et al., 2008). Cadmium present in contaminated agricultural soils can enter into crops and ultimately pose high threats to human health *via* food consumption (Simmons et al., 2005). It is also a potential factor in cardiovascular diseases, reproductive impairments and cancers (An et al., 2008). In China, Cd has posed a serious problem for safe crop and food production, and at least 13,330 hm^2 of farmland involving more than 11 provinces in China have been contaminated by varying levels of Cd (Zhang and Huang, 2000). Therefore, it is urgent to establish remediation programs to decrease the risk to human health through the soil-food–human pathway. Especially in China, a country

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with the largest population in the world, Cd contamination in soils has become one of the most important barriers to agricultural sustainability (Zhang and Huang, 2000; Chen et al., 2007).

Recently, great strides have been concerning various techniques of remediation of Cd-contaminated soils. Traditional methods of dealing with metal pollution involve either the extremely costly process of removal and burial or simply isolation of the contaminated sites (Nanda Kumar et al., 1995). However, these methods have their drawbacks in terms of effectiveness, duration and economics (Liu et al., 2003). Phytoremediation *i.e.*, using plants to remove Cd from contaminated soil, has developed as an emerging and promising technology (Zhou and Song, 2004). Although phytoremediation by hyperaccumulating wild plants has been proposed as an environmentally friendly restoration technology for Cd-contaminated soils, the small biomass of hyperaccumulators and accumulators and their limited removal efficiencies and limited suitability to various environments pose a major challenge to wide application of this technology (Murakami and Ae, 2009). Previous studies have highlighted that, even at low levels, soil Cd contamination could pose a significant risk to human health through the soil–plant–human exposure pathway (Li et al., 2009). Thus, it is important to select Cd-excluding cultivars with high biomass that are also suitable for local weather conditions and cultivation techniques (Hernandez-Allica et al., 2008). Cd-excluding cultivars are those cultivars accumulating low levels of Cd that are safe for consumption of their edible tissues when grown in slightly or moderately Cd-polluted soils.

The heavy metal forms in artificially simulated soils equilibrated for short times do not reflect those in industrially or naturally contaminated soils (Komarek et al., 2007). Therefore, in this study, we used industrially contaminated soils containing Cd.

Soybean (*Glycine max* L.) is one of the most widespread crops (*e.g.*, in USA, Argentina and China) and is an excellent source of plant protein. In a previous work, we found that Chinese soybeans tend to have a low Cd accumulation under low Cd stress (1.0 mg/kg). Thus, it is probable that Cd-excluding cultivars of Chinese soybean cultivars could be selected that would effectively limit the extent of Cd contamination in the seeds.

The objectives in this paper were to assess the capability for uptake, enrichment, and translocation of cadmium among soybean cultivars and identify potential Cd excluder cultivars for food safety.

1. Materials and methods

1.1. Experimental site and soil characterization

The pot-culture experiment was arranged and conducted in open field conditions in the Shenyang Station of Experimental Ecology, Chinese Academy of Sciences (41°31′N and 123°41′E), which is located to the south of Shenyang City, Liaoning Province, China. The experiment was carried out from June 20 to October 15, 2010 and the average temperature was 15–25°C during the 4 months at the station. The tested soils were collected from the surface layer (0–20 cm) of three fields without or with low to moderate Cd concentration: Shenyang Station of Experimental Ecology (A, without Cd pollution in soils), Chinese Academy of Sciences, Fengcheng Qingchengzi Mining Area (B, with low Cd contamination), and Shenyang Zhangshi Irrigation Area (C, with moderate Cd contamination). The main sources of Cd appeared to be mining wastes (B) and irrigation by industrial wastewater containing high levels of heavy metals (C). The soil samples were air-dried and ground to pass a 2-mm sieve, then 2.5 kg of soil was filled into each plastic pot (Φ = 20 cm, H = 15 cm). Table 1 shows the details of the basic properties of the soils. The percentage of soil organic matter was determined according to standard methods (Lu, 1999). The pH was measured in 1:5 of soil: water suspension in triplicate (Salazar et al., 2012). Other characteristics were analyzed according to routine analytical methods for agricultural chemistry in soils (Lu, 1999).

