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Cadmium Accumulation and its Effects on Nutrient Uptake and Photosynthetic Performance in Cucumber (*Cucumis sativus* L.)

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The phytotoxicity of different concentrations (0, 10, 25, 50, 100 and 200 μM) of cadmium (Cd) on cucumber (*Cucumis sativus* L.) seedlings was studied. Cucumber growth was negatively affected by increasing Cd concentrations, and biomass decreased significantly at concentrations of more than 25 μM, while the total antioxidant capacity decreased in all tissues. Moreover, Cd was accumulated primarily in roots, and Cd concentration increased with increasing Cd concentrations in solution. Cd induced a decrease in the photosynthetic performance (i.e., net photosynthetic rate, stomatal conductance, and transpiration rate), while there was an increase in intercellular CO_2 level at Cd concentrations higher than 100 μM. In addition, Cd induced alterations in some nutrient elements; for instance, it significantly decreased shoot Zn, Cu and Mn concentrations and reduced their concentrations in roots up to the 25 μM Cd treatment. In terms of macroelement, stem/root Mg, leaf Ca, and K decreased significantly after the Cd treatments, indicating a negative correlation with Cd. Leaf Mg and stem/root Ca decreased evidently only in seedlings exposed to 50 and 100 μM Cd, respectively. In general, cucumber is highly sensitive even at very low Cd concentrations. Increasing Cd stress in cucumber not only inhibited plant growth, but also affected a series of macronutrient and micronutrient concentrations both in shoots and roots.

Key Words: antioxidant capacity, cadmium toxicity, cucumber (*Cucumis sativus* L.), nutrient, photosynthesis

Abbreviations: Cd – cadmium, *Ci* – intercullar CO_2 concentration, CUPRAC – cupric reducing antioxidant capacity, DW – dry weight, GAE – gallic acid equivalent, GIR – growth inhibition rate, *Gs* – stomatal conductance, *Pn* – net photosynthetic rate, SPAD – Soil Plant Analysis Development, *Tr* – transpiration rate

INTRODUCTION

Heavy metal contamination has become a worldwide problem, leading to losses in agricultural yield and hazardous human health effects via the food chain. Cd is one of the most toxic heavy metals that negatively affect plant growth and development at concentrations much lower than those of other heavy metals, where it might endanger crop productivity and food quality (Shukla et al. 2003). The presence of excessive Cd in plants usually elicits many stress symptoms, as several authors have already reported that Cd could induce morphological, physiological, biochemical and structural disorders in plants. Cd can also affect the photosynthetic system as in cases of chlorosis, growth inhibition, and browning of root tips, and may therefore strongly reduce biomass production (Benavides et al. 2005; Wang et al. 2011; Lin et al. 2012; Liu et al. 2015). As a matter of fact, at least 70% of the Cd intake by humans originates from plant foods (Wagner 1993). Consequently, today, special consideration should be given to dangerous Cd pollution in the soil and in plant systems.

Cd, in particular, is related to interactions between uptake and translocation of mineral nutrients in plants. The effect of the interaction between Cd and essential nutrients on uptake and distribution in crops is a public concern and may provide clues to understanding the nature of Cd accumulation in crops (Liu et al. 2003). Previous studies have indicated that leaf chlorosis from excess Cd appeared to be associated directly or indirectly with Zn (Turner 1973) or Fe (Root et al. 1975; Foy et al. 1978). Interactions between Cd and other nutrients are seen as changes in the nutrient content of different plant tissues, and manifested by physiological disorders and a diminution of growth. Several important metabolic processes in plants, i.e., a wide range of enzymes, either contain or are activated by the essential micronutrient Mn (Marschner 1995). It is therefore important to study the effect of Cd, particularly on Ca (Wang 1987) as well as on physiologically important micronutrients such as Zn, Cu

and Mn (Kim et al. 1988; Chen et al. 2007; Janicka-Russak et al. 2012).

