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The effect of chromium and aluminum on growth, root morphology, photosynthetic parameters and transpiration of the two barley cultivars

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Abstract

The effect of aluminum and chromium on two barley genotypes differing in Al tolerance was studied in a hydroponic experiment. Al stress decreased plant growth, biomass production, chlorophyll content and photosynthetic efficiency determined as variable to maximum chlorophyll fluorescence ratio (F_v/F_m), net photosynthetic rate (P_N), intercellular CO_2 concentration (c_i), stomatal conductance (g_s) and transpiration rate (E) less in an Al-tolerant genotype Gebeina than in an Al-sensitive genotype Shang 70-119. Cr stress also caused marked reduction in growth and photosynthetic traits in barley plants. Higher reduction was observed at pH 4.0 as compared to pH 6.5. Combined stress of Cr and Al, caused further reduction in growth and photosynthetic parameters.

Additional key words: acidity, chlorophyll content, chlorophyll fluorescence, *Hordeum vulgare*, stomatal conductance.

Introduction

Occurrence of toxic metals in agricultural soils is a severe and persistent problem. Increased Al and Cr contents can arise in soil due to a number of factors. Al and Cr are abundant elements in Earth's crust (Kochian 1995, Sinha *et al*. 2005). On the other side, pollutants released by industrial wastes contain appreciable amounts of Cr and Al (Tahir *et al*. 2009). Some organic and inorganic fertilizers also contain considerable amount of Al and Cr (Mc Grath 1995). Moreover, Cr and Al availability in soil increases markedly with the decrease of soil pH (Kochian 1995, Zeng *et al*. 2008a, Miller *et al*. 2009). In acidic soils, Al is a major constraint, posing a serious threat to crop production. Al inhibits root growth and elongation by different mechanisms, including Al interactions within symplast, plasma membrane and cell wall (Kochian 1995, Pineros and Kochian 2001, Yang *et al*. 2008). Several studies revealed that Al stress decreased net photosynthetic rate (PN) and chlorophyll (Chl) content in tomato (Simon *et al*. 1994), maize (Lidon *et al*. 1999, Mihailovic *et al*. 2008), *Citrus* spp. (Jiang *et al*. 2008, Chen *et al*. 2005a, b), and soybean (Zhang *et al*. 2007). Relatively little attention was given to Cr toxicity (Shanker *et al*. 2005). There are two main available forms of chromium in the soil, Cr^{3+} and Cr^{6+} and the latter is more mobile and toxic to plants (Von Burg and Liu 1993). The plants exposed to Cr stress exhibited decrease of growth and yield, as found in cauliflower (Chatterjee and Chatterjee 2000), vegetable crops (Zayed *et al*. 1998), *Lolium perenne* (Vernay *et al*. 2007), and *Amaranthus viridis* (Liu *et al*. 2008). Cr stress can cause growth inhibition by decreasing Chl content, P_N and stomatal conductance (Pandey *et al*. 2005, Ganesh *et al*. 2007, Liu *et al*. 2008, Subrahmanyam 2008).

Recently, the responses of plants to individual metal were extensively studied (*e.g*. He *et al*. 2008, Daud *et al*. 2009b, Nenova *et al*. 2009). However, in natural soil-plant systems, plants often have to face multiple metal stresses, and the interactive effects of two or more elements may be far from additive (An *et al*. 2004). Interaction of toxic metals can affect growth, biomass and photosynthesis of plants, such as Al and Cd in barley (Guo *et al*. 2004) and soybean (Shamsi *et al*. 2008), Cd and As in *Solanum nigrum* (Sun *et al*. 2008), Al and Mn in soybean (Yang *et al*. 2009), and Cd and Cr in *Dalbergia sissoo* (Shah *et al*. 2008). However, the knowledge about concurrent behavior of Al and Cr is

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Abbreviations: Chl - chlorophyll; c_i - intercellular CO_2 concentration; E - transpiration rate; F_m - maximum fluorescence; F_v - variable fluorescence; g_s - stomatal conductance, P_N - net photosynthetic rate.

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still scarce. Thus, a hydroponic experiment was conducted to investigate single and combined effects of Al and Cr stresses on growth, biomass, root morphology and gas exchange characteristics using two barley genotypes differing in Al tolerance.