We selected five Chinese soybeans (Shennong 10, Tiefeng 31, Tiedou 36, Tiefeng 37 and Liaodou 21) as cultivars in the experiment. These five soybean seeds were purchased from Doufeng Company in Shenyang, China, and selected as a result of our previous research showing that the five cultivars could accumulate comparatively low Cd in their seeds. The seeds were sterilized in 2% (V/V) hydrogen peroxide for 10 min and then washed several times with distilled water. Six seeds were sown per pot in June 2010. The pots were allowed to grow in open field conditions and no fertilizers were applied. Tap water was used to reach 70%–80% of the field water-holding capacity and maintain the soil moisture by everyday watering, and a dish was placed under each pot to gather potential leachate during the experimental period. Within 14 d after germination, the plants were thinned to three per pot. The selected plants were about 6–7 cm high with two leaves. The tested plants were harvested at the seed-maturity stage.

1.2. Sample preparation and analysis

Plants were first washed thoroughly three times with running tap water, followed by deionized water for about 3 min. The plants were separated into roots, stems, leaves, pods and

Table 1 – Physicochemical property and total Cd concentration in different soils before sowing.

Soil property	Soil		
	A	B	C
Type	Meadow	Meadow	Meadow
pH	6.5	6.6	6.0
CEC (cmol/kg)	20.7	19.7	21.6
Organic matter (%)	1.94	1.25	1.37
Total-N (%)	0.89	1.12	1.08
Available-P (mg/kg)	0.35	0.43	0.46
Available-K (mg/kg)	10.96	12.32	11.76
TOC (%)	1.52	1.76	1.69
Total Cd (mg/kg)	0.15	0.75	1.12

A: Shenyang Station of Experimental Ecology; B: Fengcheng Qingchengzi Mining Area; C: Shenyang Zhangshi Irrigation Area.

seeds. The plants were dried at 105°C for 5 min, and further at 70°C to constant weight in an oven. The dried plants were weighed to determine the biomass and ground into powder form. Soil samples were air-dried and ground using a mortar and pestle, and then passed through a 60 μm sieve. A Cd analysis of the soils was performed by an extraction method with 0.1 M HCl (1:5 *w*/V, 1 hr shaking horizontally) to analyze the exchangeable Cd fraction in soil (Murakami and Ae, 2009).

The soil samples (0.50 g) and plant samples (0.50 g) were digested with a solution containing 87% of concentrated HNO_3 and 13% of concentrated $HClO_4$ (*V/V*) (Wei et al., 2005). The concentrations of exchangeable Cd in soil and Cd, Fe, Zn, Cu, Mn, Ca and Mg in seeds of soybean cultivars were determined by using an inductively coupled plasma-atomic emission spectrometer (Thermo Electron, ICP-AES, USA). Certified reference material for soybean (GBW10013, Qinghai Province, China) was used to check the recovery of metals from the plants. Geochemical standard samples were used in this study to validate the soil analyses. The recovery rates for the certified reference soybean material and geochemical standard samples were 91%–101% and 93%–102%, respectively. The coefficient of variation of replicate analyses was calculated for different determinations, and variations were found to be less than 15%.

1.3. Safety standard for Cd-excluding cultivars and statistical analysis

The National Food Safety Standard of China (NFSSC) was employed to measure safety regarding consumption of Chinese soybean seeds grown in Cd-contaminated soils. The maximum permissible concentration (MPC) for safe consumption of Cd in soybeans is 0.2 mg/kg dry weight (DW) according to NFSSC (GB2762-2012) (Liu et al., 2009).

The enrichment factor (EF) (Chen et al., 2004; Liu et al., 2009) was calculated to assess the potential of a plant to accumulate heavy metals using the following equations:

$$\mathrm{EF} = C_{\mathrm{seed}}/C_{\mathrm{soil}}$$

where, C_{seed} is the average Cd concentration (DW) of the seed of each cultivar, and C_{soil} is the total concentration of Cd in the corresponding soil.

To evaluate the transfer potential of Cd from root to seed, we calculated the translocation factors (TF) (Baker and Whiting, 2002) as follows:

$$\mathrm{TF} = C_{\mathrm{seed}}/C_{\mathrm{root}}$$

where, C_{root} is the average Cd concentration (DW) of the root of each corresponding cultivar.

