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RESEARCH ARTICLE

Low-Cd tomato cultivars (*Solanum lycopersicum* L.) screened in non-saline soils also accumulated low Cd, Zn, and Cu in heavy metal-polluted saline soils

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Abstract
Many reclaimed tidal flat soils feature high salinity and heavy metal (HM) accumulation. Consumption of vegetables cultivated in this type of cropland may cause health risks. Low-Cd tomato cultivars (*Solanum lycopersicum* L.) were identified in non-saline soil in our previous studies (Tan et al. 2014). However, further research should determine whether these low-Cd cultivars will maintain in the repeatability and stability in saline soil and whether they have low accumulation abilities for accompanying metals (such as Zn and Cu). A soil-pot trial was implemented to measure Cd, Zn, and Cu concentrations in low- and high-Cd cultivars of both common and cherry-type tomatoes grown on HM-polluted reclaimed tidal flat saline soil. Then, cultivar differences in dissolution of Cd, Zn, and Cu in soil and their uptake and redistribution in plants were analyzed. Results showed that the cherry type accumulated more Cd, Zn, and Cu than the common type. Low-Cd cultivars of both types in saline soil accumulated low concentrations of Cd, Zn, and Cu in fruits. Low HM accumulation in fruits is partly attributed to a low root/shoot (*R*/*S*) biomass ratio. Low amounts of soil HMs were dissolved because of the low level of rhizosphere organic compounds, which possibly decreased HM uptake by the roots. Low-Cd cultivars of both tomato types had a higher ability to retain HMs in the roots than their high-Cd cultivars. These findings may provide a scientific guidance for the safe cultivation of HM-polluted saline soils.

Keywords Common and cherry tomato · Heavy metals · Change dissolution by mobilization
Redistribution by distribution or partitioning

Introduction

With the rapid urbanization and degradation of soil environment, worldwide arable lands have continually declined (Jiao et al. 2012; Zarkovic and Blagojevic 2007). Coastal tidal flats serve as an important cultivated land reserve resource that gains increasing attention (Li et al. 2014). However, large amounts of heavy metal (HM) pollutants from industrial development in coastal cities are discharged and accumulated in tidal flat sediments (Li et al. 2016; Li et al. 2011). Therefore, many reclaimed tidal flat soils feature high salinity and HM accumulation (Guo et al. 2016; Yang et al. 2016). Consumption of crops grown on reclaimed farmland has become an important part of coastal urban diet; however, vegetables cultivated in this type of cropland may accumulate high amount of HMs and pose serious health problems when consumed by humans (Li et al. 2012; Xu et al. 2017; Zhang et al. 2018). Soil salinity significantly enhances HM accumulation in crops (Li et al. 2010; Manousaki et al. 2008; Ondrasek et al. 2012); this condition results from the formation of chloro-HM complexes and/or the competitive effects of Na and other HMs on soil particles, which enhance rhizospheric HM mobilization (Acosta et al. 2011; López-Chuken and Young 2010). Therefore, how to reduce HM accumulation in edible parts of crops has been an important health issue for

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environmental scientists, especially in HM-contaminated saline soils. However, the mechanisms underlying the low accumulation of multiple HMs have yet to be fully elucidated.

The Cd and Zn accumulation in above-ground tissues (shoots or fruits) is considerably determined by the efficiency of roots to mobilize, uptake, and translocate insoluble Cd and Zn in soil from roots to shoots or fruits (Chen et al. 2003; Farinati et al. 2010; Jiang et al. 2012; Xue et al. 2012). Studies have also reported previously Cu and Zn mobilization by dissolved organic compounds of dicotyledonous plants in soil (Degryse et al. 2008). He et al. (2015) and Xu et al. (2017) observed that low Cd-accumulating water spinach (*Ipomoea aquatica*'Forsk') and edible amaranth (*Amaranthus mangostanus* L.) presented low concentrations of bioavailable Cd and dissolved organic compounds in their rhizosphere solution. Furthermore, Meng et al. (2014) and Cheng et al. (2010) found that cultivars with strong Cd and Zn retention abilities in root cell walls generated more Cd and Zn in the form of pectate/protein complexes. Similar phenomena have been observed in a low Cd-accumulating cultivar of *Brassica parachinensis* (Sun et al. 2017). Following the uptake by roots, xylem loading of HMs is suggested as the next essential transport process for HM accumulation in above-ground plant parts (Deng et al. 2013; Hassan and Aarts 2011; Mori et al. 2009). The key controlling genes (*HMA*s) responsible for Zn/Cd root-to-shoot translocation have been tested by silencing *HMA*2 and *HMA*4 in Thale Cress (*Arabidopsis thaliana* L.) (Wong and Cobbett 2009). Yamaguchi et al. (2010) reported a downregulated gene (FRD3) responsible for xylem-loading citrate transporter after 3 h of Cd treatment, which inhibits root-to-shoot Cd translocation, thereby significantly decreasing Cd concentration in low Cd-accumulating eggplant (*Solanum torvum* L.). However, whether these mechanisms in other plants may explain cultivar differences in Cd, Zn, and Cu concentrations among tomato cultivars grown in HM-polluted saline soils remains unknown.