Materials and methods

The experiment was conducted in a greenhouse of Huajiachi Campus, Zhejiang University, Hangzhou, China. Seeds of two barley (*Hordeum vulgare* L.) genotypes, Al-tolerant Gebeina and Al-sensitive, Shang 70-119 (Guo *et al*. 2004), were obtained from the College of Agriculture and Biotechnology, Zhejiang University, China. Seeds were surface sterilized in 3 % H_2O_2 for 20 min, rinsed with distilled water thoroughly and soaked in deionized water in the dark for 12 h. Then, seeds were sown into moist quartz sand in a controlled chamber with a 16-h photoperiod, irradiance of 225 ± 25 μmol m^{-2} s^{-1}, day/night temperature of 22/18 °C and relative humidity 85 %. Thirteen days after sowing, at second leaf stage, morphologically uniform barley seedlings were selected and transplanted into 5 dm^3 pots with nutrient solution. Every pot was covered with a polystyrol-plate with seven evenly spaced holes and placed in a greenhouse. In each hole two seedlings were located. The basic nutrient solution was comprised of (mg dm^{-3}): $(NH_4)_2SO_4$ 48.2, $MgSO_4$ 65.9, K_2SO_4 15.9, KNO_3 18.5, Ca $(NO_3)_2$ 59.9, KH_2PO_4 24.8, Fe citrate 6.8, $MnCl_2 . 4\ H_2O$ 0.9, $ZnSO_4 . 7H_2O$ 0.11, $CuSO_4 . 5\ H_2O$ 0.04, H_3BO_3 2.9, H_2MoO_4 0.01. Half strength nutrient solution was applied for the first 4 d and then changed to full strength nutrient solution for 8 d. After 12 d, Cr as $K_2Cr_2O_7$ and Al as $AlCl_3 . 6\ H_2O$ were added to the corresponding pots, and the solution pH was adjusted with HCl and NaOH to form the following six treatments: T1 (control) - pH 6.5; T2 - pH 4.0; T3 - pH 6.5 + 100 μM Cr; T4 - pH 4.0 + 100 μM Cr; T5 - pH 4.0 + 100 μM Al; T6 - pH 4.0 + 100 μM Cr + 100 μM Al. The experiment was laid out in completely randomized block design with six replications for each treatment. The pH of the solution was adjusted every other day in each pot with HCl or NaOH as required. The nutrient solution in the pots was continuously aerated with pumps and renewed every 4 d.

Growth traits were measured in terms of plant height, shoot and root dry mass after 50 d of treatment using 7 plants from each replication of all treatments. Roots attached on the intact plants were rinsed with distilled water. Then, root morphological parameters, including diameter, surface area, volume and number of root tips were determined by using root scan apparatus (*MIN-MAC, STD1600*$^+$) equipped with *WinRHIZO* software (*Epson,* USA) in randomly selected three plants.

Plant samples for chlorophyll content measurement were harvested after 20 and 40 d of treatment. Fresh leaves (0.2 g) were extracted in dark at room temperature with 10 cm^3 of acetone and ethanol (1:1, v/v) mixture. Absorbance at 663 and 645 nm was determined using a spectrophotometer (*AA6300*, *Shimadzu*, Kyoto, Japan). The chlorophyll *a* and chlorophyll *b* contents were calculated according to Lichtenthaler (1987). At the same time, efficiency of the photosynthetic apparatus determined as variable to maximum fluorescence ratio (F_v/F_m), was measured at room temperature with a portable fluorometer (*FMS-2*, *Hansatech Instruments*, Kink's Lynn, UK). The measured plant leaves were firstly dark-adapted with a Hansatech clip for 15 min. The basic fluorescence (F_0) was determined under irradiance < 0.05 μmol m^{-2} s^{-1}. The F_m was measured using a saturation pulse of 1200 μmol m^{-2} s^{-1} and F_v was calculated as F_m - F_0. Six replications were taken for each treatment.

Gas exchange parameters were measured by using a *LICOR-6400* portable photosynthesis system (*LICOR*, Lincoln, NE, USA). Photosynthetic rate, intercellular CO_2 concentration, stomatal conductance and transpiration rate were measured under irradiance of 1200 μmol m^{-2} s^{-1}, relative air humidity 60 % and CO_2 concentration 500 μmol mol^1 on the topmost fully expanded leaf after 2 h of acclimation in a growth cabinet. Six replications were taken for each treatment.

