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ALUMINUM EFFECTS ON PLANT AND NUTRIENT UPTAKE PARAMETERS OF SOIL AND SOLUTION GROWN SORGHUM GENOTYPES

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ABSTRACT: Recently, controlled environmental screening techniques have been preferred to field trials to identify sorghum genotypes that can tolerate aluminum (Al) stress. Soil and solution culture experiments were undertaken under greenhouse conditions to evaluate the effect of Al on plant growth and nutrient uptake parameters of three sorghum genotypes: 1) SC283, 2) BR003R, and 3) BR007B. Earlier field studies indicated that the order of tolerance to Al decreased from genotype 1 to 3. A dark red latosol was used with seven levels of dolomitic lime (0, 0.50, 0.75, 1.0, 2.0, 4.0, and 8.0 t/ha) and solution culture with seven levels of Al (0, 0.15, 0.20, 0.25, 0.30, 0.60, and 1.20 mmol/L). Plant growth (shoot and root weight; root length; specific root length, SRL; and relative shoot and root growth reduction, RGR) and nutrient uptake (total uptake; influx; nutrient efficiency ratio, ER; and percent of nutrient inhibition, PI) parameters were influenced similarly by Al in solution culture and soil experiment. Significant differences were observed for genotype-Al interactions and there was a stimulating effect, among genotypes, by low Al concentrations (up to 0.15 mmol/L). However, the plant growth and nutrient uptake parameters were negatively affected by Al stress. The performance of the genotypes in relation to Al tolerance in both solution

and soil experiments was the same as observed in the field: SC283 > BR003R > BR007B.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal crop in the world (18) because of its tolerance to drought, mineral element stress, and relatively low fertilizer requirements when compared with other crops. Tropical and subtropical regions are the potential areas for its expansion, particularly the Savanna (Cerrado) areas in Brazil, where approximately 200 million ha are available (13). In the Cerrado soils, Al saturation is in the order of 60%, reaching 90% in many virgin soils. This results in acute deficiencies of phosphorus (P), calcium (Ca), magnesium (Mg), and some micronutrients, principally zinc (Zn) (13,15).

Considerable research is being devoted to locate and identify sorghum genotypes that can tolerate acid soil conditions with low inputs (1,2,6,8,9,10,11, 15,16). In both temperate and tropical regions, various techniques, either in nutrient solutions, in greenhouse soils, or in the field have been developed to assess the differential tolerance to soil acidity (12). Controlled environmental screening methods have been preferred to the field trials because they are more rapid, less expensive and assess more germplasms in a given period of time (9). The screening technique selected must be able to detect differential response of plants to Al and also should consider the appropriate combination of factors that represents the Al toxicity (8,12). Relative and net shoot and root (seminal and total) growth are well established plant parameters to measure effects of Al in short term experiments (6,12). Nutrient uptake parameters such as concentration, total uptake, influx, and transport have been successfully used to differentiate genotypes into efficient and inefficient nutrient utilizer under Al stress (1,2,15,16).

Degree and differences among genotypes and cultivars of various species is being assessed either in solution culture or in soil culture medium (1,2,10,11,12, 17). However, information is lacking on the degree of similarity or differences in the physiological traits of plants grown either in solution or soil culture. The current study was undertaken to evaluate the effects of Al in soil and solution culture medium on growth and nutrient uptake parameters of sorghum genotypes having different degrees of tolerance to soil acidity.

MATERIALS AND METHODS

Solution and soil culture experiments were conducted in greenhouse conditions at EMBRAPA-CNPMS (National Maize and Sorghum Research Center), Sete

Lagoas, MG, Brazil, with three sorghum (*Sorghum bicolor* L. Moench) genotypes differing in the tolerance to soil acidity. Air temperature in the greenhouse was maintained at 25/20 (±5°C) in the day/night period, respectively. The sorghum genotypes used were: (1) SC283, (2) BR003R, and (3) BR007B, selected from earlier field studies that indicated the order of tolerance to soil acidity declined from genotypes 1 to 3.