Tomato (*Solanum lycopersicum* L.), which contains a rich supply of carotenoids, vitamin C, and B-complex vitamin, originated in South America but is now extensively cultivated worldwide (Dewanto et al. 2002). This crop includes two types, namely the common type (*L. esculentum var. commune*) and the cherry type (*L. esculentum var. cerasiforme*). Worryingly, tomatoes have been reported to be one of the easiest species that can easily accumulate Cd and Zn in their fruits (López-Millán et al. 2009; Sbartai et al. 2012). Therefore, studies on measures and technologies to reduce the health risks associated with the consumption of HM-contaminated tomato fruits are highly imperative. Our previous study tested 29 tomato cultivars grown on non-saline soils contaminated with Cd and found that the maximum 3.34-fold variations of Cd concentration in fruits occurred in all the 29 tomato cultivars (Tan et al. 2014). Based on Cd concentration in their fruits, a few low- and high-Cd cultivars were identified (Tan et al. 2014). In the present study, these low- and high-Cd cultivars screened from non-saline soils were used further to explore their variation in HM (Cd, Zn, and Cu) accumulation grown on saline soils contaminated with HM. Our hypothesis is that low-Cd tomato cultivars screened in non-saline soil also might accumulate low Cd, Zn, and Cu when grown on saline soils. To verify this hypothesis, we measured Cd, Zn, and Cu concentrations in tomatoes grown on reclaimed tidal flat saline soil polluted with HM. We further investigated the low accumulation mechanisms of HMs by analyzing (i) variations in the concentrations of Cd, Zn, Cu, dissolved organic carbon (DOC), organic acids, and amino acids in rhizospheric soil solution between contrasting cultivars; (ii) variations in root uptake and redistribution of Cd, Zn, and Cu between two tomato types; and (iii) the statistical relationship between fruit Cd, Zn, and Cu concentrations and the above-mentioned indices. It is expected that results of this study can be used as a reference in exploring new methods of growing efficient safe cultivars of tomato or other fruit vegetables cultivated under the combined pollution of multiple HMs in saline soils.

Materials and methods

Plant materials and soil preparation

Two cherry tomato cultivars ('Taiwanhong' and 'Meiwei') and two common tomato cultivars ('Yiselie3098' and 'Zhongshu') tested in this experiment were selected according to their fruit-Cd accumulation grown in non-saline soil with a Cd concentration of 3.48 mg kg^{-1} dry soil in our previous study (Tan et al. 2014). The tomatoes were defined as low- ('Taiwanhong' and 'Yiselie3098') and high ('Meiwei' and 'Zhongshu')-Cd cultivars.

The HM-polluted reclaimed tidal flat saline soils were used for the pot experiment and were collected from a reclaimed field (0–20 cm of top soil) in the mouth of the Pearl River estuary, China (Fig. S1). The area is a typical region of reclaimed tidal flat in southern China. The physicochemical properties of the soils are listed in Table 1. The soils were mixed intensively, sieved through a 10-mm mesh to remove clastic rocks, air-dried at room temperature, and then used for follow-up experiments.

Experimental design and chemical analysis

The soil-pot experiment was conducted in a greenhouse with full-automatic shading at Jinnan University (120° 58′ E/23° 58′ N) under a temperature of 25 °C/15 °C and a relative humidity of 70%. The carbendazim-soaked seeds were subsequently sown in 48 (4 cultivars × 4 replicates × 3 rhizobags) rhizobags, which were placed in black polyvinyl chloride pots

Table 1 Basic physicochemical properties of soils collected from the reclaimed tidal flat fields in Pearl River estuary

Soil property		Standard reference[a]
Soil texture	Loam soil	
pH	5.60 ± 0.31	≤ 6.5
CEC (cmol kg^{-1})	20.9 ± 1.22	
Organic C (g kg^{-1})	35.4 ± 1.46	
Total organic matter (g kg^{-1})	61.0 ± 2.52	
Total salt content (g kg^{-1})	3.47 ± 0.22	≤ 1
Total N (g kg^{-1})	0.88 ± 0.06	
Total P (g kg^{-1})	0.50 ± 0.04	
Total Ca (g kg^{-1})	39.2 ± 3.99	
Total Cd (mg kg^{-1})	2.90 ± 0.12	≤ 0.3
Total Zn (mg kg^{-1})	347.77 ± 20.09	≤ 200
Total Cu (mg kg^{-1})	69.98 ± 1.81	≤ 50

[a] The Chinese farmland environmental quality evaluation standards for edible agricultural products (HJ 332–2006). The data were expressed on a soil dry weight basis. Values are means (± SD; $n = 5$)

(15 cm in diameter and 20 cm in height) with 3.5 kg of dry soil in each pot. The rhizobags were made of nylon with a mesh size of 60 μm. The soils in rhizobags were arbitrarily denoted as rhizospheric soil. The pots were arranged in a randomized complete block design, with each pot including four replicates. The soil moisture content was maintained at 75% of the field water-holding capacity by using tap water. A petri dish was placed under each pot to collect the potential leachate during the experiment. No fertilization was applied to the cultures. Two weeks after sowing, the seedlings were thinned to two individuals per pot. The plants were harvested, and their capacities to accumulate Cd, Zn, and Cu were determined upon fruit maturity.

The roots, shoots, and fruits of each tomato plant were separated. Afterward, fresh weight was determined, and the fruiting rate (number of fruits per plant) was calculated. All samples were dried to a constant weight at 70 °C. The oven-dried samples were ground separately by using a Retsch grinder (2 mm type, Germany) and then digested with HNO_3/H_2O_2 in a microwave digestion system (CEM-MARS5, USA). The Cd, Zn, and Cu concentrations in the fruits, roots, and shoots were determined by atomic absorption spectrometry or graphite furnace atomic absorption spectrometry (PerkinElmer, USA). The elemental recovery rates for the standard material (GBW07603, bush branches and leaves provided by the National Research Center for certified reference material, China) exceeded 90%. The rhizospheric soil solution was sequentially collected by soil stripping, centrifugation, and filtration (Xu et al. 2017). The collected solution was stored in a freezer at − 20 °C to determine the concentrations of Cd, Zn, Cu, DOC (Shimadzu TOC-VCSH, Japan), amino acids, and organic acids (Dionex ICS-900, USA).

Statistical methods

The Cd, Zn, and Cu concentrations in the plants were expressed on a plant dry weight basis (mg kg^{-1} DW). The Cd, Zn, Cu, and dissolved organic compound concentrations in the rhizospheric soil solution were expressed on a soil dry weight basis (mg kg^{-1} or g kg^{-1} DW). Data were statistically analyzed using one-way (independent-sample t test) and two-way ANOVA on SPSS 11.5. All graphs were charted using Origin 9.2.

