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EFFECT OF ALUMINUM ON PLANT GROWTH, PHOSPHORUS AND CALCIUM UPTAKE OF TROPICAL RICE (*Oryza sativa*), MAIZE (*Zea mays*), AND SOYBEAN (*Glycine max*)

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ABSTRACT

Aluminum toxicity is the most limiting factor to plant growth on acid soils. Structural and functional damages in the root system by Al decrease nutrient uptake and lead to reduce plant growth and mineral deficiency in shoot. Greenhouse experiment was conducted to study the effect of Al on plant growth, and P and Ca uptake of rice, maize, and soybean. The plants were grown in hydroponic solution added with 0, 5, 10, and 30 ppm Al, at pH 4.0. The results showed that relative growth of shoots and roots of upland rice, lowland rice, maize, and soybean decreased with an increase of Al level. However, sometimes the low Al level (5 ppm) stimulated shoot and root growth of some varieties in these species. According to total Al_{RG50} values, which is Al concentration in solution when relative growth decreased to 50%, Al tolerance of species was in order of barley < maize < soybean < lowland rice < upland rice. For maize, Al tolerance was in the order of Arjuna < Kalingga < P 3540 < SA 5 < SA 4 < PM 95A < SA 3 < Antasena; for soybean was Wilis < INPS < Galunggung < Kerinci < Kitamusume; for lowland rice was RD 23 < Kapuas < Cisadane < KDML 105 < IR 66 < RD 13, and for upland rice was Dodokan < IAC 165 < Cirata < Oryzica sabana 6 < Danau Tempe < Laut Tawar. Based on the rank of Al tolerance, rice was the useful crop to be planted in acid soils. Antasena (maize), Kitamusume (soybean), RD 13 (lowland rice), and Laut Tawar (upland rice) were also recommended for acid soils. P and Ca concentration in shoots and roots commonly decreased with an increase of Al level. However, the low Al level stimulated absorption of P and Ca, which caused an increase of P and Ca concentrations in shoots and roots.

[*Keywords*: *Oryza sativa*; *Zea mays*; *Glycine max*; aluminum; growth; phosphorus; calcium, nutrient uptake]

INTRODUCTION

In humid tropical area, including Indonesia, leaching of calcium, magnesium, potassium, and other basic elements from the soil increases hydrogen ion absorption on soil colloids or particle surfaces, consequently, increases soil acidity. Indonesia has about 47 million ha of acid upland soils which are mainly Ultisols and Oxisols. Highly acid soils are relatively low in productivity because of essential nutrient deficiencies and nonessential element toxicities. Essential plant nutrients that are often so slowly available as to be deficient in strongly acid soils include N, P, K, Ca, Mg, and Mo, while nonessential elements that release in high concentration as to be toxic to plants are Al and Fe. From all constraints, Al toxicity is the most limiting factor for crop growth on acid soils (Foy *et al.*, 1978). The relative importance of these constraints depends on many factors, such as plant species and genotypes, soil type and horizon, soil parent material, soil pH, concentration and species of Al, soil structure and aeration, and climate.

Structural and functional damages in the root system caused by high concentration of Al decrease nutrient uptake and lead to reduce plant growth and mineral deficiency in shoots. Root growth inhibition by toxic Al would further be increased by P deficiency in acid mineral soils, in addition to other growth-limiting factors, e.g., Mg deficiency. Ca, Mg, and P uptake are most affected by Al (Foy *et al.*, 1978). Wheat seedling exposed to Al decreased significantly in concentration of Ca, Mg, and P, accompanying with the decrease of root and shoot growth (Foy *et al.*, 1978; Taylor and Foy, 1985; Taylor, 1988).

