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# Effect of Al in soil on photosynthesis and related morphological and physiological characteristics of two soybean genotypes

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**ABSTRACT.** Ecological impact assessments of contaminated soil on plants has been an interesting area in the last few years as restoration of contaminated environments for better ecological health is addressed. In this study, the photosynthetic and related morphological and physiological characteristics of two soybean (*Glycine max* Merrill.) varieties were evaluated in response to aluminum (Al) stress in soil. The pot-grown soybean plants were cultured with different supplemental aluminum, and measurements was conducted during the 5-foliate period. Results indicate that Al at low concentrations in the soil is helpful to growth, and Al is toxic to plants only when the concentration exceeds a certain threshold. Increased leaf area, root surface area, specific leaf weight (SLW), and lower malondialdehyde levels were found in soybean plants under a 200 mg/kg $Al^{3+}$ treatment. However, higher aluminum concentrations (800 mg/kg) caused declining chlorophyll contents, depressed photosynthesis rates ($P_N$), enhanced transpiration rates, and decreased PAR utilization efficiency (PUE) and water utilization efficiency. No significant difference in stomatal conductance or leaf water potential was observed among soybean plants under the various aluminum treatments. Moreover, higher aluminum concentration significantly increased lipid peroxidation, decreased cell membrane stability, and changed the activities of superoxide dismutase (SOD) in the leaves of both plants. It is concluded that soybean plants maintain relatively higher SLW, $P_N$, PUE, WUE, SOD activity to cope with high aluminum stress. Our study produces insights into plant behavior under contamination stress, which may be useful in the selection and breeding of aluminum-tolerant soybean cultivars for the sustainable development of agriculture and ecology.

**Keywords:** Aluminium; Photosynthetic characteristics; Physiological characteristics; Soybean.

**Abbreviations:** **LA,** leaf area; **RSA,** root surface area; **SLW,** specific leaf weight; $\boldsymbol{P_N}$**,** net photosynthetic rate; **TR,** transpiration rate; **PAR,** Photosynthetically Active Radiation; $\mathbf{g_s}$**,** stomata conductance; $\mathbf{r_s}$**,** stomata resistance; **Chl,** Chlorophyll; **PUE,** PAR utilization efficiency; **WUE,** water utilization efficiency; **LWP,** leave water potential; **MDA,** malondialdehyde; **SOD,** superoxide dismutase.

## INTRODUTION

Ecological impact assessment of contamination stresses on plants has been an interesting area in the last few years as restoration of the natural environment and remediation of contaminated soil and/or groundwater require a better understanding of the relationship between ecological health and environmental contamination. Metals are among the major contaminants found in both contaminated lands and natural soils. Aluminium is a light metal that makes up 7% of the earth's crust, occurring in the form of harmless oxides and aluminosilicates. If the soil becomes acidic, Al is solubilized into toxic forms like $[Al\ (H_2O)_6]^{3+}$, generally referred to $Al^{3+}$, which is now present in 40% of the arable lands in the world. Excess $Al^{3+}$ in soil enters roots, resulting in reduced plant vigor and yield (Delhaize and Ryan, 1995; Matsumoto, 2000; Ciamporová, 2002). The initial symptom of Al toxicity is the inhibition of root elongation, which has been proposed to be caused by a number of different mechanisms, including Al interactions within the cell wall (Massot et al., 1999), the plasma membrane (Piňeros and Kochian, 2001), or the symplast (Kochian, 1995).

Given the increasing frequency of acid rain, a strategy should be established to protect soybean plants from aluminum toxicity stress in high Al soils. This requires a better understanding of the physiological responses of soybean to this stress. Good progress in this field has

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been made during the last few decades, and competent compilations and critical reviews on several aspects of this field have been published, e.g. Clarkson, 1969; Foy et al., 1978; Foy, 1984; Haug, 1984; Taylor, 1988; Rengel, 1992; Kochian, 1995; Delhaize and Ryan, 1995; Horst, 1995; Barceló et al., 1996; Matsumoto, 2000; Ma, 2000; Ma et al., 2001; Ryan et al., 2001; Barceló and Poschenrieder, 2002. Most of the mechanisms studied are related to limited root growth and development or their consequences; however, no breakthrough in these mechanisms has been made. Hence, it is suggested that more attention should be paid to aerial tissues in future studies, which are important in revealing Al toxicity and mechanisms of plant tolerance to Al stress. The knowledge obtained from aerial plant tissues in acclimation to aluminum toxicity in previous studies has been limited. Leaf necrosis as a visible symptom of Al stress, was found to be accompanied by decreasing chlorophyll concentrations and photosynthetic rates in *Picea abies* (Schlegel and Godbold, 1991), rice (Shi, 2004), and *Dimocarpus Longana* (Xiao, 2002). Due to reduction in absorbing surfaces (Stienen, 1986), root-water permeability (Zhao et al., 1987) and stomata aperture (Hampp and Schnabl, 1975), Al has generally been found to decrease transpiration rates. In contrast, Schlegel and Godbold (1991) observed enhanced transpiration rates of spruce needles due to Al. Further investigations on aerial tissues are needed to seek better stress elimination solutions or strategies for growing soybean plants in Al contaminated soil.

