

COMPARISON ON THE TOLERANCE AND ACCUMULATION OF HEXAVALENT CHROMIUM BY DIFFERENT CROPS UNDER HYDROPONIC CONDITIONS

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Abstract. Seedlings of six crops including wheat, radish, cucumber, Chinese cabbage, oilseed rape, and lettuce were treated with hexavalent chromium (Cr(VI)) in a hydroponic system. Root surface area, tissue biomass, the activities of superoxide dismutase (SOD) and peroxidase (POD), and chromium contents were determined to evaluate the tolerance and accumulation of Cr(VI) by these crops. The results showed that the biomass reduction of wheat was the lowest, and that of lettuce was the highest. Significant decrease in SOD activity was observed in 1 mg/L Cr(VI) treatment for Chinese cabbage and radish. While significant activation effect on the POD was observed in 1 mg/L or 5 mg/L Cr(VI) treatment for Chinese cabbage and oilseed rape. Moreover, the activities of the two antioxidant enzymes in cucumber leaves did not change significantly at the two levels of Cr(VI) concentrations. The transfer coefficient of Chinese cabbage was the highest, while that of lettuce was the lowest. In conclusion, Chinese cabbage has a certain tolerance to Cr(VI) and exhibits the highest accumulation of Cr in the edible parts. Therefore, when planting crops in low and medium Cr contaminated soil, concerns should be addressed on the food safety issues from leafy vegetables, especially Chinese cabbage.

Keywords: *crop, chromium (VI), physiological and biochemical properties, accumulation*

Introduction

Crops are one of the most important sources of human food, providing the essential energy and nutrients for the human body. There is increasing concern regarding the health risks arising from the absorption and accumulation of heavy metals by the edible parts of crops (Noli and Tsamos, 2016). Among all the heavy metals, chromium (Cr) is considered as a serious environmental contaminant for the biota (Kabata-Pendias, 2011). Consumption of contaminated foods is considered to be the most common pathway of human exposure to Cr compared to inhalation and dermal contact (Wang et al., 2011). Cr(III) and Cr(VI) are the two main forms of chromium, among which Cr(VI) has higher water solubility and thus higher bioavailability. Due to its high redox potential, Cr(VI) can interfere with photosynthesis and respiration processes, uptake of water and minerals, enzyme activity, and leads to damage on the membrane lipid and DNA, resulting in a severe decline in crop yield and quality (Singh et al., 2013). Mutagenic and carcinogenic to humans, Cr(VI) is identified as a class A carcinogen (Prado et al., 2016; Feng et al., 2004). Therefore, studying the biotoxicity of Cr(VI) is essential for the safe production of agricultural products and the protection of the environment and human health.

There are some differences on the stress response and accumulation of Cr by different crops due to the differences in external morphology, internal structure as well as physiological and biochemical mechanisms on the absorption of heavy metals. For example, Bashri et al. (2016) studied the physiological and biochemical characteristics

of two *Amaranthus* species, in which they found the species with higher antioxidant defense system exhibited higher tolerance to Cr(VI) stress. It was reported that members of the Brassicaceae family can absorb and transfer high concentrations of Cr into the edible parts (Singh et al., 2013; Cervantes et al., 2001). Furthermore, difference in the physiological and biochemical response and accumulation of Cr by different cultivars of the same crop was also reported. For example, Guo et al. (2015) observed that the growth of Lumai 22 (Cr tolerant wheat cultivar) was less inhibited than Zhoumai 9 (Cr sensitive wheat cultivar). Moreover, a greater proportion of Cr was accumulated in the roots and the cell walls of the aerial parts in Lumai 22 compared with those of Zhoumai 9. Gill et al. (2015) found the ultrastructural damage in leaf mesophyll and root tip cells was most pronounced in Zheda 622 cultivar among the four different cultivars of *Brassica napus* L. Plants have specific mechanisms to protect from oxidative damages, such as enzymatic antioxidants and non-enzymatic antioxidants, which scavenge the reactive oxygen species (ROS). Wang et al. (2012) studied the tolerance of three species of grasses to Cr(VI) stress, in which they found *Medicago sativa* was less tolerant to Cr compared with *Trifolium repens* and *Festuca arundinacea*, which is likely due to the reduced activities of peroxidase (POD) and superoxide dismutase (SOD) of *Medicago sativa* with the increase of chromium concentration. Most of the above researches focused on the comparison of different cultivars of the same crop under the Cr stress. There are still knowledge gaps with regard to the stress response and accumulation of Cr by different crops.