The ability of roots and shoots to maintain higher concentration of macro- and micronutrient cations usually associated with Al-resistant cultivar under soluble Al (Taylor, 1988). In acid mineral soils, Al toxicity may inhibit shoot growth by limiting supply of nutrients and water by poorer subsoil penetration or lower root hydraulic conductivity (Kruger and Sucoff, 1989). On the other hand, under certain conditions and in some species or genotypes with high Al tolerance, low levels of Al may have beneficial effects on the growth of higher plants (Clark, 1977). It was also reported that growth of many native plants growing in acid soils is enhanced by Al (Watanabe *et al.*, 1997). The mechanisms of beneficial effect of Al may be summarized as follows: (1) blocking negatively charged sites on cell walls and thereby promoting P uptake, (2) correcting or preventing P toxicity (Clark, 1977), (3) altering the distribution of growth regulator in roots of peach seedlings, and (4) preventing Cu and Mn toxicities.

Several approaches have suggested to increase crop production in acid soils considering both soil and crop improvement. Soil improvement is principally aimed to reduce acidity or Al toxicity by using soil amendment, such as lime, organic matter, P fertilizer, and silicon. However, in intensive agriculture, soil improvement by using soil amendment is not always economically feasible, especially in strongly acid soils. Selection or screening of plants, which are resistant to soluble Al in the root environment, is considered as a useful alternative approach.

The objectives of present study are to investigate the effects of Al on P and Ca uptake and growth of different varieties of upland and lowland rice (*Oryza sativa* L.), maize (*Zea mays* L.), and soybean (*Glycine max* L.)

MATERIALS AND METHODS

Plant Materials

The experiment was conducted in greenhouse of the Laboratory of Plant Nutrition, Faculty of Agriculture, Hokkaido University from May to October 1999. Seeds of Al-sensitive and Al-tolerant varieties of upland rice, lowland rice, maize, and soybean taken from Indonesia, Thailand, South America, and Japan were used in this experiment (Table 1). While one very sensitive variety of barley (Ryofu) was used for comparison.

Table 1. Seeds of crops used in experiment.

Crop	Variety	Origin	Al tolerance
Upland rice	IAC 165	USA	*
	Oryzica sabana 6	USA	*
	Dodokan	Indonesia	Sensitive
	Cirata	Indonesia	Moderate
	Danau Tempe	Indonesia	Tolerant
	Laut Tawar	Indonesia	Tolerant
Lowland rice	RD 23	Thailand	*
	KDML 105	Thailand	*
	RD 13	Thailand	*
	Kapuas	Indonesia	*
	Cisadane	Indonesia	Sensitive
	IR66	Indonesia	Moderate
Maize	P 3540	Japan	*
	PM 95A	Japan	*
	SA 3	America	Tolerant
	SA 4	America	*
	SA 5	America	Sensitive
	Arjuna	Indonesia	Moderate
	Kalingga	Indonesia	Tolerant
	Antasena	Indonesia	Tolerant
Soybean	Kitamusume	Japan	*
	INPS	America	*
	Wilis	Indonesia	Moderate
	Galunggung	Indonesia	Moderate
	Kerinci	Indonesia	Tolerant
Barley	Ryofu	Japan	Sensitive

*Unknown

Culture Solution

Seeds were sterilized with 1% sodium hypochlorite for 10 minutes, washed with deionized water, and germinated on moist perlite and vermiculite with nutrient solution standard composition. Three-week (rice), one-week (maize, soybean, and barley) after germination seedlings were precultivated in a complete nutrient solution consisted of 30 mg N l^{-1} (NH_4NO_3), 1 mg P l^{-1} ($NaH_2PO_42H_2O$), 30 mg K l^{-1} (K_2SO_4:KCl=1:1), 50 mg Ca l^{-1} ($CaCl_22H_2O$), 20 mg Mg l^{-1} ($MgSO_47H_2O$), 2 mg Fe l^{-1} ($FeSO_47H_2O$), 0.5 mg Mn l^{-1} ($MnSO_44H_2O$), 0.5 mg B l^{-1} (H_3BO_3), 0.2 mg Zn l^{-1} ($ZnSO_47H_2O$), 0.01 mg Cu l^{-1} ($CuSO_45H_2O$), and 0.005 mg Mo l^{-1} ($(NH_4)_6Mo_7O_{24}4H_2O$) (Osaki *et al.*, 1997). The pH of the solution was adjusted to 5.0 $\pm$ 0.1 for rice and to 4.7 $\pm$ 0.1 for soybean and maize.