Solution Culture Experiment

Seeds of the different genotypes were initially treated with $HgCl_2$ for surface sterilization and then wrapped in moist germination paper and placed into a germinator at 25°C for three days. The seedlings were then placed for an additional three day period in an elongation chamber containing diluted nutrient solution (0.25 of regular strength). Two 6-day-old uniform seedlings were transferred to 9.5-liter PVC containers, containing solution with following composition: 2.5 = Ca, 3.03 = K, 1.00 = Mg, 8.00 = N-NO_3, 1.00 = N-NH_4, 0.96 = Cl, 1.27 = S, 0.13 = P, 0.30 = Fe (as Fe EDTA) in mmol/L, and 7 = Mn, 19 = B, 1.8 = Zn, 0.5 = Cu, and 0.6 = Mo in µmol/L. Seven Al levels were used: 0, 0.15, 0.20, 0.25, 0.30, 0.60, and 1.20 mmol/L applied as $KAl(SO_4)_2{\cdot}12H_2O$. The nutrient solutions were initially adjusted to pH 4.6. Plants were grown for 15 days in continuously aerated solution and water added as needed to maintain the original volume in the pots. All treatments were replicated twice. At harvest, plants were water rinsed, blotted dry, and separated into roots and shoots.

Soil Experiment

The top 15 cm layer of a dark red latosol (Typic Haplorthox) under 'Cerrado' vegetation, was used in the experiment. It was passed through 2-mm mesh screen. The soil had the following characteristics: sand, silt, and clay contents, 12, 17, and 71%, respectively; pH (H_2O) = 4.6; organic matter = 5.7%; exchangeable Al, Ca, Mg, and K, 1.65, 1.00, 0.27, and 0.14 cmol(+)/kg, respectively; and available P, 3 mg/kg.

Soil samples were incubated with dolomitic lime (54.85%, CaO; 19.6% MgO, and 125% of calcium carbonate equivalency) at 60% of the field capacity (33 kPa tension). Seven lime rates were used: 0, 0.50, 0.75, 1.00, 2.00, 4.0, and 8.0 t/ha. At the end of 10 weeks of incubation, soils received a basal fertilizer consisting of 100, 114, and 137 mg/kg of N, P, and K, respectively, as NH_4NO_3 and KH_2PO_4. Zinc was also added at 10 mg/kg soil as $ZnSO_4{\cdot}7H_2O$. Soils were incubated for an additional week and 2.0 kg soil was placed in 2.5-L capacity pots. Sorghum seedlings were prepared similarly to the solution experiment. On the 6th day, roots were trimmed to 5 cm to enhance branching and three uniform seedling were planted per pot. Soil moisture was adjusted to 60% of water content at 33 kPa tension every other day by addition of water. Seedlings at transplanting were used for initial measurements. All treatments were replicated three times. Plants were harvested 15 days after transplanting and separated into roots and shoots and dry weight recorded.

Analysis and Determinations

Plant samples were digested in HNO_3-H_2SO_4-$HClO_4$ (10:1:4) mixture and analyzed for N (by micro-Kjeldahl digestion method), and for their Ca, Mg, K, Fe, Zn, and Mn contents by atomic absorption spectrophotometry, and P by the chlorostannous reduced molybdophosphoric acid method. The following plant parameters were calculated: growth (root growth rate; k; specific root length, SRL; relative growth reduction, RGR) and nutrient uptake parameters (influx, IN; nutrient efficiency ratio, NER; and percent of nutrient inhibition of uptake, PI) (1,2):

$$\mathbf{k = (\ln RL_2 - \ln RL_1) / (T_2 - T_1)} \quad [1]$$

where: **RL** refers to root length (m) and time **T** (second), subscript **1** refers to initial (6 days) and subscript **2** refers to final (21 days) harvest.

$$\mathbf{SRL = m\ of\ root / g\ of\ root} \quad [2]$$

$$\mathbf{RGR = [1 - (Growth\ with\ Al / growth\ without\ Al)] \times 100} \quad [3]$$

where: **Growth with Al** represents shoot or root dry weight at different Al levels in solution culture or different Al saturation in soil experiment and **Growth without Al** represents shoot or root dry weight in treatments without Al in solution or soil with 8 t lime/ha.

$$\mathbf{IN = [(U_2 - U_1)/(T_2 - T_1)][(\ln RL_2 - \ln RL_1)/(RL_2 - RL_1)]} \quad [4]$$

where: **U** refers to element content (mmoles) in shoot, and **RL_1**, **RL_2**, **T_2**, and **T_1** as previously defined, and with **IN** expressed in pmoles/m root sec.

$$\mathbf{NER = mgs\ of\ dry\ shoot/mg\ of\ element\ in\ shoot} \quad [5]$$

$$\mathbf{\%PI = [(U\ without\ Al - U\ with\ Al)/U\ without\ Al] \times 100} \quad [6]$$

with all terms previously defined.