The metal concentration ratios of the root and shoot to the fruit were calculated as follows (Cheng et al. 2012):

$$\text{fruit : shoot} = M_{\text{fruit}}/M_{\text{shoot}} \quad (1)$$

$$\text{fruit : root} = M_{\text{fruit}}/M_{\text{root}} \quad (2)$$

where M_{root}, M_{shoot}, and M_{fruit} are the metal concentrations in the roots (mg kg^{-1} DW), shoots (mg kg^{-1} DW), and fruits (mg kg^{-1} DW), respectively.

The metal uptake ability of the plants was calculated according to the following formula (Xin et al. 2013):

$$\text{Root}_{\text{net}} = (M_{\text{root}} \times \text{biomass}_{\text{root}} + M_{\text{shoot}} \times \text{biomass}_{\text{shoot}} + M_{\text{fruit}} \times \text{biomass}_{\text{fruit}})/\text{biomass}_{\text{root}} \quad (3)$$

where Root_{net} is the net uptake of metals via the roots (mg kg^{-1} DW) and $\text{biomass}_{\text{root}}$, $\text{biomass}_{\text{shoot}}$, and $\text{biomass}_{\text{fruit}}$ are the dry weights of the roots (g), shoots (g), and fruits (g), respectively.

The metal (M) distribution percentages (MDP, %) in the different organs were calculated according to the following formula:

$$\text{MDP}\ (\%) = 100 \times (M_{\text{organ}})/(M_{\text{plant}}) \quad (4)$$

where M_{organ} and M_{plant} are the metal amount (mg) in an organ and metal amount (mg) in the whole plant, respectively.

Results and discussion

Cd, Zn, and Cu accumulation in low-Cd cultivars grown on saline soils

According to the data listed in Table 1, the total Cd (2.90 mg kg^{-1} dry soil), Zn (347.77 mg kg^{-1} dry soil), and Cu (69.98 mg kg^{-1} dry soil) concentrations in the reclaimed tidal flat saline field distinctly exceeded their respective limits corresponding to the Farm Land Environmental Quality

Evaluation Standard for Edible Agricultural Products (HJT 332–2006, China). The soil salinization reached a mild to moderate level (3.47 g kg^{-1} dry soil). Many studies reported that soil salinity causes a large increase in plant-available soil HMs (Wang et al. 2014; Zeng et al. 2017). Therefore, vegetables cultivated on this type of field may engender health risks (Luo et al. 2011; Yang et al. 2013).

The Cd, Zn, and Cu concentrations in the roots, shoots, and fruits of low-Cd cultivars of both tomato types were significantly lower than those of high-Cd cultivars (Table 2; $p <$ 0.05). Results reconfirmed the repeatability and stability of differences in Cd accumulation between the low- and high-Cd cultivars grown both on non-saline (Tan et al. 2014) and on saline soils. The low-Cd cultivars of both tomato types also exhibited low-accumulating abilities for Zn and Cu in saline soils. He et al. (2015) reported that certain breeds of water spinach concurrently accumulated less Cd, Cr, Cu, Pb, and Zn amounts. A similar phenomenon has been observed in certain breeds of wheat (*Triticum aestivum* L.) (Liu et al. 2015) and Turkey tangle fogfruit (*Phyla nodiflora* L.) (Yoon et al. 2006). Hence, cultivation of cultivars with low accumulation abilities for various HMs is an efficient approach to mitigate HMs entering the human food chain. In our previous study on non-saline soil contaminated with Cd, the cherry cultivars accumulated less Cd in their fruits (average, 0.75 mg kg^{-1} DW) compared with the common cultivars (average, 1.16 mg kg^{-1} DW) ($p < 0.05$) (Tan et al. 2014). However, in the present study on reclaimed tidal flat saline soils, higher average concentrations of Cd, Zn, and Cu in the fruits were observed in the tested cherry type ('Taiwanhong' and 'Meiwei') than in the common type ('Yiselie3098' and 'Zhongshu') (Table 2; $p < 0.05$). No Cd-safe cultivars were observed in reclaimed tidal flat saline soils, and fruit Zn and Cu contents did not exceed safe values for Zn and Cu in vegetables (Table S1). Additionally, saline soil significantly accelerated Cd accumulation in their fruits, especially in the cherry-type tomatoes, compared with those in non-saline soil (Tan et al. 2014). Therefore, cherry-type tomatoes should be cultivated in reclaimed tidal flat fields as less as possible.

Biomass allocation within tomato organs and its effects on Cd, Zn, and Cu accumulation

As shown in Fig. 1, the shoot and fruit biomasses of low-Cd cultivars of both tomato types were significantly higher than those of high-Cd cultivars ($p < 0.05$). However, the root biomass of both tomato types displayed an opposite trend between the low- and high-Cd cultivars. A lower root/shoot biomass (*R*/*S*) ratio was observed in the low-Cd cultivars than in the high-Cd cultivars of both tomato types ($p < 0.05$). Several studies reported that plants with low *R*/*S* ratios exhibited a lower root uptake ability of nutrients from rhizospheric soil compared with plants with a high *R*/*S* ratio (Cheng et al. 2011; Ho et al. 2005; Walk et al. 2006). A *R*/*S* ratio more or less optimized to capture N and P can result in differences in metal uptake if the differences for the *R*/*S* ratio are not balanced by a corresponding increase/decrease in the specific (relative to biomass) root uptake capacity for metal uptake. The cultivars with a low *R*/*S* ratio may have low root biomass or high shoot and fruit biomass relatively to high *R*/*S* ratio

Table 2 Cd, Zn, and Cu concentrations in the roots, shoots, and fruits of low- and high-Cd cultivars in two types of tomato cultivars