Therefore, in this study, two levels of Cr(VI) were used for hydroponic treatment to study the stress response and accumulation of Cr by six crops including wheat, radish, cucumber, Chinese cabbage, oilseed rape, and lettuce. It can provide theoretical support for the rational and safe cultivation of crops in low and medium Cr-contaminated soil.

Materials and methods

Materials

The seeds of six crops including wheat (Jimai 22), radish (Zheda Chang), cucumber (green cucumber), Chinese cabbage (Jiaoyan 5869), oilseed rape (Shanghai Qing), and lettuce (four seasons lettuce) were purchased from Shandong Academy of Agricultural Sciences (Jinan, China), Ma'anshan Qiutian Seed Industry (Nanjing, China), Nanjing Jinshengda Seed (Nanjing, China), Qingdao Jiaoyan Seedling (Qingdao, China), Nanjing Jinshengda Seed (Nanjing, China), and Nanjing Green Collar Seed Industry Co., Ltd (Nanjing, China), separately.

Hydroponic experiment

The seeds were firstly sterilized with 10% H₂O₂ for 20 min, then washed thoroughly with distilled water. Subsequently, the seeds were germinated on filter paper saturated with deionized water and placed in the dark at 25 °C for 24 h. The germinated seeds were grown in plastic pots filled with quartz sand, which were placed in an artificial climate chamber with the daylight/night time of 14/10 h, daylight/night temperature of 24 ± 2 °C/18 ± 2 °C, the light intensity of 25000 lux, and the relative humidity of 75%. Wheat, radish, and cucumber were cultured for 2 weeks. Chinese cabbage, oilseed rape, and lettuce were grown to the stage of 4 leaves and 1 core. Then uniform seedlings were selected and transferred to glass containers with 400 mL of modified Hoagland nutrient

solution aerated with an air pump (4 seedlings per container). The nutrient solution (pH = 6.0) consists of 944 mg/L Ca(NO₃)₂, 490 mg/L MgSO₄, 136 mg/L KH₂PO₄, 510 mg/L KNO₃, 2.86 mg/L H₃BO₃, 1.81 mg/L MnCl₂, 0.22 mg/L ZnSO₄, 0.09 mg/L (NH₄)₆Mo₇O₂₄, 0.08 mg/L CuSO₄, and 3.67 mg/L NaFe-EDTA. After 3 days of acclimatization, the crops were exposed to 0, 1 mg/L and 5 mg/L of Cr(VI) (K₂CrO₄). Each treatment had three replicates. The nutrient solution was renewed every 3 days.

Measurement of gas exchange parameters

The photosynthetic gas exchange parameters of the crops, including photosynthetic rate, stomatal conductance, and transpiration rate, were measured using a portable photosynthesis instrument (LC pro-SD, ADC, England) after 15 days of treatment.

Measurement of growth and morphological parameters

Crops were harvested and separated into roots and the aerial parts after 15 days of exposure, then washed with deionized water and dried with filter paper to measure the fresh biomass. The aerial parts were placed in an oven at 105 °C for 30 min, then dried at 70 °C. The dry biomass was weighed. The roots were first scanned using a root scanner (ScanMaker i800plus, Shanghai Zhongjing Technology Co., Ltd., China) to measure the surface area, then were dried to measure the dry biomass. The dried crop tissues were pulverized with a stainless steel pulverizer for later use.

Determination of antioxidant enzyme activity

Frozen leaves were homogenized in 6 mL pre-cooled potassium phosphate buffer (50 mM, pH = 7.8) containing 1% (w/v) polyvinylpyrrolidone (PVP) with a chilled mortar and pestle. The homogenate was centrifuged at 10,000 g for 15 min at 4 °C and the supernatant obtained was used for enzymes assay.