After preculture, the seedlings (two plants $hill^{-1}$) were transferred to the hydroponic solution (container 360 l) treated with 0, 5, 10, and 30 ppm Al using $Al_2(SO_4)_3$. The Al and P concentrations in the solution had been adjusted by the addition of an adequate amount of Al and P until Al-P equilibrium state was reached at pH 4.0 $\pm$ 0.1. Each treatment was replicated four times. During the experiment, culture solution was constantly aerated, pH was controlled at 4.0 $\pm$ 0.1, and the nutrient concentration was readjusted to the initial concentrations every 10 days.

Growth Measurements

Rice and barley were harvested at 14 days after Al treatment, whereas maize and soybean were harvested at 7 and 12 days, respectively. After being washed with deionized water, samples were separated into roots and shoots. Dry weight of each organ was measured after drying in the air-dried oven at 80°C for 2 days. Relative growth (RG) of shoots and roots was calculated as follow:

$$RG = (DW\ Al_X - DW\ O)/(DW\ Al_0 - DW\ O)$$

where DW Al_X is plant dry weight treated with some Al concentration (g $hill^{-1}$) after Al treatment; DW Al_0 is plant dry weight without Al (g $hill^{-1}$) after Al treatment; and DW O is plant dry weight at 0 day after Al treatment (g $hill^{-1}$). Order of relative Al tolerance was determined according to Al_{RG50} value, defined as Al concentration in water culture when RG decreased up to 50% by Al treatment. The highest value was called as the most tolerant variety, on the contrary the lowest value was the most sensitive one.

Plant P and Ca Analyses

Shoot (0.10 g) and root (0.06 g) samples were grounded, digested with H_2SO_4 (95%) -H_2O_2 (30%) and adjusted the volume to 25 ml. Then, concentration of P and Ca in shoots and roots of each plant were analyzed. Plant extracts were filtered by using filter paper type 5C (Advantec Toyo). P was determined by vanado-molybdate yellow method and Ca by atomic absorption spectrophotometry.

RESULTS AND DISCUSSION

Plant Growth

Relative growth (RG) of the treated upland and lowland rice (Fig. 1), maize and soybean (Fig. 2) decreased with an increase of Al level. The toxic action of Al was primarily seen on root system (Taylor, 1988). The root system became stubby as a result of inhibition of elongation of the main axis and lateral roots (Klotz and Horst, 1988). Inhibition of shoot growth was a secondary response to Al because Al reduced nutrient uptake by reducing root absorptive area, by impairing the structural integrity of plasma membrane leading to alteration of permeability, and by directly interfering with the efficiency of ion transporting system embedded in the plasma membrane (Huang *et al.*, 1992; Rengel, 1992).

Figure 1 showed that among upland rice varieties tested, RG of Dodokan and IAC 165 decreased more markedly than the others. In lowland rice, RG of RD 23 and Kapuas also decreased more markedly than other varieties. Among maize varieties, RG of Arjuna and Kalingga decreased more markedly than other varieties, while among soybean varieties, RG of Wilis and INPS decreased more markedly than the others (Fig. 2). Among all species tested, the RG of barley var. Ryofu decreased drastically (Fig. 3). It means that barley was the most sensitive species. Dodokan, RD 23, Arjuna, and Wilis were the most sensitive varieties among varieties of upland rice, lowland rice, maize, and soybean, respectively. The severity rate of inhibition of root and shoot growth is a suitable indicator of genotypical differences in Al toxicity. Farid Jan (1991) reported that there was a marked decrease in fresh weight of shoots and roots of rice cultivars with increasing Al treatments. The effect of Al was clearer in the sensitive cultivars (IR45) than that in tolerant cultivars (BG 35 or DA 14). Pintro *et al.* (1996) reported that growth of Al-tolerant maize