Cultivar	Organ	Cd (mg kg^{-1} DW)	Zn (g kg^{-1} DW)	Cu (mg kg^{-1} DW)
L-○*Yiselie3098*	Root	9.25 ± 0.60*	0.14 ± 0.00*	14.66 ± 0.52**
($N = 4$)	Shoot	10.77 ± 0.20**	0.16 ± 0.01**	7.07 ± 0.11**
	Fruit	0.98 ± 0.04**	0.06 ± 0.01*	4.88 ± 0.06**
H-○*Zhongshu*	Root	10.17 ± 0.11	0.17 ± 0.01	18.42 ± 0.74
($N = 4$)	Shoot	14.53 ± 0.15	0.20 ± 0.01	9.12 ± 0.23
	Fruit	1.68 ± 0.07	0.08 ± 0.00	7.48 ± 0.29
○Average ($N = 8$)	Fruit	1.33 ± 0.35 A	0.07 ± 0.01 A	6.18 ± 1.01 A
L-●*Taiwanhong*	Root	19.10 ± 0.15**	0.42 ± 0.05*	19.21 ± 0.41**
($N = 4$)	Shoot	11.27 ± 0.20*	0.26 ± 0.05*	9.91 ± 0.28**
	Fruit	1.84 ± 0.04**	0.09 ± 0.01**	5.33 ± 0.09**
H-●*Meiwei*	Root	21.31 ± 0.56	0.58 ± 0.03	28.61 ± 0.53
($N = 4$)	Shoot	15.21 ± 0.13	0.41 ± 0.01	18.37 ± 0.66
	Fruit	4.02 ± 0.13	0.16 ± 0.00	11.91 ± 0.10
●Average ($N = 8$)	Fruit	2.93 ± 1.01 B	0.13 ± 0.03 B	8.62 ± 0.94 B

Symbols (○ and ●) represent common and cherry tomatoes, respectively. L and H represent low- and high-Cd cultivars, respectively (similarly hereinafter). Asterisks (* and **) denote significant difference between the same organs of low- and high-Cd cultivars in the same tomato type for one element (*t* test; $p < 0.05$, $p < 0.01$, respectively). Different capital letters indicate significant difference between the average values of the fruits from both tomato types for one element (*t* test; $p < 0.05$). Values are presented as means (±SD)

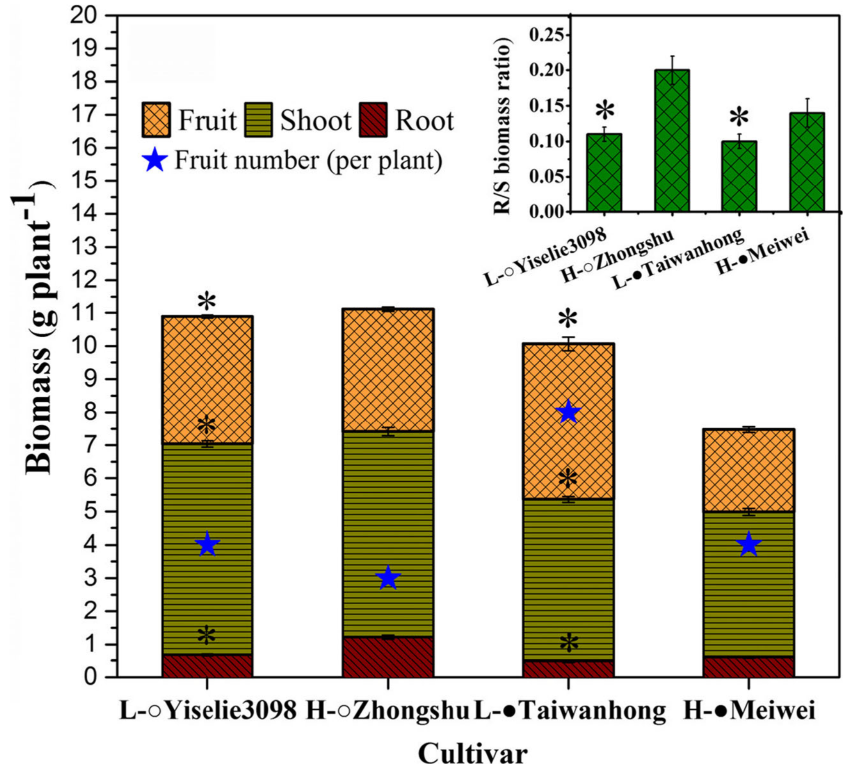

Fig. 1 Biomass, fruit number, and *R/S* biomass ratio of both tomato types. Symbols empty and filled circles represent common and cherry tomatoes, respectively. L and H represent low- and high-Cd cultivars, respectively. An asterisk denotes the significant difference between low- and high-Cd cultivars of the same tomato type (*t* test, $p < 0.05$). Values are means ($\pm$ SD; $n = 8$)