In this study, we compared photosynthetic and related morphological and physiological characteristics in two soybean varieties Huachun No.18 and Zhechun No.3 in the 5-trifoliate period. We tried to elucidate the responses of the soybean aerial tissues to the aluminum toxicity in the soil, reveal causes involved in these processes, and thus provide a foundation for selection and breeding of aluminum-tolerant soybean cultivars. This research will be useful in obtaining insights into physiological behavior under Al contamination stress, which would aid in the selection and breeding of aluminum-tolerant soybean cultivars for sustainable agricultural and ecological development.

## MATERIALS AND METHODS

### Plant materials and treatments

This research was conducted in the greenhouses of Zhejiang Normal University, Jinhua, China. Two soybean cultivars (*Glycine max* Merrill.) "Huachun No.18" and "Zhechun No.3" are widely planted in Zhejiang. The selected seeds of soybean were disinfected with 0.01% (w/v) $HgCl_2$ solution for 5 min and then rinsed five times with de-ionized water. Subsequently, the seeds were soaked in de-ionized water for 2 h and germinated in salvers covered with sterilized gauze at 25°C. Both soybean cultivars (*Glycine max* Merrill.) "Huachun No.18" and "Zhechun No.3" were grown in pots (height 23 cm and diameter 18 cm) under natural irradiance in the middle of May 2004 after the seeds had germinated. Each pot was filled with 5 kg of soil, the physicochemical characteristics of which can be given as follows: pH=5.96, water content 3.04%, organic C 8.1 $g \cdot kg^{-1}$, total N 0.205 $g \cdot kg^{-1}$, $NO_3$-N 20.2 $mg \cdot kg^{-1}$, $NH_4^+$-N 30.5 $mg \cdot kg^{-1}$, total P 0.423$g \cdot kg^{-1}$, available P 8.15 $mg \cdot kg^{-1}$, available K 98.2 $mg \cdot kg^{-1}$. The soils were supplied with five Al concentration treatments: $Al_2(SO_4)_3 \cdot 18H_2O$: 0 $g \cdot kg\ soil^{-1}$ (CK), 0.2 $g \cdot kg\ soil^{-1}$ (R1), 0.4 $g \cdot kg\ soil^{-1}$ (R2), 0.6 $g \cdot kg\ soil^{-1}$ (R3), 0.8 $g \cdot kg\ soil^{-1}$ (R4), respectively. Four repetitions (pots) with five plants in each pot were performed in each treatment. After a 25-day treatment, the plants had entered a 5-foliate period, and the topmost three fully-expanded leaves of each plant were sampled. Each experiment was carried out at least three times.

### Measurements

Leaf area (LA) was determined from the fully expanded leaves (abaxial surface) of soybean plants using a leaf area analysis system (Win/Mac FOCTA STD l200P, Regent, Canada), and the root surface area (RSA) of soybean plant roots was determined using a scanner connected to an image-analysis system (Win/Mac RHIZO STD l600$^+$, Regent, Canada). Specific leaf weight (SLW, leaf mass per area) was calculated as the ratio of leaf dry weight to LA; Chlorophyll (Chl) was extracted using ethanol and acetone according to Zhang et al. (1983). The concentrations of Chl a and Chl b in extracts were determined from absorbance at 663 and 645 nm, respectively, with a Leng-Guang 752 spectrophotometer (Leng-Guang, Shanghai, China). At least three repetitions were used in determination of the LA, SLW and Chl contents.

Photosynthetic rate ($P_N$), transpiration rate (TR), photosynthetic active radiation (PAR) on leaf surface, stomatal conductance ($g_s$), and stomatal resistance ($r_s$) were monitored using a portable photosynthesis and transpiration measurement system (LCA-4, ADC, UK) between 9:00 am and 11:00 am under field conditions. Measurements were conducted on attached and fully expanded leaves (abaxial surface) of soybean plants. All parameters were calculated by the software operating in LCA-4, and at least ten repetitions were carried out for determination. Water utilization efficiency (WUE) was calculated as WUE = $P_N$ / Tr; and PAR utilization efficiency (PAR) was calculated as PUE = $P_N$ / PAR.

Leaf water potential was determined from the topmost three attached and fully-expanded leaves (abaxial surface) of soybean plants with a PSYPRO water potential measurement system (PSYPRO, Wescor, America), with at least ten repetitions for each measurement.

