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THE EFFECT OF ALUMINIUM UPON THE GROWTH AND NUTRIENT COMPOSITION OF OATS (*AVENA SATIVA* L.)

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Oat seedlings were grown in nutrient solution to study the effect of aluminium on plant growth and mineral nutrition. Aluminium toxicity resulted in abnormal root development with many short thick roots. Chlorosis on the young leaves of Al-toxic plants appeared when iron was applied as ferric iron. It was suggested that this was due to interference in Fe^{3+} reduction to Fe^{2+} by aluminium. Iron concentration in young plant leaves in aluminium-toxic plants was not affected by iron source (Fe^{2+} or Fe^{3+}). Experiments with ferrous iron source revealed that aluminium has no clearly apparent interference with Fe^{2+} utilization.

The dry matter yield of oat tops and roots decreased progressively with an increase in Al-levels. The concentration of P was greater in roots of Al-toxic plants than control plants but a converse effect was recorded in tops. The overall uptake as well as utilization and translocation of P was affected in Al-treated plants.

The concentration of P, K, Ca, Mg and Mn substantially decreased in plant tops with increased Al levels, while the concentration of Al and Zn increased in plant tops and roots.

INTRODUCTION

Numerous research workers have reported the effects of soluble-Al on dry matter production [8,10,11,15,19,21, 22,28,38], root production [2,7,23,34] and nutrient accumulation of the tops of various plant species [6,9,16,17,31, 39].

Aluminium in soluble or ionic form restricts the root development of many agronomic plants, thereby reducing the yields [29,36,37]. Roots are usually first affected when plants are exposed to toxic aluminium levels with damage to the tops occurring latter. The roots generally develop a brownish cast and lose turgidity. Main roots fail to elongate rapidly and become thick, swollen and distorted.

Aluminium toxicity in several plant species is associated with P deficiency [13,18,24]. Phosphorus-deficiency is often a prominent symptom of Al-toxicity of plants grown in acid soils or in nutrient solution [9]. The symptoms are, abnormally dark green leaves and a purpling of stems and leaf veins.

Aluminium has been shown to inhibit plant uptake of Ca [10,25] and Mg [25]. Aluminium and phosphate have been found to accumulate in the roots of various plant species [5,32,36]. In roots of sainfoin, Rorison [35] found Fe uptake to be depressed by Al. Otsuka [30] reported that Al induced an Fe-deficiency chlorosis in wheat and barley varieties which are sensitive to acid soils. Lee [22] found that Al inhibited the transport of P to potato plant tops, decreased the absorption of Ca, Mg and Zn by roots and caused the accumulation of P, Al, Mn, Cu and Fe in plant roots. The objective of this work was to study further the effects of variable levels of Al on the growth and mineral composition of oats (*Avena sativa* L.) using nutrient solution.

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MATERIALS AND METHODS

Oat seeds, no. 56183, were soaked overnight in aerated tap water. The seeds were then placed in a tray and kept in the dark for a few days. When the seeds had germinated, the tray was placed into a green house.

Experiment 1. Ten-day old oat seedlings grown in a tray were transplanted at the rate of 3 seedlings per pot containing 300 ml nutrient solution. The nutrient solution was ½ strength and its pH was 4.9. The plants were grown in a green-house in natural, unsupplemented light. The composition of the nutrient solutions is listed in Table 1.

Plants were grown for 10 days in ½ strength nutrient solution and then for 4 days in full strength solution. Aluminium was added to the culture solution at the levels 0.0, 0.2, and 0.6 mM as $Al_2(SO_4)_3$. Each treatment was replicated four times. The culture solution was changed after every third day, and after 14 days of treatment the plants were harvested, tops and roots washed, and dried for

Table 1. The composition of nutrient solution.

Element	Level (mM)	Salt used
Nitrogen	10.0	NH_4NO_3
Potassium	2.0	K_2SO_4
Calcium	1.5	$CaCl_2.6H_2O$
Phosphorus	1.0	KH_3PO_4
Magnesium	1.0	$MgSO_4.7H_2O$
Sulphur	1.0	The above salts
Iron	0.1	Fe-EDTA
Boron	0.03	H_3BO_3
Manganese	0.01	$MnSO_4.H_2O$
Copper	0.001	$Cu\ SO_4.5H_2O$
Zinc	0.001	$ZnSO_4.7H_2O$
Molybdenum	0.0002	$(NH_4)_6MO_7O_{24}.4H_2O$

48 hr at 75°. Total P, Ca, K, Mg, Fe, Mn, Cu, Zn and Al were determined from different plant parts.

Total P was determined colorimetrically [14] and Al was determined by aluminon reagent [4]. Ca, K and Mg were determined flame-photometrically on diluted aliquots of the digest, and Fe, Mn, Zn and Cu were read out directly from the digest using an EEL atomic absorption spectrophotometer.

