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EFFECT OF ALUMINUM ON GROWTH AND MINERAL ELEMENTS OF Al-TOLERANT AND Al-INTOLERANT CORN*

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SUMMARY

Growth and P, K, Ca, Mg, Mn, Zn, Fe, and Cu concentrations and contents were determined in Al-tolerant and Al-intolerant corn (*Zea mays* L.) inbreds when grown at various levels of Al. B57 was more tolerant to Al than was Oh40B. Relatively low Al levels (up to 5 mg/l) enhanced B57 growth but inhibited Oh40B growth. With few exceptions, Oh40B root and leaf concentrations of the elements decreased with added Al. The decreases in element concentrations were not as large for B57 as they were for Oh40B. The Mg concentrations and contents decreased more than the other elements in all inbreds with added Al. Root Mg decreased more than leaf Mg. Total uptake of some elements were higher at low Al than with no Al. Inasmuch as Mg has a pronounced effect on root growth, low Mg may be an important response in plants sensitive to Al.

INTRODUCTION

The growth and uptake and accumulation of mineral elements are altered extensively in plants grown with Al. Reduced P and Ca uptake are most commonly reported with Al toxicity, but reduced uptake of other mineral elements have been reported. Many of the specific effects of Al on mineral element uptake and utilization have recently been reviewed[3 8]. Growth of plants is usually reduced when grown with Al, however, beneficial effects of low Al on growth have been reported[1 11 12]. Interactions of Al with other mineral elements have been suggested as factors affecting both beneficial[11] and in-

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hibitory effects of Al[8]. Plant growth is reduced when essential mineral elements become limited or are in excess, and deficiencies of certain elements inhibit top growth more than root growth and vice versa[4].

In earlier studies[5 6] differential responses of corn inbreds to Mg and P were noted. The more P-efficient inbred Pa36 was found to be more tolerant to Al than the P-inefficient inbred WH[6] and the more Mg-efficient inbred B57 has been found to be more tolerant to Al

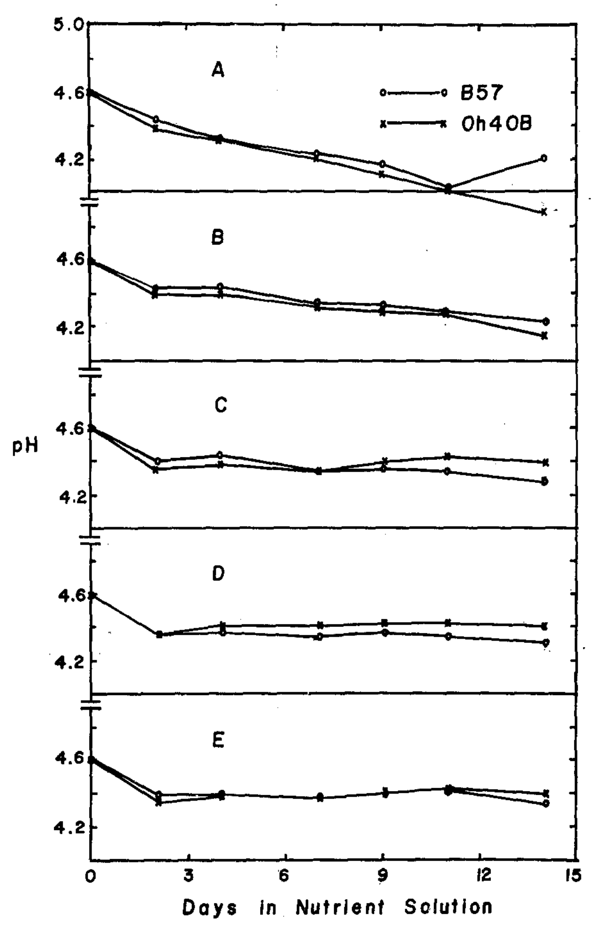

Fig. 1. pH of nutrient solutions with time of B57 and Oh40B corn inbreds grown at various levels of Al. (Levels of Al in solution were **A** 0, **B** 2.5, **C** 5, **D** 10, **E** 20 mg/l).

than Mg-inefficient inbred Oh40B. The objective of this study was to determine the effects of Al on the growth and uptake and accumulation of mineral elements by corn inbreds which showed differential responses to P and Mg.

