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Full Length Research Paper

Effects of aluminum on nutrient uptake in different parts of four pineapple cultivars

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Pineapple *(Ananas comosus* (L.) Merrill.) contains many nutrients and enzyme. It is mostly grown on strongly acid soils in Taiwan. In strongly acid soils, aluminum (Al) is biotoxic and may inhibit growth of crops. This study is to evaluate the effects of different Al concentration in hydroponic solutions on the nutrient uptakes in the roots, stems and leaves of four important Taiwan *Ananas comosus* (L.) Merrill. (Cayenne, Tainung No.6, Tainung No.13 and Tainung No.17). Cayenne is known as the Al resistance, however, Tainung No.6, Tainung No.13 and Tainung No.17 are Al sensitivity. After cultivating for four weeks, the contents of nutrients in different parts of Cayenne would increase when the Al concentration in the hydroponic solution was increased. However, the nutrient uptake in different parts of the other three cultivars would decrease with increase Al concentration, indicating that the nutrient uptake was inhibited, especially that of Ca and Mg. Our experiments indicate that increases in the uptake of Ca and Mg are important to the reduction of Al toxicity when Cayenne is treated with high Al concentration. If Al concentration was increased, Tainung No.6, Tainung No.13 and Tainung No.17 would reduce their uptake of Ca and Mg which might be one of the reasons for the damage of their root apices.

Key words: Acid soil, aluminum (Al), *Ananas comosus* (L.) Merrill., nutrient uptake, root apices.

INTRODUCTION

Acid soil comprises about 40% of the arable soil in the world. Acid soil is mainly distributed in tropical, subtropical and temperate zones (Kochian, 1995). In the earth crust, aluminum (Al) is composed of about 7% of its mass (Delhaize and Ryan, 1995) . Soil acidity influences the solubility and precipitation of Al (Carver and Ownby, 1995; Haynes and Mokolobate, 2001). In strongly acid soil (pH<5), solubilization of Al is enhanced by low pH, and Al toxicity becomes a major factor limiting plant production in acid soil (Abruna-Rodriguez et al., 1982). Therefore, the attention must be paid to the threat of Al toxicity on agricultural productivity (Kochian, 1995; Matsumoto, 2000).

Due to Al toxicity, many crops were subject to physiological illness (Larson et al., 1997). The symptoms were similar to those of nutrient deficiency (example, P, Ca and Mg) (Lopez- Bucio et al., 2000). Al can often inhibit growth of the roots in crops (Delhaize and Ryan, 1995), causing root apices and lateral roots to become coarse and fine lateral roots and root hair to be greater reduced. After subject to Al toxicity for 1 to 2 h, the cell often loses its normal function (Kochian, 1995), thus inhibiting the nutrient uptake by roots (example, Ca^{2+}, Mg^{2+}, K^{+}, NH_4^{+}, No_3^{-}, $H_2PO_4^{-}$, etc) (Rengel and Robinson, 1989; Rengel and Elliott, 1992; Nichol et al., 1993; Durieux et al., 1995; Miyasaka and Hawes, 2001;), affecting productivity later. Therefore, Al toxicity was recognized as the biggest problem in affecting crop production in strongly acid soil (Rengel, 1996; Ma and Hiradate, 2000). Marion et al. (1976) estimated that about 75 to 80% of Al was in Al^{3+}, 15 to 20% in $Al(OH)_2^{+}$, and about 5% in other forms. The former two Al forms were toxic to crops. On the studies of Al toxicity to crops, closely examined the relationship between Al and P and conditions for Al toxicity as early as 1928 were closely examined. Later studies by others found that the extent of Al toxicity to plants was quite different, depending on kinds of plants and different types of their genes. Al tolerance was different in terms of its concentration for different plants. For example, *Brassica napus var napus L.* could grow in strongly acid environment with 20 M Al concentration but was inhibited

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Figure 1. The planting of pineapples (left graph) and the growth of pineapple root (right graph).

Table 1. The composition of nutrient solution used in the hydroponic solution.