SOD (EC 1.15.1.1) activity was determined by the nitroblue tetrazolium (NBT) method (Gonzalez et al., 1998). The assay mixture contained 50 mM phosphate buffer (pH 7.8), 130 mM methionine, 750 μM NBT, 100 μM EDTA-Na₂, and 20 μM riboflavin. A total volume of 3.3 mL assay mixture was placed under a 4000 lx fluorescent lamp for 15-20 min and then determined using an ultraviolet visible spectrophotometer (UV-2550, Shimadzu, Japan) at 560 nm. One unit of SOD activity is the amount of enzyme that is required to cause 50% inhibition in the reduction of NBT. POD (EC 1.11.1.7) activity was determined using the guaiacol method (Zhou and Leul, 1998). The reaction mixture was comprised of 50 mM phosphate buffer (pH = 7.8), 30% H₂O₂, 20 mM guaiacol, and 100 μL enzyme extract. Activities of POD were assayed by measuring the absorbance at 436 nm with 3 mL of the mixture. One unit of POD activity was defined as the amount of enzyme catalyzing the oxidation of 1 μmol of guaiacol in 1 min.

Determination of Cr contents in the crop tissues

For determination of Cr contents, a certain amount of the roots or the aerial parts was weighed into a digestion tube. Ten milliliter digestion solution consisting of HNO₃ and H₂O (1:1, V/V) was added soaking overnight. A graphite digestion instrument (EE, USA) was used to digest the tissues for about 12 h at temperature of 105 °C. Then 1 mL of H₂O₂ was added to the remaining digestion solution and continue to digest to obtain

clear solution. The solution was made up to 50 mL using Milli-Q water. Chromium contents were measured by ICP-MS (iCAP Q, Thermo Fisher Scientific, America).

Statistical analysis

Bio-concentration factor (BCF) is the ratio of the concentration of heavy metals in the roots or the aerial parts of plants to that in soil or solution (Ding et al., 2016). The transfer factor (TF) is the percentage of Cr concentration in the aerial parts to that in the roots, indicating the ability of heavy metals to be translocated from the roots to the aerial parts (Ali et al., 2013). The tolerance index (TI) is the percentage of the biomass of crop at Cr stress to that of the control treatment (Wilkins, 1978).

Data processing and analysis were performed using Excel and SPSS 22. One-way ANOVA and the least squares deviation (LSD) test were used to compare the difference among different treatments. Statistical significance was accepted at $p < 0.05$. The figures were graphed using Origin 2017 software. The data results were expressed as mean \pm standard error.

Results

Effect of Cr(VI) on the growth traits of crops

The fresh biomass and root area of the six crops showed a decreasing tendency with increasing Cr(VI) concentration (*Table 1*). For the treatments of 1 mg/L of Cr(VI), the root biomasses of wheat and Chinese cabbage were not significantly different from those of the control, while those of radish, cucumber, oilseed rape, and lettuce decreased significantly compared with those of the control, with reduction of 25%, 73%, 30%, and 71%, respectively. Treatments with 5 mg/L of Cr(VI) significantly reduced the root biomasses of all the six crops. The reduction in root biomass was the lowest for wheat (25%), followed by radish (49%), oilseed rape (59%), Chinese cabbage (68%), cucumber (76%), and lettuce (92%). The aerial biomasses of the six crops were reduced significantly under the two levels of Cr(VI) treatments. Similar to those of the roots, wheat showed the lowest reductions in the aerial biomass, which were 27% and 49%, respectively. While lettuce presented the highest reduction, which were 82% and 94%, respectively. Under 5 mg/L of Cr(VI) stress, the root and shoot TI of wheat were 75% and 51%, respectively. While the root and shoot TI of lettuce were 7% and 6%, respectively. The results indicated that wheat has stronger tolerance to Cr(VI) toxicity, while lettuce showed less tolerance compared with other crops.

Under the two levels of Cr(VI) stress, except for cucumber, the TI values for the aerial parts of the other five crops were all lower than those of the roots, indicating the biomasses of the aerial parts other than roots of these five crops are more sensitive to Cr(VI) toxicity and could be used as biomarkers.