Many studies have reported that Cd influences the uptake and translocation of nutrients in some crops such as wheat (Zhang et al. 2002), tomato (Dong et al. 2006), rice (Lin et al. 2012), barley (Sun et al. 2014), and tobacco (Liu et al. 2015). However, contradictory results have been found, which may be attributed to species or cultivar differences, interactions between cultivars and metals, and between metals within plant tissues. Thus, further studies are needed to investigate the interactions between contaminants and nutrients in order to encourage selection for enhanced uptake efficiency of desirable nutrients and reduction in uptake of undesirable ones (Liu et al. 2003).

Since cucumber (*Cucumis sativus* L.) is an important vegetable crop not only in China but also all over the world, which can also be used as an indicator species to assess ecotoxicity of soils polluted by contaminants (Cargnelutti et al. 2006; Pereira et al. 2006), it is therefore necessary to study Cd toxicity in cucumber. The available information on Cd toxicity in cucumber has mainly focused on the effects of Cd on the antioxidant system in cucumber seedlings such as protein oxidation, lipid peroxidation, catalase (CAT), ascorbate peroxidase (APX), and superoxide dismutase (SOD) activities, and ascorbic acid (AsA), non-protein thiol groups and total soluble protein concentrations (Gonçalves et al. 2007). Such information has also included studies on biomass production, yield and chlorophyll content in cucumber leaves under different doses, and time of exposure to Cd (Moreno-Caselles et al. 2000), and on nitrate metabolism (Feng et al. 2010), H^+-ATPase activity (Janicka-Russak et al. 2012) in root, the accumulation of phytochelatins (PCs) (Hawrylak-Nowaka et al. 2014), and nicotinamide adenine dinucleotide phosphate (NADPH) oxidase activity in the plasma membrane (Jakubowska et al. 2015) in cucumber root. In addition, Piterková et al. (2015) examined the role of reactive oxygen species (ROS), nitric oxide (NO) and reactive nitrogen species (RNS) in the responses of cucumber cell culture to high Cd concentration. With regard to nutrient uptake, Cd and some nutrient uptake by cucumber under 10 μM Cd stress was tested (Savvas et al. 2013); however, to our knowledge, no research is available to date regarding the impact of different doses of Cd exposure on Cd and nutrient uptake by different cucumber tissues.

Therefore, recognizing the problem that may be due to either contradictory results concerning Cd influences on the uptake and translocation of nutrients in some crops, or a lack of research in relation to the nutritional status of cucumber seedlings, the present study aimed (1) to assess how stress resulting from different Cd levels affects the uptake and translocation of nutrients in cucumber leaves, stems and roots, accompanying Cd accumulation in cucumber seedlings, and (2) to investigate the role of chlorophyll content, photosynthetic parameters, total antioxidant capacity, biomass, and some growth parameters under Cd stress. Such information may lead us to understand the possible phytotoxic effect of Cd on uptake of particular nutrients and to define its possible biochemical roles in cucumber.

MATERIALS AND METHODS

Plant Material and Experimental Design

The hydroponic experiment was conducted in the North Campus, Taiyuan University of Science and Technology, Taiyuan, China during the growth season in 2015, using Jinyan 4, a commonly cultivated cucumber variety. Healthy cucumber seeds were surface-sterilized and then germinated in sterilized moist sand in an incubator at 25 ° C. After 10 d, the uniformly healthy seedlings were selected and transplanted to 5-L containers filled with 4.5-L basic nutrient solution, with pH 5.6 ± 0.1, and with 7 plants per container (Sun et al. 2014). On the 7th day after transplanting, six treatments were established by addition of Cd (as $CdCl_2$) to the nutrient solution, with Cd concentration in solution as 0 (control), 10, 25, 50, 100 and 200 μM. There were three replicates for each treatment, and the nutrient solution was continuously aerated with pumps and renewed at 5 d interval. After 10 d of Cd exposure, all the selected seedlings were used as materials for fresh samples.

Analysis of Chlorophyll Content and Photosynthesis Parameters

The chlorophyll content, measured as Soil Plant Analysis Development (SPAD) values, was determined using a chlorophyll meter (SPAD-502, Konica Minolta Sensing, Japan). The net photosynthetic rate (*Pn*), transpiration rate (*Tr*), stomatal conductance (*Gs*) and intercellular CO_2 concentration (*Ci*) were measured using a LI-6400 portable photosynthesis system (LI-COR, Lincoln, NE, USA).