Elements	Chemicals	Concentrations (mg/L)
NH_4-N	$(NH_4)_2SO_4$	14
NO_3-N	$Ca(NO_3)_2$ $4H_2O$	196
P	Na_2HPO_4	31
K	K_2SO_4	234
Ca	$CaCl_2$ $2H_2O$	160
Mg	$MgSO_4$ $2H_2O$	48
Fe	Fe-EDTA	50
B	H_3BO_3	0.5
Mn	$MnSO_4$ H_2O	0.5
Zn	$ZnSO_4$ $5H_2O$	0.05
Cu	$CuSO_4$ $7H_2O$	0.02
Mo	Na_2MoO_4 $2H_2O$	0.01

when Al concentration reached 60 M (Clune and Copeland, 2001). *Hordeum volgare L.* was not affected when exposed to Al concentration below 100 M, but its cell membrane would be damaged if exposed to Al over 100 M for more than 15 min, resulting in uptake reductions of 69% for Ca, 40% for ammonium N and 13% for K (Nichol et al., 1993). Giannakoula et al. (2008) conducted experiments on both Al resistance and non- Al resistance wheats with 480 M Al solution (pH 4.2) for 7 days. They found that the root apex of Al-resistance wheat was not affected but that of non-Al resistance wheat was severely inhibited. The uptakes of Ca, Mg and K ions were much greater for the former than for the latter. Le Van and Masuda (2004) pointed out that Al-resistance pineapple could grow in 300 M Al environment while non- Al resistance *Ananas comosus* (L.) Merrill. Suffered root growth and nutrient uptake in 200 M Al environment.

Ananas comosus (L.) Merrill. commonly known as pineapple is a kind of economical plants which mainly grown at central and south districts of Taiwan. The largest area is located in Pingtung county (~36%) . It is rich in vitamin B, organic acids, enzyme, calcium, phosphorus, iron and potassium which are important for human nutrition. Except that, it can supply nutrients and increase the digesting capacity of human being. This study was conducted to examine the effects of different Al concentration on the nutrient uptake of root, stem and leave of four *Ananas comosus* (L.) Merrill. cultivars in strongly acid environment.

MATERIALS AND METHODS

Methodology

Seedlings of four *Ananas comosus* (L.) Merrill. cultivars (Cayenne, Tainung No.6, Tainung No.13 and Tainung No.17) were selected at similar fresh weight (81±8 g) for the experiments. After cleaning with deionized water, these cultivars were cultivated in hydroponic solutions contained in circular plastic containers (25 cm inner diameter and 30 cm height) (Figure1). Each composition of the hydroponic solution was modified from that of Hoagland and Arnon (1938) (Table 1). After germination of root, the treatments of different $AlCl_3$ concentration (0, 100, 200, and 300 µM $AlCl_3$) were proceeded, respectively, each for three replicates. The pH of the hydroponic solution was adjusted to 4.5 with 0.1 N HCl and 0.1 N NaOH for each treatment. Each circular plastic was then aerated evenly with air compressor and moved to a growth chamber (Hipoint, FH-302, RH6, Taiwan) which was controlled at 27 C (14 h, RH 65%) in day time and 23 C (10 h, RH 85%) at night. The hydroponic solution was replaced once a week.

Nutrient analysis on root, stem and leaf

After cultivating four weeks, the plant was cleaned with water and collected separately for its root, stem and leaf. The fresh weight was determined before putting into an oven (70 to75 C) for 2 to 3 days to dry. The dry weight of each part was weighed and then ground to ash for measurements of N, P, K, Ca, Mg, Fe, Mn, Cu, Zn, B and Al contents. In order to determine the Al content in root apices, the sample was loaded into an Eppendoff tube together with 2 ml of 2 N HCl for 48 h in room temperature. After filtration and suitable dilution, its Al concentration was determined with an atomic absorption spectrophotometer (Shimadzu, AA-6601F). The Al content in the root was determined from the filtered solid phase which was dried and ground again. The dried stem and leaf portions were also analyzed separately for their Al content.