Effect of Cr(VI) on the photosynthetic properties of crops

The photosynthetic rate and transpiration rate of the six crops responded differently under the two levels of Cr(VI) treatments (*Table 2*). Under 1 mg/L of Cr(VI) treatment, the stomatal conductance and transpiration rate of wheat, cucumber, and oilseed rape did not change significantly, while those of radish, Chinese cabbage, and lettuce decreased significantly. The stomatal conductance and transpiration rate of the six crops were significantly reduced under 5 mg/L of Cr(VI) treatment. The transpiration rates in

the leaves of wheat, radish, cucumber, Chinese cabbage, oilseed rape, and lettuce were reduced by 63%, 79%, 56%, 60%, 71%, and 87%, respectively. The stress of Cr(VI) on the transpiration rate in the leaves of wheat, cucumber, and Chinese cabbage is relatively low, which may account for the insignificant change in the leaf water contents of these three crops under Cr(VI) treatment of 1 mg/L (Fig. 1). The photosynthetic rates of wheat, radish, and Chinese cabbage did not change significantly, while those of cucumber, oilseed rape, and lettuce were significantly reduced under 1 mg/L of Cr(VI) treatment. Under 5 mg/L of Cr(VI) treatment, the photosynthesis rates of wheat, radish, cucumber, Chinese cabbage, oilseed rape, and lettuce decreased significantly, with reductions of 51%, 61%, 55%, 41%, 79%, and 80%, respectively. The effects of Cr(VI) on the photosynthetic rates of wheat and Chinese cabbage are less than those of other crops, while are higher than those of oilseed rape and lettuce.

Table 1. Effect of Cr (VI) on the growth traits of crops

Parameters	Cr(VI) (mg/L)	Wheat	Radish	Cucumber	Chinese cabbage	Oilseed rape	Lettuce
Root biomass (g per container)	0	3.20±0.23a	0.91±0.07a	8.72±1.78a	2.65±0.26a	2.47±0.71a	9.98±2.08a
	1	2.92±0.19ab	0.68±0.04b	1.94±0.32 bc	2.10±0.65ab	1.71±0.51bc	2.88±1.43bc
	5	2.41±0.10b	0.47±0.05c	1.75±0.54c	0.84±0.14b	1.02±0.19c	0.78±0.07c
Aerial biomass (g per container)	0	4.98±0.39a	15.1±0.37a	19.6±1.45a	23.7±1.33a	22.4±2.04a	63.0±9.2a
	1	3.62±0.16b	9.87±0.06b	8.61±1.55b	15.1±4.64b	12.7±1.94b	11.6±5.43bc
	5	2.56±0.03c	5.16±0.05c	5.70±0.34c	5.53±0.87c	6.63±0.59c	3.84±0.44b
Root area (cm ²)	0	99.7±4.48a	26.0±4.94a	188±19.40a	32.0±1.28a	32.2±1.46a	157±24.9a
	1	80.7±10.89b	14.6±0.44bc	36.2±8.26bc	29.8±4.70ab	21.3±2.59bc	38.3±2.93bc
	5	53.4±2.12c	12.1±1.65c	35.9±6.67c	18.8±1.12c	17.3±0.68c	18.8±0.89c
Root TI	1	91	74	22	79	69	28
	5	75	51	20	40	41	7
Shoot TI	1	72	60	43	63	49	18
	5	51	34	29	23	25	6

Values are presented as means and standard error. Different letters indicate statistically significant difference between different treatments

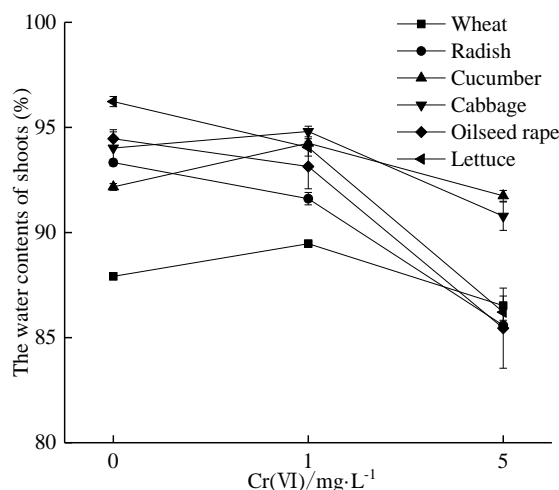


Figure 1. Effect of Cr(VI) on the water contents (%) of the six crops. (Bars indicate standard error)