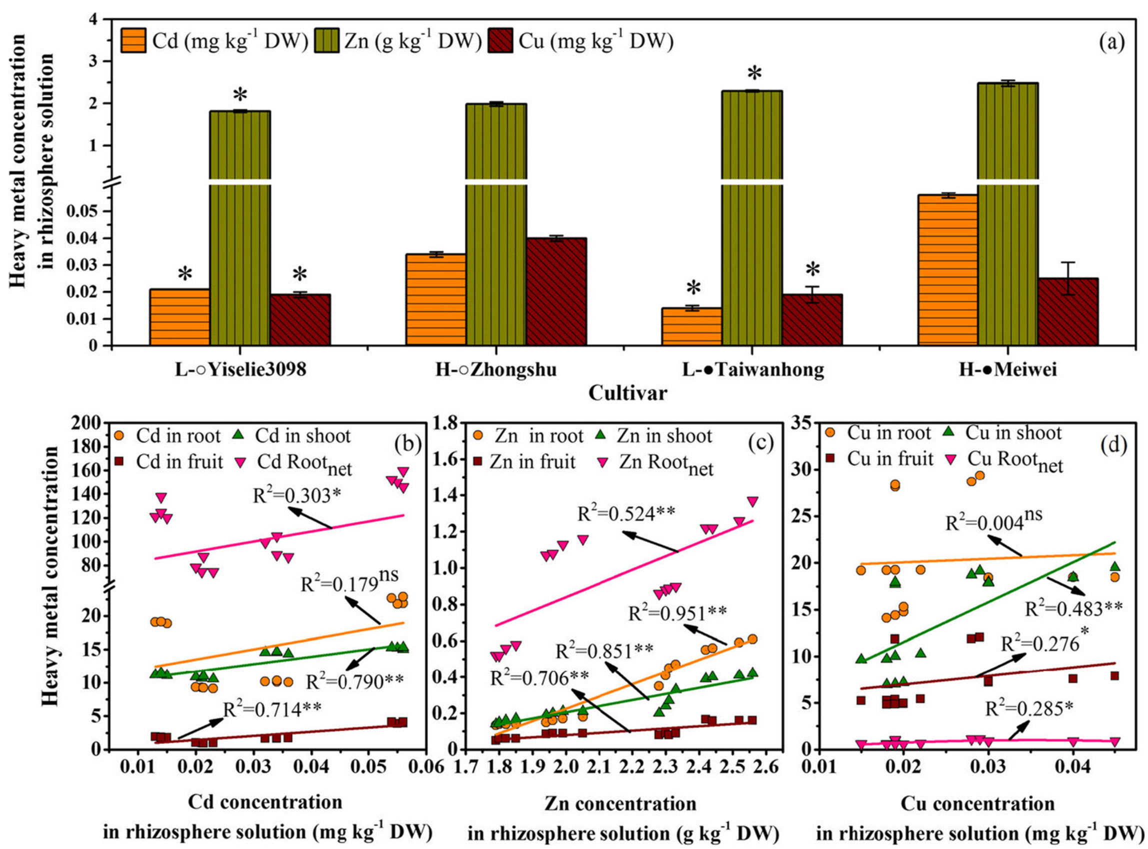

Fig. 2 Cd, Zn, and Cu concentrations in the rhizospheric soil solution of both tomato types (**a**); correlation analysis between Cd, Zn, and Cu concentrations in the rhizospheric soil solution and their concentrations in the roots, shoots, and fruits, and their Root$_{net}$ (**b**, **c**, and **d**). L and H represent low- and high-Cd cultivars, respectively. One asterisk and two asterisks denote significance at the 0.05 and 0.01 levels, respectively. ns, not significant. Values are means ($\pm$ SD; $n = 4$)

Table 3 DOC, amino acid, and organic acid concentrations (mg kg^{-1} dry soil) in the rhizosphere soil solution of low- and high-Cd cultivars in two types of tomato cultivars

Cultivar	DOC	Amino acid	Organic acid							
			Formic acid	Acetic acid	Propionic acid	Malic acid	Tartaric acid	Oxalic acid	Citric acid	Succinic acid
L-○*Yiselie3098*	86.94 ± 1.34**	1.49 ± 0.15*	0.01 ± 0.00 ns	0.84 ± 0.06 ns	0.02 ± 0.00 ns	0.15 ± 0.01 ns	17.45 ± 0.33*	0.09 ± 0.01 ns	0.18 ± 0.00*	0.04 ± 0.00 ns
H-○*Zhongshu*	100.40 ± 5.17	2.11 ± 0.11	0.01 ± 0.00	0.75 ± 0.04	0.02 ± 0.00	0.16 ± 0.00	22.88 ± 0.24	0.11 ± 0.01	0.25 ± 0.00	0.04 ± 0.00
L-●*Taiwanhong*	78.63 ± 1.21**	1.63 ± 0.17**	0.01 ± 0.00 ns	0.68 ± 0.04 ns	0.02 ± 0.00 ns	0.14 ± 0.01 ns	18.35 ± 0.21**	0.06 ± 0.00 ns	0.17 ± 0.00**	0.04 ± 0.00 ns
H-●*Meiwei*	141.41 ± 2.31	4.73 ± 0.13	0.01 ± 0.00	0.76 ± 0.04	0.02 ± 0.00	0.11 ± 0.02	20.15 ± 0.08	0.06 ± 0.00	0.22 ± 0.00	0.04 ± 0.00

Asterisks (* and **) denote significant difference between low- and high-Cd cultivars in the same type of tomato cultivar for one index (*t* test; $p < 0.05$, $p < 0.01$, respectively). Values are presented as means (± SD; $n = 4$)

ns not significant

cultivars, which may result in a small root surface area for mobilizing and absorbing Cd, Zn, and Cu or dilute more Cd, Zn, and Cu, resulting in low Cd, Zn, and Cu concentrations in the fruits. Krämer et al. (1997) and Werner et al. (2010) found that the high accumulation of Ni, Zn, and Mn in the shoots results from the high *R*/*S* ratio in the two contrasting genotypes of *Thlaspi goesingense* and *A. thaliana*, and tobacco (*Nicotiana tabacum* L.). Certainly, the biomass partitioning may be not the only reason for the low accumulation. A *R*/*S* ratio may be one of the important factors influencing cultivar variations in terms of Cd, Zn, and Cu accumulation in fruits.

Cultivar variations in dissolved organic compounds in the rhizospheric soil solution and their effects on soil Cd, Zn, and Cu dissolution

The concentration of plant-available HMs in the rhizospheric soil solution determines the concentration gradient of HMs across the cytoplasmic membrane, thereby affecting HM uptake by plant roots (He et al. 2015). The bioavailability of HMs in the rhizospheric soil solution is mainly governed by free ion concentrations, which is further influenced by the dissociation of metal complexes, by the sorption/ desorption/ dissolution of HMs from the soil solid phase, and by precipitation/dissolution of HM. Hence, studies on HM release from soil media to soil solutions could partly reveal the mechanism underlying low HM accumulation (Dessureault-Rompré et al. 2010). In the present study, in both tomato types, the Cd, Zn, and Cu concentrations in the rhizosphere solution from the low-Cd cultivars were significantly lower than those from the high-Cd cultivars (Fig. 2a; $p < 0.05$). Furthermore, the Cd, Zn, and Cu concentrations in the shoots and fruits, and the Cd, Zn, and Cu net uptake via the roots ($Root_{net}$), were significantly positively correlated with the Cd, Zn, and Cu concentrations in the rhizospheric soil solution from both tomato types (Fig. 2b–d; $p < 0.05$). These results suggested that the low-Cd cultivars feature lower abilities to solubilize Cd, Zn, and Cu from the soil into the rhizospheric solution compared with the high-Cd cultivars. Solubilization of soil Cd, Zn, and Cu is in part determined by dissolved organic substances released from the roots and by microbial activity, and acidification is likely to be the major determinant (Potysz et al. 2017; Xin et al. 2015; Zhao et al. 2007).