The method for Al analysis is briefly described as follows: the dried sample weighed at 0.2 g was mixed with 5 ml concentrate

Table 2. The fresh weight, dried weight and elements content (dried base) of Cayenne pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	7.3[b4]	0.78[b]	14[a*]	1.0[a]	17[a]	3012[a]	1466[a]	155[a]	40[b]	4.9[a]	33[b]	8.1[a]	3.7[d]
Al_1	7.7[b]	0.82[b]	14[a]	1.1[a]	16[a]	3021[a]	1481[a]	167[a]	51[b]	5.0[a]	36[ab]	9.3[a]	13[c]
Al_2	8.3[a]	0.89[a]	16[a]	1.1[a]	18[a]	3111[a]	1502[a]	181[a]	70[a]	6.1[a]	40[a]	8.6[a]	21[b]
Al_3	8.5[a]	0.92[a]	16[a]	1.0[a]	18[a]	3123[a]	1520[a]	177[a]	73[a]	6.2[a]	43[a]	8.9[a]	25[a]

[1]FW: fresh weight.[2]DW: dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively. [4]Values within columns followed by the same letter are not significant at P<0.05 (Duncan's multiple range test).

H_2SO_4 and heated at 400 C to dissociate the sample into dark brown substance which was decolorised with 30% H_2O_2. After cooling, it was filtered and diluted to 50 ml for further analyses. Concentrations of nutrients were measured from suitable amount of the above 50 ml solution. For Kjeldahl N, 5 ml of above diluted solution was loaded into distilled bottle with saturated 8 ml NaOH for distillation. The condensed solution was collected into 20 ml of H_3BO_3 solution (20 g L^{-1}) until 70 ml, then titrated with 0.01 N H_2SO_4 (Bremner, 1965). For P determination, the diluted solution was subject to Molybdenum treatment for spectrophotometric measurement at 882 nm wavelength to obtain P content based on its absorption (Murphy and Riley, 1962). K was determined with flame spectrophotometer (Corning 401) (Knudsen et al., 1982). Atomic absorption spectrophotometer (Shimadzu, AA- 6601F) was used to determine concentrations of Ca, Mg, Fe, Mn, Cu and Zn on the diluted solution with further suitable dilution (Lanyon and Heald, 1982). The analytical method for Al accumulated in root apex and Al contents in root, stem and leaf is briefly stated as follows. Al standard solutions of 2, 4, 6, 8 and 10 ppm were diluted from 1000 ppm Al solution. Standard calibration curve was obtained from these Al concentrations, A sample of 20 l was drawn and dried for 40 s at 140 C. This was followed by pretreatment at 700 C for 20 s and Al was atomized at 2700 C for 5 s. The Al content was calculated by integrating the peak area of its absorption.

Statistical analysis

Windows SPSS 10.0 was applied to treat the data statistically for variables analysis. Duncan's multiple range test were used to differentiate the differences. It was significantly different if P<0.05.

RESULTS

Effects of Al concentrations on root weight and its nutrient contents

Table 2 shows that the fresh weight and dried weight of Cayenne increase as Al concentration increases, reaching apparent level at 200 M $AlCl_3$. There is an increasing trend for N, P, K, Ca, Mg, Fe, Mn, Cu, Zn and B as Al concentration is increased, but not in significant level for N, P, K, Ca, Mg, Fe, Cu and B. Treated with 200 M $AlCl_3$, both Mn and Zn have increased significantly. The Al content in root increases with increasing Al concentration, indicating that Al concentration may affect the Al content in root.

Table 3 shows that the fresh weight and dried weight of Tainung No.6 reach maximum when it is treated with 100 M $AlCl_3$ but both weights decrease significantly when treated with 300 M $AlCl_3$. The contents of N, P, K, Cu, Zn and B are not affected by Al concentration. However, the contents of Ca, Mg, Fe and Mn are apparently reduced when treated with 300 M $AlCl_3$. The Al content in root of Tainung No.6 is comparable to that of Cayenne, showing an increasing trend with Al concentration. This indicates that Al concentration may affect the Al content in its root. Table 4 shows highest fresh weight and dried weight of Tainung No.13 root are obtained at 100 M $AlCl_3$ solution. Both fresh and dried weights of the root are clearly reduced at 300 M $AlCl_3$ solution. The contents of N, P, K, Mn, Cu, Zn and B are not significantly affected by Al concentration, but those of Ca, Mg and Fe are apparently reduced at 300 M $AlCl_3$ solution. The Al content in root of Tainung No.13 is similar to those of Cayenne and TainungNo.6, increasing with $AlCl_3$ concentration, and so the Al content in its root is also affected by $AlCl_3$ concentration.

