THE EFFECTS OF ALUMINUM ON GROWTH AND UPTAKE OF AL AND P BY RICE[1]

N.K. FAGERIA[2], V. C. BALIGAR[3] and R.J. WRIGHT[4]

ABSTRACT - Aluminum toxicity is an important factor limiting plant growth in acid soils. The effect of five Al levels (0, 371, 742, 1484, and 2226 μM) in nutrient solution on the growth and uptake of Al and P by two rice cultivars (Suvale 1 and IRGA 408) was studied. Aluminum reduced root and shoot growth in both cultivars, but the reduction was greater in IRGA 408. Aluminum uptake was increased with increasing levels of Al in the two cultivars. The effect was greater in the roots as compared to the shoots. The tolerant cultivar Suvale 1 absorbed more phosphorus to susceptible cultivar IRGA 408. The uptake and use efficiency of P was highly correlated with the growth of the rice plant. Toxic Al level in the nutrient solution were 260 μM for shoot growth and 280 μM for root growth, respectively.

Index terms: Al toxicity, nutrient solution, root growth, shoot growth.

EFEITO DO ALUMÍNIO NO CRESCIMENTO E ABSORÇÃO DE AL E P POR ARROZ

RESUMO - Toxidez de alumínio é um fator importante, que limita o crescimento das plantas em solos ácidos. Foi estudado o efeito de cinco níveis de Al (0, 371, 742, 1484 e 2226 μM) em solução nutritiva sobre o crescimento e absorção de Al e P pelas cultivares de arroz Suvale 1 e IRGA 408. O alumínio reduziu o crescimento das raízes e da parte aérea nas duas cultivares, mas a redução foi maior para a cultivar IRGA 408. A absorção de Al aumentou com o aumento de níveis de Al nas duas cultivares. O efeito foi maior nas raízes do que na parte aérea. A cultivar tolerante Suvale 1 absorve mais fósforo que a cultivar sensível IRGA 408. A absorção e a eficiência de utilização de P foram altamente correlacionadas com o crescimento das plantas. Os níveis tóxicos de Al em solução nutritiva foram de 260 μM para a parte aérea, e de 280 μM para as raízes.

Termos para indexação: toxidez de Al, solução nutritiva, crescimento da parte aérea, crescimento de raízes.

INTRODUCTION

Aluminum toxicity is most common on acid soils and reduces crop production. Several factors such as soil fertility level, organic matter content, soil texture, plant species and cultivar within species determine Al toxicity. Toxic level of Al in the growth medium reduces growth of roots and shoots. Reduction of root growth is related to the uptake of water and nutrients and consequently, crop yield.

Liming reduces Al toxicity in the plow layer, over a period of several years, in the subsoil as well. Work reported in the literature shows that plant species and genotypes within species differ widely in tolerance to Al toxicities (Fageria & Carvalho 1982, Foy et al. 1978). Until subsoil Al is reduced, the best practice for producing good crop yields in acid soils is the combination of liming and use of tolerant cultivars.

The objective of the present study was to determine effects of Al on growth and uptake of Al and P by two rice cultivars from Brazil.

[1] Accepted for publication on February 8, 1989.

[2] Eng. - Agr., Ph.D., EMBRAPA/Centro Nacional de Pesquisa de Arroz e Feijão (CNPAF), Caixa Postal 179, CEP 74000 Goiânia, GO.

[3] Soil Scientist, Ph.D., USDA-ARS, P.O. Box 867, Beckley, WV 25802 USA.

[4] Soil Scientist, Ph.D., USDA-ARS.

MATERIALS AND METHODS

A greenhouse experiment was conducted to study the influence of Al on growth and uptake of Al and P by two rice cultivars (*Oryza sativa* L. cv. Suvale 1 and IRGA 408). Seeds of the two cultivars were germinated in pure sand using 30 cm x 45 cm x 8 cm plastic trays. Eight to ten days after sowing, four uniform seedlings were transplanted to acrylic discs with holes in the center. The seedlings were held in place with cotton. These discs were then transferred to plastic pots containing 7.5 liters of nutrient solution. Each pot had three discs with four plants each.

