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Interactions of cadmium and aluminum toxicity in their effect on growth and physiological parameters in soybean*

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Abstract: The effect of Al and Cd on the growth, photosynthesis, and accumulation of Al, Cd and plant nutrients in two soybean genotypes were determined using hydroponic culture. There were six treatments: pH 6.5; pH 4.0; pH 6.5+1.0 μmol/L Cd; pH 4.0+1.0 μmol/L Cd; pH 4.0+150 μmol/L Al; pH 4.0+1.0 μmol/L Cd+150 μmol/L Al. The low pH (4.0) and Al treatments caused marked reduction in root length, shoot height, dry weight, chlorophyll content (SPAD value) and photosynthetic rate. Al-sensitive cv. Zhechun 2 accumulated comparatively more Al and Cd in plants than Al-tolerant cv. Liao 1. Compared with pH 6.5, pH 4.0 resulted in significant increase in Cd and Al concentration in plants. Combined application of Cd and Al enhanced their accumulation in roots, but caused a reduction in shoots. The concentrations of all 10 nutrients (P, K, Ca, Mg, Fe, Mn, Cu, Zn and B), except Mo were also increased when plants were exposed to pH lower than pH 6.5. Al addition caused a reduction in the concentration of most nutrients in plant roots and shoots; but K, Mn and Zn in roots were increased. Treatments with Cd alone or together with Al reduced the concentrations of all the plant nutrients in plants. Al-sensitive genotype Zhechun 2 has lower nutrient concentration than Al-tolerant genotype Liao 1. The current findings imply that Al and Cd are synergistic in their effect on plant growth, physiological traits and nutrient uptake.

Key words: Soybean, Cadmium, Aluminum, Photosynthesis, Antagonism
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INTRODUCTION

Heavy metals accumulating in the food chain, pose risk for health of animals and humans, who are less sensitive to metal toxicity than plants, but can concentrate heavy metals in certain tissues and organs (Mantovi *et al*., 2003). Cytotoxicity of heavy metals in plants has been well documented (Delhaize and Ryan, 1995; Marienfeld *et al*., 2000). Cadmium (Cd) is a toxic heavy metal, causing phytotoxicity, and its uptake and accumulation in plants pose a potential threat to human health (Shah and Dubey, 1997). Its accumulation causes reductions in photosynthesis, diminishes water and nutrient uptake (Sanità di Toppi and Gabbrielli, 1999), and results in visible symptoms of injury in plants, such as chlorosis, growth inhibition, browning of root tips, and finally death (Kahle, 1993).

Aluminum (Al) toxicity is a major agricultural problem in acid soil, and has been intensively studied in plants. Plants grown in acid soils due to Al solubility at low pH have undeveloped root system and exhibit a variety of nutrient-deficiency symptoms, consequently decrease in yield. Al interferes with uptake, transport and utilization of essential nutrients including Ca, Mg, K, P, Cu, Fe, Mn and Zn (Foy, 1984; Guo *et al*., 2003). Soil acidification could bring about many other changes of physical and chemical properties in soil, which in turn affect plant growth and development (Chen *et al*., 2000). Soil chemical factors that limit root growth in acid soils and de-

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crease crop production include Al, Mn and various cations, and also deficiency or unavailability of Ca, Mg, P, Mo, and Si, while others, such as Mn and B could be toxic to plants. These effects are further complicated by interactions of Al with other ions in different plant genotypes and under stress conditions (Foy, 1992). It is generally known that plants grown in acid soils reduce root growth and nutrient uptake. The bio-availability of some heavy metals in soil is also strongly affected by pH. It has shown that Cd availability increases with reduced soil pH (Wu and Zhang, 2002).