Plant Growth and Biomass, and Element Determination

After 10 d of treatment, plant height and root length of each plant were measured, then the plants were separated into leaves, stems and roots. The roots were soaked in 20 mM Na_2-EDTA for 20 min to eliminate adsorbed ions and possible chemical contamination on the root surfaces, and then rinsed in deionized water. For determination of element, all tissues were dried at 80 °C, weighed and powdered and then digested in a mixture of HNO_3–$HClO_4$ (5:1). Concentrations of Cd, Zn, Cu, Mn, Mg, Ca and K were determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES) (SPS 1200 VR, Seiko Co., Ltd., Japan). Growth inhibition rate (GIR, %) was calculated using the formula:

$$\text{GIR\%} = (\text{values under Cd stress} - \text{values under control})/\text{values under control} \times 100$$

Antioxidant Capacity Determination

The fresh samples were directly used for determining total antioxidant capacity, which was done by the cupric reducing antioxidant capacity (CUPRAC) assay according to our previous study (Li et al. 2015), and the final results were given as g gallic acid equivalents (GAE).

Statistical Analysis

All data were means of three replicates that were analyzed using analysis of variance (ANOVA). Differences among treatments were evaluated by the Duncan's Multiple Range Test (SSR) at a significance level of $P \leq 0.05$.

RESULTS AND DISCUSSION

Cd-Dose-Response of Cucumber Seedling Growth, Biomass and Chlorosis

Considering that Cd, even in small concentrations, could exhibit toxic effects on plants, its contamination has become a growing concern in recent years. Growth inhibition is a common response to heavy metal stress and is also one of the most important agricultural indices of heavy metal tolerance (Van Belleghem et al. 2007; Malar et al. 2014). The effect of heavy metal on seedling growth seems to be different with regard to plant species, cultivars and organs (Sainger et al. 2011; Lin et al. 2012). Cucumber seedlings exposed to different Cd concentrations exhibited different inhibition responses of both root and shoot growth, with a significant declining trend in plant height. Increasing Cd concentration reduced plant height progressively with increasing Cd dosage. At higher concentration, the growth inhibition rate (GIR, %) in plant height compared with the control was more significant, e.g., under 200 μM Cd stress, the GIR of plant height was 38.6%. A similar response was observed in the root length, which was found to be reduced by 5.0%, 12.9%, 22.5%, 28.8% and 40.5% under 10, 25, 50, 100 and 200 μM Cd exposure, respectively. Furthermore, with increasing supply of Cd, the total dry weight (DW) showed a clear negative linear response. After 10 d of 200 μM Cd treatment, the GIR of DW was 42.0% (Table 1).

Leaf chlorosis is one of the most universal symptoms of Cd exposure to plants according to many previous studies, and it can be used as an index to evaluate heavy metal tolerance, which was consistent with the present results, expressed as SPAD value. The effects of different concentrations of Cd treatment (10 to 200 μM) on SPAD value are presented in Table 1. The reduction percentage was 23.1% in the 50 μM Cd treatment, and 40.5% reduction in the 200 μM Cd treatment compared with the control (Table 1).

Cd-Dose-Response for Cd Accumulation in Different Parts of Cucumber

It has been shown that Cd incorporation is proportional to the Cd concentration in the medium and/or to the incubation time in maize seedlings (Wójcik and Tukiendorf 2005) and in rice (Cao et al. 2015). In the present study, accumulation of Cd content in cucumber seedlings was dependent on the concentration present in the growth medium, as Cd concentration in cucumber seedlings increased with increasing Cd level in the medium, and the Cd accumulation level was found to be higher in roots, followed by stem and leaf tissues. The level of Cd accumulation in roots, stems and leaves showed positive linear relationships with the Cd concentration in the nutrient solution. These results agreed with the findings of Cao et al. (2015). Moreover, the increasing rate of Cd concentration with elevating medium Cd level was increased significantly from low Cd concentration to high Cd concentration treatments; however, there was almost no significant difference between the 10 μM and the 25 μM Cd treatment in leaves (Fig. 1a).