Table 2. Effect of Cr(VI) on the photosynthetic parameters of crops

Parameters	Cr(VI) (mg/L)	Wheat	Radish	Cucumber	Chinese cabbage	Oilseed rape	Lettuce
Stomatal conductance (mol/m ² /s)	0	0.40±0.02a	0.21±0.01a	0.14±0.03a	0.42±0.19a	0.24±0.05a	0.46±0.04a
	1	0.35±0.08ab	0.10±0.02b	0.09±0.01ab	0.18±0.02bc	0.17±0.01ab	0.13±0.01b
	5	0.11±0.01c	0.03±0.01c	0.05±0.04b	0.05±0.02c	0.06±0.01bc	0.02±0.00c
Transpiration rate (mol/m ² /s)	0	3.14±0.44ab	2.09±0.43a	1.22±0.18ab	3.47±0.66a	2.37±0.34a	3.09±0.20a
	1	3.58±0.08a	1.20±0.1b	1.44±0.06a	2.55±0.13b	2.26±0.34ab	1.81±0.12b
	5	1.68±0.18c	0.44±0.08c	0.54±0.18c	1.00±0.36c	0.95±0.18c	0.42±0.08c
Photosynthetic rate (µmol CO ₂ /m ² /s)	0	17.3±4.42a	4.44±0.45a	3.53±0.26a	9.00±1.0a	6.68±0.11a	8.76±0.38a
	1	11.6±2.19ab	3.64±0.08ab	1.98±0.16bc	5.16±0.08b	4.87±0.26ab	7.07±0.25b
	5	8.5±1.28b	1.77±0.30c	1.61±0.15c	1.96±0.39c	3.96±0.98bc	1.89±0.11c

Values are presented as means and standard error. Different letters indicate statistically significant difference between different treatments

Effects of Cr(VI) on the activities of antioxidant enzymes

The effects of Cr(VI) on the SOD and POD activities of the six crops are shown in Figure 2.

As can be seen, Cr(VI) treatment of 5 mg/L significantly inhibited the SOD activity of all the crops except that of cucumber. Moreover, for Chinese cabbage and radish, significant decrease in SOD activity was observed at 1 mg/L of Cr(VI) treatment. Especially for radish, SOD activity was not detected at the two levels of Cr(VI) treatments. It is suggested that Chinese cabbage and radish are sensitive to the stress of Cr(VI). Similar to that of SOD, Cr(VI) treatment of 5 mg/L resulted in significant inhibition on POD activity of all the crops except cucumber and oilseed rape. For Chinese cabbage and oilseed rape, significant activation effect on the POD was observed at 1 mg/L or 5 mg/L of Cr(VI) treatment. Interestingly, the SOD and POD activities of cucumber did not change significantly at the two levels of Cr(VI) treatments. This indicated that cucumber is not sensitive to the stress of Cr(VI).

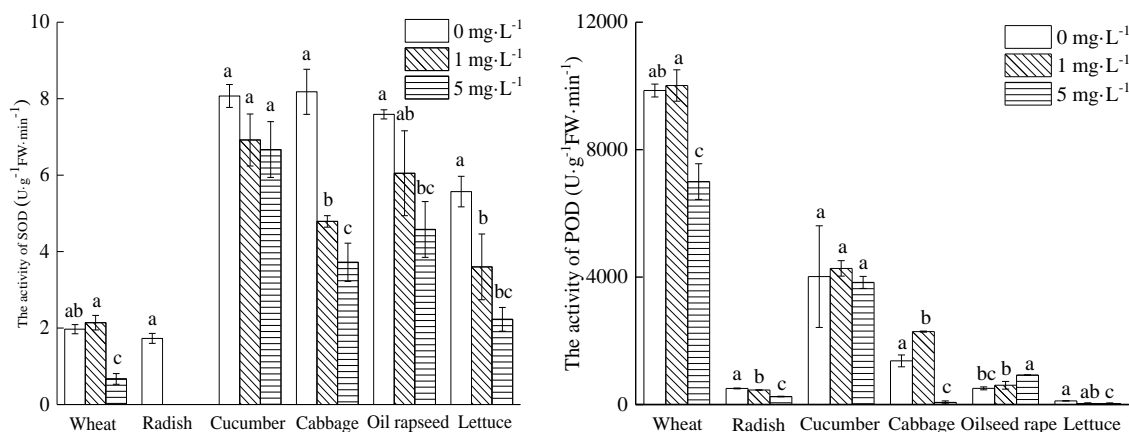


Figure 2. Effect of Cr (VI) on the activities of antioxidant enzymes in crops. (Bars indicate standard error)