Soil pollution by heavy metals is a multi-element problem, so that several studies have been conducted to investigate the synergistic effect of heavy metals on some plant species. However, the combinational effect of Cd and Al on plants is little known, although their individual toxicity is well established. Al toxicity is a complex event, which may be manifested as a deficiency of P, Ca, Mg or Fe (Foy, 1988). Interactions between Cd and essential elements lead to changes in plant nutrient content and physiological disorders as well as retardation of growth and yield (Sandalio *et al*., 2001; Mazen, 2004). Available experimental reports address the long-term effect of low Cd concentration, inducing chronic stress different from the one induced by short-term exposure to high concentrations of the pollutant (Larbi *et al*., 2002).

The current study is aimed mainly at determining the relationship between Cd and Al in their effect on growth, photosynthesis and nutrient uptake, and the possible difference in the response to Al and Cd toxicity between soybean cultivars with different Al tolerance.

MATERIALS AND METHODS

Plant materials and treatments

The study was undertaken at Zhejiang University, Huajiachi Campus, Hangzhou, China, during 2004. Two soybean genotypes differing in Al tolerance were used, namely, Liao 1, relatively tolerant and Zhechun 2, relatively sensitive. Soybean seeds were surface sterilized in 0.2% (w/v) $Na(OCl)_2$ for 20 min, rinsed 8 times with distilled water, and germinated in moist quartz sand in a greenhouse. After the first complex leaf appeared (10 d after sowing), seedlings were selected for uniformity and transplanted to a 4-L container covered with a foamed plastic plate with evenly spaced holes and placed in a greenhouse. The composition of the basic nutrient solution was (μmol/L): NH_4NO_3 362.7, $NaH_2PO_4{\cdot}2H_2O$ 182.2, K_2SO_4 91.2, $MgSO_4$ 508.8, $CaCl_2$ 590.3, Fe-citrate 4.47, $MnCl_2{\cdot}4H_2O$ 0.45, $ZnSO_4{\cdot}7H_2O$ 0.4, $CuSO_4{\cdot}5H_2O$ 0.22, H_3BO_3 2.9, H_2MoO_4 0.01. One week after transplanting to the basic culture solution, Cd as $CdCl_2$ and Al as $AlCl_3{\cdot}6H_2O$ were added to the corresponding containers, and the solution pH was adjusted with HCl to form the following six treatments each with three replications: T1, pH 6.5; T2, pH 4.0; T3, pH 6.5+1.0 μmol/L Cd; T4, pH 4.0+1.0 μmol/L Cd; T5, pH 4.0+150 μmol/L Al; T6, pH 4.0+1.0 μmol/L Cd+150 μmol/L Al. The experiment was laid out in completely randomized design. The solution pH in each container was adjusted every other day with HCl or NaOH as required. The nutrient solution in the growth container was continuously aerated with pumps and renewed every five days.

Sampling and measurements

At the 20th day after treatment, the second fully expanded leaves were selected for measuring chlorophyll content with a chlorophyll meter (Minolata SPAD-502, Japan) and photosynthetic parameters with an Infra Red Analyzer (LI-6400 System, Li-COR Company, USA).

On the 28th day after treatment, shoot height and root length were measured, and plants were harvested and washed thoroughly with distilled water, separated into roots and shoots (stems and leaves), dried at 80 °C and weighed. Mineral elements were determined with inductively coupled plasma atomic emission spectroscopy (ICP-AES, Japan) after digesting the samples with HNO_3-$HClO_4$ mixture (2:1, v/v).

Statistical analysis

All data presented here are mean values. The measurements were done with three replicates for growth characters, Al, Cd, and nutrient concentration. Statistical analyses were carried out by one-way ANOVA (analysis of variance) to compare the significance of difference between the treatments using SSR test.

RESULTS

Plant growth

Soybean growth as affected by the stresses of pH and Cd toxicity was evaluated in terms of length and dry biomass of plant roots and shoots. There was statistically significant difference in these growth characteristics between the two genotypes, with Liao 1 showing higher values than Zhechun 2 in all the treatments (Table 1). Compared with the control (pH 6.5), the treatment pH 6.5+1.0 μmol/L Cd resulted in a little better growth, indicating the stimulating effect of lower Cd level on soybean growth. At pH 4.0, the growth inhibition was more severe in the treatment of 150 μmol/L Al addition than in the treatment of 1.0 μmol/L Cd addition. Also, there was significant difference in growth inhibition between pH 6.5 and pH 4.0 treatments with the same Cd level, indicating the interaction of Cd toxicity with acidity in the medium. More pronounced and statistically significant reduction in all the growth parameters of both the genotypes was observed in the treatment of combined application of Cd and Al at pH 4.0, indicating that Al and Cd are synergistic in toxic effect on soybean growth.