The accumulation of Cd was found to be very high in the presence of 200 μM Cd concentration in the growth medium, and the maximum accumulation of Cd content was 9363 mg kg^{-1} DW in roots, followed by stem (1765 mg kg^{-1}) and leaf tissues (137 mg kg^{-1}) (Fig. 1). The translocation factor value was found to be less than 1. Although Cd was largely stored in plant roots exposed to 200 μM Cd treatment, only lesser amounts of Cd were translocated to aerial parts of the plants. These results indicated that Cd mainly accumulated in the roots, and only small amounts of them were translocated into the shoots of cucumber seedlings. We have been able to show that Cd can enter cucumber seedlings very quickly and accumulate to high concentrations especially in the roots, and although the final destination of the metal has not

Table 1. Effects of different Cd levels on growth parameters of cucumber seedlings.

Treatment (μmol/L)	Plant Height (cm)	Root Length (cm)	Dry Weight (mg/plant)	SPAD Value	Growth Inhibition Rate (GIR, %)			
					Shoot	Root	SPAD	DW
0.0	19.95 ± 0.36^{a*}	15.10 ± 0.82^{a*}	92.77 ± 1.90^{a*}	25.87 ± 0.84^{a*}	0.0	0.0	0.0	0.0
10	18.45 ± 0.81^{a}	14.35 ± 0.76^{ab}	89.33 ± 2.12^{a}	22.77 ± 0.91^{b}	7.52	4.97	11.98	3.70
25	18.35 ± 0.77^{ab}	13.15 ± 0.61^{ab}	83.33 ± 1.87^{ab}	21.40 ± 0.62^{b}	8.02	12.91	17.28	10.17
50	16.85 ± 0.52^{b}	11.70 ± 0.64^{b}	74.99 ± 1.52^{b}	19.90 ± 0.69^{c}	15.54	22.52	23.08	19.17
100	15.75 ± 0.81^{bc}	10.75 ± 0.56^{b}	64.90 ± 1.67^{c}	18.53 ± 0.71^{c}	21.05	28.81	28.37	30.04
200	12.25 ± 0.51^{d}	7.25 ± 0.47^{bc}	53.82 ± 1.96^{d}	15.40 ± 0.82^{d}	38.60	51.99	40.47	41.99

*Values are expressed as mean ± SE (n = 3). Different letters in each column indicate significant differences ($p \leq 0.05$) among the treatments.
DW – dry weight, SPAD – Soil Plant Analysis Development

been determined, it is known that Cd can be complexed by phytochelatins and sequestered in the vacuole (Wójcik et al. 2005).

Effects of Cd Treatment on Cucumber Photosynthetic Parameters

Investigations have demonstrated a notable reduction in photosynthesis by Cd in different plant species (Toth et al. 2012; Lukacova et al. 2013), and the decrease in photosynthetic capacities is one result of Cd-reduced pigment. In our experiment, the extent of the negative effect of Cd stress on photosynthesis was found in cucumber seedlings. *Pn* was reduced by 6.7%, 6.7% and 7.8% under 10, 25 and 50 μM Cd treatments, respectively, compared with the control, and markedly decreased by 28.5% and 51.0% under 100 and 200 μM Cd, respectively (Table 2). A significant difference was observed in *Tr* between control and Cd treatments, except the 10 μM Cd treatment, with increasing Cd concentrations; however, there was no significant difference between 25 and 50 μM Cd treatments, and a similar result was found in the *Gs*. *Ci* was affected by Cd stress in cucumber seedlings, which showed a significant increase when the solution Cd concentration was up to 100 μM, i.e., it was significantly increased by 14.9% and 23.5% under 100 and 200 μM treatments, respectively.