Table 5 indicates that the fresh and dried weights of Tainung No.17 root are reduced when treated with 300 M $AlCl_3$ solution. The contents of N, P, K and Zn do not vary much with $AlCl_3$ concentration but those of Ca, Mg, Fe, Mn and Cu are clearly reduced at 200 M $AlCl_3$ concentration. The content of B is drastically reduced at 300 M $AlCl_3$ solution. The Al content in root of Tainung No.17 is comparable to those of other three pineapple cultivars, showing a clear increase with increasing $AlCl_3$ concentration and effect of $AlCl_3$ concentration on the Al content in its root.

Table 3. The fresh weight, dried weight and elements content (dried base) of Tainung No.6 pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	7.1^{a4}	0.74^{a}	15^{a*}	1.4^{a}	22^{a}	2883^{a}	1796^{a}	208^{a}	75^{a}	6.5^{a}	38^{a}	11^{a}	4.8^{d}
Al_1	7.2^{a}	0.76^{a}	15^{a}	1.7^{a}	24^{a}	2758^{a}	1808^{a}	211^{a}	86^{a}	7.1^{a}	43^{a}	10^{a}	18^{c}
Al_2	6.8^{a}	0.69^{a}	17^{a}	1.8^{a}	25^{a}	2733^{a}	1812^{a}	233^{a}	81^{a}	7.0^{a}	42^{a}	12^{a}	25^{b}
Al_3	6.6^{b}	0.65^{b}	17^{a}	1.8^{a}	26^{a}	2518^{b}	1602^{b}	179^{b}	68^{b}	6.7^{a}	44^{a}	12^{a}	34^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Table 4. The fresh weight, dried weight and elements content (dried base) of Tainung No.13 pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg)	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	7.1^{a4}	0.74^{a}	14^{a*}	1.4^{a}	22^{a}	2512^{ab}	1535^{a}	292^{a}	74^{a}	7.1^{a}	40^{a}	13^{a}	2.3^{d}
Al_1	7.2^{a}	0.76^{a}	15^{a}	1.5^{a}	24^{a}	2873^{a}	1544^{a}	305^{a}	82^{a}	7.9^{a}	46^{a}	16^{a}	15^{c}
Al_2	6.8^{a}	0.69^{a}	14^{a}	1.5^{a}	22^{a}	2562^{ab}	1532^{a}	281^{a}	76^{a}	9.0^{a}	55^{a}	16^{a}	27^{b}
Al_3	6.6^{b}	0.65^{b}	14^{a}	1.4^{a}	20^{a}	2466^{b}	1399^{b}	233^{b}	73^{a}	7.6^{a}	43^{a}	15^{a}	40^{a}

[1]FW: fresh weight.[2]DW:dried weight.[3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Table 5. The fresh weight, dried weight and elements content (dried base) of Tainung No.17 which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	5.8^{a4}	0.60^{a}	17^{a*}	1.1^{a}	19^{a}	2480^{a}	1455^{ab}	198^{ab}	84^{ab}	4.5^{b}	43.0^{a}	9.8^{ab}	4.1^{d}
Al_1	6.2^{a}	0.63^{a}	18^{a}	1.4^{a}	22^{a}	2685^{a}	1600^{a}	245^{a}	112^{a}	9.3^{a}	53.5^{a}	13.0^{a}	20^{c}
Al_2	6.1^{a}	0.62^{a}	17^{a}	1.3^{a}	22^{a}	2225^{b}	1348^{b}	164^{b}	65.9^{b}	5.2^{b}	46.1^{a}	9.6^{ab}	33^{b}
Al_3	3.7^{b}	0.38^{b}	17^{a}	1.3^{a}	20^{a}	2055^{b}	1314^{b}	152^{b}	61.0^{b}	4.3^{b}	42.1^{a}	7.1^{b}	51^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Effects of Al concentration on the weight of stem and the nutrient content in root of *Ananas comosus* (L.) Merrill.