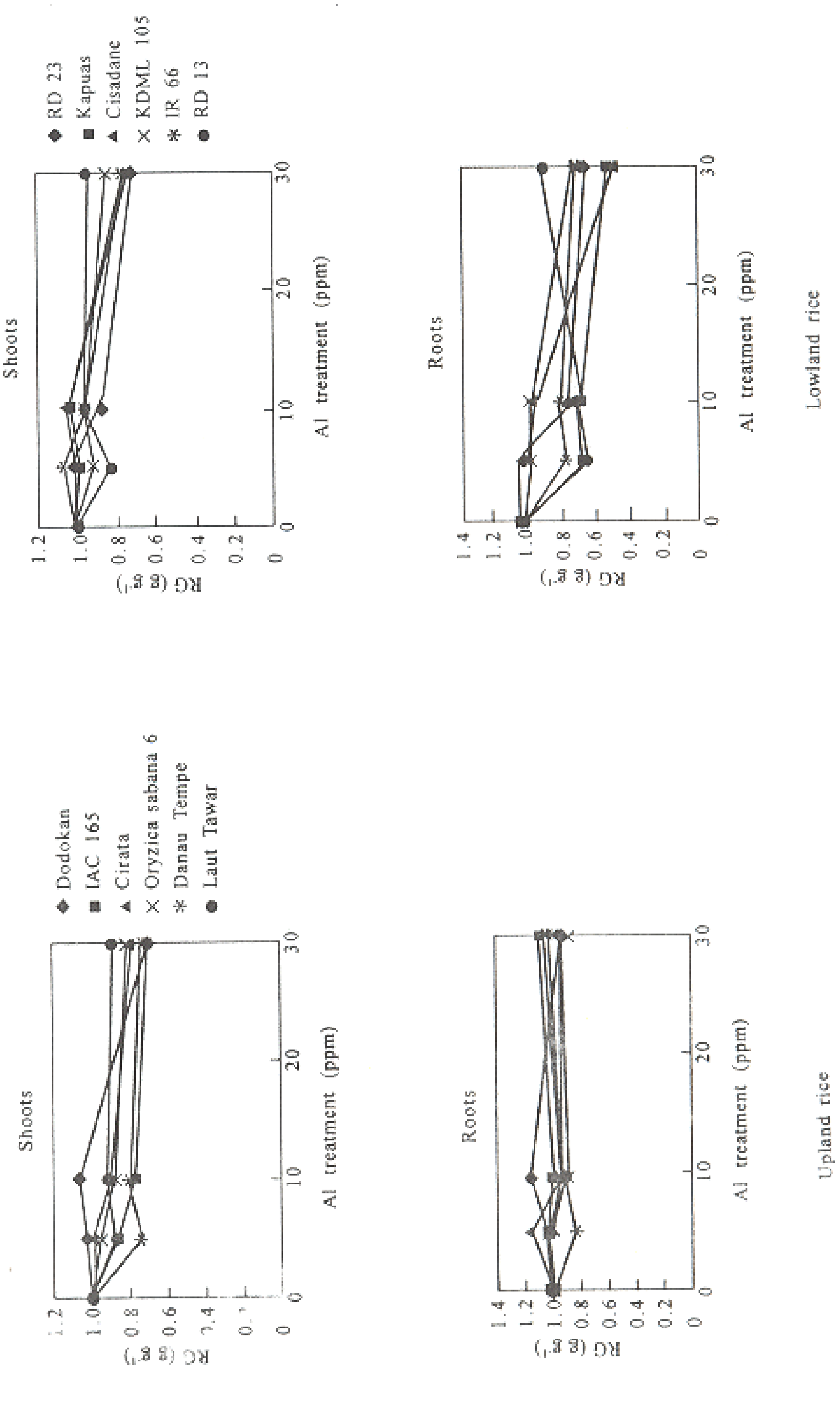

Fig. 1. Relative growth (RG) in shoots and roots of upland and lowland rice treated with Al.