With slight modifications, the solutions were based on those recommended by the International Rice Research Institute for rice. The nutrient solution had the following composition in μM: NH_4NO_3 2857; $NaH_2PO_4.H_2O$ 129; K_2SO_4 1023; $CaCl_2$ 1000; $MgSO_4.7\ H_2O$ 1645; $(NH_4)Mo_7O_{24}.4H_2O$ 0.5; $MnCl_2.4H_2O$ 9; H_3BO_3 18.5; Zn $SO_4.5H_2O$ 0.15; $CuSO_4$ 0.16; and $FeCl_3.6H_2O$ 36. Aluminum in amounts required for Al concentrations of 0, 371, 742, 1484, and 2226 μM was added as $AlCl_3$. The activities of each of the Al monomeric species were calculated by way of the GEOCHEM computer program (Sposito & Mattigod, 1980) and equilibrium constants reported by Lindsay (1979).

The nutrient solutions were changed once a week. The pH of the solution was adjusted to 4 ± 0.2 initially and every two days thereafter with 0.1M NaOH or 1.0 M HCl. The experimental designs was a randomized block with two replications. Maximum and minimum air temperature means during the experiment were 28°C ± 2°C and 18° ± 2°C, respectively.

After 20, 40, 60, and 80 days growth in Al treated solutions, plant tops and roots were harvested. Roots were rinsed thoroughly in distilled water and blotted dry. Roots and tops were dried to a constant weight at about 80°C. Plant analysis for Al and P was done simultaneously with a plasma emission spectrophotometer.

RESULTS AND DISCUSSION

In the presence of sulfate in solution, and over the pH range of four to six Al speciation can be represented by the following equation (Alva et al. 1986):

[Al monomeric] = $[Al^{3+}]$ + $[Al(OH)^{2+}]$ + $[Al(OH)_2^+]$ + $[Al(OH)_3^o]$ + $[Al(SO_4)^+]$. The calculated activities of Al monomers are presented in Table 1. The range in calculated activities of each of the Al monomers was 73.4 to 410.7 µM for Al^{3+}, 7.3 to 40.7 µM for $Al(OH)^{2+}$, 3.7 to 20.6 µM for $Al(OH)_2^+$, 0.07 to 0.41 µM for $Al(OH)_3^o$, and 125 to 495 µM for $ALSO_4^+$. The calculated values of Σ activities of monomeric Al species (Σa_{Almono}) in nutrient solution varied from 209.5 to 967.4 µM as a result of varying the concentration of Al at pH 4. The calculated activity of $ALSO_4^+$ was hihest followed by Al^{3+} activity. The activity of $Al(OH)_3^o$ was the lowest at all added Al concentrations.

Rice cultivar growth parameters as influenced by Al treatment at different growth stages are presented in Tables 2 and 3. All growth parameters were reduced at 742 µM or higher Al concentrations in the nutrient solution. At a low concentration (371 µM), there was a beneficial effect of Al. Howeler & Cadavid (1976), Thawornwong & Van (1974) also reported rice growth stimulation at low concentrations of Al in nutrient solution. Cultivar Suvale 1 produced more growth at all Al concentrations and at all growth stages compared to cultivar IRGA 408. Hence, Suvale 1 cultivar is more tolerant to Al than is cultivar IRGA 408. To identify which growth parameter is the most sensitive to Al toxicity, root length, plant height, and root and shoot weight

TABLE 1. Calculated activites of Al monomers in nutrient solution.

Added Al Conc.	$a_{Al^{3+}}$	$a_{Al(OH)^{2+}}$	$a_{Al(OH)_2^+}$	$a_{Al(OH)_3^o}$	$aAlSO_4^+$	Σa_{Almono}
			µM			
371	73.4	7.3	3.7	0.07	125	209.5
742	144.7	14.5	7.3	0.14	227	393.6
1484	279.4	27.8	14.1	0.28	384	705.6
2226	410.7	40.7	20.6	0.41	495	967.4

TABLE 2. Influence of Al on growth parameters of rice cultivars.

Al levels	Suvale 1				IRGA 408			
	Root length	Plant height	Root weight	Shoot weight	Root length	Plant height	Root weight	Shoot weight
µM	cm		g/4 plants		cm		g/4 plants	
0	29.87	64.75	1.98	22.61	26.75	48.25	1.15	6.85
371	31.75	65.75	2.13	23.05	28.50	46.12	1.31	10.45
742	27.12	61.25	1.53	16.72	24.50	44.50	0.95	7.62
1484	12.12	49.50	0.87	10.52	9.75	33.25	0.58	6.71
2226	9.12	37.75	0.28	4.37	8.12	26.63	0.21	2.56
LSD (P = 0.05)	0.81	2.57	0.09	0.83	1.01	1.25	0.08	0.54

Values in the table represent an average across 4 stages of plant growth.

TABLE 3. Growth parameters of rice cultivars as influenced by plant age.