Based on the information from previous literature (Liu et al., 2009; Li et al., 2012; Zhan et al., 2013; Zhi et al., 2014), in this research, we used 4 standards to select Cd-excluding cultivars for food safety: (1) Cd concentration in their edible organs should not exceed 0.2 mg/kg DW (MPC) of the NFSSC (GB2762-2012); (2) EF values can indicate the potential of cultivars to accumulate Cd, and lower EF values show lower accumulation of Cd for the cultivar. Thus, EF lower than 1.0 was used as a criterion for a Cd-excluding cultivar; (3) TF values indicated the capacity of cultivars to transport Cd from root to seed. So TF < 1.0 should be another standard for Cd-excluding cultivar; (4) to be a Cd-excluding cultivar, the yield should not decrease when growing in Cd-polluted soils.

Data were analyzed using Excel 2007 and SPSS 18.0. The pots were arranged in a complete randomized block design with three replicates per treatment to minimize experimental errors. All values were expressed as mean ± standard deviation (S.D.) of three replicates. Differences among treatments and cultivars were considered significant at $p < 0.05$. Statistical analyses were made with one-way ANOVA with Duncan's multiple range tests to separate means. All results were expressed on the basis of dry weight.

2. Results

2.1. Cadmium tolerance in the tested soybean cultivars

The biomasses of seeds and roots of the five soybean cultivars grown on the three soils at harvest are shown in Table 2. For each soil, the seed biomass of the cultivars varied as follows: Liaodou 21 < Tiefeng 37 < Tiedou 36 < Tiefeng 31 < Shennong 10. The seed biomass of Shennong 10, which had the maximum seed biomass in C, was found to be 1.42 times as high as that of Liaodou 21. The seed biomass of the five soybean cultivars in the soils B and C did not decrease significantly ($p > 0.05$) compared with those in A (control). Moreover, the seed biomass of Shennong 10 and Tiefeng 31 even increased in soils B and C, and the highest root biomass was found in Shennong 10 in each soil. Meanwhile, the cultivars appeared normal and no obvious toxicity symptoms could be observed in plants grown in each soil.

2.2. Cd concentration of the five soybean cultivars

We observed significant differences ($p < 0.05$) in seed Cd concentrations among the five soybean cultivars, which were tested in the soils of Shenyang Station of Experimental Ecology (A), Fengcheng Qingchengzi Mining Area (B), and Shenyang Zhangshi Irrigation Area (C) (Table 2). The Cd concentration in seeds from the cultivars ranged from 0.05 to 0.17; 0.12 to 0.23; and 0.19 to 0.57, with mean Cd concentrations of 0.10, 0.18 and 0.34 mg/kg DW, respectively. The seed Cd concentrations in Tiefeng 37 and Liaodou 21 exceeded the MPC value in B soil. In C soil, the Cd concentrations in seeds of all tested cultivars were higher than the MPC value except for Tiefeng 31. The seed Cd concentrations of Tiefeng 31 were significantly lower than those of the other cultivars in each soil. Similar to the seed Cd concentrations of the soybeans, there were significant differences ($p < 0.05$) in root Cd concentrations among the five soybean cultivars in the three soils. The root Cd concentration of Tiefeng 31 was the lowest in each soil.

2.3. Analysis of pH, OM and exchangeable Cd in soils

Exchangeable Cd concentration, pH and OM (%) in soils B and C before sowing and after harvesting are shown in Table 3. In the soils of B, the soil pH after harvesting did not vary significantly

Table 2 – Biomass dry weight and Cd concentration measured in seeds and roots of five soybean cultivars grown in different soils contaminated with Cd.