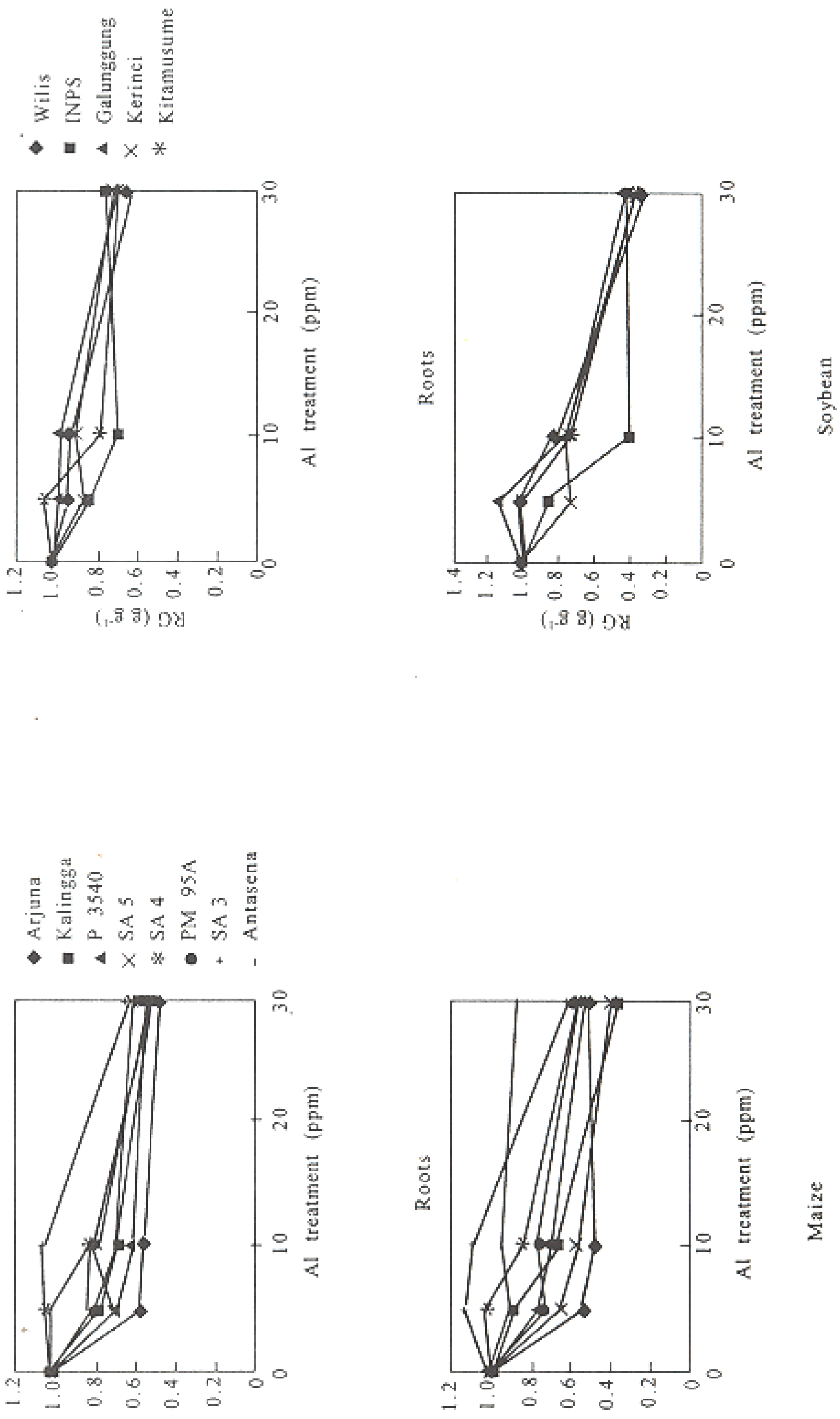

Fig. 2. Relative growth (RG) in shoots and roots of maize and soybean treated with Al.