In both tomato types, the DOC and amino acid concentrations from the rhizosphere of the high-Cd cultivars were significantly higher than those from low-Cd cultivars (Table 3; $p < 0.05$). The present study revealed a strong positive correlation among DOC, amino acid, and HM (Cd, Zn, and Cu) concentrations in the rhizospheric soil solution (Fig. 3a–c; $p < 0.05$). High concentrations of DOC or organic acids in the high-Cd cultivars might partly contribute to the amount of

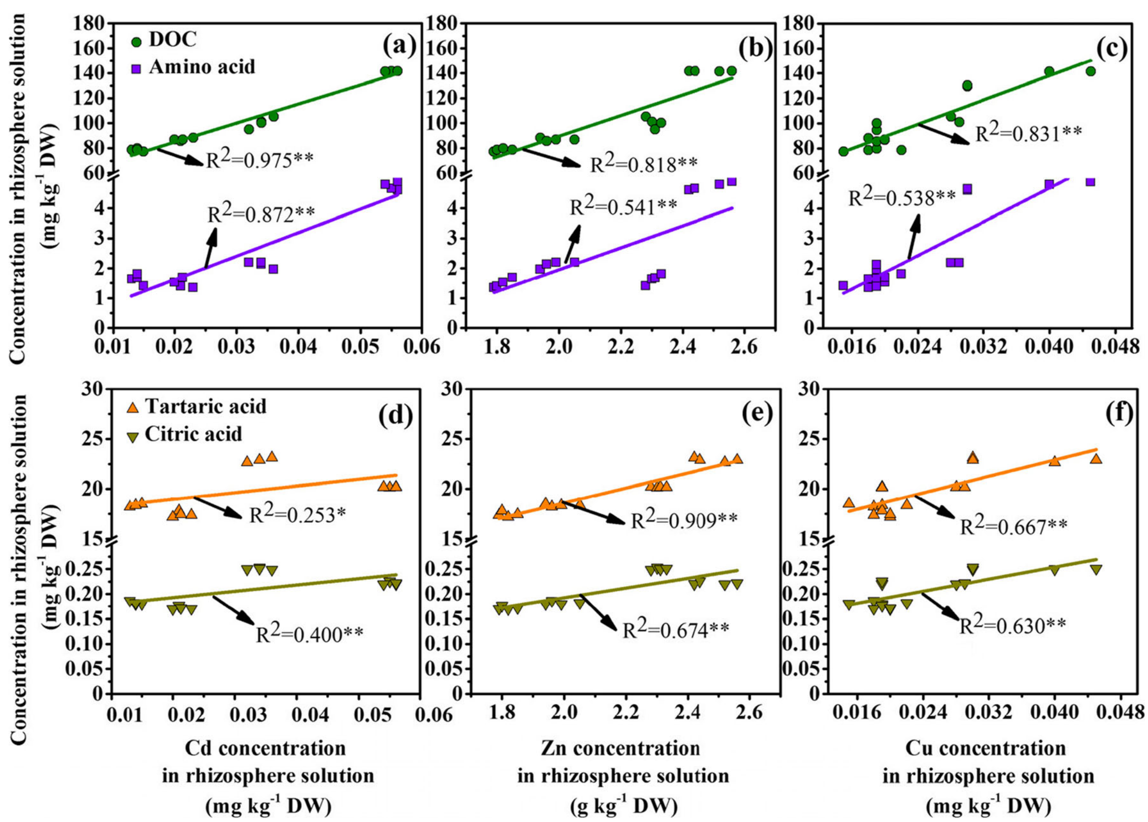

Fig. 3 Correlation analysis between Cd, Zn, Cu, DOC, amino acid, tartaric acid, and citric acid concentrations in the rhizospheric soil solution. One asterisk and two asterisks denote significance at the 0.05 and 0.01 levels, respectively. ns, not significant

HMs in the soil solution by forming metal-organic complexes or acidizing the rhizospheric environment (Xu et al. 2017; Yanai et al. 2006). Among the organic acids, tartaric and citric acid concentrations from the rhizosphere of the high-Cd cultivars of both tomato types were significantly higher than those of the low-Cd cultivars (Table 3; $p < 0.05$). No significant differences were observed in the concentrations of formic acid, acetic acid, propionic acid, oxalic acid, and succinic acid between the low- and high-Cd cultivars (Table 3; $p > 0.05$). Besides, tartaric acid and citric acid concentrations showed a significant positive correlation with Cd, Zn, and Cu concentrations in the rhizosphere solution (Fig. 3d–f; $p < 0.05$). The chemical groups from the ionized anions of citric acid and tartaric acid, respectively, can bind divalent cations strongly and form stable complexes on soil colloidal particles due to the relatively high proton dissociation constants (Ka_1, Ka_2) of tartaric acid (1.04×10^{-3}, 4.55×10^{-5}) and citric acid (7.10×10^{-4}, 1.68×10^{-4}) (Jiang et al. 2012; Nigam et al. 2001; Xu et al. 2003; Zhou et al. 2003). Previous studies reported that citric acid and tartaric acid in the rhizosphere could facilitate Cd, Mn, Cr, and Pb uptake by plants (Duarte et al. 2007; Michael et al. 1997; Zeng et al. 2008). Michael et al. (1997) and Huang and Cunningham (2010) reported that compared with the free metal ions, some metal complexes by water-soluble organic substances are electrically neutral and are easier to migrate to the root surface through mass flow and diffusion, which may provide opportunities for HM uptake. Some metal-organic complexes can be directly absorbed through the cytomembrane, endodermis, and rip of casparian strip in the roots of Indian Mustard (*Brassica juncea* L.) (Jiang et al. 2003) and sunflower (*Helianthus annuus* L.) (Lesage et al. 2005). Hence, low-level dissolved organic compounds in the rhizospheric soil solution might partly explain the low Cd, Zn, and Cu accumulation in the low-Cd cultivars of both tomato types.