The level of lipid peroxidation in leaf tissue was measured in terms of malondialdehyde (MDA) content, which was determined by the thiobarbituric acid reaction following the procedure of Špundová et al. (2003). The activity of SOD (superoxide dismutase) was assayed

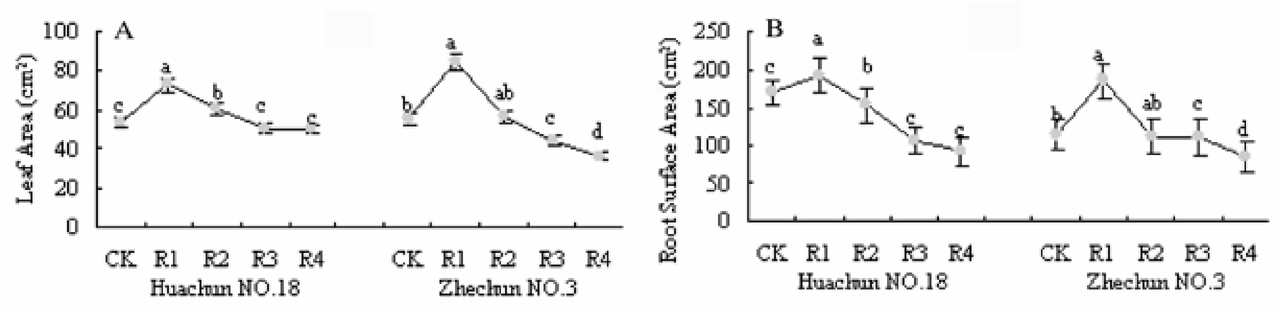

**Figure 1.** Effect of Al on LA (A) and RSA (B) of the soybean plant in the 5-trifoliate period. The subscripts represent the difference significant at $p$=0.05; each value is the mean ± S.E. of three leaves from three pots, based on three determinations for each sample.

according to Wang et al. (1983) in terms of its ability to inhibit the photochemical reduction of nitro blue tetrazolium (NBT). One unit of the SOD activity is defined as the amount of enzyme required to cause a 50% inhibition of NBT auto-oxidation under assay conditions. The SOD activity was expressed as a unit per milligram of protein in the soybean leaf. MDA content and SOD activity was also determined with at least three repetitions.

### Statistical analysis

Analysis of variance (one-way ANOVA) was performed to test significant variations in response to different temperatures. In order to evaluate significant differences between treatments and varieties, the LSD-test (Least Significant Difference) was used on a significance level of $P<0.05$. Data are expressed as the means ± standard error of at least eight measurements.

## RESULTS

### Effect of Al on LA, RSA and SLW

The effect of aluminium in soil on leaf area, root surface, and specific leaf weight of the soybean plants is described in this section. It can be seen from Figure 1 and Figure 2 that leaf area and root surface area increased and then decreased in soybean plants as Al concentration in soil rose while the effects on SLW are less obvious. Results in Figure 1A show that SLW in low concentration Al treatments (200 or even 400 mg·kg$^{-1}$ Al) was higher than in control, which indicates that Al at a low concentration might be helpful to leaf growth. Higher Al$^{3+}$ treatments (600 and 800 mg·kg$^{-1}$ Al), however, slightly inhibited leaf growth, and hence the lowest leaf area was at 800 mg·kg$^{-1}$ Al. Similarly, RSA increased as Al$^{3+}$ concentration increased from 0 to 200 mg kg$^{-1}$, and decreased as Al continued to enhance, especially for Huachun No.18 (Figure 1B). It is suggested that low concentration Al (200 mg kg$^{-1}$) may increase RSA of the soybean plants, and higher concentration Al in soil may decrease LA and RSA. No clear difference in SLW emerged among the Al treatments, except for a slight increase under the 200 mg·kg$^{-1}$ Al$^{3+}$ treatment (Figure 2).

It is also suggested that low concentration Al in soil can facilitate the synthesis of carbohydrate (increase of SLW, LA and RSA) and high concentration Al can affect plant growth (decrease of LA and RSA). Variations in plant growth (RSA) also occurs between different soybean cultivars.

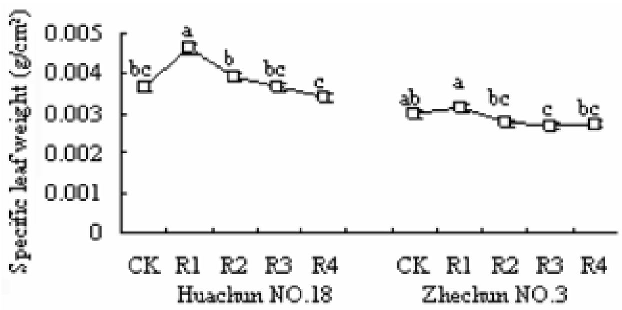

**Figure 2.** Effect of Al on leaf SLW of the soybean plants in the 5-trifoliate period. Different subscript represents the difference significant at $p$ = 0.05. Each value is the mean ± S.E. of three leaves from three pots, based on three determinations for each sample.