Overall, these findings suggested that applied Cd had a discernible effect on the *Pn* and *Ci* of cucumber leaves; the former decreased and the latter was enhanced only under higher Cd stress (Table 2). Farquhar and Sharkey (1982) mentioned that inhibition of photosynthesis was caused by stomatal and non-stomatal factors. In our study, *Pn* decrease was accompanied by a significant reduction in *Tr* and *Gs* except for 10 μM Cd stress, indicating that photosynthesis inhibition of Cd was possibly caused by stomatal factors under Cd levels lower than 50 μM. However, Ci was significantly increased under 100 and 200 μM treatments, which revealed that the effect of Cd toxicity on CO_2 assimilation was mainly due to the nonstomatal component of photosynthesis under higher Cd stress, contrary to earlier findings for rice (Cao et al. 2015), maybe because of different Cd treatment conditions. This nonstomatal photosynthesis restriction might have resulted from the inhibition of the key enzyme activities in the Calvin cycle, the photosynthetic electron transport chain and the ribulose 1,5-bisphosphate carboxylase/ oxygenase (RUBISCO) activity as well as the severe damage of guard cells and chloroplast ultrastructure damage (Souza et al. 2005). The presence of negative correlations of net photosynthesis and shoot Cd and leaf chlorosis under higher Cd concentrations of cucumber (Table 1 and Fig. 1) further substantiated these effects.

Effects of Increasing Cd Level on Element Concentrations in Different Parts of Cucumber

Cd has been shown to hamper the status of essential macro- and micronutrients in a number of plant species (Kim et al. 2003; Ghnaya et al. 2007; Lin et al. 2012; Liu et al. 2015), which is one of the important mechanisms indicating Cd toxicity in plants (Zhang et al. 2002). In this

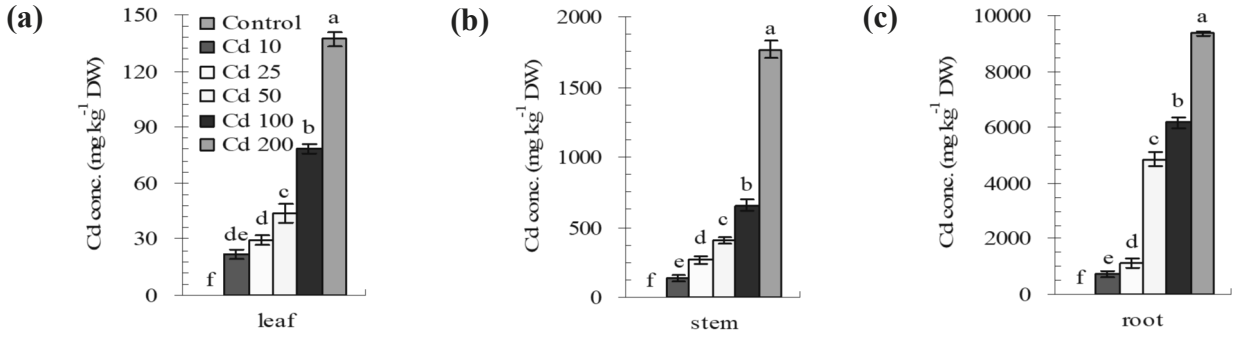

Fig. 1. Cd concentration in leaf, stem and root tissues of cucumber seedlings exposed to different Cd concentrations for 10 d. Control, Cd 10, Cd 25, Cd 50, Cd 100, and Cd 200 represent no Cd addition, 10, 25, 50, 100, and 200 μmol/L Cd, respectively. *Error bars* represent SD values (n = 3); *different letters* indicate significant differences ($p \leq 0.05$) among the treatments. Conc. – concentration, DW – dry weight. (a), (b) and (c) represent Cd concentration in leaf, stem and root, respectively.

Table 2. Effects of increasing Cd level on photosynthesis parameters of cucumber seedlings.

Treatment (μmol L^{-1})	*Pn* (μM CO_2 m^{-2} s^{-1})	*Tr* (mM H_2O m^{-2} s^{-1})	*Gs* (mM H_2O m^{-2} s^{-1})	*Ci* (μM CO_2 M^{-1})
Control	16.19 ± 0.96^{a*}	2.36 ± 0.12^{a}	110.32 ± 1.36^{a}	349 ± 13.37^{c}
10	15.10 ± 0.81^{a}	2.23 ± 0.09^{a}	106.43 ± 1.70^{a}	346 ± 12.49^{c}
25	14.92 ± 0.77^{a}	1.93 ± 0.05^{b}	87.24 ± 2.55^{b}	372 ± 18.09^{bc}
50	11.58 ± 0.52^{b}	1.87 ± 0.04^{b}	75.37 ± 3.01^{bc}	354 ± 23.02^{c}
100	7.79 ± 0.81^{c}	1.73 ± 0.11^{bc}	62.41 ± 2.63^{c}	401 ± 16.15^{b}
200	5.82 ± 0.91^{cd}	1.54 ± 0.10^{c}	49.57 ± 2.14^{d}	431 ± 13.28^{a}