Photosynthetic activity

Two soybean genotypes in the treatment of pH 6.5 with or without Cd and Al addition did not differ in chlorophyll content (SPAD value), net photosynthesis rate (Pn) and stomatal conductance (Gs). Addition of Cd into the pH 6.5 solution did not cause significant decline in these parameters (Table 2). In comparison with the plants exposed to the pH 6.5 solution, the plants grown in the pH 4.0 solution of had smaller SPAD, Pn and Gs values, indicating the injurious effect of low pH on plant growth. Addition of Cd, on the whole resulted in reduced chlorophyll content, Pn and stomatal conductance, with the reduction extent varying with solution pH, with the plants exposed to low pH being more affected. At pH 4.0, addition of 150 μmol/L Al caused greater decline in the examined three parameters than addition of 1.0 μmol/L Cd. Statistically significant reduction was recorded in the treatment with combined Al and Cd addition.

Al and Cd concentrations in plants

Significant differences in Al concentration in plant roots and shoots were found among treatments (Table 3). In comparison with the control (pH 6.5), lower pH (4.0) resulted in a significant increase in Al concentration of roots and shoots. The addition of 150 μmol/L Al into the solution drastically increased Al concentration in plant roots and shoots. The effect of Cd treatment on Al concentration varied in the presence or absence of Al in the solution as well as in plant parts. Without Al addition, Cd treatment tended to reduce Al concentration in plant parts. Whereas, in the presence of Al, Cd treatment led to an increase in root Al concentration in Liao 1 and a decrease in shoot Al concentration. The difference could be found between the two cultivars in the response of Al concentration to the treatments. The tolerant cultivar Liao 1 had lower Al concentration in root than the relatively sensitive cultivar Zhechun 2 when subjected to Al treatment, viz. 150 μmol/L Al, and 1.0 μmol/L Cd+150 μmol/L Al; but it was opposite for Al in shoots. Furthermore, three-fold higher Al concentration was observed in roots than in shoots.

Similarly, Cd concentration was also affected significantly with pH change, being higher at pH 4.0 in both plant parts and in two genotypes. Roots had about four times higher Cd than shoots under Cd treatments (Table 3). Sensitive cultivar Zhechun 2 had a little higher Cd concentration than Liao 1 in both roots and shoots. There was also an interactive effect of Cd with Al but the difference between Cd alone and Cd+Al was statistically not significant in both roots and shoots. Cd concentration in roots was enhanced due to Al addition, but it was slightly reduced in shoots.

Nutrient concentration in plants

Nutrient concentrations in roots of both soybean genotypes showed a variable response to pH and Cd treatments (Table 4). Phosphorus concentration in both genotypes was increased with lower pH (4.0) compared to that at pH 6.5. Al addition caused a significant decrease in P concentration, but Cd had no such effect whether it was applied alone or in combination with Al. Potassium concentration was significantly enhanced with Al alone, but there was a little decrease along with Cd, showing an antagonistic effect of Al and Cd on K concentration in soybean. Calcium and magnesium concentrations were reduced due to Cd and Al addition alone and their combination.

Unlike P and K, Ca and Mg concentrations were higher at pH 6.5 than at pH 4.0. The concentrations of Fe, Cu, Mn, Zn and B in roots of both genotypes differed greatly when the solution pH was changed. Cd treatment reduced concentrations of all these microelements in roots. Al increased concentration of Mn and Zn in roots, but reduced concentrations of other micronutrients (Fe, Cu, Mo and B). When applied in combination, Cd and Al reflected negative interaction for all the plant nutrients by reducing their concentrations in roots.