Table 6 shows that the fresh and dried weights as well as the contents of N, P, K, Ca, Mg, Fe and B are not changed appreciately when Al concentration increases. Treated with 200 M $AlCl_3$, Mn shows a clear increase in absorption. At 300 M $AlCl_3$, Zn also shows an increase. The Al content in stem is much lower than in root, indicating that most Al is retained in root but not transported to stem. The Al content in stem of Cayenne increases less with increasing Al concentration.

Table 6. The fresh weight, dried weight and elements content (dried base) of Cayenne pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	58^{a4}	12^{a}	12^{a*}	1.1^{a}	18^{a}	2766^{a}	1211^{a}	133^{a}	39^{b}	5.6^{a}	27^{b}	8.0^{a}	1.1^{c}
Al_1	58^{a}	12^{a}	13^{a}	1.0^{a}	16^{a}	2712^{a}	1267^{a}	141^{a}	42^{b}	5.1^{a}	26^{ab}	9.1^{a}	7.5^{ab}
Al_2	60^{a}	12^{a}	12^{a}	1.2^{a}	18^{a}	2814^{a}	1255^{a}	135^{a}	49^{a}	5.8^{a}	33^{a}	8.6^{a}	11^{ab}
Al_3	63^{a}	13^{a}	13^{a}	1.0^{a}	19^{a}	1901^{a}	1272^{a}	152^{a}	53^{a}	6.0^{a}	24^{a}	8.8^{a}	10^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Table 7. The fresh weight, dried weight and elements content (dried base) of Tainung No.6 pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	59^{a4}	11.8^{a}	14^{a*}	1.5^{a}	20^{a}	2233^{a}	1546^{a}	212^{a}	70^{a}	6.8^{a}	43^{a}	11^{a}	1.5^{d}
Al_1	60^{a}	12.2^{a}	14^{a}	1.5^{a}	22^{a}	2305^{a}	1609^{a}	201^{a}	76^{a}	7.1^{a}	44^{a}	10^{a}	6.6^{c}
Al_2	63^{a}	12.7^{a}	15^{a}	1.6^{a}	23^{a}	2344^{a}	1627^{a}	234^{a}	67^{a}	7.0^{a}	44^{a}	12^{a}	9.9^{b}
Al_3	61^{a}	12.0^{a}	15^{a}	1.5^{a}	22^{a}	2351^{a}	1582^{a}	225^{a}	69^{a}	6.9^{a}	54^{a}	12^{a}	12^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Table 7 shows that both fresh and dried weights andnutrients in stem of Tainung No.6 are not increasing appreciately when Al concentration increases. The Al content in its stem is similar to that of Cayenne, but much lower than that in root, indicating very limited Al can be transported to its stem. However, the Al content in stem increases apparently with Al concentration of the hydroponic solution.

Table 8 indicates that the fresh and dried weights of stem and its N, P, K, Ca, Mg, Zn and B contents of Tainung No.13 do not vary much with Al concentration. However, the contents of Fe, Mn and Cu apparently decrease when treated at 300 M $AlCl_3$, The Al content in stem increases with treated Al concentration.

Table 9 shows that the fresh weight of stem of Tainung No.17 does not vary with Al concentration but the dried weight is reduced substaintially at 300 M $AlCl_3$ solution. Contents of N, P, K and Zn in stem do not vary with Al concentration, but contents of Ca, Mg and Fe at 300 M $AlCl_3$ and that of Mn and Cu at 200 M $AlCl_3$ are significantly reduced. The Al content in stem increases with Al concentration, just like the aforementioned three cultivars.

Effect of al concentration on leaf weight and nutrient contents in root of *Ananas comosus* (L.) Merrill.

Table 10 shows that both the fresh and dried weights of leaf of Cayenne trends to increase slightly with Al concentration. The nutrients do not increase with Al concentration. No significant changes are observed in the contents of N, P, K, Ca, Mg, Fe, Mn, Cu, Zn and B when Al concentration increases. The Al content in leaf is quite low and shows no increase with increasing Al concentration.

Table 11 indicates that both fresh and dried weights of leaf of Tainung No.6 are apparently reduced when treated with 300 M $AlCl_3$ solution. The contents of N, P, K, Fe, Cu and B in leaf do not vary appreciably with Al concentration but the contents of Ca, Mg, Mn and Zn are apparently reduced at 300 M $AlCl_3$ solution. The Al content in leaf is quite low with small variation for any $AlCl_3$ solution. This suggests that little Al is transported from stem to leaf.