### Leaf chlorophyll content

Al in soil altered the leaf chlorophyll content of soybeans. As the Al concentration ascended, the content of Chl a and Chl b in the soybean plants declined gradually (Figure 3). Chl a content in Zhechun No.3 under R1, R2, R3, R4 decreased 18.6%, 20.6%, 26.2%, 32.2% more than in CK, respectively, and the decrease was a little more significant for Huachun No.18 with increasing Al concentration in soil ($p<0.05$). Chl b content changed in the same pattern as Chl a content did under Al treatments (Figure 3).

### Photosynthetic characteristics under Al treatment

Net photosynthetic rates ($P_N$) in the two treated cultivars were significantly reduced compared to CK ($P<0.05$) when Al concentration in soil reached 400 mg·kg$^{-1}$ (Figure 4). The $P_N$ of Huachun No.18 and Zhechun No.3 decreased noticeably (44.5% and 50.7%, relative to their controls). Further increases in Al concentration produced no further significant reductions. The transpiration rate (TR) in both plants increased significantly when the Al concentration ascended to and surpassed 400 mg·kg$^{-1}$ (Figure 5). Higher Al concentration treatments (600 or 800 mg·kg$^{-1}$) seemed to produce no marked differences in plant response. For instance, TR of R2, R3, R4 in Huachun No.18 increased 43.7%, 52.6%, 47.7%, respectively, compared with control.

A slight decrease and a subsequent increase, though not significant, were observed in the stomatal conductance ($g_s$) of the Al-treated soybean plants (Figure 6). The difference between the two cultivars was that $g_s$ in Zhechun No.3 showed a more evident change, i.e., Zhechun No. 3 had a lower $g_s$ at 400 mg·kg$^{-1}$ than control. In contrast to stomatal conductance, stomatal resistance ($r_s$) in soybeans of both varieties was enhanced under the 400 mg·kg$^{-1}$ Al treatment and fell under higher Al treatments (Figure 7).

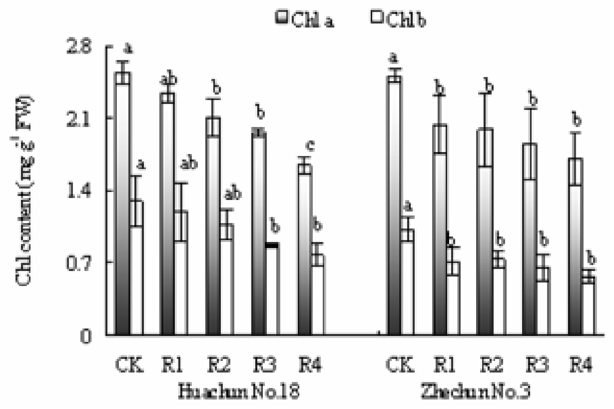

**Figure 3.** Effect of Al on chl a and chl b content of soybean leaf in the 5-trifoliate period. Different subscript represents the difference significant at $p = 0.05$. Each value is the mean ± S.E. of three leaves from three pots, based on three determinations for each sample.

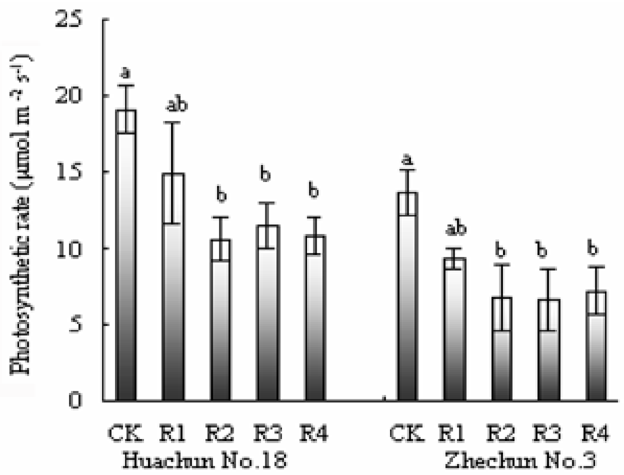

**Figure 4.** Net photosynthetic rate under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on ten determinations for each sample.

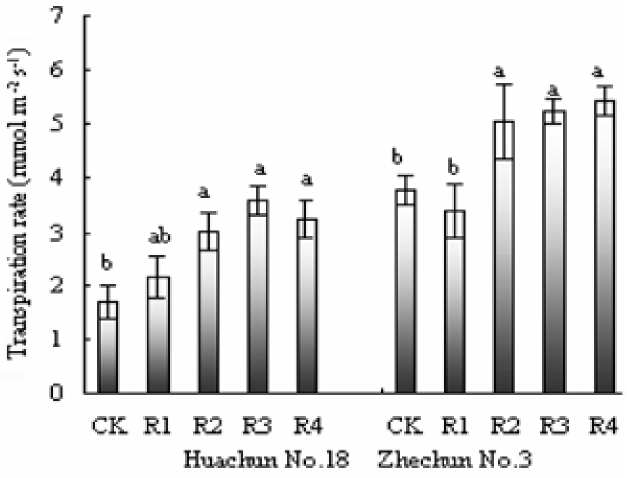

**Figure 5.** Transpiration rate under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on ten determinations for each sample.