TABLE 1. Analysis of variance for sorghum genotypes and aluminum treatments for plant growth parameters in solution culture and soil experiments.

Parameter	Genotypes		Aluminum		Gen vs. Al	
	Solution	Soil	Solution	Soil	Solution	Soil
Shoot dry wt. (g/plant)	**	**	**	**	**	NS
Root dry wt. (g/plant)	**	**	**	**	*	NS
Root length (m/plant)	**	**	**	**	**	NS
Specific root length (SRL mg/plant)	**	**	**	**	**	**
Root growth rate (k cm/sec)	**	**	**	**	**	**
RGR-Shoot (%)	**	**	**	**	**	NS
RGR-Root (%)	NS	*	**	**	**	**

*, **Significant at $P < 0.05$ and 0.01, respectively.
NS Not significant at $P > 0.05$.

RESULTS

Plant Growth Parameters

Plant growth parameters of shoot and root in both growth mediums showed a significant difference with respect to genotypes and Al levels (Table 1). With one exception, the significant differences in RGR of shoot and root were noted for genotypes and Al treatments. The SRL and k gave significant interaction effects of genotype and Al levels in both growth mediums. Overall shoot and root growth parameters in solution culture gave significant genotype and Al interactions (Table 1).

Stimulations in plant growth were observed with increase in Al from the 0 to 0.15 mmol/L in solution culture and from 0 to 5% Al saturation in the soil experiment. However, further increase in Al levels of growth medium decreased the overall plant growth parameters. In the soil medium, based on shoot and root weight and root length, the genotypes were ranked as SC283 > BR003R > BR007B (Fig. 1). This ranking was similar to their performance in the field, grown on an acid soil.

Increasing Al in solution culture or increasing Al saturation in soil decreased most of the observed growth parameter. The Al effect was less drastic on reduction

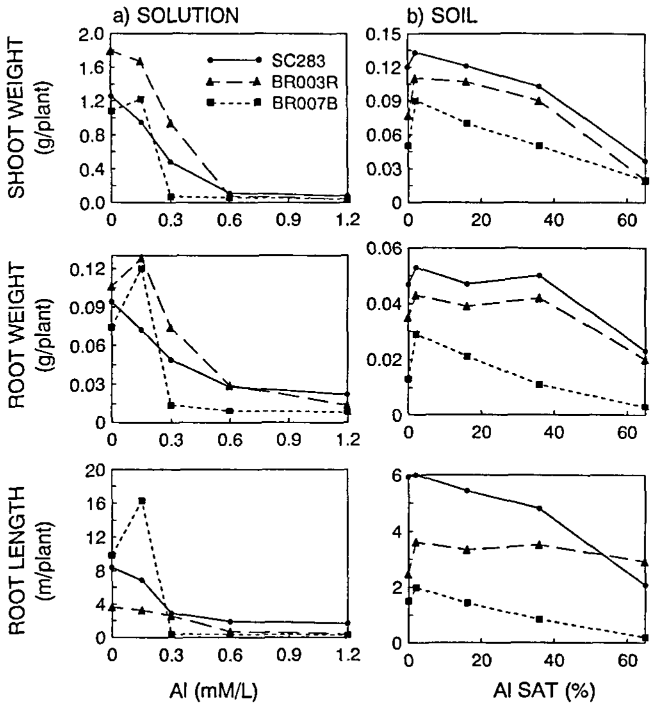

FIGURE 1. Plant growth parameters of sorghum genotypes as affected by aluminum in solution culture and soil experiments.

of growth parameters of the tolerant genotype SC283 (Figures 1 and 2). In contrast, all growth parameters of genotype BR007B, the sensitive one, and root weight of BR003R increased by increasing Al to 0.15 mmol/L in solution and about 5% Al saturation in soil. Further increase in Al toxicity, either in solution or in soil, sharply decreased their growth parameters. Stimulation of root growth by low levels of Al in these genotypes can be better observed in the RGR-root, and this is probably due to the increase of fine roots, resulting in higher total and specific root length (Figures 1 and 2).