Table 8. The fresh weight, dried weight and elements content (dried base) of Tainung No.13 pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	61^{a4}	12.1^{a}	13^{a*}	1.4^{a}	20^{a}	2399^{a}	1413^{a}	213^{a}	77^{ab}	7.8^{a}	41^{a}	14^{a}	1.2^{c}
Al_1	58^{a}	11.5^{a}	14^{a}	1.4^{a}	22^{a}	2403^{a}	1424^{a}	292^{a}	82^{a}	7.9^{a}	44^{a}	15^{a}	4.6^{b}
Al_2	57^{a}	11.0^{a}	13^{a}	1.3^{a}	21^{a}	2379^{a}	1385^{a}	233^{a}	78^{a}	7.3^{ab}	38^{a}	15^{a}	9.0^{ab}
Al_3	58^{a}	11.4^{a}	13^{a}	1.2^{a}	20^{a}	2346^{a}	1391^{a}	205^{b}	63^{b}	6.5^{b}	38^{a}	14^{a}	11.8^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Table 9. The fresh weight, dried weight and elements content (dried base) of Tainung No.17 which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	58^{a4}	10.4^{a}	15^{a*}	1.2^{a}	20^{a}	2369^{a}	1428^{ab}	186^{ab}	88^{ab}	7.7^{ab}	44^{a}	9.6^{ab}	1.9^{d}
Al_1	61^{a}	11.0^{a}	16^{a}	1.4^{a}	22^{a}	2418^{a}	1589^{a}	227^{a}	122^{a}	8.6^{a}	55^{a}	12^{a}	6.2^{c}
Al_2	59^{a}	9.8^{a}	15^{a}	1.3^{a}	21^{a}	2355^{ab}	1439^{ab}	168^{ab}	71.6^{b}	5.6^{b}	43^{a}	9.3^{b}	12.2^{b}
Al_3	57^{a}	9.5^{b}	14^{a}	1.2^{a}	20^{a}	2291^{b}	1334^{b}	151^{b}	63.8^{b}	4.5^{b}	40^{a}	7.3^{b}	14.3^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Table 10. The fresh weight, dried weight and elements content (dried base) of Cayenne pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	19.8^{b4}	3.58^{a}	14^{a*}	1.0^{a}	15^{a}	3377^{a}	1389^{a}	133^{b}	63^{a}	5.8^{a}	32^{b}	7.4^{a}	0.9^{a}
Al_1	20.3^{ab}	3.67^{a}	14^{a}	1.1^{a}	16^{a}	3398^{a}	1481^{a}	147^{a}	68^{a}	5.8^{a}	37^{ab}	8.3^{a}	1.1^{a}
Al_2	21.2^{a}	3.79^{a}	14^{a}	1.1^{a}	18^{a}	3412^{a}	1513^{a}	171^{a}	62^{a}	6.1^{a}	41^{a}	8.5^{a}	0.8^{a}
Al_3	22.5^{a}	3.88^{a}	16^{a}	1.1^{a}	19^{a}	3468^{a}	1522^{a}	176^{a}	70^{a}	6.3^{a}	42^{a}	8.9^{a}	0.9^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at $P<0.05$ (Duncan's multiple range test).

Table 11. The fresh weight, dried weight and elements content (dried base) of Tainung No.6 pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	18.8^{a4}	3.43^{a}	16^{a*}	1.3^{a}	23^{a}	2782^{a}	1781^{a}	197^{a}	58^{a}	7.2^{a}	36^{ab}	12^{a}	0.8^{a}

Table 11. Contd.

Al_1	20.3^{a}	3.63^{a}	16^{a}	1.3^{a}	24^{a}	2801^{a}	1808^{a}	219^{a}	66^{a}	7.1^{a}	41^{a}	12^{a}	1.2^{a}
Al_2	20.1^{a}	3.55^{a}	16^{a}	1.3^{a}	22^{a}	2733^{ab}	1772^{a}	196^{a}	57^{a}	7.0^{a}	40^{a}	11^{a}	1.3^{a}
Al_3	18.6^{b}	3.31^{b}	15^{a}	1.2^{a}	22^{a}	2606^{b}	1654^{b}	184^{a}	49^{b}	6.7^{a}	33^{b}	10^{a}	1.1^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at P<0.05 (Duncan's multiple range test).