*Values are expressed as mean ± SE (n = 3). Different letters in each column indicate significant differences ($p \leq 0.05$) among the treatments.
Pn – net photosynthetic rate, *Tr* – transpiration rate, *Gs* – stomatal conductance, *Ci* – intercellular CO_2 concentration

study, Cd was found to compete with essential trace elements during the process of uptake and a gradual decrease, especially in Zn, Cu, Mn, K and Ca, with increasing Cd concentration in the growth solution (Fig. 2 and 3). Statistical analysis of the data indicated significant differences in the cucumber tissues and Cd levels for the concentrations of Zn, Cu and Mn, and the maximum concentration of these microelements was found in roots, followed by stem and leaf tissues. Compared with the control, concentration was decreased at all Cd levels. Root Zn concentration showed a significant reduction under 50 μM Cd or more, with the largest decrease by 38.1% under 200 μM Cd stress (Fig. 2a).

On the other hand, root Zn, Cu and Mn decreased at Cd levels exceeding 25 μM, and leaf and stem Zn, Cu and Mn decreased at all Cd levels, although the reduction percentage was low (Fig. 2). According to Dong et al. (2006), mineral deficiencies/imbalances and depression of plant growth would be a consequence of excessive Cd accumulation that affects the rate of uptake and distribution of certain nutrients in plants. This finding revealed that cucumber seedlings appeared to lack nutrients under high Cd stress, thereby showing decreased growth.

The maximum concentration of Mg and Ca was found in leaves, followed by stem and root tissues. The results indicated a decline in the concentrations of leaf Mg, with reduction percentages of 24.3%, 36.4% and 46.6% at Cd concentrations of 50, 100 and 200 μM, respectively, compared with the control. Stem and root Mg concentrations were reduced also in cucumber seedlings treated with Cd compared with their controls (Fig. 3a). Cucumber plants exposed to Cd significantly reduced leaf Ca concentration compared with the control. Stem and root Ca were not affected at any level of Cd except at 100 and 200 μM Cd treatments, in which Ca concentration decreased by 18.9% and 32.1% in stems and roots for 200 μM Cd treatments, respectively, when compared with the control (Fig. 3b). K concentration in stems was significantly higher than that in leaves and roots, and stem K showed a continuous decrease with increasing Cd treatments. For instance, after 10 d of Cd exposure, stem K concentration decreased by 7.4%, 14.1%, 26.9%, 38.9% and 48.8% in the 10, 25, 50, 100 and 200 μM Cd treatments, respectively, when compared with the control. Similar trends were observed in leaf and root K concentrations (Fig. 3c).