Experiment 2. A second set of oat seedlings was grown in pots containing 300 ml of ½ strength nutrient solution. They were then allowed to grow as before. Al levels 0.0, 0.2 and 0.6 mM were added and after two weeks the plants were harvested. Symptoms were observed as in the first experiment.

Experiment 3. This experiment was set up to study the content of elements in the youngest and 4th leaf of chlorotic and nonchlorotic plants. Oat seedlings were grown in 8 pots for 14 days in ½ stregneth solution. Then 4 pots were treated with 0.6 mM Al solution and another 4 were kept as control pots. The plants were grown for 14 days. At the end of the experiment the youngest and 4th leaf were collected from each pot. The leaves and roots were washed, dried and then divided into duplicate samples. Total P, Fe, Mn, and Al were determined from plant parts.

Experiment 4. Oat seedlings were grown in 20 pots for 10 days in ½ strength solution and then grown for 6 days in solution without P. The following treatment were given to four pots of each treatment: plus P minus Al, plus P plus Al (0.6 mM), plus P, plus higher Mn (0.02 mM) minus Al, plus P plus higher Mn (0.02 mM) plus Al (0.6 mM), and minus P minus Al. Plants were grown for 14 days after treatment applications. Visual observations were noted, plant harvested, tops and roots washed and dried. Total P, Fe, Mn and Al were determined from plant parts.

Experiment 5. This experiment was designed to study the effect of Al on growth and mineral content in the presence of $FeSO_4$ and a low level of P (0.33 mM). Oat seedlings were grown for 14 days in ½ strength solution; afterwards similar treatments were given to 4 pots each as experiment 4, but a minus P plus Al (0.6 mM) treatment was included here. Plants were grown for 2 weeks. Other observations were the same as in the previous experiment.

Experiment 6. This experiment was set up to study the effect of Al on plants receiving different sources of Fe. Six pots were supplied with one of the following sources of Fe: ferric–EDTA, ferric citrate and ferrous sulphate making a total of 18 pots. Afterwards Al treatment (0.6 mM) was given to 3 pots of each Fe source while three pots of each Fe source were kept without an Al treatment. They were grown for 14 days as usual. The solution was renewed on three occasions. At the end of the experiment, the youngest leaf of each plant of each treatment was collected and bulked together. The bulked samples were divided into two lots. The third leaf was collected similarly. The stems plus remaining leaves and roots were harvested in a similar manner. The harvested parts were analysed for Al, P, Fe and Mn.

RESULTS AND DISCUSSION

In the first experiment the dry-matter yield of oat tops decreased progressively with an increase in Al level. The yield of roots was effected in similar way.

The first visual symptom of an abnormality in plant growth caused by Al was apparent after 10-days Al treatment (Table 2). Spotty chlorosis appeared on the youngest leaves. This symptom was highly developed on high Al plants but occurred to a lesser degree on leaves of plants grown at the lower Al level. The symptom was suspected to be due either to Mn or Fe deficiency. Table 3 shows that there was a decrease in Mn content in tops and roots of oats with an increase in Al level. This effect was not shown with Fe and so the possibility of Mn deficiency being the cause of the chlorotic symptom was examined first.

A second experiment was carried out to study the symptoms further. Similar deficiency symptoms appeared on the leaves. The trend in Mn content of both tops and roots was the same as recorded in the first experiment (data of the second experiment was not included for discussion).

A third experiment was carried out to compare Mn levels in nonchlorotic and chlorotic leaves. It was found from Table 4 that differences in Mn contents in leaves were very narrow and apparently the leaves were above the deficiency range. For further confirmation, a fourth ex-

Table 2. Visual observations on oats.

Al levels (mM)	Leaves (days) 5*	10	At harvest	Stems (days) 5	10	At harvest	Roots At harvest
0.0	Normal green	Normal green	Normal and healthy	Normal	Normal	Normal thick	White, healthy and branched
0.2	Normal	Slight spotty chlorosis	Inter-veinal chloro-sis	Normal	Normal	Normal	Healthy, slight yellowish white
0.6	Normal	Spotty chloro-sis	Inter veinal chloro-sis	Purple	Purple	Purple	Thick brown with little branching

*The number of days after the initiation of the Al treatment.

Table 3. Effect of Al on the yields and P, K, Ca, Mg, Fe, Mn, Zn, Cu and Al contents of oats (experiment 1).