Age in days	Suvale 1				IRGA 408			
	Root length	Plant height	Root weight	Shoot weight	Root length	Plant height	Root weight	Shoot weight
	cm		g/4 plants		cm		g/4 plants	
20	16.8	26.6	0.17	0.58	14.9	21.5	0.15	0.49
40	20.3	48.2	1.02	5.13	18.1	33.7	0.65	3.11
60	23.9	61.5	1.76	18.23	20.9	43.3	1.06	8.32
80	27.0	86.9	2.47	37.88	24.2	60.5	1.52	15.45
LSD (P = 0.05)	0.92	1.55	0.04	0.43	0.67	1.48	0.05	0.41

Values in the table represent an average across 5 levels of Al.

reduction were calculated at highest Al level in comparison to maximum growth (Table 4). Root and shoot weight parameters were more sensitive to Al-toxicity than were root length and plant height. Plant height was the least sensitive. Generally, root length is used as a parameter to evaluate Al toxicity of crop genotypes. These results suggest that root or shoot weight can better be used for this purpose and are easier to measure than root lengths. The critical toxic Al level in the solution was 260 μM for shoot growth and 280 μM for root growth for the tolerant cultivar Suvale (Fig. 1). This critical level corresponds to 90% of maximum yield.

TABLE 4. The effect of high Al elevels on growth parameters of two rice cultivars.

Cultivar	Root length	Plant height	Root weight	Shoot weight
Suvale 1	71	43	87	81
IRGA 408	72	45	84	76

$$\text{Yield reduction} = \frac{\text{Maximum yield - yield of highest Al level}}{\text{Maximum yield}} \text{X100}$$

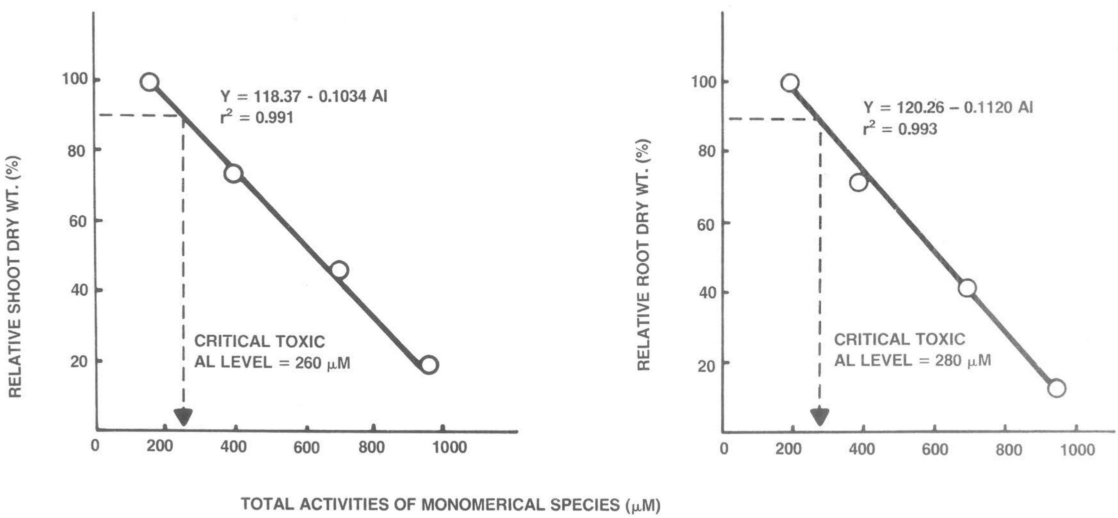

FIG. 1. Relative dry weight of shoot and root as influenced by total activities of Al monomerical species.

Aluminum concentrations in the two rice cultivars at all growth stages were increased with increasing levels of Al in the growth medium as expected and were higher in roots as compared to shoots. Aluminum content (dry matter x concentration) was higher in shoots as compared to roots at all stages of plant growth. This was related to the greater dry matter production of shoots. Aluminum tolerant cultivar Suvale had higher Al concentrations in the roots compared to the susceptible cultivar IRGA 408 especially at higher Al levels (Table 5).

Phosphorus uptakes under different levels of Al and at different stages of plant growth are presented in Table 6. Over time, phosphorus was increased by 371 μM Al, but was significantly reduced by higher Al applications. This was especially true at high levels of Al in the roots as well as shoots at all stages

TABLE 5. Aluminum concentration and uptake by shoot and root of 2 rice cultivars at different Al levels and stages of growth.