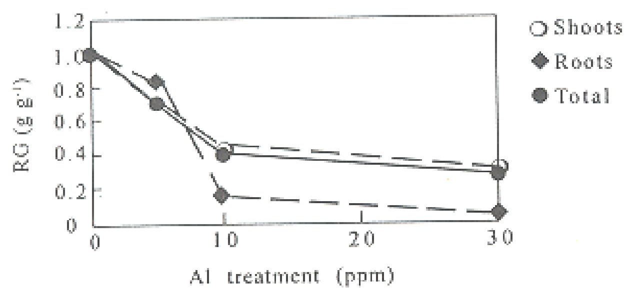

Fig. 3. Relative growth (RG) in shoots and roots of barley var. Ryofu treated with Al:

cultivar (C525-M) was less affected by Al treatment than that of Al-sensitive cultivar (HS7777). While Spehar (1994) reported that in soybean, the effect of Al was stronger in susceptible varieties (UFV-1 and IAC-8) than that in tolerant varieties (IAC-9 and IAC-2).

Low Al level (5 ppm) stimulated plant growth of some varieties tested, such as upland rice (Dodokan and Cirata), lowland rice (RD 23 and KDML 105) (Fig. 1), maize (SA 4 and SA 3), and soybean (Kitamusume and Galunggung) (Fig. 2). The stimulation in plant growth by low Al level was reported by Baligar *et al.* (1995) in sorghum genotypes and by Watanabe *et al.* (1997) in rice var. Michikogane. Osaki *et al.* (1997) also reported that growth of *Leucaena leucocephala* and *L. barbatum* was stimulated by low Al application. However, mechanisms of the stimulation are still not clear. The possible explanation is that low level of Al might aleviate H^+ toxicity (Kinraide,1993) and increase P uptake (Osaki *et al.*, 1997). The prevention of Cu and Mn toxicities was also suggested by Marschner (1997).

Al Tolerance

According to the Al_{RG50} values of roots and shoots, Al tolerance of that species tested was in the order as follows: barley < maize < soybean < lowland rice < upland rice. For maize, the Al tolerance was in the order of Arjuna < Kalingga < P 3540 < SA 5 < SA 4 < PM 95A < SA 3 < Antasena; for soybean was Wilis < INPS < Galunggung < Kerinci < Kitamusume; for lowland rice was RD 23 < Kapuas < Cisadane < KDML 105 < IR 66 < RD 13; and for upland rice was Dodokan < IAC 165 < Cirata < Oryzica sabana 6 < Danau Tempe < Laut Tawar (Table 2).

Plant growth inhibition, especially root inhibition is an indicator of genotypical differences in Al toxicity. It was showed that Al treatment decreased RG of roots and shoots of barley (Fig. 3) and maize (Fig. 2) than that of soybean (Fig. 2) and rice (Fig. 1). Marschner (1997) also found that barley was the most sensitive plant followed by wheat (sensitive/intermediate), ray (intermediate), maize and soybean (intermediate/tolerant), and rice (tolerant).

The use of crops tolerant to Al toxicity in acid soils was suggested to minimize the application of soil amendment. Based on the rank of Al tolerance, rice was the useful crop to be planted in acid soils. In addition, Antasena (maize), Kitamusume (soybean), RD 13 (lowland rice), and Laut Tawar (upland rice) were also recommended for the soils.

P and Ca Uptake

In all varieties, P and Ca concentration was higher in the shoots than that in the roots (Figs. 4-7). In general, P concentration in shoots and roots increased with an increase of Al level in nutrient solution until 10 ppm and decreased with higher concentration of Al (Figs. 4 and 5). Al concentration of more than 10 ppm decreased P concentration in shoots and roots of maize drastically (Fig. 5).