The accumulation of Cr by crops

With the increase of Cr(VI) concentration in hydroponic solution, the Cr contents in the crop tissues increased significantly except the roots of cucumber and Chinese cabbage (Table 3). Under Cr(VI) treatment of 1 mg/L, the Cr content in lettuce roots is the highest (1024 µg/g), followed by oilseed rape (772 µg/g), Chinese cabbage (736 µg/g), cucumber (695 µg/g), radish (651 µg/g), and wheat (246 µg/g). For 5 mg/L of Cr(VI) treatment, the Cr content in lettuce roots is also the highest (2823 µg/g), followed by radish (1453 µg/g), oilseed rape (1161 µg/g), Chinese cabbage (876 µg/g), cucumber (700 µg/g), and wheat (427 µg/g). The Cr contents in the aerial parts of the six crops were far below those of the roots. Under Cr (VI) treatment of 1 mg/L, the Cr content in the aerial parts of Chinese cabbage is the highest (35.9 µg/g), followed by oilseed rape (19.5 µg/g), lettuce (16.2 µg/g), radish (13.4 µg/g), wheat (13.2 µg/g), and cucumber (9.00 µg/g). Under Cr(VI) treatment of 5 mg/L, the Cr contents in the aerial parts of the six crops followed the same order.

Table 3. *The uptake, accumulation, and translocation of Cr by crops*

	Cr(VI) (mg/L)	Wheat	Radish	Cucumber	Chinese cabbage	Oilseed rape	Lettuce
Cr contents in roots (µg/g DW)	1	246±22.3b	611±0.67b	695±38.9ab	736±67.3ab	772±20.9b	1024±105b
	5	427±0.29a	1453±9.20a	700±35.5a	876±55.8a	1161±60.2a	2823±260a
Cr contents in the aerial parts (µg/g DW)	1	13.2±1.38b	13.4±1.79b	9.00±0.09b	35.9±5.55b	19.5±0.32b	16.2±2.96b
	5	38.3±1.91a	38.2±3.94a	25.0±1.53a	209±3.18a	104±3.79a	63.8±10.5a
Aerial BCF	1	13.0±1.10a	13.4±1.79a	9.00±0.09a	35.9±5.55ab	19.5±0.32ab	16.2±2.96a
	5	7.66±0.38b	9.95±2.36ab	5.00±0.31b	41.8±0.64a	20.8±0.75a	15.3±2.79ab
Root BCF	1	246±22.3b	603±7.75a	784±91.2a	736±67.3a	862±90.9a	737±89.8a
	5	111±25.5a	290±1.84b	140±7.10b	210±36.1b	279±47.4b	565±52.1b
TF (%)	1	5.12±0.57b	2.06±0.16ab	1.16±0.11b	4.93±1.21b	2.48±0.26b	1.57±0.15b
	5	9.06±0.76a	3.02±0.69a	4.67±0.94a	18.6±3.51a	8.97±0.14a	2.92±0.21a

Values are presented as means and standard error. Different letters indicate statistically significant difference between different treatments

For the roots, the BCF values of the six crops decreased significantly with the increase of Cr(VI) treatment concentration. Under Cr(VI) treatment of 1 mg/L, the BCF for wheat roots was significantly lower than those of other crops. Under 5 mg/L of Cr(VI) treatment, the root BCF of lettuce was the highest, followed by radish, oilseed rape, Chinese cabbage, cucumber, and wheat. For the aerial parts, the BCF of Chinese cabbage, oilseed rape, lettuce, and radish did not change significantly at the two levels of Cr(VI) treatments, while those of wheat and cucumber decreased significantly with the increase of Cr(VI) treatment concentration. The BCF of the aerial parts of Chinese cabbage is the highest, and that of cucumber is the lowest.