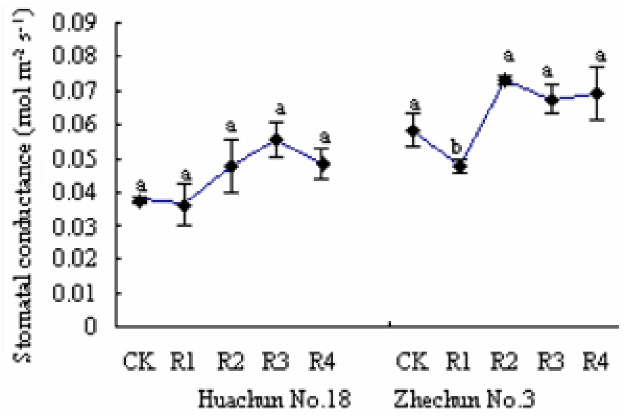

**Figure 6.** Stomata conductance under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on ten determinations for each sample.

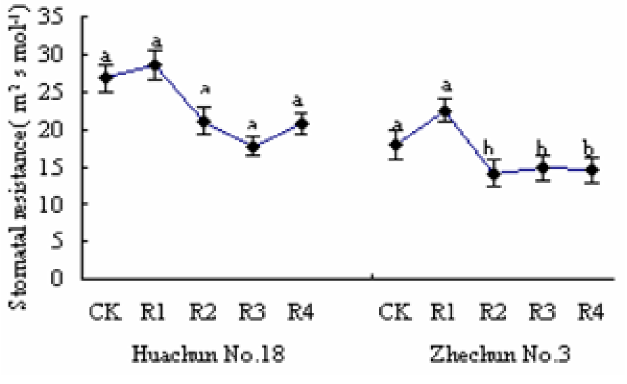

**Figure 7.** Stomata resistance under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on ten determinations for each sample.

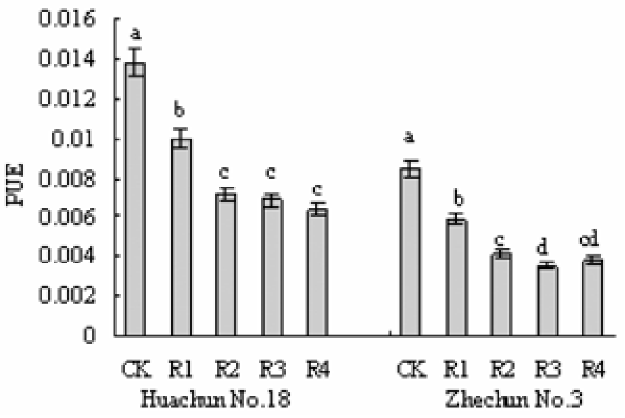

**Figure 8.** PAR utilization efficiency (PUE) under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on ten determinations for each sample.

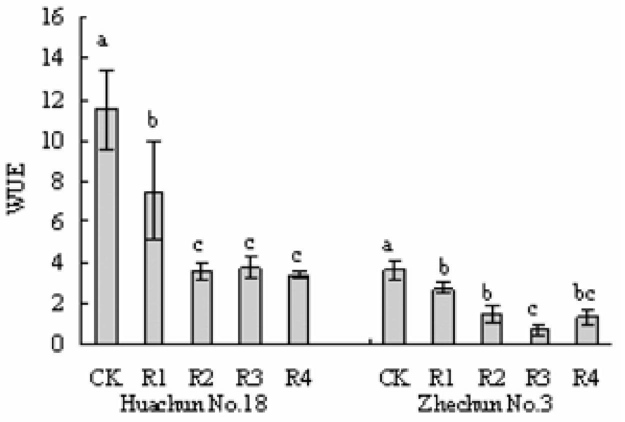

**Figure 9.** Water utilization efficiency (WUE) under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on ten determinations for each sample.

No statistical differences emerged among the $r_s$ values of Huachun No.18 under different treatments, but significant decreases were observed in R3, R4 for Zhechun No.3 ($P<0.05$).

## PUE under Al treatment

PUE represents the PAR utilization efficiency during photosynthesis, and a high PUE guarantees a high crop yield. Figure 8 depicts a sharp drop of PUE in aluminium-treated plants, 45% and 48.8% on average for Huachun No.18 and Zhechun No.3, respectively. The toxicity of Al in soil is considered to exert a remarkable influence on a plant's PAR utilization, which then affects the whole process of photosynthesis.