MATERIALS AND METHODS

Corn (*Zea mays* L.) inbred seed was germinated and seedlings grown in dilute nutrient solutions as described elsewhere[5 6]. Four 7-day-old seedlings were transferred to 17-liter pots containing full-strength nutrient solutions with Al treatments added. Plants were grown for 14 days before they were harvested. Full-strength nutrient solutions consisted of (m*M*): 2.50 Ca, 1.74 K, 0.62 Mg, 6.50 NO_3–N, 0.93 NH_4–N, 0.42 Cl, 0.50 S, 0.065 P, 0.018 B, 0.0066 Mn, 0.0017 Zn, 0.0006 Mo, 0.0005 Cu and 0.036 Fe as FeHEDTA (ferric hydroxyethylenediaminetriacetate). Aluminum as $AlK(SO_4)_2$ was added at 0, 2.5, 5, 10, and 20 mg Al/l. The nutrient solutions were adjusted to pH 4.6 initially to ensure that Al would be toxic. The pH was not adjusted as plants grew, but was recorded regularly (Fig. 1). Experiments were conducted twice and the results were similar. At harvest, plants were thoroughly water-rinsed, blotted dry, separated into tops and roots, dried at 70°C, weighed, ground to pass a 20-mesh stainless-steel screen, and analyzed for P, K, Ca, Mg, Mn, Fe, Cu, Zn, and Al by an emission spectrograph. In addition, Mg was determined by atomic absorption on HNO_3-digested subsamples because in many samples, Mg was too low for accurate analysis by the spectrograph.

RESULTS AND DISCUSSION

Inasmuch as the responses and mineral element concentrations and contents of B57 were similar to those of Pa36 and results of Oh40B were similar to those of WH, only the data for B57 and Oh40B are reported here. The corn inbreds grew well in nutrient solutions, but Al greatly inhibited their growth, especially the roots (Fig. 2). Leaves of plants grown with Al at inhibitory levels became spindly and brittle, were deep purplish-red and had P-deficiency symptoms. The leaves of Oh40B plants grown at high Al (10 and 20 mg/l) also had Mg-deficiency symptoms. Roots of plants grown at high Al became stubby, thick, coralloid, brittle, and brown. Aluminum-injured root systems initiated more adventitious roots and fibrous roots developed less than did normal root systems. The adventitious roots that initiated did not elongate.

B57 was more tolerant to Al than Oh40B (Fig. 2). Higher Al levels were required to inhibit top and root growth of B57 than of Oh40B

Fig. 2. B57 and Oh40B corn roots grown at (*left to right*) 20, 10, 5, 2.5, and 0 mg Al/l (2 mg P/l).

(Fig. 3). At 2.5 mg Al/l, B57 tops and roots produced more dry matter than when grown with no added Al. In contrast, dry-matter yields of Oh40B decreased at all Al levels. Dry-matter yields were not decreased for B57 unless Al in solution was greater than 5 mg/l. Although B57 roots grown at the lower Al levels showed some stubbiness, their dry-matter yields increased.

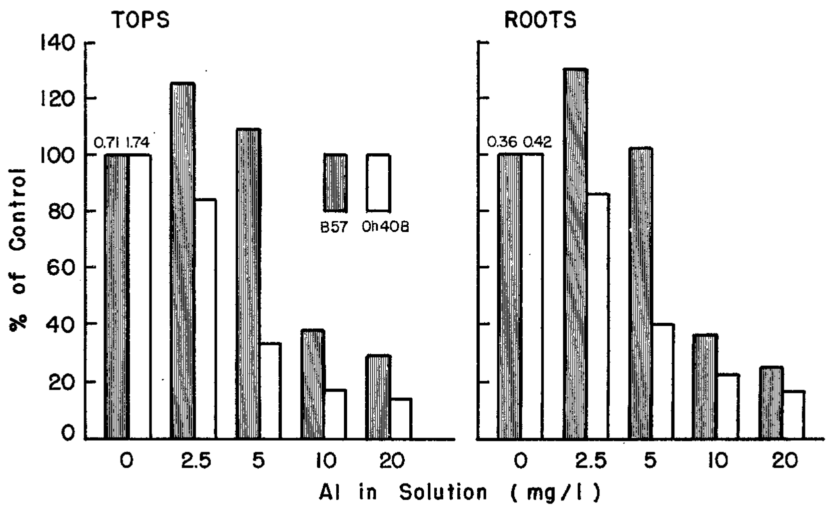

Fig. 3. Dry-matter yields of B57 and Oh40B tops and roots grown at five levels of Al. Numbers above the bars are dry weights at 0 mg Al/l. (LSD .05 for tops = 16%, and roots = 19%.)