P concentration in shoots of RD 23 (Al sensitive lowland rice) was lower than that of other varieties (Fig. 4), while that of Antasena (Al tolerant maize) was higher than other varieties (Fig. 5). P concentration in shoots and roots of upland rice and soybean was not different (Figs. 4 and 5).

Ca concentration in shoots and roots was higher in maize and soybean than that in upland and lowland rice. In general, Ca concentration in shoots and roots decreased with an increase of Al level in nutrient solution (Figs. 6 and 7). Ca concentration in shoots and roots decreased sharply in maize and soybean than that in upland and lowland rice. Among varieties of upland rice, Ca concentration in shoots of Dodokan (Al sensitive variety) was lower than that of other varieties (Fig. 6). Also in lowland rice, Ca concentration in shoot of RD 23 (Al sensitive variety) was lower than the others. In soybean, Ca concentration in shoot and roots of Wilis (Al sensitive variety) decreased drastically than Kitamusume (Al tolerant variety) (Fig. 7). While in maize, Ca concentration in shoots and roots was not different among varieties (Fig. 7).

P and Ca concentrations in plant tissues decreased with an increase of Al level. Structural and functional damages in the roots by Al reduce nutrient uptake by reducing root absorption area. In addition, high Al

Table 2. Al_{RG50} value of different varieties of lowland rice, upland rice, maize, and soybean.

Crop	Variety	Al_{Rg50} value (ppm)		
		Shoots	Roots	Total
Lowland rice	RD 23	50	42	49
	Kapuas	58	31	51
	Cisadane	62	32	51
	KDML 105	72	57	69
	IR66	87	56	79
	RD 13	> 200	> 200	> 200
Upland rice	Dodokan	50	124	57
	IAC 165	50	> 200	63
	Cirata	67	128	72
	Orizyca sabana 6	80	116	85
	Danau Tempe	81	> 200	103
	Laut Tawar	168	> 200	> 200
Maize	Arjuna	23	25	24
	Kalingga	29	23	28
	P 3540	29	30	29
	SA 5	36	22	32
	SA 4	31	36	32
	PM 95A	32	39	34
	SA 3	45	43	44
	Antasena	41	> 200	50
Soybean	Wilis	42	23	36
	INPS	61	20	38
	Galunggung	49	27	40
	Kerinci	55	23	43
	Kitamusume	46	25	46
Barley	Ryofu	18	11	17

Al_{RG50} = Al concentration when RG (relative growth) decreased by 50%. RG = (DW Al_x - DW 0)/(DW Al_0 - DW 0), where DW Al_x is plant dry weight treated by some Al concentration (g hill^{-1}) after Al treatment; DW Al_0 is plant dry weight without Al treatment (g hill^{-1}) after Al treatment; and DW 0 is plant dry weight at 0 day after Al treatment (g hill^{-1}).

level in nutrient solution enhanced the competitive absorption of Al over Ca and Mg (Marschner, 1997). The decrease of these mineral concentrations in plant tissues with an increase of Al level was more drastic in maize (sensitive crop) than that in other crops. Among varieties of some crops, the decrease of these mineral concentrations with an increase of Al level was more clearly in sensitive variety than that in tolerant variety. In sensitive variety, the structural and functional damages in roots were more serious than that in tolerant variety.

Low Al level (5 ppm) sometimes increased nutrient concentration in plant tissue. Figures 4 and 5 show that P concentration in shoots and roots is generally increased by the low Al level. Figures 6 and 7 also show that the low Al level increased Ca concentration in roots of Cirata (upland rice), in shoots and roots of Cisadane, in roots of RD 13 (lowland rice), in roots of Arjuna (maize), and in shoots of Kitamusume (soybean).

P and Ca concentration in shoots and roots commonly decreased with an increase of Al level. However, sometimes the low Al level (5 ppm) stimulated absorption of P and Ca, which caused increasing P and Ca concentration in shoots and roots. It was mentioned that the low Al level stimulated plant growth, especially roots. The stimulation of root growth by low Al level induces increasing nutrient uptake by roots.