## WUE under Al treatment

WUE is one of the indexes that evaluates the degree of damage to plants by water utilisation under ionic stresses. Results show that WUE in both treated cultivars fell as the Al concentration ascended (Figure 9). As Al concentration increased from 0 to 400 $mg \cdot kg^{-1}$, WUE plummeted. However, further increases in Al concentration produced no significant difference. Compared to Zhechun No.3, WUE for Huachun No. 18 was much higher in CK and dropped more obviously as Al stress was applied. WUE for Huachun No.18 and Zhechun No.3 under other treatments dropped 60.4% and 56.9% on average, respectively, relative to their controls. This indicates that Zhechun No.3 is more tolerant than Huachun No.18, and shows that keeping a stable WUE can relieve the side-effects of soil aluminum stress.

## LWP variations

Soybean plants were able to balance the internal water potential even with high aluminium concentrations in their leaves. As the data in Figure 10 make clear, no significant difference existed in leaf water potential (LWP) among different treatments ($P>0.05$). The two cultivars' response

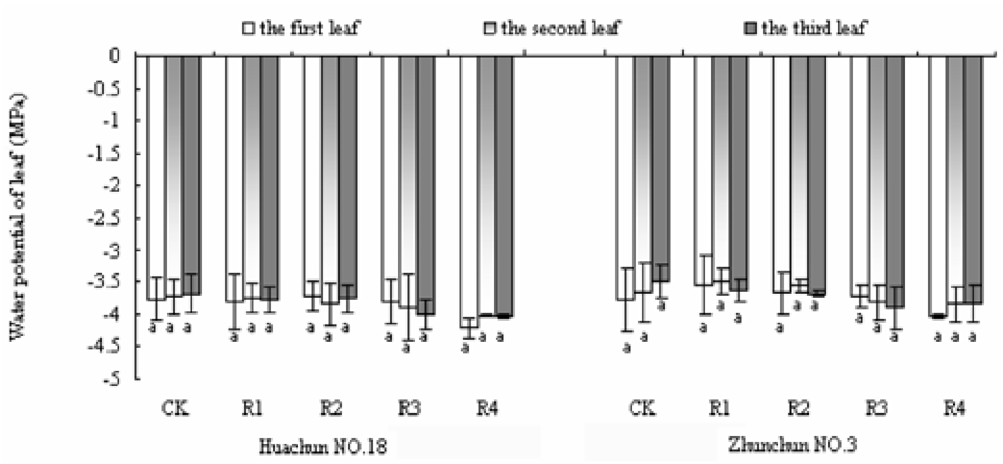

**Figure 10.** Leave water potential (LWP) under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of the first, second, third leaves from three pots, based on ten determinations for each sample.

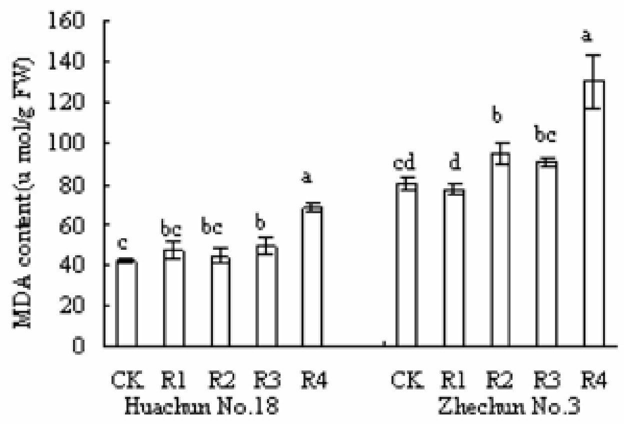

**Figure 11.** MDA content under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on three determinations for each sample.

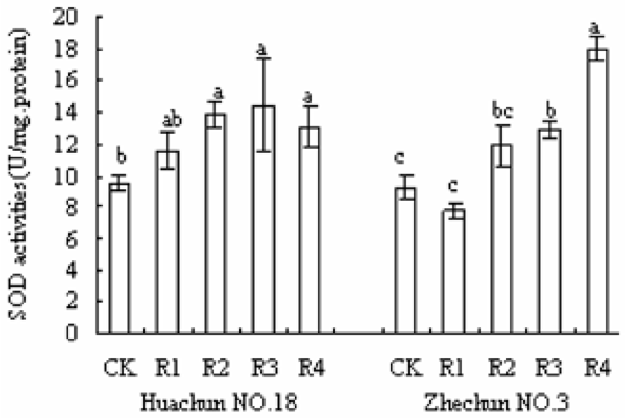

**Figure 12.** SOD activity under different Al treatments. Different subscript represents the difference significant at $p = 0.05$. Each point is the mean ± S.E. of 3~9 leaves from three pots, based on three determinations for each sample.

differed little in the first leaf. There was a slight increase at 200 mg·kg$^{-1}$ before a continuous decrease at higher Al concentrations in Zhechun No.3 while no increase was observed in Huachun No.18. This effect may be magnified in drought areas.