Cultivar	A		B		C	
	Biomass dry weight (g/pot)	Cd (mg/kg)	Biomass dry weight (g/pot)	Cd (mg/kg)	Biomass dry weight (g/pot)	Cd (mg/kg)
Seed						
Shennong 10	44.2 ± 0.01a	0.09 ± 0.10a	45.8 ± 0.03a	0.15 ± 0.02a	46.3 ± 0.01a	0.34 ± 0.01a
Tiefeng 31	41.7 ± 0.03a	0.05 ± 0.02a	43.6 ± 0.01a	0.12 ± 0.03a	44.7 ± 0.02a	0.19 ± 0.01b
Tiedou 36	40.8 ± 0.02ab	0.09 ± 0.09b	37.4 ± 0.03b	0.18 ± 0.01ab	36.3 ± 0.02b	0.25 ± 0.01b
Tiefeng 37	39.1 ± 0.01b	0.11 ± 0.05b	38.5 ± 0.02b	0.21 ± 0.01b	38.3 ± 0.01b	0.57 ± 0.03c
Liaodou 21	35.4 ± 0.01b	0.08 ± 0.03c	33.6 ± 0.04c	0.23 ± 0.01b	32.7 ± 0.04b	0.36 ± 0.02c
Root						
Shennong 10	6.7 ± 0.04a	0.20 ± 0.04a	6.5 ± 0.02a	0.43 ± 0.03a	7.1 ± 0.03a	0.54 ± 0.01a
Tiefeng 31	6.3 ± 0.01a	0.16 ± 0.05a	6.5 ± 0.01a	0.41 ± 0.02b	6.9 ± 0.02a	0.48 ± 0.01a
Tiedou 36	5.7 ± 0.02ab	0.17 ± 0.01b	5.2 ± 0.01ab	0.38 ± 0.02ab	4.9 ± 0.01ab	0.52 ± 0.02ab
Tiefeng 37	5.3 ± 0.05b	0.19 ± 0.02a	5.1 ± 0.01ab	0.55 ± 0.05b	4.7 ± 0.03ab	0.77 ± 0.03a
Liaodou 21	4.9 ± 0.02b	0.17 ± 0.03b	4.5 ± 0.04b	0.42 ± 0.06a	4.3 ± 0.02b	0.69 ± 0.03b

A: Shenyang Station of Experimental Ecology; B: Fengcheng Qingchengzi Mining Area; C: Shenyang Zhangshi Irrigation Area.
Data are presented as mean ± SD (n = 3).
Data in the same column followed by the same letter are not significantly different at $p < 0.05$ based on Duncan's multiple-comparison test.

($p > 0.05$) compared with that before sowing (Table 3). The same trend was found for OM. The post-harvesting soil exchangeable Cd concentrations decreased in the following order: Shennong 10 > Liaodou 21 and Tiedou 36 > Tiefeng 31 and Tiefeng 37 (Table 3).

In the soils of C, we did not find significant changes in soil pH and OM before sowing and after harvesting (Table 3). Similarly, the post-harvesting soil exchangeable Cd concentrations also decreased in the following order: Shennong 10 > Liaodou 21 and Tiedou 36 > Tiefeng 31 and Tiefeng 37 (Table 3).

Correlation coefficients between concentration of exchangeable soil Cd fraction, soil pH and OM are shown in Table 4. The pH was significantly correlated with exchangeable Cd in B and C soils. The OM percentage was also significantly correlated with exchangeable Cd in B and C soils.

2.4. *Enrichment factor and translocation factor for five soybean cultivars*

The EF value showed a significant ($p < 0.05$) difference among different soybean cultivars in A, B and C soils, ranging from 0.33 to 0.60, from 0.16 to 0.31 and from 0.17 to 0.51, with the mean of 0.53, 0.24 and 0.30, respectively (Table 5). The average EF values in the five soybean cultivars were <1.0, and the lowest EF was found in Tiefeng 31 for each soil.

In A, B and C soils, the TF values in the five soybean cultivars varied from 0.31 to 0.58, from 0.29 to 0.55 and from 0.40 to 0.74, with mean values of 0.47, 0.41 and 0.55, respectively (Table 5). The average of TF values of all soybean cultivars was lower than 1.0, indicating low Cd accumulation from soil and low Cd transfer potential from root to seed.

Table 3 – Chemical characters in different soils before sowing and after harvesting. Note: (B) Fengcheng Qingchengzi Mining Area and (C) Shenyang Zhangshi Irrigation Area.