Except for radish, the TF of other crops increased significantly with the increase of Cr(VI) treatment concentration. Under Cr(VI) treatment of 1 mg/L, the TF values of the six crops ranged from 1.16 to 5.12, following the order of wheat > Chinese cabbage > oilseed rape > radish > lettuce > cucumber. Under Cr(VI) treatment of 5 mg/L, the TF values of the six crops ranged from 2.92 to 18.6. Different from that of 1 mg/L

treatment, the order is Chinese cabbage > wheat > oilseed rape > cucumber > radish > lettuce.

Discussion

It has been demonstrated that Cr could inhibit the growth of plant, cause chlorosis in newly budded leaves and the decrease in root surface area. These indicators have been used to assess the responses of crops to the Cr stress (Bashri et al., 2016; Anjum et al., 2017; Liu et al., 2008; Pandey et al., 2005; Tiwari et al., 2009). In the present study, the biomasses of crop tissues decreased with the increase of Cr(VI) concentration in the nutrient solution (*Table 1*). The results are consistent with those of wheat seedlings exposed to Cr(VI) (Guo et al., 2015). All the six crops were stressed by 1 mg/L of Cr(VI), and the aerial parts of the six crops were more sensitive to Cr stress than the roots except for cucumber (*Table 1*). This may be due to the reduced root activity, which inhibits the transport of nutrients from roots to the aerial parts. The growth parameters of the six crops were significantly reduced because the crops could not acquire abundant nutrients to maintain normal physiological activity (Ali et al., 2013). The TI can be used to indicate the tolerance of crops to heavy metals, the greater the value, the stronger the tolerance of plants to heavy metals (Liu and Wang, 2002). In the present study, the growth parameters and the TI values indicated that wheat exhibited strong tolerance to Cr(VI) among the six crops, while lettuce was relatively less tolerant to Cr(VI).

The main parameters affecting crop photosynthesis and transpiration include stomatal conductance, transpiration rate, and photosynthetic rate. In this study, as the Cr(VI) treatment level increased, the stomatal conductance, transpiration rate, and photosynthetic rate of the six crops showed a decreasing tendency. The increase of chlorophyllase activity in crops resulted in the decomposition of chlorophyll under the stress of heavy metals (Hegedus and Erdei, 2001), which led to lower capacity for light-harvesting, thus the decrease in photosynthetic rate. On the other hand, the decrease of the photosynthetic rate under Cr(VI) stress may be attributed to the interference of Cr on nutrient absorption, respiration rate, and cell membrane permeability. In addition, Cr(VI) can induce chloroplast ultrastructural abnormalities, such as the alteration of thylakoid (Luisa Brito et al., 2009). The treatment of 5 mg/L Cr(VI) significantly reduced the stomatal conductance of the crop leaves. This can be explained by the damage to the stomatal guard cells of crop leaves caused by the high oxidation potential of Cr(VI) (Hayat et al., 2012). Former study has found that Cr can reduce the tracheary diameter of bean plants, thereby reducing the longitudinal movement of water (Barceló and Poschenrieder, 1990), which may bring about the reduced transpiration rate of the crops. Similar results have also been reported by Gill et al. (2015), Liu et al. (2008), and Ali et al. (2011), in which they found that high concentrations of Cr can reduce the net photosynthetic rate, stomatal conductance, and transpiration rate of oilseed rape, *Amaranthus viridis* L and barley. Heavy metal stress results in severe dehydration of plant shoots by interfering with the water transport from roots to shoots. In general, heavy metals can affect water contents through water absorption, water transformation of plastids and protoplasts, and stomatal function (Poschenrieder and Barceló, 1999). In this study, under the stress of 5 mg/L of Cr(VI), the water contents of wheat and cucumber did not change significantly, while those of radish, Chinese cabbage, oilseed rape, and lettuce decreased significantly.