### Lipid peroxidation and antioxidant enzyme activities

Figures 11and 12 show the responses of lipid peroxidation and antioxidant enzyme activities to the various aluminium treatments. Al in soil increased leaf membrane peroxidation and SOD activities in the Huachun No.18 soybean leaves. As the concentration of Al increased, the malondialdehyde (MDA) content in Huachun No.18 increased progressively to 64.16% over control. The SOD activities were also enhanced progressively under the Al treatments (Figure 12). However, contrasting with the MDA content trend, the highest SOD activity was at 600 mg·kg$^{-1}$, and some decline was observed at 800 mg·kg$^{-1}$ for Zhechun No.18. For Zhechun No.3, the MDA content declined by 3.74% under the 200 mg·kg$^{-1}$ treatment and then recovered 17.93%, 12.63%, 61.68% under the 400, 600, 800 mg·kg$^{-1}$ Al treatments, respectively, compared with control. Variations of the SOD activities were similar to those of the MDA content in a larger margin. These results show that Al at middle or high concentrations causes oxidative damage while Al at low concentrations helped Zhechun No.3 soybean plants resist peroxidation.

## DISCUSSION

Many studies (Kidd and Proctor, 2000; Yan et al., 2003; Yang et al., 2005; Liu et al., 2006; Ying et al., 2006) have reported that the low-level Al does not affect or even accelerate plant growth. Though Al is a nonessential element to plants, such studies are useful for the management of Al contaminated soil and agricultural development. In this study, the leaf area and specific leaf weight of both cultivars increased under 200 mg kg$^{-1}$ Al treatment. Neither chlorophyll content, photosynthetic rate, lipid peroxidation, nor antioxidant enzyme activities were significantly affected in the low-aluminum treated plants. These results confirmed that Al at low soil concentrations is helpful to soybean growth and that it is toxic only when the concentration exceeds a certain threshold. Therefore, Al toxicity to plants has a critical value in crop management. The threshold value varies with the plant involved, such as 40 mmol kg$^{-1}$ for *Triticum aestivum* and *Brassila campestris* var. *oleifera* (soil cultured), 44 mmol kg$^{-1}$ for *Arachis hypogaea* (soil cultured), 48 mmol kg$^{-1}$ for *Zea mays* (Qin and Chin, 1999). This critical value also varies with different growth phases (Li et al., 2000) and crop genotypes (Pan et al., 1998). In our soil culture study, the critical values for Zhechun No.3 and Huachun No.18 were above 200 mg L$^{-1}$. Higher concentrations of Al, however, affected plant growth, depressed photosynthesis, enhanced transpiration, and induced lipid peroxidation.

Photosynthesis is probably the most important metabolic event on earth and is certainly the most important process to understand in attempting to maximize crop productivity and minimize the side-effects of soil contamination. However, it is a physiological process affected by environmental factors, especially various stresses, including aluminum toxicity stress. Since photosynthesis runs a complicated course, the depression of photosynthesis refers to several factors. Schnable and Ziegler (1975) found that 1 mM $Al^{3+}$ inhibits stomata opening in the illuminated epidermal strips of *Vicia faba*, by preventing $K^+$ accumulation and starch mobilization in the guard cells. In our study, however, the stomatal conductance and stomatal resistance under Al treatments changed so slightly that it made no statistical difference when the photosynthetic rate declined. Hence, most attention was paid to non-stomata factors in this study. First, the decrease of the chlorophyll content in leaves should be considered. Several investigations have shown that many tree species respond to Al exposure with various amount of mineral uptake (Asp et al., 1988; Bengtsson et al., 1988; Van Praag et al., 1991; Ericsson et al., 1995; Van Praag et al., 1995; 1997). An Al-induced reduction in Mg concentrations in beech roots (Bengtsson, 1992) was also reported. Our work in buckwheat (*Fagopyrum esculentum* Moench) also revealed that as the in vitro aluminum concentration increased, the Al content in both root and leaf surged, and the Mg contents in both root and leaf decreased correspondingly (Chen et al., 2006). Therefore, we speculated that the reduction in both Chl a and Chl b contents (Figure 3) under Al toxicity stress may be due to decreased Mg concentrations, which at least partly resulted in a correspondingly decreased PAR utility efficiency (Figure 8) and affected the photosynthetic capacity. Secondly, decrease of water utility efficiency should be partly responsible for photosynthesis reduction. Water use efficiency is an important characteristic that provides information on the potential of a species or variety to adapt to contamination stress (Poschenrieder and Barcelo, 1999). The decrease in the photosynthetic activity of soybean plants and the preservation of high transpiration induced a reduction in water use efficiency. Besides, no significant drop was found in the leaf water potential (Figure 10), from which can be deduced that transpiration competes with photosynthesis for water under Al toxicity stress, and the water deficiency subsequently restrains photosynthesis.