As regards the macronutrient concentration in soybean shoots, P concentration was enhanced while K, Ca and Mg concentrations was reduced significantly at pH 4.0 in comparison with that at pH 6.5 (Table 5). Al and Cd treatments either singly or combined exerted negative impact on the concentrations of all nutrients, except K in Liao 1 when Al was added alone. Zhechun 2 had higher nutrient concentrations in shoot than Liao 1. The concentrations of Fe, Cu, Mn, and B increased in shoots at pH 4.0 than at pH 6.5, while there was an opposite effect of pH level on Zn and Mo. Cd treatments at both pH levels showed decreased concentration of micronutrients, although not significantly for most of the elements. Al also caused a reduction in the concentrations of all the plant nutrients. There was an interactive effect of Al and Cd on nutrient concentration in both genotypes.

Table 1 Effect of pH, Al and Cd treatments on some soybean growth parameters in soybean

Genotype	Treatment	Root length (cm)	Shoot height (cm)	Dry biomass (g/plant)	
				Root	Shoot
Liao 1	pH 6.5	32.2 a	29.5 ab	2.20 ab	3.59 a
	pH 4.0	30.6 a	25.9 abc	2.15 abc	3.39 a
	pH 6.5+Cd^{2+}	37.5 a	34.7 a	2.25 a	3.70 a
	pH 4.0+Cd^{2+}	28.5 a	21.1 bc	2.15 abc	3.27 a
	pH 4.0+Al^{3+}	27.9 a	20.9 bc	2.05 bc	2.70 b
	pH 4.0+Cd^{2+}+Al^{3+}	18.3 b	19.3 c	2.00 c	2.49 b
Zhechun 2	pH 6.5	23.2 b	22.8 b	2.15 ab	2.91 b
	pH 4.0	22.7 b	20.1 b	2.05 bc	2.74 b
	pH 6.5+Cd^{2+}	33.9 a	29.2 a	2.30 a	3.40 a
	pH 4.0+Cd^{2+}	16.4 c	17.6 bc	2.00 bc	2.65 b
	pH 4.0+Al^{3+}	16.0 c	16.7 bc	2.00 bc	2.17 bc
	pH 4.0+Cd^{2+}+Al^{3+}	15.0 c	12.0 c	1.90 c	1.99 c

Note: The different letters after data within a column represent significant difference at 95% probability

Table 2 Effect of pH, Al and Cd treatments on chlorophyll content and photosynthesis in soybean

Genotypes	Treatment	Chlorophyll content (SPAD value)	Photosynthetic rate [μmol CO_2/(m^2·s)]	Stomatal conductance [mmol/(m^2·s)]
Liao 1	pH 6.5	33.7 a	11.6 a	0.37 a
	pH 4.0	31.8 ab	10.0 b	0.27 ab
	pH 6.5+Cd^{2+}	33.0 a	11.1 a	0.35 ab
	pH 4.0+Cd^{2+}	30.2 ab	10.8 ab	0.25 ab
	pH 4.0+Al^{3+}	29.6 ab	4.8 c	0.19 ab
	pH 4.0+Cd^{2+}+Al^{3+}	26.7 b	4.7 c	0.16 b
Zhechun 2	pH 6.5	35.6 a	11.3 a	0.34 a
	pH 4.0	31.4 ab	8.7 b	0.29 ab
	pH 6.5+Cd^{2+}	32.4 ab	10.9 a	0.31 ab
	pH 4.0+Cd^{2+}	28.3 bc	7.3 c	0.26 ab
	pH 4.0+Al^{3+}	25.5 c	7.1 c	0.23 b
	pH 4.0+Cd^{2+}+Al^{3+}	16.9 d	5.1 d	0.19 ab

Note: The different letters after data within a column represent significant difference at 95% probability

Table 3 Effect of pH, Al and Cd treatments on Al and Cd concentrations in soybean