Al levels	Suvale 1				IRGA 408			
	Al conc.	Al uptake	Al conc.	Al uptake	Al conc.	Al uptake	Al conc.	Al uptake
μM	μg.g^{-1}	mg/4 plants	μg.g^{-1}	mg/4 plants	μg.g^{-1}	mg/4 plants	μg.g^{-1}	mg/4 plants
	Shoot		Root		Shoot		Root	
20 days								
0	193	0.16	578	0.11	282	0.18	755	0.16
371	302	0.24	1125	0.31	338	0.24	1326	0.28
742	629	0.40	2605	0.41	783	0.43	2180	0.29
1484	2018	0.81	3233	0.41	1170	0.42	2605	0.26
2226	2353	0.54	3520	0.35	2383	0.41	3256	0.26
LSD (0.05)	6.08	0.08	20.19	0.07	20.84	0.09	30.93	0.06
40 days								
0	257	1.83	255	0.49	266	1.09	615	0.69
371	440	3.66	1785	2.61	407	1.97	1670	1.77
742	568	2.99	4095	4.29	687	1.89	2814	1.46
1484	1026	3.51	5871	3.09	759	1.68	4700	1.53
2226	2071	3.24	4950	0.69	1475	2.13	4830	0.56
LSD (0.05)	7.49	0.40	21.51	0.42	24.88	0.51	24.60	0.63
60 days								
0	605	11.88	534	1.33	618	4.81	1055	1.24
371	701	21.11	1680	4.11	633	7.44	1911	3.29
742	828	16.97	3085	6.92	857	9.08	3175	4.36
1484	946	14.96	3964	5.15	1255	10.33	3730	2.89
2226	2160	11.01	4063	1.32	2089	6.79	4100	1.03
LSD (0.05)	17.62	0.84	20.19	0.49	45.21	1.24	18.89	0.21
80 days								
0	527	33.07	610	2.02	501	7.46	704	1.48
371	574	30.42	1527	6.65	725	17.76	1760	4.01
742	731	29.61	3234	8.56	800	13.28	3645	6.49
1484	1041	23.42	5450	8.45	833	13.17	3875	4.16
2226	2479	26.28	5695	2.91	1180	6.33	3938	1.62
LSD (0.05)	7.84	2.79	19.12	0.51	17.07	1.24	92.39	0.43

of plant growth. Phosphorus content in the roots as well as shoots was higher in the Al tolerant cultivar Suvale 1 as compared to the Al susceptible cultivar IRGA 408. These results suggest that Al tolerance is related to P nutrition.

Coefficients for correlations between growth parameters of the rice cultivar Suvale 1 and uptake of Al and P are presented in Table 7. All growth parameters were positively correlated but highest correlation was obtained between shoot weight and plant height and shoot weight and root weight. Aluminum concentrations in roots and shoots were negatively correlated with all growth parameters. Phosphorus uptake in roots and shoots were highly correlated with root length, plant height, root and shoot weight.

TABLE 6. Phosphorus concentration and uptake by shoots and roots of 2 rice cultivars at different Al levels and stages of growth.

Al levels	Suvale 1				IRGA 408			
	P conc.	P uptake	P conc.	P uptake	P conc.	P uptake	P conc.	P uptake
μM	μg.g^{-1}	mg/4 plants	μg.g^{-1}	mg/4 plants	μg.g^{-1}	mg/4 plants	μg.g^{-1}	mg/4 plants
	Shoot		Root		Shoot		Root	
20 days								
0	9200	7.55	8650	1.70	8300	5.62	9100	1.91
371	8100	6.68	4300	1.16	7100	4.91	4500	0.92
742	8250	5.16	6500	1.01	5700	3.34	4100	0.56
1484	4300	1.72	3500	0.44	4200	1.52	3500	0.35
2226	2200	0.51	1700	0.17	2800	0.47	1900	0.13
LSD (P = 0.05)	293.09	0.61	634.89	0.45	689.76	0.53	325.16	0.41
40 days								
0	5000	35.25	3100	6.02	5200	21.45	3500	3.93
371	4200	34.81	4300	5.83	3800	18.45	4200	4.20
742	3000	12.19	4100	4.31	3100	8.55	3400	1.75
1484	1800	6.17	2500	1.315	1900	4.47	2000	0.82
2226	1900	2.96	2400	0.34	1900	2.76	2500	0.29
LSD (0.05)	229.92	5.68	281.59	1.38	430.14	2.63	745.03	0.20
60 days								
0	4000	78.64	4200	10.42	4700	36.40	7600	8.93
371	4200	126.41	4800	11.79	4200	49.37	7800	13.46
742	2800	57.35	4300	9.68	3100	32.92	6100	8.37
1484	2100	33.21	4400	5.41	2200	18.08	4400	3.42
2226	2200	11.23	2400	0.79	2300	7.45	2700	0.68
LSD (0.05)	325.16	5.38	281.59	0.86	363.54	6.03	860.28	1.02
80 days								
0	4600	288.93	4200	13.86	5000	67.33	5600	11.77
371	4200	222.60	4700	20.46	4400	107.60	7300	16.61
742	2600	101.20	4200	11.08	2700	44.64	5100	9.07
1484	2300	51.80	4000	6.20	2600	41.37	5200	5.53
2226	2100	22.26	2700	1.38	2300	12.27	3300	1.35
LSD (0.05)	229.92	16.64	708.66	2.56	947.98	20.83	1114.6	1.33