The data were analyzed using a statistical package, *SPSS* version *16.0* (SPSS, Chicago, IL, USA). A two-way analysis of variance (*ANOVA*) was carried out, followed by the Duncan's multiple range test.

Results

Exposure of plants to low pH (4.0) and Al stress resulted in a significant decrease in examined plant growth parameters as compared to the control. However, Shang 70-119 showed more reduction than Gebeina in each growth parameter between the treatment of low pH or Al stress and the control (Table 1). Addition of Cr to the solution inhibited all plant growth parameters as compared to the control. It was found that significantly more reduction occurred at pH 4.0 than at pH 6.5. The combined stress of Al and Cr resulted in further growth inhibition than Al or Cr stress alone, and Gebeina was much less affected than Shang 70-119.

The plants exposed to the solution with pH 4.0 and Al had significantly lower values for all examined root

Table 1. The effect of pH, aluminum and chromium on plant height, shoot dry mass, number of tillers, and root characteristics of two barley genotypes. The same letters within a column means no significant difference at 95 % probability level; *, ** indicate significance at the $P < 0.05$ and $P < 0.01$, respectively; ns - non significant.

Genotypes	Treatment	Plant height [cm]	Shoot dry mass [g plant $^{-1}$]	Number of tillers [plant $^{-1}$]	Root dry mass [g plant $^{-1}$]	Root diameter [cm plant $^{-1}$]	Surface area [cm^2 plant $^{-1}$]	Number of tips [plant $^{-1}$]	Volume [cm^3 plant $^{-1}$]
Gebeina	Control	60.99 a	2.25 a	2.97 ab	0.637 a	6.07 a	625.5 a	20149 a	0.977 b
	pH 4.0	59.17 ab	2.01 b	2.78 b	0.359 b	3.83 b	456.1 b	7359 b	0.853 c
	pH 6.5+Cr	35.50 e	0.57 f	2.39 c	0.267 cd	1.60 d	295.4 cd	1761 d	0.614 e
	pH 4.0+Cr	28.01 g	0.29 h	1.31 e	0.123 e	0.58 fg	117.1 efg	1208 def	0.597 e
	pH 4.0+Al	57.23 b	1.65 d	2.37 c	0.329 bc	0.91 ef	214.7 de	1358 de	0.755 d
	pH 4.0+Cr+Al	26.75 gh	0.23 hi	1.23 ef	0.102 e	0.51 gh	86.5 fg	722 ef	0.482 g
Shang 70-119	Control	60.13 a	2.29 a	3.11 a	0.642 a	6.24 a	662.9 a	20857 a	1.020 a
	pH 4.0	53.33 c	1.77 c	2.47 c	0.298 bc	2.79 c	361.9 bc	5172 c	0.796 d
	pH 6.5+Cr	32.82 f	0.46 g	2.04 d	0.219 d	1.10 e	203.7 de	1243 def	0.584 ef
	pH 4.0+Cr	24.52 h	0.21 hi	1.14 ef	0.066 e	0.38 gh	80.7 fg	835 ef	0.545 f
	pH 4.0+Al	50.12 d	1.23 e	1.92 d	0.231 d	0.73 fg	165.8 ef	1019 def	0.482 g
	pH 4.0+Cr+Al	21.76 i	0.16 i	1.00 f	0.065 e	0.22 h	47.3 g	459 f	0.427 h
Genotypes (G)		**	*	**	**	**	**	**	**
Treatments (T)		**	**	**	**	**	**	**	**
G × T		*	**	ns	**	**	*	**	**

growth parameters as compared to the control. However, less reduction was observed in Gebeina than in Shang 70-119. Exposure of plants to Cr stress decreased significantly all root parameters as compared to the control, but more reduction may be found at pH 4.0 than at pH 6.5 in case of root diameter and surface area. Plants exposed to combined stress of Al and Cr resulted in further reduction as compared to Al or Cr stresses alone, especially in case of average root volume where significant difference was observed. On the whole, less reduction was observed in Gebeina than in Shang 70-119 (Table 1).