Treatment	pH value		Organic matter (%)		Exchangeable Cd fraction (mg/kg)	
	B	C	B	C	B	C
Before sowing	6.6 ± 0.21a	6.0 ± 0.11a	1.25 ± 0.04a	1.37 ± 0.19a	0.32 ± 0.07a	0.52 ± 0.33a
After harvesting						
Shennong 10	6.3 ± 0.03a	5.7 ± 0.32a	1.04 ± 0.02c	1.12 ± 0.21c	0.12 ± 0.36c	0.25 ± 0.89c
Tiefeng 31	6.4 ± 0.38a	5.9 ± 0.25a	1.09 ± 0.17b	1.19 ± 0.39b	0.25 ± 0.15ab	0.45 ± 0.81ab
Tiedou 36	6.3 ± 0.65a	6.0 ± 0.51a	1.10 ± 0.67ab	1.15 ± 0.24b	0.17 ± 0.25b	0.38 ± 0.67b
Tiefeng 37	6.5 ± 0.27a	5.8 ± 0.22a	1.12 ± 0.35ab	1.17 ± 0.22b	0.22 ± 0.57b	0.34 ± 0.51b
Liaodou 21	6.3 ± 0.88a	5.8 ± 0.40a	1.08 ± 0.36b	1.16 ± 0.06b	0.16 ± 0.36b	0.29 ± 0.32c

B: Fengcheng Qingchengzi Mining Area; C: Shenyang Zhangshi Irrigation Area.
Data are presented as mean ± SD (n = 3).
Data in the same column followed by the same letter are not significantly different at $p < 0.05$ based on Duncan's multiple-comparison test.

Table 4 – Correlation coefficient between soil pH, OM (%) and exchangeable soil Cd fraction in different soils.

	Cd_{Exch}	pH	OM
B			
pH	0.75 **	1	
OM	0.72 **	0.68 **	1
C			
pH	0.78 **	1	
OM	0.81 **	0.46 *	1

B: Fengcheng Qingchengzi Mining Area; C: Shenyang Zhangshi Irrigation Area; Exch: exchangeable soil Cd fraction.
* $p < 0.05$.
** $p < 0.01$.

2.5. *Effects of Cd on mineral nutrient elements of five soybean cultivars*

The concentrations of the six mineral nutrient elements (Ca, Cu, Fe, Mg, Mn and Zn) in the seeds of the five cultivars are shown in Fig. 1. Manganese concentrations were lower relative to other nutrients in the seeds of the tested soybean cultivars in response to Cd treatments. On average, the seed Mn concentration was found to decrease by 17.4% and 33.8% in B and C soil, respectively in these cultivars. Iron and zinc concentrations increased with increasing Cd concentration in all of the five cultivars. In comparison with CK, the iron concentration of seeds increased by 13.1% and 33.9%, in B and C soil, respectively. Meanwhile, the Zinc concentration of seeds increased by 24.6% and 40.1% compared with the control, respectively. There was no significant difference in the concentration of the other three elements in the five soybean cultivars in the soil of B and C. The response of the concentration of nutrients to Cd in the five cultivars generally showed the following pattern: Ca > Mg > Fe > Zn > Mn > Cu.

3. Discussion

In recent years, Cd contamination in agricultural soils has received global interest (Zhou and Huang, 2001), mainly because Cd shows strong toxicity to human health. Therefore it is significant to select Cd-excluding crop species or cultivars with high yield and strong disease-resistance for food safety. In this study, the five soybean cultivars did not significantly decrease in seed and root biomass under Cd treatment, and no symptoms of toxicity were found in the five soybean cultivars. The seed biomass of Shennong 10 and Tiefeng 31 even increased when they were grown in soils of B and C (compared with the control). The results indicated that the tested soybean cultivars had considerable tolerance to Cd-polluted soil. Similar positive and neutral responses of biomass to heavy metal stress have also been observed in paddy rice (Yu et al., 2006), asparagus bean (Zhu et al., 2007), tomato (Zhu et al., 2006), welsh onion (Li et al., 2012) and other crop species. The positive responses of plant growth under low cadmium treatments could be due to the fact that metal ions can serve as activators of enzyme(s) in cytokinin metabolism, which accelerates the growth of plants (Shentu et al., 2008). Therefore, further studies are required to investigate the positive and neutral responses of plant growth under heavy metal stress.

Our results identified Shennong 10, Tiefeng 31 and Tiedou 36 soybean cultivars as Cd-excluding cultivars, where Cd concentration (<0.2 mg/kg) in edible parts was regarded as the standard, in the soil of B (Table 2). Moreover, the EF and TF were found to be lower than 1.0 in these cultivars (Table 5). As per our fourth standard, Tiedou 36 could not be considered a Cd-excluding cultivar due to its low yield due to Cd toxicity as measured by seed biomass. In C soil, the Cd concentrations in seeds of all tested cultivars were higher than the MPC value except for Tiefeng 31. The phenomenon indicated that although even when grown on low-Cd contaminated soils, some Chinese soybean cultivars might have high Cd accumulation that would cause harm to human health. Several similar results have been reported by prior researchers (Peralta-Videa et al., 2009; Li et al., 2012).