The reduction of photosynthesis by aluminum stress is also related to inactivation of many chloroplast enzymes, such as ribulose 1, 5-bisphosphate carboxylase/oxygenase (Rubisco) and fructose 1, 6-bisphosphate aldolase (FBPase) (Bengtsson et al., 1988), which may be induced by oxidative stresses. Oxidative stress can cause lipid peroxidation and consequently membrane injury, protein degradation, and enzyme inactivation (Meriga et al., 2004). Therefore, the abilities to maintain cell membrane integrity and diminish oxidative stress have been proposed as good indicators of tolerance in plants. Our results suggest that high Al stress significantly increased membrane lipid peroxidation in both cultivars, especially in Huachun No.18 (Figure 11). Along with the occurrence of oxidative damage during Al stress, these two plants responded by activating antioxidant enzymes like SOD, POD or CAT for detoxification and other antioxidative substances like free proline. In our study, variations of SOD activities in Zhechun No.3 and Huachun No.18 under stress conditions (Figure 12) were observed. In comparison to the control plants, the SOD activities decreased slightly in Zhechun No.3 as Al concentration increased from 200 to 400 mg kg$^{-1}$ while Huachun No.18 increased relatively less. This result, along with responses of the corresponding MDA level, indicates that the cell membranes in Huachun No.18 were more susceptible to aluminum stress than in Zhechun No.3 and that the ROS scavenging ability in Huachun No.18 was lower than in Zhechun No.3. Under high concentration Al treatment, MDA content increased significantly in both cultivars while SOD activities were only enhanced in Zhechun No.3. This suggests that the stressed soybean plants also had an effective system for detoxifying active oxygen species at low and intermediate concentration Al treatments, but this system may have collapsed and peroxidation may have gotten out of control under high concentration Al treatments, e.g. above 800 mg kg$^{-1}$. In addition, Yang et al. (2000, 2003) reported that photosynthesis plays an important role in the exudation of citrate exudation, which is an important Al tolerance mechanism in aluminum-tolerant soybean plant, but the contribution of shoots combined with light to Al-induced secretion of citrate still needs confirmation. Further research is planned.

Many studies have reported on large genotypic variations in plant growth, physiology, and quality in response to Al (Tang et al., 2001; Liu et al., 2004). Two soybean varieties in our experiment exhibited some of these variations. In addition to the SOD ability mentioned above, the root surface area, PAR utilization efficiency, and water utilization efficiency of the Zhechun No.3 soybean plants were somewhat less adversely affected than those of Huachun No.18 under high Al treatment in soil. These results suggest that Zhechun No.3 is slightly more tolerant than Huachun No.18 to aluminum. This agrees well with our previous studies on the root physiological characteristics of soybean Huachun No.18 and Zhechun No.3 under Al toxicity (Liu et al., 2004). In those studies, decreases in the main length, system volume, dry weight, root activity, and membrane permeability of root cells and increases in the proline content, MDA, and soluble carbohydrate were observed more in soybean Huachun No.18 than in soybean Zhechun No.3 under increased of aluminum contamination. Therefore, these indices tested in our experiment are useful for screening Al-tolerant soybean cultivars. As a light metal in the soil occurring naturally or by contamination, Aluminium has influenced crop production. The use of lime, organic fertilizer and silicon can relieve the toxicity of the soil, but these are not permanent solutions. Comparing aluminum-tolerance characteristics in soybean cultivars like the ones this study to screen for aluminum-tolerant cultivars, can provide a foundation for transforming aluminum-tolerant genes to the soybean cultivars of high quality and productivity thus resolve the problem of high aluminum stress in acid soil. This research can ultimately be useful to develop a strategy of sustainable agricultural development and promote environmental and ecological health.

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# 土壤中鋁污染對兩種大豆品種光合特性及相關形態和生理特性的影響

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從光合特性及其相關的形態和生理特性方面研究了土壤中鋁對兩種大豆品種的影響。我們以 2 個大豆（*Glycine max* Merrill.）品種華春 18、浙春 3 號為材料，設置不同的鋁濃度進行盆栽土培，在五葉期取樣測定各項指標。結果表明：微量鋁對大豆的生長具有一定的促進作用，鋁僅在超出一定值時才對植物產生毒害。200 mg / kg $Al^{3+}$ 處理下，葉面積和比葉重較對照有所增加，丙二醛含量有所降低。高濃度的鋁對大豆產生了不利影響。鋁濃度大於 800 mg/kg 情況下，葉綠素含量下降，光合速率降低，蒸騰速率增高，光利用率和水分利用率下降，而對氣孔導度和葉水勢沒有顯著影響。並且，高濃度的鋁顯著提高了膜脂過氧化程度，降低了細胞膜穩定性，改變了大豆葉 SOD 活性。植物通過保持 SLW、$P_N$、PUE、WUE 和 SOD 活性來適應高鋁脅迫。本研究結果為日後進行耐鋁型大豆的選育工作提高了基礎。

**關鍵詞：**大豆；鋁；光合特性。