Exposure of plants to pH 4.0 resulted in a significant decrease of chlorophyll (Chl) content and F_v/F_m value in Shang 70-119, but no significant difference could be detected in Gebeina except F_v/F_m at 15d. Addition of Al in growth medium markedly decreased Chl content and F_v/F_m as compared to the control, Gebeina being less affected than Shang 70-119. Under Cr stress significant decrease in both these parameters was observed in the two genotypes. Significant effect of pH was found, indicating that Cr toxicity effect is more severe at lower pH in cultivation solution. Under combined stress of Al and Cr further reduction in Chl content and F_v/F_m was observed as compared to any stress alone (Table 2).

The pH 4.0 reduced significantly net photosynthetic rate (P_N), intercellular CO_2 concentration (c_i), stomatal conductance (g_s) and transpiration rate (E) after 40-d exposure, while in Shang 70-119 also after 20-d exposure. A marked adverse effect of Al stress on all observed gas exchange parameters was found in the two genotypes. Gebeina had consistently higher P_N, c_i, g_s and E than Shang 70-119, irrespective of duration of stress. Cr stress treatments had significant adverse effects on gas exchange parameters in the two genotypes and the effect was more pronounced at pH 4.0 relative to pH 6.5. Combined treatment of Al and Cr slightly reduced P_N and c_i values, but significantly reduced g_s and E. On the whole, less reduction was observed in Gebeina than in Shang 70-119 for these gas exchange parameters (Table 3).

Table 2. The effect of pH, aluminum and chromium on F_v/F_m and Chl content in leaves of two barley genotypes. The same letters within a column mean no significant difference at 95 % probability level; ** indicate significance at the $P < 0.01$, ns - non significant.

Genotype	Treatment	F_v/F_m		Chl [mg g^{-1}(f.m.)]	
		20 d	40 d	20 d	40 d
Gebeina	Control	0.816 a	0.821 ab	1.10 a	1.12 a
	pH 4.0	0.809 bc	0.812 abc	1.07 ab	1.09 a
	pH 6.5+Cr	0.786 d	0.778 de	0.82 e	0.74 d
	pH 4.0+Cr	0.758 ef	0.746 f	0.71 g	0.64 e
	pH 4.0+Al	0.806 bc	0.803 bc	1.02 bc	0.99 b
	pH 4.0+Cr+Al	0.755 f	0.712 g	0.65 h	0.55 f
Shang 70-119	Control	0.826 a	0.829 a	1.09 a	1.13 a
	pH 4.0	0.798 c	0.796 cd	1.01 c	1.03 b
	pH 6.5+Cr	0.768 e	0.762 ef	0.76 f	0.69 d
	pH 4.0+Cr	0.716 g	0.676 h	0.59 i	0.47 g
	pH 4.0+Al	0.782 d	0.775 de	0.91 d	0.85 c
	pH 4.0+Cr+Al	0.683 h	0.614 i	0.52 j	0.45 g
G		**	**	**	**
T		**	**	**	**
G × T		**	**	ns	**

Discussion

Aluminum exposure can lead to numerous biochemical and physiological changes in plants. In the present investigation, Al stress reduced plant height, biomass, number of tillers per plant and root parameters including diameter, surface area, number of root tips and volume. Our results are consistent with the previous findings (Dong *et al*. 2002, Zhang *et al*. 2007, Jiang *et al*. 2009). Moreover, the Al-sensitive genotype Shang 70-119 showed more reduction, confirming the findings of the previous studies (Ma *et al*. 1997, Guo *et al*. 2004, Shamsi *et al*. 2008). The possible reasons could be less Al uptake and/or accumulation in Al tolerant genotype than in sensitive genotype (Ali *et al*., in press). Al sensitive genotypes of soybean also accumulated more Al than tolerant genotypes (Silva *et al*. 2000). The current results also showed that Al significantly reduced Chl content, F_v/F_m and gas exchange parameters, especially in Shang 70-119. Ohki (1986) also reported reduced photosynthesis and Chl content in wheat and sorghum with the increasing Al concentration in nutrient solution. Direct injection of Al into xylem in beans caused a significant reduction in photosynthetic and activated translocation of photosynthates (Hoddinott and Richter 1987).