Table 12. The fresh weight, dried weight and elements content (dried base) of Tainung No.13 pineapple which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	20.2^{a4}	2.99^{a}	13^{a*}	1.3^{a}	20^{a}	2181^{ab}	1462^{a}	231^{b}	63^{a}	6.3^{a}	33^{a}	11^{a}	0.3^{b}
Al_1	22.6^{a}	3.21^{a}	15^{a}	1.5^{a}	23^{a}	2684^{a}	1544^{a}	279^{a}	82^{a}	6.9^{a}	36^{a}	12^{a}	0.5^{b}
Al_2	20.8^{a}	2.87^{a}	15^{a}	1.4^{a}	20^{a}	2304^{ab}	1417^{ab}	222^{a}	66^{a}	5.8^{a}	29^{a}	11^{a}	1.1^{a}
Al_3	18.9^{b}	2.75^{b}	14^{a}	1.4^{a}	18^{a}	2016^{b}	1389^{b}	195^{b}	61^{a}	5.1^{a}	28^{a}	10^{a}	1.2^{a}

[1]FW: fresh weight.[2]DW:dried weight. [3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at P<0.05 (Duncan's multiple range test).

Table 13. The fresh weight, dried weight and elements content (dried base) of Tainung No.17 which planted in the hydroponic solution that contained 0, 100, 200, 300 M $AlCl_3$ for four weeks.

Treatments	FW[1] (g)	DW[2] (g)	N(g/kg)	P(g/kg	K(g/kg)	Ca(mg/kg)	Mg(mg/kg)	Fe(mg/kg)	Mn(mg/kg)	Cu(mg/kg)	Zn(mg/kg)	B(mg/kg)	Al(mg/kg)
Al_0[3]	21.1^{a4}	2.86^{a}	15^{a*}	1.3^{a}	23^{a}	2401^{a}	1429^{a}	165^{a}	77^{a}	6.8^{ab}	33^{a}	10.1^{a}	0.4^{b}
Al_1	20.2^{a}	2.80^{a}	15^{a}	1.3^{a}	23^{a}	2322^{a}	1412^{a}	161^{a}	67^{a}	9.3^{a}	31^{a}	9.2^{a}	0.6^{b}
Al_2	18.7^{ab}	2.73^{a}	14^{a}	1.2^{a}	22^{a}	2065^{b}	1366^{ab}	156^{a}	61^{ab}	5.3^{b}	28^{a}	7.6^{ab}	0.6^{b}
Al_3	18.2^{b}	2.52^{b}	13^{a}	1.1^{a}	20^{a}	2050^{b}	1304^{b}	136^{b}	48^{b}	4.1^{b}	26^{a}	7.0^{b}	1.1^{a}

[1]FW: fresh weight.[2]DW:dried weight.[3]Al_0, Al_1, Al_2 and Al_3 indicated that the concentration of $AlCl_3$ were 0, 100, 200 and 300 M in the hydroponic solution, respectively.[4]Values within columns followed by the same letter are not significant at P<0.05 (Duncan's multiple range test).

Table 12 shows that both fresh and dried weights of leaf for Tainung No.13 are reduced apparently at 300 M $AlCl_3$ solution, similar to the case for Tainung No.6. No apparent changes occur in the contents of N, P, K, Mg, Mn, Cu, Zn and B in leaf when treated with different Al concentration. However Ca content is greatly reduced at 300 M $AlCl_3$ solution. The Al content in leaf is low and does not change when treated with increasing Al concentration, indicating very few Al is transported from stem to leaf.

Table 13 shows that the fresh and dried weights of leaf for Tainung No.17 are clearly reduced when treated with 300 M $AlCl_3$ solution. No significant changes are observed in the contents of N, P, K, Zn and B in leaf when treated with different Al concentration. Significant decreases are observed in the contents of Ca and Cu at 200 M $AlCl_3$ solution and in the contents of Mg, Fe, Mn, Cu and B at 300 M $AlCl_3$ solution. The Al content in leaf of Tainung No.17 is very low and not varied with different Al concentration, similar to the other three cultivars. This also indicates that little Al is transported to leaf from stem.