Subjected to Cr stress, crops are stimulated to produce reactive oxygen species (ROS), such as H₂O₂, OH⁻, O²⁻, which bring about oxidative damage to biomolecules such as lipids, proteins, and nucleic acids. Therefore, crops control the production of peroxidative radicals by developing a complex enzymatic antioxidant system to prevent plants from being oxidatively damaged (Ashraf et al., 2015). This defense mechanism includes various antioxidant enzymes such as SOD, catalase (CAT), and POD. Crop cells increase the activity of antioxidant enzymes and eliminate excess ROS to maintain ROS balance (Gill and Tuteja, 2010). The differences in antioxidant defense mechanisms induced by heavy metals depend on the species of heavy metal and crops (Hayat et al., 2012). SOD and POD are vital enzymes in crop antioxidant defense mechanisms. SOD is the most critical substance accounting for plant stress tolerance, providing a first line of defense to reduce the toxic effects caused by elevated levels of ROS. In general, the activities of antioxidant enzymes will be promoted under low concentration of heavy metal exposure while be inhibited under high concentrations of heavy metal exposure. Huang et al. (2011) showed that 10⁻⁶ mol/L of Cr(VI) stress had no significant effect on SOD and POD activities in maize, while 10⁻⁵ mol/L of Cr(VI) stress showed significant decreases in SOD and POD activities. In this study, under the stress of Cr(VI), the antioxidant enzyme activities of different crops were very different. The SOD and POD activities of wheat, cucumber, and oilseed rape as well as the POD activity of lettuce did not change significantly when treated with 1 mg/L of Cr(VI). The activities of SOD and POD in the leaves of radish and the activity of SOD in the leaves of Chinese cabbage and lettuce significantly decreased, while the activity of POD in the leaves of Chinese cabbage significantly increased. It showed that under 1 mg/L of Cr(VI) stress, wheat was tolerant to the Cr stress, while lettuce presented its sensitivity to the Cr stress. The increase of antioxidant enzyme activity may be attributed to the blockage of electron transport chains in mitochondria induced by Cr(VI), which directly affects the production of superoxide radicals. With the increase of Cr concentration, the enzyme activity decreases, which is due to the inhibition of Cr(VI) to the enzyme system (Hayat et al., 2012). Also, Huang et al. (2011) found that the dramatic changes in antioxidant enzyme activity may be related to the expression of isoenzymes during the transformation of nutritional mode.

The six crops showed considerable differences in the absorption, translocation, and accumulation of Cr. Wang et al. (2012) have found different oil crops showed different tolerance and accumulation of Cr. In this study, Cr was mainly retained in the roots of the six crops, ranging from 2823 µg/g (lettuce) to 426.5 µg/g (wheat). However, due to the difference in the translocation of Cr by different crops, the TF of Chinese cabbage (18.6%) was the highest, which resulted in the highest content of Cr (208.8 µg/g) in the aerial parts of Chinese cabbage. The Cr contents in the aerial parts of oilseed rape and lettuce are significantly higher than those of the other three crops. It has been found that transpiration plays a vital role in the translocation of heavy metals by crops (Ji et al., 2017). In this study, there is a significant positive correlation between the TF of Cr and the transpiration rate of the six crops under Cr(VI) treatment of 1 mg/L ($R^2 = 0.75$), which was not observed under Cr(VI) treatment of 5 mg/L because of the higher toxic effect of Cr(VI) at this level.

Based on the above analysis, it can be found that wheat is more tolerant to Cr(VI) and has a weaker accumulation ability for Cr, while lettuce is more sensitive to Cr(VI) and has a stronger ability to accumulate Cr. Therefore, lettuce will bring more risks than wheat when planted in low and medium concentration Cr(VI)-contaminated soils. This

study is limited to the sensitivity and accumulation of Cr (VI) by six crops under hydroponic conditions. The treatment level of 5 mg/L Cr(VI) may be too high, which resulted in excessive toxicity and high Cr contents in crops. Although the results can reflect the tolerance of crops to Cr(VI), the tolerance, the translocation and accumulation of Cr by these six crops in soil systems remain to be further studied.

Conclusions

Under Cr(VI) stress conditions, the growth traits and photosynthetic characteristics of the six crops were more inhibited with increasing treatment concentration. Among them, wheat showed the strongest tolerance to Cr(VI), with the lowest accumulation of Cr in the shoots. Lettuce presented to be the most sensitive vegetables, with most Cr accumulated in the roots. Chinese cabbage had a certain tolerance to Cr(VI) and showed the highest accumulation of Cr in the edible parts, which may pose a threat to the safety of agricultural products if planted in Cr contaminated soils. In this study, the results on the tolerance and accumulation of Cr were based on the hydroponic conditions, the accumulation of Cr in soil systems by these crops should be further studied in the future.

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