The concentration of exchangeable Cd showed significant ($p < 0.01$) positive correlation with pH and OM in B and C soils. These results indicate that pH and OM are important factors in B and C soils' exchangeable Cd concentration, and they would be associated with the bioavailability of Cd for plants. Similar responses of Cd have also been found by Kashem and Singh (2001) and Salazar et al. (2012).

The soil quality was important for Cd-excluding soybean cultivars. The concentrations of Zn and Fe in the seeds of selected soybean cultivars were found to increase with excessive Cd application (Fig. 1). These results are similar to the reports by Salt and Kramaer (2000) and Zhu et al. (2007).

Table 5 – Enrichment Factor (EF) and Translocation Factor (TF) in five soybean cultivars in the three soils.

Cultivar	EF			TF		
	A	B	C	A	B	C
Shennong10	0.60 ± 0.14a	0.20 ± 0.11b	0.30 ± 0.03b	0.45 ± 0.17b	0.35 ± 0.16b	0.63 ± 0.13b
Tiefeng 31	0.33 ± 0.27c	0.16 ± 0.07c	0.17 ± 0.11c	0.31 ± 0.35c	0.29 ± 0.12c	0.40 ± 0.15c
Tiedou 36	0.60 ± 0.21a	0.24 ± 0.41b	0.22 ± 0.14c	0.53 ± 0.28a	0.47 ± 0.13b	0.48 ± 0.17c
Tiefeng 37	0.58 ± 0.29a	0.28 ± 0.19a	0.51 ± 0.07a	0.58 ± 0.69a	0.38 ± 0.04b	0.74 ± 0.14a
Liaodou 21	0.53 ± 0.55b	0.31 ± 0.15a	0.32 ± 0.15b	0.47 ± 0.48b	0.55 ± 0.08a	0.52 ± 0.07bc

A: Shenyang Station of Experimental Ecology; B: Fengcheng Qingchengzi Mining Area; C: Shenyang Zhangshi Irrigation Area.
Data are presented as mean ± SD ($n = 3$).
Data in the same column followed by the same letter are not significantly different at $p < 0.05$ based on Duncan's multiple-comparison test.