Chromium stress also induced a significant decline in growth parameters of both barley genotypes. Similarly, reduction in growth of plants under Cr stress was observed in *Lolium perenne* (Vernay *et al*. 2007), wheat, oat and sorghum (Lopez-Luna *et al*. 2009) and *Datura innoxia* (Vernay *et al*. 2008). The presented results also showed that Cr stress decreased Chl content, F_v/F_m and gas exchange parameters in two studied barley genotypes. Similarly, it was reported that Cr had negative impact on photosynthetic parameter in other plants (Pandey *et al*. 2005, Ganesh *et al*. 2007, Subrahmanyam 2008). Higher concentration of hexavalent chromium decreased F_v/F_m, P_N, c_i, g_s and E in *Amaranthus viridis* (Liu *et al*. 2008). Chatterjee and Chatterjee (2000) found that Cr stress reduced g_s and E in cauliflower. Dramatic inhibition in P_N, g_s and E by Cr was reported in *Phaseolus vulgaris* (Zeid *et al.* 2000). The present study also showed that Cr toxicity on all measured parameters varied with pH level of the nutrient solution. Cr stress under pH 4.0 had more drastic effect on barley plants than under pH 6.5. It was reported that availability of Cr in soil increased with decreased soil pH (Zeng *et al*. 2008). Hence, chromium toxicity could more easily occur in the soils with low pH.

It could be stated that our paper is the first study concerning the effect of Al and Cr interaction on two barley genotypes differing in Al tolerance. Our results showed that Al and Cr interaction caused further reduction in shoot and root growth, Chl content, F_v/F_m and photosynthetic gas exchange than each stress alone. Similarly, the interaction between Al and Cd can affect plant growth and photosynthetic parameters more than each metal alone (Guo *et al*. 2004, Shamsi *et al*. 2008). Our other study showed that Cr and Al interaction had effects on Al and Cr uptake and accumulation (Ali *et al.*, in press). Similarly, it was reported that Cd and Al had synergetic effects on uptake of these metals in soybean (Shamsi *et al*. 2007).

Table 3. The effect of pH, aluminum and chromium on P_N, c_i, g_s and E in leaves of two barley genotypes measured at irradiance of 1200 µmol m^{-2} s^{-1}, relative air humidity 60 % and CO_2 concentration 500 µmol mol^1 on the topmost fully expanded leaf after 2 h of acclimation . The same letters within a column means no significant difference at 95 % probability level; *, ** indicate significance at the $P < 0.05$ and $P < 0.01$, respectively; ns - non significant.

Genotypes	Treatment	P_N [µmol m^{-2} s^{-1}]		c_i [µmol mol^{-1}]		g_s [mol m^{-2} s^{-1}]		E [mmol m^{-2} s^{-1}]	
		20 d	40 d	20 d	40 d	20 d	40 d	20 d	40 d
Gebeina	Control	19.71 a	22.57 a	508 ab	778 a	0.361 a	0.413 a	3.49 a	4.01 a
	pH 4.0	19.48 a	19.58 b	475 bc	701 b	0.357 b	0.358 b	3.45 a	3.46 b
	pH 6.5+Cr	11.85 de	10.68 d	441 cde	515 e	0.217 f	0.195 c	2.11 d	1.89 e
	pH 4.0+Cr	10.83 ef	6.73 f	395 fg	443 g	0.198 g	0.123 g	1.89 e	1.19 g
	pH 4.0+Al	17.88 b	14.36 c	469 cd	579 d	0.327 c	0.263 d	3.15 b	2.54 d
	pH 4.0+Cr+Al	9.61 f	6.06 fg	371 gh	429 g	0.176 h	0.111 h	1.72 f	1.07 gh
Shang 70-119	Control	20.24 a	23.13 a	516 a	795 a	0.370 a	0.423 a	3.58 a	4.09 a
	pH 4.0	15.48 c	17.97 b	443 cde	645 c	0.283 d	0.329 c	2.74 c	3.18 c
	pH 6.5+Cr	9.69 f	8.73 e	410 efg	470 f	0.178 h	0.161 f	1.73 f	1.52 f
	pH 4.0+Cr	8.27 g	5.49 fg	348 hi	399 h	0.150 i	0.101 i	1.46 g	0.97 h
	pH 4.0+Al	12.68 d	10.93 d	431 def	512 e	0.232 e	0.200 e	2.24 d	1.93 e
	pH 4.0+Cr+Al	7.44 g	4.49 g	324 i	381 h	0.136 j	0.082 j	1.32 g	0.79 i
Genotypes (G)		**	**	**	**	**	**	**	**
Treatments (T)		**	**	**	**	**	**	**	**
G × T		**	*	*	**	**	**	**	**

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