Al levels (mM)	Dry wt (g/pog)	Nutrient % in dry wt P	K	Ca	Mg	Nutrient μg/g dry wt Fe	Mn	Zn	Cu	Al
					Tops					
0.0	1.38	0.71	3.10	0.08	0.16	209	36.5	60.6	25.3	152
0.2	1.24	0.65	3.03	0.07	0.12	180	37.8	74.4	19.4	173
0.6	1.21	0.51	2.48	0.06	0.08	179	29.3	75.3	16.9	215
LDS at 5%	NS	0.13	0.04	0.01	0.02	NS	NS	10.8	4.13	28
					Roots					
0.0	4.45	0.77	2.00	0.07	0.14	554	32.9	168	47.7	184
0.2	0.42	0.82	1.81	0.05	0.12	700	19.6	310	36.2 406	406
0.6	0.37	0.99	1.47	0.04	0.08	828	22.1	296	39.0	833
LSD at 5%	NS	0.13	0.36	0.01	0.01	162	5.6	38	6.8	62

periment was carried out which included a higher Mn supply. A similar deficiency symptom appeared in the Al-treated plants grown at a higher Mn level (0.02 mM) even though the Mn concentration in the leaves was much more than in the previous experiments. Thus it was concluded that the symptoms were due to a deficiency of an element other than Mn and probably Fe.

A fifth experiment was carried out using iron as $FeSO_4$ and adding one level of Al. There was not any symptoms of chlorosis this time. This demonstrates that the source of iron is the main factor causing chlorisis in nutrient solution containing Al.

A sixth experiment was set up using 3 different iron compounds alongwith a high Al level. During the experiment, it was observed that plants receiving Al and having iron as ferric EDTA and ferric-citrate developed chlorosis as noted before but the plants receiving iron as ferrous sulphate did not. It was thus concluded that the symptoms appearing on plant leaves in previous experiments were due to the deficiency of iron.

Table 4. Effect of Al on P, Fe, Mn and Al contents of leaves and roots of oats (experiment 3).

Treatment	OAl			Al (0.6 mM)		
Nutrient contents	Leaf		Roots	Leaf		Roots
	Youngest	4th		Youngest	4th	
(P%)	0.58	0.73	0.52	0.47	0.63	0.66
	Nutrient content (µg/g dry wt)					
Fe	174	240	600	153	351	610
Mn	50.3	88.0	100	50.0	73.4	76.8
Al	98.1	136	218	133	198	1313

Table 5. Effect of Al on the content of P, Fe, Mn and Al in oats grown in nutrient solution (experiment 4)..

Treatment*	Dry wt (g/pot)		Nutrient content in tops				Nutrient content in roots			
	Shoot	Root	P (%)	Dry wt (µg/g) Fe	Mn	Al	P (%)	Dry wt (µg/g) Fe	Mn	Al
A	0.65	0.27	1.03	97.5	51.0	11.8	0.62	280	104	330
B	0.55	0.23	0.97	95.0	48.5	43.9	0.66	176	880	728
C	0.67	0.29	0.97	50.0	62.5	9.6	0.64	318	132	218
D	0.52	0.25	0.48	50.0	43.5	13.8	0.70	217	83.5	625
E	0.51	0.27	0.28	87.5	61.3	13.2	0.45	148	30.0	180

*A = plus P minus Al; B = plus P plus Al (0.6 mM); C = plus P plus higher Mn (0.02 mM) minus Al; D = plus P plus higher Mn (0.02 mM); E = minus P minus Al.

In experiments 1, 3 and 4 when iron was used as Fe^{3+} EDTA, there was very little difference between the concentration of Fe in the tops of Al-treated plants and the control. When Fe was used as $FeSO_4$ it was supplied at the same level of Fe as the other two forms. In experiment 6 where 3 iron sources were examied, the Fe-content in chlorotic leaves was similar to, or greater than the concentration in nonchlorotic leaves (Table 7). Also the Al-toxic but nonchlorotic leaves of plants receiving iron as ferrous sulphate did not contain higher concentrations of Fe than equivalent chlorotic leaves of plants receiving Fe as Fe^{3+} EDTA or Fe^{3+} citrate.

It was observed from the two ferric iron sources used, that Al did not prevent the translocation of Fe to the tops, but its effect is possibly concerned with utilization of Fe^{3+}. Experiments with an Fe^{2+} source revealed that Al has no clearly apparent interference with F^{2+} utilization. It may be suggested that the possible cause for the chlorosis on young leaves of Al-toxic plants was due to Al^{3+} inhibiting the reduction of ferric iron to ferrous iron. The chlorotic symptom appeared only in leaves because of the requirement for iron in the formation of chlorophyll. It is an established fact that chlorophyll synthesis is affected at a very early stage of deficiency and most of the leaf iron is found in chloroplasts. Iron fulfils a number of essential functions in plants and a deficiency has far-reaching effects on intermediary metabolism. Its detailed involvement in plant system is not thoroughly understood. However, the enzyme aconitase present in TCA is known to require Fe^{2+} for its activity.