Although excretion of organic compounds making complexes with metals indeed favors solubilization, it could also reduce bioavailability by decreasing the concentration of free ions through complexation (Lin et al. 2014). Meanwhile, rhizospheric soil pH is an important factor controlling the bioavailability of HMs in the rhizosphere (mobilization and speciation) via desorption of metals from the solid phase by competition with H^+ (Xu et al. 2017). Xu et al. (2017) also reported that rhizosphere acidification induced by an imbalance of cation over anion uptake under salinity treatment is more serious in high-Cd edible amaranth cultivar than in low-Cd edible amaranth cultivar, which obviously increase soil Cd bioavailability. Guo et al. (2018) further confirmed the cultivar difference of rhizosphere acidification induced by salinity between high-Cd and low-Cd edible amaranth cultivar using metabolomic analysis. However, the pH of the rhizosphere soil solution of this experiment was not determined and need to be investigated in future studies. Apart from rhizosphere acidification induced by plant roots and microbial activity, salinity may also directly involved in accelerating the soil HM dissolution by the complexation of Cl^- ions with HMs and the exchange of Na^+ ions and other HMs on soil particles (Laing et al. 2008; Usman et al. 2005).

Cultivar comparison in terms of Cd, Zn, and Cu uptake and redistribution and their roles in fruit Cd, Zn, and Cu accumulation

Apart from rhizosphere HM mobilization, HM uptake and redistribution are two of the crucial processes controlling HM accumulation in fruits (Impa et al. 2013; Malandrino et

Table 4 Net uptake of Cd, Zn, and Cu via the roots ($Root_{net}$), and Cd, Zn, and Cu concentration ratios of root and shoot, to the fruit of low- and high-Cd cultivars in two types of tomato cultivars

Cultivar		Cd (mg kg^{-1})	Zn (g kg^{-1})	Cu (mg kg^{-1})
L-○*Yiselie3098*	$Root_{net}$	78.87 ± 5.97*	0.55 ± 0.03**	0.59 ± 0.02*
	Fruit: root	0.11 ± 0.00**	0.41 ± 0.03**	0.33 ± 0.01**
	Fruit: shoot	0.09 ± 0.00*	0.38 ± 0.03 ns	0.69 ± 0.05 ns
H-○*Zhongshu*	$Root_{net}$	95.12 ± 8.32	1.11 ± 0.04	0.92 ± 0.04
	Fruit: root	0.28 ± 0.01	0.54 ± 0.03	0.41 ± 0.01
	Fruit: shoot	0.12 ± 0.01	0.40 ± 0.01	0.82 ± 0.07
L-●*Taiwanhong*	$Root_{net}$	125.87 ± 8.08*	0.88 ± 0.02**	0.63 ± 0.02**
	Fruit: root	0.08 ± 0.00**	0.17 ± 0.01**	0.28 ± 0.00**
	Fruit: shoot	0.16 ± 0.02**	0.35 ± 0.01 ns	0.54 ± 0.05 ns
H-●*Meiwei*	$Root_{net}$	151.96 ± 5.90	1.27 ± 0.07	1.09 ± 0.09
	Fruit: root	0.18 ± 0.00	0.24 ± 0.01	0.42 ± 0.00
	Fruit: shoot	0.27 ± 0.02	0.39 ± 0.01	0.65 ± 0.06

Asterisks (* and **) denote significant difference between low- and high-Cd cultivars in the same type of tomato cultivar for one index (*t* test; $p < 0.05$, $p < 0.01$, respectively). Values are presented as means (± SD; $n = 4$)

ns not significant

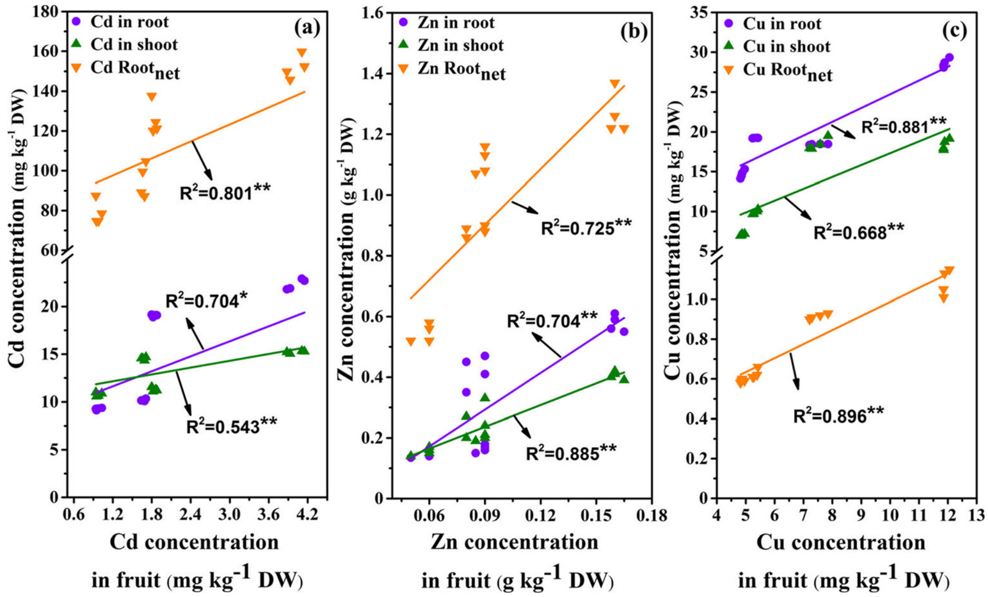

Fig. 4 Correlation analysis between Cd (**a**), Zn (**b**), and Cu (**c**) concentrations in the fruits and their concentrations in roots and shoots, and their Root$_{net}$. One asterisk and two asterisks denote significance at the 0.05 and 0.01 levels, respectively. ns, not significant