DISCUSSION

Based on the above results, the nutrient uptake of Cayenne is not affected by Al concentration. Actually the nutrient uptake is increased when Al concentration is increased. For the other three cultivars, the nutrient uptake is inhibited when the Al concentration reaches 200 M AlCl3, especially for Ca and Mg uptake. Most Al is retained in root and the Al accumulation may cause differences in Al resistance characteristics in different pineapple cultivars. It can be assured that the Al transported to stem and leaf is rather low for all cultivars. The nutrient uptake in root of crops is related to selective characteristics of mass membrane. Toxic substance may interfere with the nutrient uptake by changing permeability of the membrane and affecting transport of elements through the membrane (Gussarsson 1994). Based on the effects of nutrient uptake by different Al concentration for the above four *Ananas comosus* (L.) Merrill. cultivars, one finds that the nutrient uptake by Cayenne tends to increase (not prominent) with increasing Al concentration. The contents of Ca, Mg, Fe and Mn are apparently reduced at 300 M $AlCl_3$ treatment for Tainung No. 6. The contents of Ca, Mg and Fe are clearly reduced at 300 M $AlCl_3$. The contents of Ca, Mg, Fe, Mn, Cu and B are clearly reduced when Tainung No. 17 is treated with 200 M $AlCl_3$ solution. The nutrient uptake by root of Cayenne is not affected by treatment of different Al concentration. However, the nutrient uptake by root of the other three cultivars is severely affected by Al concentration, especially for Ca and Mg. The contents of major nutrient elements in stem of Cayenne and Tainung No. 6 are not affected by Al concentration. The contents of Fe, Mn and Cu in stem of Tainung No. 13 are clearly reduced at 300 M $AlCl_3$ solution, indicating significant reduction of these elements being transported from root to stem. The contents of Ca, Mg, Fe, Mn, Cu and B being transported from root to stem are apparently reduced for Tainung No. 17, leading to much lower dried weight of the stem. Moral et al. (1994) conducted experiments on tomato which was heavy- metal resistant. They found that the uptake of P and K was increased in heavy-metal environment. This study found that the contents of P and K in root of Cayenne tend to increase with increasing Al concentration. The contents of Ca and Mg in root of Cayenne are not affected by Al concentration. However, the contents of Ca and Mg in root are apparently inhibited for the other three cultivars at 200 to 300 M $AlCl_3$ solution. Calcium may bond in large quantity with the cell wall of root and the surface of mass membrane, providing connection with internal molecules. They play an important role in stabilizing the cell wall and cell membrane. Wang (1992) suggested that strong interaction between Ca and cell wall structure could provide sufficient Ca for mass membrane to maintain stability. Brune and Dietz (1995) studied effect of Cd on *Brassica juncea* and found similar results. They found that Ca uptake by *Brassica juncea* was increasing with increasing Cd concentration. However, when Cd concentration surpassed its tolerance, Ca uptake was reduced. When Cayenne was treated with high Al concentration, the Ca uptake was increased and thus reduced the Al toxicity as an important mechanism. When Al concentration was raised, the Ca uptake was reduced for Tainung No. 6, Tainung No. 13 and Tainung No. 17, resulting in damage of internal defense mechanism as one of the symptoms. Silva et al. (2001) pointed out that Mg might induce the root of bean synthesize citric acid and secreted from the root under the existence of Al. Therefore Al toxicity could effectively be retarded. Puzzis et al. (1994) suggested that phosphoglycerate kinase was one of the important proteins of plants in an unfavorable environment. However, the Mg content in cell might affect the activity of phosphoglycerate kinase, as Mg was its supplementary. When Tainung No. 6 and Tainung No. 13 were treated with 300 M $AlCl_3$ and Tainung No. 17 with 200 M $AlCl_3$, their Mg uptake was clearly reduced, causing insufficient synthesis of phosphoglycerate kinase. Therefore, they were less Al resistance than Cayenne.

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