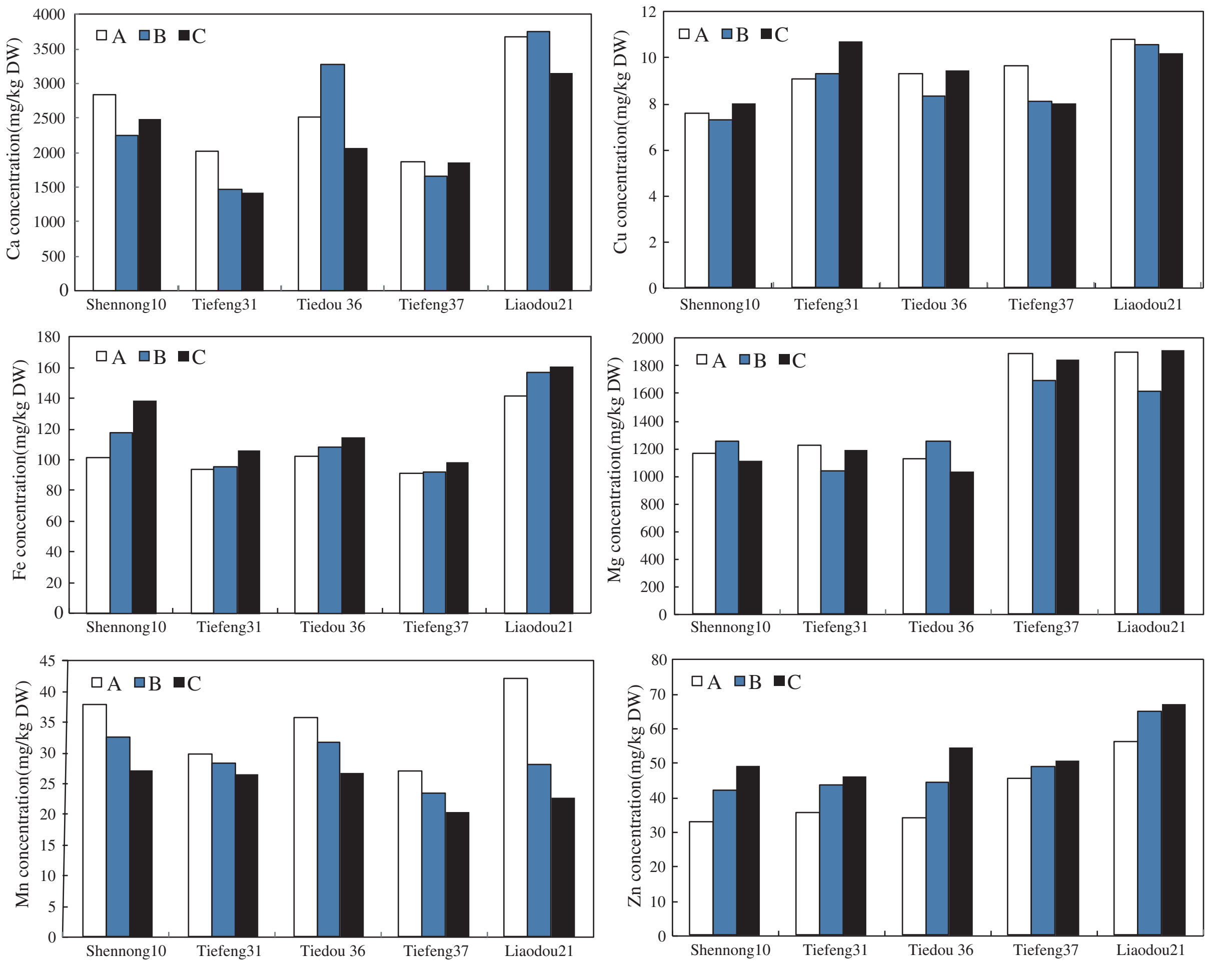

Fig. 1 – Concentration of Ca, Cu, Fe, Mg, Mn and Zn (mg/kg, DW) corresponding to different soybean seed cultivars. A: Shenyang Station of Experimental Ecology; B: Fengcheng Qingchengzi Mining Area; C: Shenyang Zhangshi Irrigation Area.

Moraghan (1993) also reported that Cd uptake by flax seed was increased by adding Zn to soils. Lasat et al. (2000) have found *ZNT1* — genes of the Zn transporter, which can enhance the translocation of Cd in crops. The mechanisms of the long distance transport of Cd in crops may be the same as those of Zn (Liu et al., 2003).

The concentrations of Mn in the seeds of selected soybean cultivars were observed to decrease with excessive Cd application. Nevertheless, Liu et al. (2008) found that Cd inhibited the accumulation of Ca, Mg, Mn and Zn in shoots of Chinese cabbage, and the inhibition degree differed among different cultivars. In addition, contrasting results were reported in the interaction between Cd and mineral nutrient element uptake in cultivars (Huang et al., 2008). Oliver et al. (1994) also found that uptake and translocation of Cd from roots to shoots in plants might be interfered with by Zn. The contradictions may be attributable to differences among cultivars, differences in metals, different mechanisms in Cd uptake and distribution, and the interactions between cultivars and metals (Liu et al., 2003). Therefore, the changes in the absorption and tranlocation of other nutrient elements in crops caused by Cd pollution are very complicated. Further studies are needed to determine the complementary mechanisms of mineral ion uptake into cells, and to examine the interactions between Cd and mineral nutrient elements to select Cd-excluding cultivars with high uptake of desirable microelements.

4. Conclusions

In this research, Cd concentrations in seeds showed significant ($p < 0.05$) differences among the five studied soybean cultivars in response to the three soils. Our study indicated that the cultivar Tiefeng 31 could be selected as a Cd-excluding cultivar. Our results also showed that Cd concentration in soil disturbed the uptake of mineral nutrient elements by inhibiting the uptake of Mn and by enhancing the accumulation of Zn and Fe in the seeds of the five soybean cultivars. Screening of Cd-excluding cultivars is an effective way to minimize the transfer of cadmium into the human food chain, but even when growing in low-Cd contaminated soils, some Chinese soybean cultivars might have high Cd accumulation, and the use of Cd-excluding cultivars would not ensure food safety.

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