Reasons for the enhanced effect of Al on plant growth of B57 are not clear. Similar effects were noted for the corn inbred Pa36 and for other plants[1 12] and roots were affected more than tops[12]. Beneficial effects of Al have been attributed to the displacement of Fe on bound sites to overcome Fe distribution and to increased Fe solubility and availability[11], and to decreased growth of harmful microorganisms that may otherwise grow in association with roots[15]. Beneficial effects of small amounts of Al on plant growth may also be due to inactivation of P. Phosphorus inhibits growth of some plants[2 9 10]. Phosphorus was inhibitory to corn roots grown in nutrient solutions at 2 to 4 mg P/l[6]. A small amount of Al could possibly inactivate enough P to reduce some of the P inhibitory effects on root growth. Root growth benefited more from low Al than did the tops[12] (Fig. 3).

The pH of nutrient solutions in which B57 and Oh40B were grown decreased slightly with time (Fig. 1). The pH remained near 4.2 to 4.4 for both inbreds and at pH values where Al is readily soluble and should have pronounced effects on plant growth[14]. No differences in pH were noted between B57 and Oh40B.

Only small amounts of Al were translocated from the roots to the tops (Table 1). Leaf Al concentrations increased gradually as Al in solution increased. Roots contained a relatively high Al concentration even at low levels of Al in solution. Root Al concentrations increased slightly as solution Al increased but not in proportion to the amount of Al added to the solutions. Aluminum has been located in cell walls and in the free space of barley roots[7], and noted as an Al-phosphate complex in mucilaginous layers on root surfaces and in intercellular regions of root tips[13]. In addition, very little Al pass-

TABLE 1

Concentrations of Al (μg/g) in corn inbreds grown in nutrient solutions at five levels of Al (mg/l)

Al level	Tops		Roots	
	B57	Oh40B	B57	Oh40B
0	29	30	107	116
2.5	59	38	2220	2150
5	86	142	2550	2470
10	146	163	2580	2500
20	208	282	2820	2730

TABLE 2

Concentrations of Mg, P, Ca, and K (% of control) in B57 and Oh40B tops and roots of plants grown at five levels of Al (mg/l)

Al level	Mg		P		Ca		K	
	B57	Oh40B	B57	Oh40B	B57	Oh40B	B57	Oh40B
Tops								
0	100	100	100	100	100	100	100	100
2.5	62	54	114	86	77	54	113	90
5	53	42	109	47	86	46	116	58
10	61	32	79	48	75	43	78	53
20	44	25	84	49	43	34	76	51
LSD .05	17		14		17		11	
Control (%)	0.348	0.252	0.86	1.16	0.65	0.82	4.17	5.46
Roots								
0	100	100	100	100	100	100	100	100
2.5	76	41	133	113	133	89	126	86
5	34	18	112	93	100	50	128	58
10	34	7	83	76	117	67	89	55
20	18	2	90	76	108	56	89	40
LSD .05	12		22		28		9	
Control (%)	0.119	0.310	0.96	0.92	0.12	0.18	3.32	5.04

ed beyond the cortical cells of intact corn roots[16]. The Al tolerance of these corn inbreds did not appear to be directly related to Al concentration in the tops or roots.

Tables 2 and 3 show concentrations of Mg, P, Ca, K, Mn, Zn, Fe, and Cu in B57 and Oh40B plants grown at various Al levels. With no added Al, Oh40B tops contained higher concentrations of P, Ca, K, Mn, and Zn and lower concentrations of Mg and Cu than did B57 tops. Oh40B roots also contained higher concentrations of Mg, Ca, K, Mn, and Zn and lower concentrations of Fe and Cu than B57 roots with no added Al. Root P concentrations and leaf Fe concentrations were similar for both inbreds. Except for Fe, concentrations of the mineral elements in tops and roots of Oh40B decreased as Al in solution increased. Iron in tops of both inbreds decreased at the low Al levels but increased at the higher levels. In roots of B57, Fe concentrations remained constant but in roots of Oh40B, Fe in-

TABLE 3

Concentrations of Fe, Mn, Zn, and Cu (% of control) in B57 and Oh40B tops and roots of plants grown at five levels of Al (mg/l)