al. 2011; Uraguchi et al. 2009). In the present trial, lower net uptake of Cd, Zn, and Cu by the roots (Root$_{net}$) was observed in the low-Cd cultivars of both tomato types than in the high-Cd cultivars (Tables 4; $p < 0.05$). The Cd, Zn, and Cu concentrations in the fruits showed a significant positive correlation with the Cd, Zn, and Cu concentrations in the roots and shoots and net uptake of Cd, Zn, and Cu by the roots (Root$_{net}$) (Fig. 4a–c; $p < 0.01$). Results suggested that root uptake ability was also an important factor influencing Cd, Zn, and Cu concentrations in tomato fruits. Zhou et al. (2016) revealed that the genes involved in Cd and Zn absorption, such as the members of the gene families of yellow stripe-like and *ZRT*/*IRT* protein, showed low expression in low Cd-accumulating pakchoi (*Brassica chinensis* L). By contrast, Xin et al. (2013) found no significant variation in root uptake ability between low- and high Cd-accumulating hot pepper cultivars (*Capsicum frutescens* L.). Therefore, the difference in root uptake ability of tomato cultivars may be governed by the expression of related genes and other possible reasons including differences in affinity of transporters for Cd, in root CEC, in apoplastic barriers extension.

A redistribution of HMs within organs after HM entry into plants could partly influence the HM accumulation in the fruits (Greger and Lofstedt 2004). Liu et al. (2015) also found a strong correlation between Cd redistribution and grain Cd concentration in rice. In the present experiment, HMs (Cd, Zn, and Cu) were mostly accumulated in the shoots followed by the roots of both tomato types (Table 5). The Cd, Zn, and Cu distribution percentages (MDP, %) in the roots of the low-Cd cultivars of the two types of tomato cultivars were

Table 5 Cd, Zn, and Cu distribution percentages (MDP, %) in different organs of low- and high-Cd cultivars in two types of tomato cultivars

Cultivar	Organ	Cd	Zn	Cu
L-○*Yiselie3098*	Root	23.22 ± 1.32**	17.90 ± 1.72**	25.24 ± 2.74**
	Shoot	73.66 ± 2.08*	78.22 ± 1.12*	72.45 ± 2.04*
	Fruit	3.12 ± 0.32**	3.88 ± 0.12*	2.31 ± 0.74**
H-○*Zhongshu*	Root	14.69 ± 1.04	14.50 ± 1.26	17.25 ± 2.04
	Shoot	79.44 ± 1.45	81.12 ± 1.06	78.56 ± 1.94
	Fruit	5.87 ± 0.45	4.38 ± 0.14	4.50 ± 0.64
L-●*Taiwanhong*	Root	12.90 ± 2.15**	12.57 ± 2.55**	8.60 ± 1.74**
	Shoot	80.66 ± 2.37*	82.20 ± 2.34*	85.25 ± 1.46*
	Fruit	6.44 ± 0.85**	5.23 ± 1.04**	6.15 ± 0.44*
H-●*Meiwei*	Root	3.11 ± 0.71	2.26 ± 1.15	3.54 ± 1.54
	Shoot	86.34 ± 2.08	88.36 ± 2.01	88.21 ± 1.14
	Fruit	10.55 ± 1.07	9.38 ± 1.19	8.25 ± 0.84

Asterisks (* and **) denote significant difference between the same organs of low- and high-Cd cultivars in the same tomato type for one element (*t* test; $p < 0.05$, $p < 0.01$, respectively). Values are presented as means (± SD; $n = 4$)

significantly higher than those in the high-Cd cultivars (Table 5; $p < 0.01$). However, the Cd, Zn, and Cu distribution percentages in the shoots and fruits of low-Cd cultivars of the two types of tomato cultivars were lower than those in the shoots and fruits of high-Cd cultivars (Table 5; $p < 0.05$ or $p < 0.01$). The results indicated that the low-Cd cultivars of both tomato types had a higher ability to retain HMs in the roots than the high-Cd cultivars. Furthermore, the fruit to root ratios of HMs in the low-Cd cultivars of both types of tomato cultivars were significantly lower than those in the high-Cd cultivars (Table 4; $p < 0.01$). Only the fruit to shoot ratios of Cd in the low-Cd cultivars in both tomato types were lower than those in the high-Cd cultivars (Table 4; $p < 0.05$). No significant differences in the fruit to shoot ratios of Zn and Cu were observed between the low- and high-Cd cultivars (Table 4; $p > 0.05$). This result suggested that both roots and shoots possibly impeded Cd accumulation in the fruits of low-Cd cultivars, but only the roots possibly impeded Zn and Cu accumulation in the fruits of low-Cd cultivars. These findings disagree with the results for rice, in which the redistribution ability of Cd in shoots may been regarded as a pivotal effect on Cd translocation to fruits (Kashiwagi et al. 2009; Zhang et al. 2018). Furthermore, cultivar difference in fruit HM accumulation may also be controlled by transpiration stream and/or other factors (Yamaguchi et al. 2012; Yoneyama et al. 2010). However, how redistribution of HMs within organs occurs and why Cd, Zn, and Cu exhibit different redistribution mechanisms need to be further investigated in future.

Conclusion

Low-Cd cultivars of cherry and common tomato types screened from non-saline soil displayed low accumulation abilities for Cd, Zn, and Cu in fruits when grown on reclaimed tidal saline soil contaminated with HMs. Cherry-type tomatoes exhibited greater health risks compared with common-type tomatoes. The finding suggests that cultivation of cherry-type tomatoes in HM-contaminated saline soil should be avoided. A low *R*/*S* biomass ratio may be one of the important factors reducing Cd, Zn, and Cu accumulation in fruits. Low-level dissolved organic compounds in the rhizospheric soil solution correlated with less Cd, Zn, and Cu from the soil into the rhizosphere solution and might partly result in low Cd, Zn, and Cu accumulation in the fruits of low-Cd cultivars of both tomato types. However, the speciation of HMs and the pH of rhizospheric soil solution need to be investigated in future studies. Additionally, the low-Cd cultivars of both tomato types had a higher ability to retain HMs in the roots than the high-Cd cultivars. Overall, the study provided insights into the low accumulation mechanisms of multiple HMs, and therefore might provide guidance for the safe utilization of reclaimed tidal flat soils.

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