Nutrient Uptake Parameters

Significant differences in Ca and P uptake, influx, NER, and percent inhibition of uptake were observed for genotypes and Al levels (Table 2). With a few exceptions, significant interaction effects for Al and genotypes were noted for P and

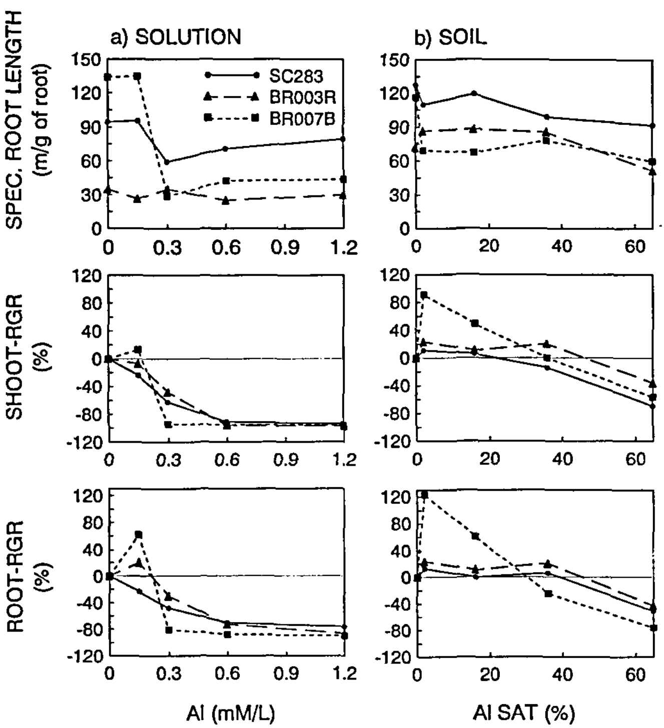

FIGURE 2. Specific root length and relative growth reduction (RGR) for shoot and root of sorghum genotypes as affected by aluminum in solution and soil experiments.

Ca nutrient uptake parameters. The Al uptake parameters followed similar significance as that of Ca uptake parameters.

The P and Ca uptake parameters declined in all genotypes with increasing Al levels in both the mediums (Figures 3 and 4).

Relation Between Solution and Soil Experiments

Significant correlations were found for shoot and root weight, uptake, and PI of P and Ca for genotypes grown in solution and soil culture medium (Table 3). However, such a relation for IN of P and Ca were nonsignificant.

With one exception in both growth mediums, the uptake and influx of Ca and P gave highiy significant positive correlation with shoot and root weight (Table 4).

TABLE 2. Analysis of variance for sorghum genotypes and aluminum treatments for nutrient parameters in solution culture and soil experiments.

Parameter	Genotypes		Aluminum		Gen vs. Al	
	Solution	Soil	Solution	Soil	Solution	Soil
Uptake						
P	**	**	**	**	*	NS
Ca	**	**	**	**	**	**
Al	**	**	**	**	**	**
Influx						
P	**	**	**	**	**	**
Ca	**	**	**	**	**	*
Al	**	ND	**	ND	**	ND
NER						
P	NS	**	**	**	*	**
Ca	**	**	**	**	**	**
Al	*	**	**	**	**	**
PI						
P	**	**	**	**	**	NS
Ca	**	**	**	**	**	*
Al	**	**	**	**	**	**

*, **Significant at $P < 0.05$ and 0.01, respectively.
[NS]Not significant at $P > 0.01$.
[ND]Not determined.

With a few exceptions, the NER and PI for Ca and P gave negative significant relations with shoot and root weight of genotypes grown in both growth mediums.

DISCUSSION

Stimulation in root growth, and consequently the increase in shoot growth and nutrient uptake in the presence of low concentrations of Al, in either soil or nutrient medium, has been reported in the literature (7,14). Even though the mechanism is not clear (7), possible explanations of the beneficial effects include the prevention of toxicity of other elements (Cu, Mn, and P) by Al and that Al may also serve as a fungicide against certain types of root rot (14).