TABLE 7. Simple correlations between shoot and root growth and uptake of Al and P by cultivar Suvale 1.

Variables	Root length	Plant height	Root weight	Shoot weight
Root length	1.00			
Plant height	0.72**	1.00		
Root weight	0.83**	0.91**	1.00	
Shoot weight	0.68**	0.90**	0.91**	1.00
AICS	-0.77**	-0.38*	-0.47**	-0.31NS
AIUS	0.45**	0.88**	0.74**	0.88**
AICR	-0.69**	-0.19 NS	-0.42**	-0.28 NS
AIUR	0.34*	0.71**	0.58**	0.57**
PCS	0.34*	-0.22 NS	-0.11 NS	-0.13 NS
PUS	0.69**	0.81**	0.87**	0.96**
PCR	0.47**	0.09 NS	0.11 NS	0.10 NS
PUR	0.83**	0.88**	0.98**	0.90**
ER-AIR	-0.69**	-0.19 NS	-0.42 NS	-0.28 NS
ER-PR	0.46**	0.08 NS	0.10 NS	0.09 NS
ER-AIS	-0.77**	-0.37*	-0.48**	-0.31 NS
ER-PS	0.33*	-0.22 NS	-0.11 NS	-0.13 NS

AICS = Al concentration in shoot, AIUS = Al uptake by shoot, AIUR = Al uptake by root, PUS = P uptake by Shoot, PCR = P concentration in root, PUR = P uptake by root, AICR = Al concentration in root, ER-AIR = Efficiency ratio of Al in Root, ER-PR = Efficiency ratio of P in root.

Efficiency ratio (ER) = mg dry matter produced/mg of element absorbed.

Uptake = nutrient concentration x dry wt. of shoot or root.

NS = Not significant.

*, ** Significant at the 5 and 1% level of probability, respectively.

CONCLUSIONS

1. The cultivar Suvale 1 was more tolerant of Al toxicity than the cultivar IRGA 408.

2. Shoot and root weight are more susceptible to Al toxicity than plant height and root length.

3. Phosphorus uptake is greater in the tolerant cultivar.

4. Critical toxicity level in nutrient solution was established as 260 μM for shoot growth and 280 μM for root growth for the tolerant cultivar Suvale 1.

5. Aluminum inhibits uptake of P in the root as well as the shoot.

REFERENCES

ALVA, A.K.; EDWARDS, D.G.; ASHER, C.J.; BLAMEY, F.P.C. Effects of phosphorus/aluminum molar ratio and calcium concentrations on plant response to aluminum toxicity. **Soil Sci. Soc. Am. J., 50**:133-7, 1986.

FAGERIA, N.K. & CARVALHO, J.R.P. Influence of aluminum in nutrient solutions on chemical composition in upland rice cultivars. **Plant Soil, 69**:31-44, 1982.

FOY, C.D.; CHANEY, R.L.; WHITE, M.C. The physiology of metal toxicities in plants. **Ann. Rev. Plant Physiol., 29**:511-66, 1978.

HOWELER, R. & CADAVID, L.F. Screening of rice cultivas for tolerance to Al toxicity in nutrient solutions as compared with a field screening method. **Agron. J., 68**:551-5, 1976.

LINDSAY, W.L. **Chemical equilibrium in soils.** New York, John Wiley and Sons, 1979.

SPOSITO, G. & MATTIGOD, S.V. **GEOCHEM:** A computer program for the calculation of chemical equilibrium in soil solution and other natural water systems. Riverside, Kearney Foundation of Soil Science, University of California, 1980.

THAWORNIWONG, N. & VAN, D.A. Influence of high acidity and aluminum on the growth of lowland rice. **Plant Soil, 41**:141-59, 1974.