The concentration of Fe in plant tops was not greatly affected by Al, although Fe concentration in plant tops was slightly less in all plant treatment receiving Al compare to the controls in majority of the cases (Tables 3 – 7). In experiment 6, when Fe was supplied as $FeSO_4$ there was a higher concentration of Fe in the roots of the Al-treated plants than from the other two Fe sources.

In experiment 4, where plants were transferred to a nutrient solution without phosphorus, purpling of stems and a deep green colour of older leaves was a preminent symptom of P-deficiency and appeared after 10 days. Following the addition of P in the culture solution, the

Table 6. Effect of Al on the yields and nutrient content of oat (experiment 5).

Treatment*	Dry matter (g/ pot)	Dry wt. root (g/ pot)	Nutrient content in tops				Nutrient content in roots			
			P (%)	Dry wt (μg/g)			P (%)	Dry wt (μg/g)		
				Fe	Mn	Al		Fe	Mn	Al
A	0.36	0.23	0.92	1438	31.3	14.9	1.52	8973	29.8	335
B	0.37	0.16	0.80	688	15.0	18.0	159	7851	26.0	623
C	0.42	0.27	0.82	3749	83.3	10.7	1.46	5623	30.6	375
D	0.39	0.17	0.76	573	40.0	20.0	1.57	6742	39.4	920
E	0.34	0.21	0.31	9.37	25.0	5.3	0.81	6055	40.0	400
F	0.41	0.17	0.19	463	14.6	24.5	0.75	2144	28.0	540

*A, B, C, D and E as experiment 4: F = minus P plus Al (0.6 mM).

Table 7. Effect of Al on P, Fe, Mn and Al content of leaves, stems, and roots of (experiment 6).

Treatment*		Nutrient content in plant parts															
		First leaf				Third leaf				Stem plus remaining leaves				Roots			
		P (%)	Dry wt (μg/g)			P (%)	Dry wt (μg/g)			P (%)	Dry wt (μg/g)			P (%)	Dry wt (μg/g)		
			Fe	Mn	Al		Fe	Mn	Al		Fe	Mn	Al		Fe	Mn	Al
Ferric	OAl	1.01	219	49	15	1.44	440	79	94	0.91	144	31	68	0.43	1045	26	48
EDTA	Al	0.96	454	42	23	1.21	625	70	38	0.87	108	60	77	0.48	970	21	536
Ferric	OAl	0.96	725	35	31	1.28	408	56	42	0.83	169	17	67	0.52	7200	19	32
Citrate	Al	0.83	219	28	40	1.20	394	39	96	0.62	267	38	113	0.67	3852	14	615
Ferrous	OAl	1.02	618	30	67	1.39	900	38	60	0.71	368	33	61	1.14	6600	17	34
Sulphate	Al	0.82	350	23	36	1.07	448	19	29	0.54	206	14	82	1.31	8892	17	511

*Level of Fe in nutrient solution in all cases was 0.1 mM Al = 0.6 mM

plants recovered within 5 days. However, when Al and P was added to the solution, the symptoms remained thus indicating an effect of Al on P nutrition.

When tops and roots were analyzed for P, it was found that the concentration of P was greater in roots of Al-toxic plants than the control plants but a converse effect was recorded in tops. The overall uptake as well as utilization and translocation of P was effected in Al-treated plants (Tables 3 – 7). This supports other research evidence that Al interacts with P in the plant root system [20,26,27,32, 36,40]. Toxic Al is responsible for the immediate immobilization of added P in acid soils [3] and retention of P in acid growth media decrease the solubility and availability of P to plants.

Applications of Al decreased the dry matter yield of tops and roots. The Al toxicity resulted in abnormal root development with many short thick roots. The roots in the control plants were normal and healthy.

The concentration of Mn in plant tops and roots decreased progressively in all experiments with increased Al levels. The data suggest that Al competes with Mn for root absorption sites and thus depresses Mn uptake by plant root. Potassium, calcium and magnesium in the roots decreased with increased Al levels, while similar but less marked decreases in % K, Ca and Mg occurred in plant tops. The results support the findings of other workers [17, 22].

The concentration of Zn in plant tops and roots increased gradually with increased Al levels. The data indicate that aluminium stimulates plant roots to take up more Zn. The content of Cu in plant tops and roots was generally higher in the control compared to the Al-treated plants. Al possibily inhibits Cu absorption by the root of oat plant.

As expected the Al concentration in plant tops and roots increased progressively with increased Al levels (Tables 3 – 7). These results indicate that Al and P accumulate to the greatest extent in the roots of plants grown

in Al solutions. Al and P have been shown to accumulate within the roots of corn [32], sainfoin [36] and barley [40]. Evidence is increasing that Al enters the roots, particularly the meristem [12, 33].

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