Al level	Fe		Mn		Zn		Cu	
	B57	Oh40B	B57	Oh40B	B57	Oh40B	B57	Oh40B
Tops								
0	100	100	100	100	100	100	100	100
2.5	85	67	82	32	92	40	100	71
5	88	87	77	24	100	39	89	64
10	130	103	86	28	104	41	89	64
	127	112	68	28	104	43	89	64
LSD .05	30		11		12		11	
Control (µg/g)	172	190	22	50	24	70	9	14
Roots								
0	100	100	100	100	100	100	100	100
2.5	106	183	89	74	86	70	83	81
5	104	203	78	26	76	52	75	75
10	92	210	78	33	68	66	75	61
20	96	193	78	28	72	42	75	56
LSD .05	22		33		20		20	
Control (µg/g)	776	399	9	46	50	77	12	16

creased twofold as Al in solution increased. Magnesium and Ca concentrations of B57 tops and Mg concentrations of B57 roots decreased significantly as Al concentration in solution increased. Both Mn and Zn concentrations in Oh40B tops decreased markedly with small additions of Al. Overall, Mg concentrations in both tops and roots of Oh40B and B57 decreased the most of any element with added Al. Decreases were greater for roots than for tops. At 20 mg Al/l, the Mg concentration in Oh40B roots was only 2% and in B57 roots it was 18% that of roots grown without Al.

Contents of the eight elements in Oh40B tops and roots decreased markedly when Al was added to solutions (Table 4 and 5). Only the Fe content in Oh40B roots increased above that of plants grown without Al. Except for Mg, mineral contents generally decreased more in tops than in roots. Except for P and Fe, mineral contents in Oh40B tops and roots at 5 mg Al/l was less than 20% that of plants grown without Al. In contrast, mineral contents in B57 tops and

TABLE 4

Contents of Mg, P, Ca, and K (% of control) in B57 and Oh40B tops and roots of plants grown at five levels of Al (mg/l)

Al level	Mg		P		Ca		K	
	B57	Oh40B	B57	Oh40B	B57	Oh40B	B57	Oh40B
Tops								
0	100	100	100	100	100	100	100	100
2.5	77	45	142	72	96	45	141	76
5	58	14	119	16	94	15	127	19
10	23	5	30	8	36	7	30	9
20	13	4	24	7	12	5	22	7
LSD .05	14		10		11		10	
Control (mg/ plant)	2.47	4.37	6.11	20.13	4.62	14.23	29.6	94.7
Roots								
0	100	100	100	100	100	100	100	100
2.5	100	35	174	98	173	76	164	75
5	34	7	115	37	103	20	131	23
10	12	2	30	33	42	15	32	12
20	5	<1	22	13	27	9	22	7
LSD .05	10		17		16		13	
Control (mg/ plant)	0.43	1.29	3.49	3.82	0.44	0.75	12.1	20.9

roots (except Mg) increased or showed only slight decreases until solution levels of Al were greater than 5 mg/l. Magnesium contents decreased in B57 tops as the solution Al increased and in B57 roots at Al levels above 2.5 mg/l. With few exceptions, Oh40B mineral contents decreased more than did B57 contents.

Even though Al inhibited the uptake and accumulation of all mineral elements, Mg and Mn concentrations and contents decreased more than those of any of the other mineral elements as Al increased in solution. One of the most distinguishing symptoms of Al toxicity is the marked reduction in root growth. Inasmuch as Mg has a marked effect on root growth[5], one of the major Al toxicity effects may be to decrease Mg uptake and utilization. Even though calcium and P concentrations and contents were relatively high in Al-affected roots, concentrations of these elements seemed adequate to maintain good

TABLE 5

Contents of Fe, Mn, Zn, and Cu (% of control) in B57 and Oh40B tops and roots of plants grown at five levels of Al (mg/l)

Al level	Fe		Mn		Zn		Cu	
	B57	Oh40B	B57	Oh40B	B57	Oh40B	B57	Oh40B
Tops								
0	100	100	100	100	100	100	100	100
2.5	107	56	102	27	115	34	125	60
5	96	29	85	8	109	13	97	21
10	50	18	33	5	40	7	34	11
20	20	16	20	4	30	6	25	9
LSD .05	10		10		11		10	
Control (µg/ plant)	122	330	15.6	86.8	17.0	121.4	6.4	24.3
Roots								
0	100	100	100	100	100	100	100	100
2.5	138	137	115	64	112	61	108	65
5	106	81	79	10	78	21	77	22
10	33	45	27	7	25	14	27	18
20	24	32	18	5	18	7	19	9
LSD .05	19		17		14		14	
Control (µg/ plant)	282	166	3.3	19.1	18.2	32.0	4.37	6.64

growth. However, the amount available for plant use was not known. In this study, Mg decreased more than Ca and P in both tops and roots of young corn plants grown with Al. The Mg-inefficient inbred Oh40B was also more sensitive to Al than the Mg-efficient inbred B57. These results suggest that even though Ca and P deficiencies are commonly reported as symptoms of Al toxicity, Mg may also be closely associated with Al toxicity, especially in roots.

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