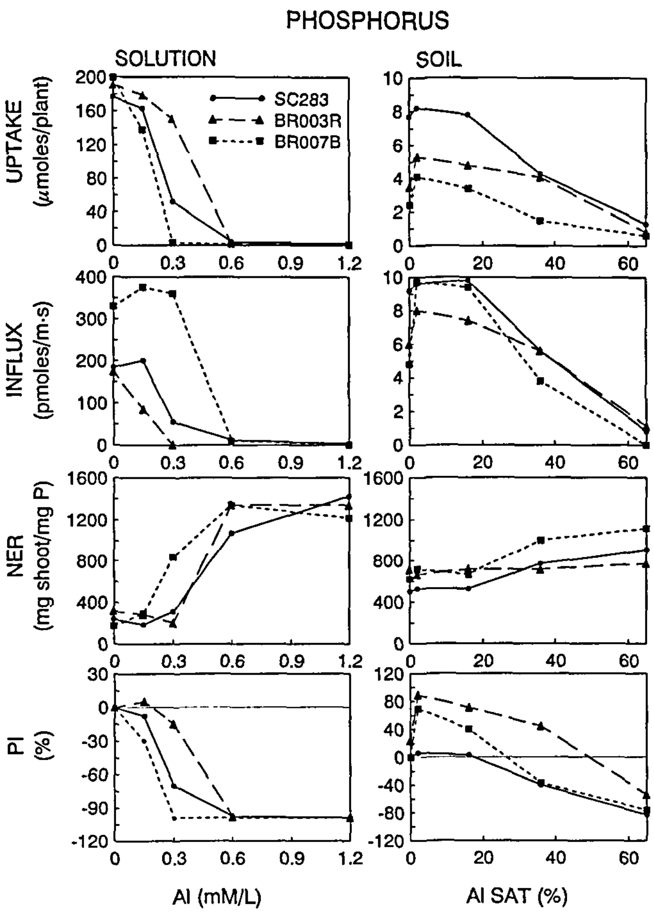

FIGURE 3. Phosphorus uptake influx; nutrient efficiency ratio, NER; percent inhibition of uptake, PI of sorghum genotypes as affected by aluminum in solution and soil experiments.

The reasons for the more similar performance of sorghum genotypes under Al stress in soil than in solution culture experiment when compared with the performance in the field (SC283 > BR003R > BR007B) can be attributed to one or more of the following possible causes: i) solution composition effects on the precipitation, polymerization, and activity of Al, and ii) the effects of specific ions

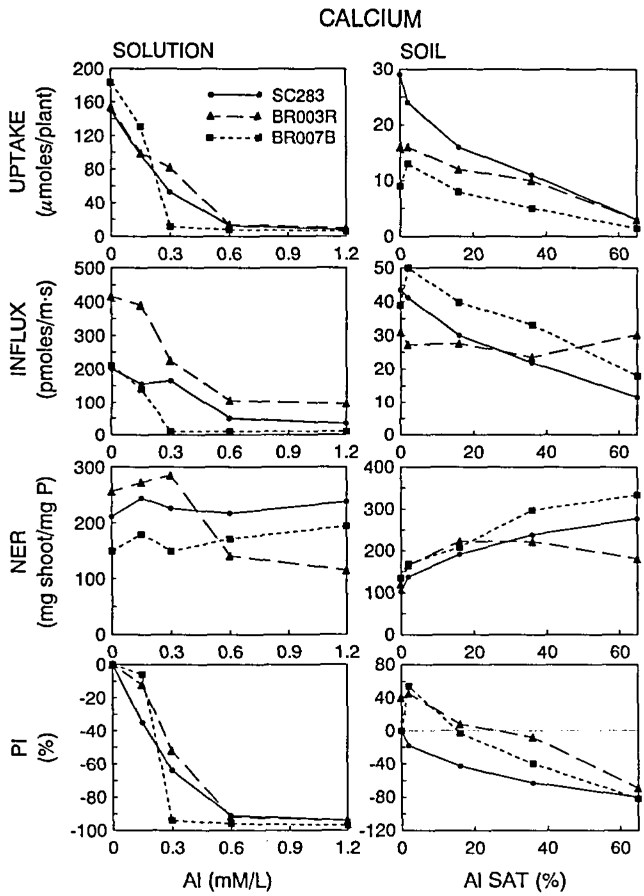

FIGURE 4. Calcium uptake influx; nutrient efficiency ratio, NER; percent inhibition of uptake, PI of sorghum genotypes as affected by aluminum in solution and soil experiments.