Genotypes	Treatment	Al concentration (μg/g)		Cd concentration (μg/g)	
		Root	Shoot	Root	Shoot
Liao 1	pH 6.5	134.6 c	104.1 d	23.3 d	12.2 c
	pH 4.0	232.4 b	173.6 c	53.3 c	21.0 b
	pH 6.5+Cd^{2+}	117.2 c	95.8 d	120.4 b	28.9 a
	pH 4.0+Cd^{2+}	204.9 b	148.1 cd	142.3 a	31.4 a
	pH 4.0+Al^{3+}	1607.0 a	565.1 a	43.9 cd	15.4 c
	pH 4.0+Cd^{2+}+Al^{3+}	1623.0 a	492.5 b	143.8 a	26.6 a
Zhechun 2	pH 6.5	165.1 c	94.3 d	27.3 c	13.1 c
	pH 4.0	254.8 b	186.9 c	55.8 b	21.4 b
	pH 6.5+Cd^{2+}	151.6 c	92.5 d	142.8 a	32.0 a
	pH 4.0+Cd^{2+}	219.6 bc	148.7 cd	148.0 a	29.7 a
	pH 4.0+Al^{3+}	1795.6 a	524.9 a	47.4 bc	15.8 bc
	pH 4.0+Cd^{2+}+Al^{3+}	1761.1 a	432.0 b	151.6 a	25.1 ab

Note: The different letters after data within a column represent significant difference at 95% probability

Table 4 Effect of pH, Al and Cd treatments on nutrient concentration in soybean roots

Cultivars	Treatments	Concentration (mg/g)					Concentration (μg/g)				
		P	K	Ca	Mg	Fe	Cu	Mn	Zn	Mo	B
Liao 1	pH 6.5	7.9 b	38.3 ab	13.2 a	6.4 a	0.65 b	21.1 d	25.1 c	11.2 b	4.9 a	8.6 b
	pH 4.0	9.4 a	40.6 ab	7.1 c	5.4 b	0.77 a	36.3 a	28.2 bc	12.1 ab	3.9 c	10.6 a
	pH 6.5+Cd^{2+}	6.7 c	36.2 b	10.4 b	6.3 a	0.65 b	18.9 d	23.2 c	11.1 b	4.5 b	7.8 c
	pH 4.0+Cd^{2+}	9.0 a	38.9 ab	6.5 cd	5.2 b	0.69 ab	28.8 b	26.9 bc	11.4 b	3.7 cd	10.2 a
	pH 4.0+Al^{3+}	3.6 d	42.0 a	5.9 d	4.3 c	0.52 c	25.6 bc	34.2 a	13.0 a	3.4 d	8.9 b
	pH 4.0+Cd^{2+}+Al^{3+}	2.6 d	39.4 ab	5.3 d	3.6 c	0.48 c	22.6 cd	29.4 b	12.0 ab	3.2 d	8.3 bc
Zhechun 2	pH 6.5	6.2 ab	37.0 b	13.3 a	7.3 a	0.73 a	30.8 cd	29.9 c	14.1 b	5.3 a	8.9 bc
	pH 4.0	7.1 a	38.1 ab	9.4 b	6.2 b	0.81 a	57.4 a	34.4 b	14.4 b	4.2 b	10.7 a
	pH 6.5+Cd^{2+}	6.5 a	38.6 ab	12.5 a	7.1 a	0.75 a	27.4 d	29.0 c	14.3 b	5.2 a	8.5 bc
	pH 4.0+Cd^{2+}	6.6 a	35.4 b	7.6 c	5.8 bc	0.74 a	38.4 b	31.2 bc	13.8 b	3.8 bc	9.8 ab
	pH 4.0+Al^{3+}	5.1 b	42.2 a	6.2 cd	5.2 c	0.62 b	35.0 bc	38.2 a	15.9 a	3.7 c	9.2 b
	pH 4.0+Cd^{2+}+Al^{3+}	4.8 b	38.0 ab	5.1 d	4.6 c	0.52 c	32.9 c	33.8 b	14.3 b	3.4 c	8.3 c

Note: The different letters after data within a column represent significant difference at 95 % probability