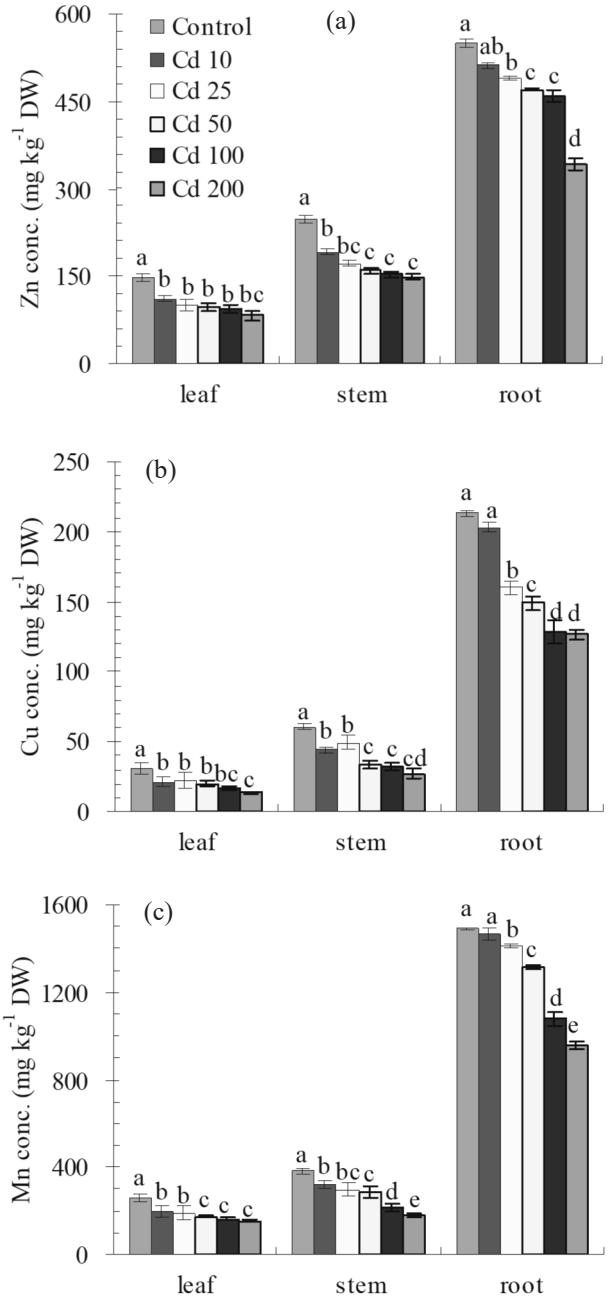

Fig. 2. Effects of increasing Cd level on microelement concentrations in leaf, stem and root tissues of cucumber seedlings. Conc. – concentration, DW – dry weight. (a), (b) and (c) represent Zn, Cu and Mn concentration, respectively.

Effects of Cd on Antioxidant Capacity of Cucumber Seedlings

Cd stress to plants could generate oxidative stress by interfering with the antioxidant defense system (Gratão et al. 2005). The total antioxidant capacity may serve as a significant indicator of its potential antioxidant activity. However, due to the chemical diversity of antioxidants, it was difficult to quantify and separate individual antioxidants (i.e., parent compounds, glycosides, polymers and many isomers) from the plant matrix. Moreover, the total antioxidant power is often more useful for evaluating health beneficial effects because of the cooperative action of antioxidants (Li et al. 2015).

The total antioxidant capacity of cucumber seedlings was expressed by the values of CUPRAC (gallic acid