and ionic strength on root morphology and physiology (3) or that the tolerance of sorghum genotypes to Al stress in soil and nutrient solution involve different mechanisms as reported for alfalfa (4) and red clover (5). It would be expected, however, that the stimulation in plant growth and nutrient uptake due to low levels of Al would be mostly in the more tolerant genotypes (19). It was reported (15) that seven of the nine sorghum genotypes with better growth in presence of 100 mmoles

TABLE 3. Correlation coefficients for plant and nutrient uptake parameters of sorghum genotypes grown in solution culture versus soil experiments.

Parameters	Correlation coefficients (r)
Plant	
Shoot wt.	0.62**
Root wt.	0.62**
Uptake	
P	0.63**
Ca	0.68**
Influx	
P	0.19NS
Ca	0.24NS
NER	
P	0.49*
Ca	0.12NS
PI	
P	0.67**
Ca	0.87**

*,**Significant at P < 0.05 and 0.01, respectively.
[NS]Not significant at P > 0.05.

Al/L had their growth reduced by less than 20% in the presence of 440 mmoles Al/L.

Another possible reason for the differential growth response to the two media is the variation in the efficiency of nutrient uptake and use. Differences among sorghum genotypes in P and Ca uptake (Figures 3 and 4) are related to differential sorghum genotypes growth in both solution culture and soil media (significant correlation, see Tables 3 and 4).

Good agreement and significant correlation was found in comparisons involving growth and nutrient uptake parameters for sorghum genotypes grown in Al-stressed solution culture versus acidic field soils (10,12) and in greenhouse

TABLE 4. Correlation coefficients for growth versus nutrient uptake parameters of sorghum genotypes grown at different Al levles in solution and in soil.

Nutrient parameters	Shoot wt.		Root wt.	
	Solution	Soil	Solution	Soil
Uptake				
P	0.94**	0.96**	0.88**	0.80**
Ca	0.94**	0.87**	0.87**	0.71**
Influx				
P	0.87**	0.86**	0.78**	0.70**
Ca	0.89**	0.38*	0.77**	0.16NS
NER				
P	-0.74**	-0.62**	-0.71**	-0.50**
Ca	0.58**	-0.28*`	0.55**	-0.32**
PI				
P	-0.25NS	-0.98**	-0.21NS	-0.37**
Ca	-0.06NS	-0.31*	0.01NS	-0.23NS

*,**Significant at $P < 0.05$ and 0.01, respectively.
NS Not significant at $P > 0.05$.

versus field acidic soils (1,17). In our study, comparisons of such a parameters for sorghum genotypes grown in a wide range of Al-stressed culture solution and Al saturation in the soil gave some nonsignificant correlation coefficients (Table 3). Such differences are most probably because the genotypes used in this study might have affected differently, depending on Al level either in solution culture or in soil medium. Even considering that performance of plants can differ according with the medium (solution culture or soil), as reported for some plant species (4,5), and also considering other factors besides Al stress may be involved on plant genotypic performance, short-term laboratory techniques have been shown to be an important tool in breeding of sorghum for tolerance to Al (soil acidity) (1,10,17).

CONCLUSIONS

Aluminum/acid soil tolerance ranking of sorghum genotypes in solution/soil culture method was comparable to their ranking in field acid soil conditions.

Therefore, methods adapted here could be reliable screening techniques for selection of acid soil tolerant sorghum genotypes. Growth parameters, such as SRL, RGR, and percent inhibition of nutrient uptake for P and Ca, represent the best parameters for evaluating the plants in Al phytotoxic medium. Stimulatory effects of low levels of Al on sensitive genotype appears to be due to increase in root dry weight and branching of roots.

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