Table 5 Effect of pH and heavy metals stress on nutrient concentration in soybean shoots

Cultivars	Treatments	Concentration (mg/g)					Concentration (μg/g)				
		P	K	Ca	Mg	Fe	Cu	Mn	Zn	Mo	B
Liao 1	pH 6.5	20.9 ab	74.7 a	12.6 a	18.3 a	0.93 ab	87.2 b	87.2 ab	24.6 a	5.7 a	19.0 b
	pH 4.0	23.4 a	61.4 bc	10.5 b	11.9 c	0.95 a	132.9 a	94.9 a	24.4 a	4.6 b	22.3 a
	pH 6.5+Cd^{2+}	18.8 b	72.2 ab	11.8 ab	15.2 b	0.96 a	78.4 bc	77.7 bc	24.7 a	5.3 ab	18.6 b
	pH 4.0+Cd^{2+}	20.1 b	56.2 c	9.3 b	11.1 c	0.88 b	119.0 a	85.7 b	22.7 ab	4.3 b	20.2 a
	pH 4.0+Al^{3+}	11.9 c	65.6 b	7.3 c	8.4 d	0.65 c	82.9 bc	83.7 b	20.9 b	3.3 c	15.8 c
	pH 4.0+Cd^{2+}+Al^{3+}	10.6 c	53.8 c	6.0 c	7.2 d	0.57 d	64.5 c	74.7 c	18.6 c	2.8 d	14.0 c
Zhechun 2	pH 6.5	17.1 ab	56.5 b	15.7 a	18.3 a	0.79 b	70.1 cd	75.1 b	21.3 b	5.4 a	16.5 b
	pH 4.0	16.9 b	64.9 a	9.6 c	12.6 b	0.82 b	121.4 a	84.1 a	21.2 b	4.3 b	19.9 a
	pH 6.5+Cd^{2+}	19.5 a	62.9 ab	12.9 b	18.7 a	0.92 a	74.8 c	76.8 b	24.0 a	5.8 a	18.0 ab
	pH 4.0+Cd^{2+}	15.7 b	52.5 bc	9.3 c	11.1 b	0.74 b	95.7 b	73.9 bc	20.1 bc	3.8 c	18.2 ab
	pH 4.0+Al^{3+}	11.9 c	57.9 b	6.3 d	8.7 c	0.56 c	62.7 cd	76.8 b	17.7 c	2.8 d	14.0 c
	pH 4.0+Cd^{2+}+Al^{3+}	10.1 c	49.0 c	4.6 e	6.8 d	0.50 c	55.7 d	66.9 c	15.8 c	2.4 d	12.2 c

Note: The different letters after data within a column represent significant difference at 95% probability

DISCUSSION

Soybean growth in shoot height, root length and dry biomass was not obviously affected by Cd in this study. Interestingly only a little increase was observed at pH 6.5, which could be because Cd level in the culture solution was not high enough to cause bio-toxicity to soybean. It was noted that low Cd level had positive impact on plant growth (Wu and Zhang, 2002; Guo *et al*., 2004). On the other hand, growth was greatly inhibited when the plants were exposed to 150 μmol/L Al. Lidon and Barreiro (2002) observed that Al toxicity decreased significantly the concentrations of N, Mg, P and Fe, and hypothesized that P deficiency specifically triggers the reduction of biomass production. However, there is little understanding of the combined effects of the Cd and Al on plants. In the current study, the growth inhibition was more severe in Cd+Al treatment than in Al alone treatment, indicating that the effect of Cd and Al is synergistic. Guo *et al*.(2004) demonstrated the same results in barley.