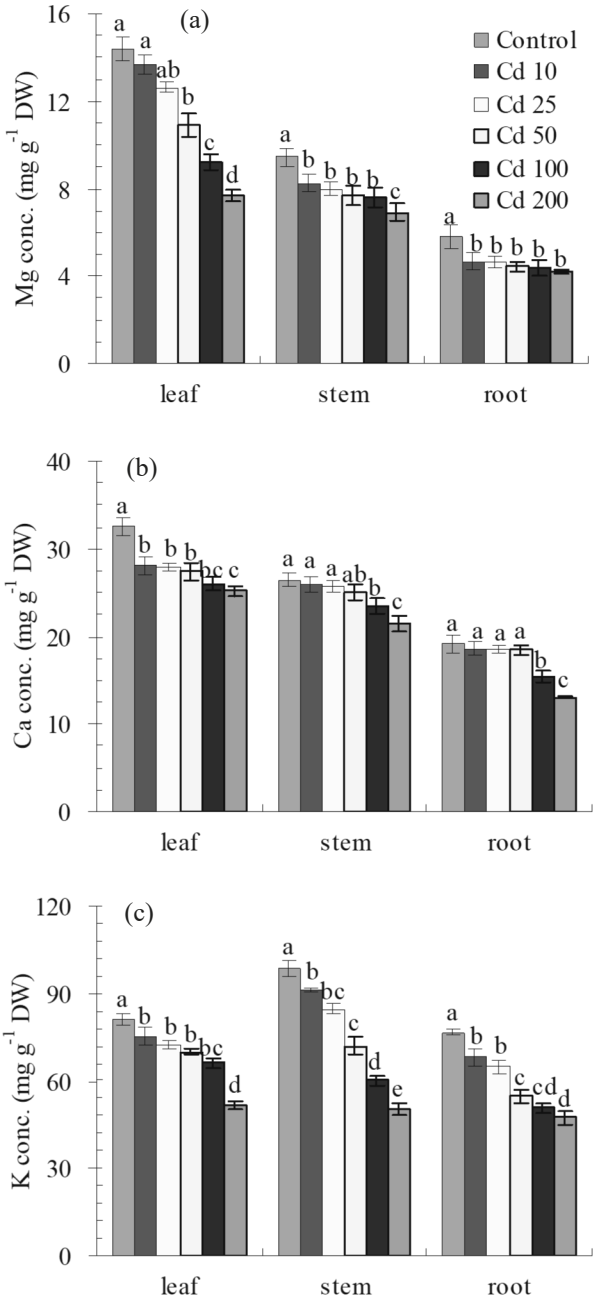

Fig. 3. Effects of increasing Cd level on macroelement concentrations in leaf, stem and root tissues of cucumber seedlings. Conc. – concentration, DW – dry weight. (a), (b) and (c) represent Mg, Ca and K concentration, respectively.

equivalents). It was observed that a Cd-dose-response relationship was found in the CUPRAC and that the value decreased as the concentration of Cd increased, which was in the range of 0.55 to 2.7 g GAE g^{-1} fresh weight. When compared with the control, the total antioxidant capacity under Cd stress was found to be lower in all tissues of cucumber, while the lowest CUPRAC value was found in the roots of cucumber under 200 μM Cd stress, with a reduction percentage at 76.5% compared with values recorded from the control seedlings (Fig. 4).

In conclusion, cucumber growth was negatively affected by increasing solution Cd and biomass decreased significantly under or more than 25 μM Cd concentration. Cd treatment in growing seedlings of cucumber impaired chlorophyll and photosynthetic performance; moreover, Cd decreased the total antioxidant capacity in all tissues in cucumber plants. Cd accumulation both in shoots and roots increased with increasing Cd concentrations in solution, especially in the roots. The microelements mainly affected by Cd were Zn, Cu and Mn in leaves, stems and in roots. These microelements in shoots decreased significantly at all Cd concentrations, while in roots an obvious difference was observed at Cd concentration higher than 25 μM. In addition, K, stem and root Mg, and leaf Ca concentrations decreased significantly under Cd treatment. Leaf Mg and stem/root Ca decreased evidently only in seedlings exposed to 50 and 100 μM Cd, respectively. Our data suggested that the influence of Cd on nutrient content in cucumber was related to the concentration of Cd in the growth medium and plant tissue, and consequently, excessive Cd may be responsible for mineral disturbances and depression of plantlet growth. However, further researches at the molecular level are needed to clarify the mechanisms involved between mineral nutrition and Cd uptake and would also provide more information for selecting plants that are tolerant to toxic ions contained in the soil.

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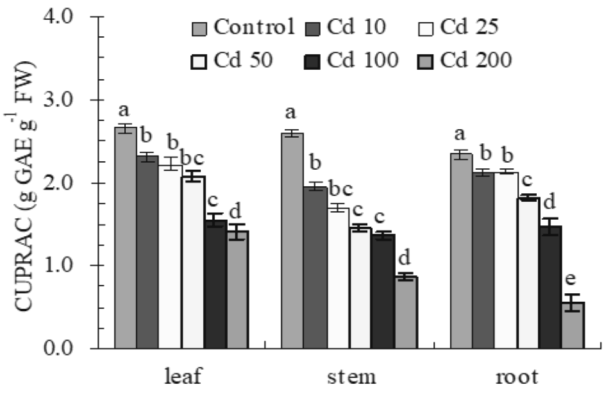

Fig. 4. Effects of increasing Cd level on Cupric reducing antioxidant capacity (CUPRAC) in leaf, stem and root tissues of cucumber seedlings. GAE – gallic acid equivalent, FW – fresh weight.

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