The current results showed that both Cd and Al significantly reduced chlorophyll content, photosynthesis rate and stomatal conductance. Akaya and Takenaka (2001) reported that Al toxicity specifically inhibited the photosynthetic apparatus of many species. Decreased plant growth caused by heavy metals is a consequence of inhibition in photosynthesis, translocation of photosynthetic products (Ruano *et al*., 1987) and cell division (Dalla Vecchia *et al*., 2005). In the current study, chlorophyll content, photosynthesis rate and stomatal conductance were more inhibited in Al-sensitive cultivar Zhechun 2 than in Al-tolerant cultivar Liao 1. A wide difference in the resistance to Al toxicity among plant species and cultivars within a species was also observed by Ma *et al*.(1997). The more severe inhibition of these photosynthetic parameters in the combined treatment with Al and Cd than the treatment with Al or Cd alone showed that the effect of the two stresses is additive.

The results also showed that low pH and Al treatments significantly increased Al concentration in plant roots and shoots. The influence of Cd treatment on Al concentration varied with plant part and genotype. Al concentration in roots did not differ significantly between Cd+Al treatment and Al alone in both genotypes; while in shoot Al concentration was significantly lower in Cd+Al treatment compared to Al alone treatment for both genotypes. It was observed that plants exposed to Cd stress had less Al transported to aboveground part. The difference between the two genotypes in Al concentration in both plant parts was distinct, with the tolerant one having lower concentration. Silva *et al*.(2000) found that Al-sensitive soybean seedlings accumulated more Al in nuclei than resistant genotypes. Growth inhibition caused by Al toxicity accorded completely with Al accumulation in plants. Al accumulation in roots was considerably higher than that in shoot, which supported the established fact that Al sensitive plants accumulate more Al in the roots than the tolerant ones, and that Al toxicity in plants is frequently associated with increased Al accumulation in roots but not generally in shoots. Kidd and Proctor (2000) found that Al concentration of Al-sensitive *Betula pendula rothin* race was higher in roots but lower in shoots, than that in other races.

Wu and Zhang (2002) showed that Cd availability increased with reduced soil pH. In the present study, similar finding was made for Cd in roots of Liao 1. Statistically similar Cd concentration was recorded in roots and shoots when Cd was applied with Al, showing the synergistic relationship of both elements in their uptake. Moreover, the difference between the two soybean genotypes in Cd concentration was distinct, with Liao 1 having lower Cd concentration than Zhechun 2. Onac and Trifu (2002) observed that heavy metal contents in soybean leaves and roots of cv. Diamant were higher than those of cv. Agat. Plant roots often serve as storage sites preventing toxic dosages from reaching the stem and grain (Grifferty and Barrington, 2000). On the basis of these results, it may be concluded that the difference in the tolerance to heavy metals (Al and Cd) toxicity among soybean genotypes is associated with uptake and accumulation of these metals by roots.

Trivedi and Erdei (1992) reported that heavy metals inhibited the normal uptake and utilization of mineral nutrients in plants. Among the macronutrients, phosphorus availability is highly dependent on pH. Both Al and Cd alone and/or combined also inhibited Ca and Mg uptake, and reduced Fe, Cu, Mo and B concentrations in roots, while Mn and Zn concentrations were enhanced. The micronutrients availability is highly sensitive to pH and is also cor-related with heavy metals. Fernandes and Henriques (1991) found Cu to be antagonistic with Cd. There are also observations that the contents of essential elements (P, K, Ca, Mg, Zn, Cu, Fe, Mn) were not significantly modified by Cd treatment, even at relatively high concentrations of this heavy metal in the growth environment (Lagriffoul *et al*., 1998). Nutrient concentration in shoots had almost similar trend as in roots for both soybean genotypes. Low pH increased concentrations of P, Fe, Cu, Mn, and B, while reducing K, Ca, Mg, Zn and Mo concentrations. Al and Cd treatments had negative impact on the concentrations of all the nutrients except K in Liao 1. Many plant species grown in high Al level usually had lower P, Ca and Mg concentrations (Simon *et al*., 1994; Lidon *et al*., 2000), but toxic Al level decreased significantly the concentrations of N, Mg, P and Fe (Simon *et al*., 1994; Lidon *et al*., 1999), whereas an opposite trend prevailed with Mn (Lidon *et al*., 1999). It may be concluded that Al and Cd had a marked interaction on nutrient uptake and accumulation in soybean.

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