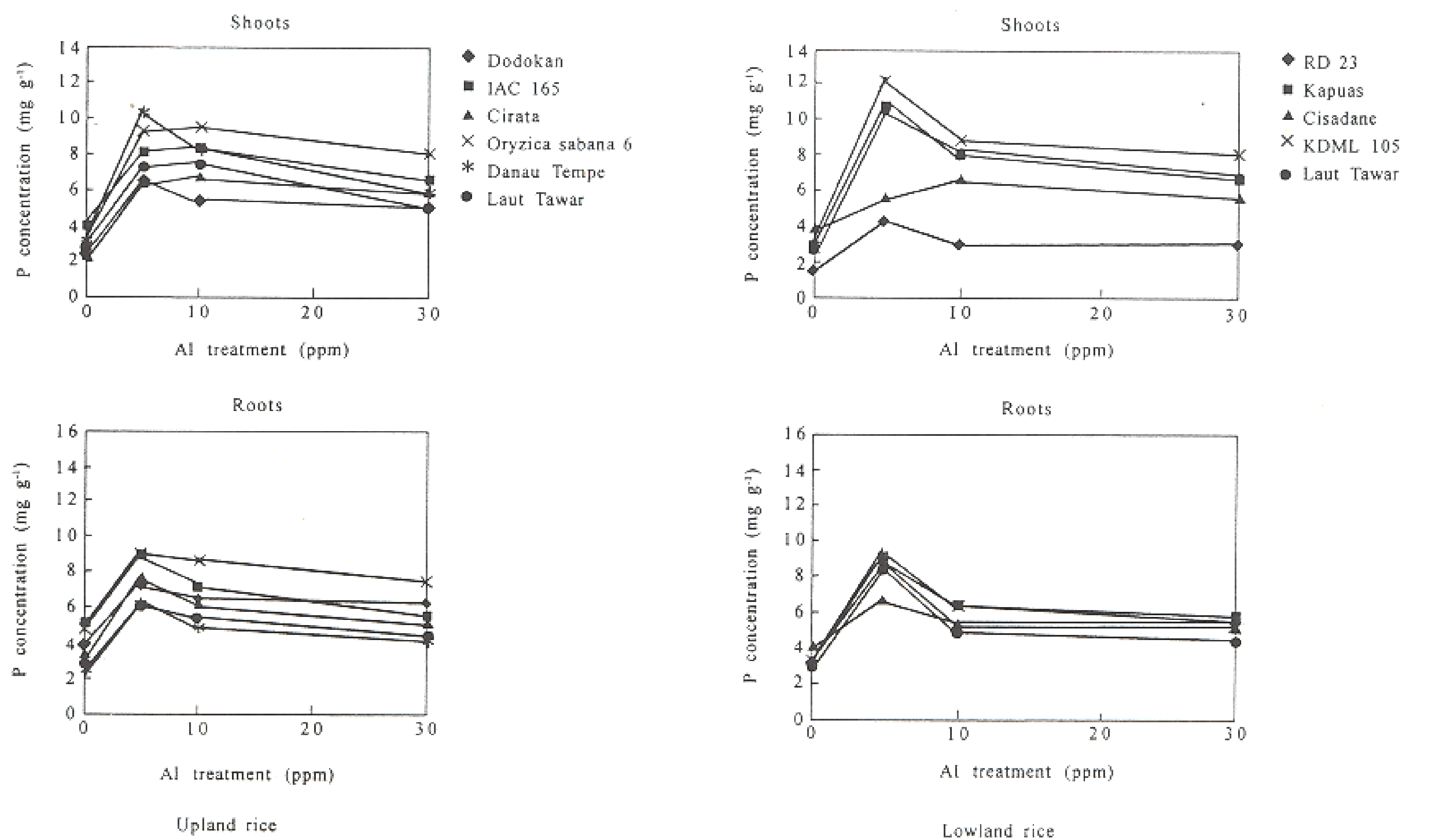

Fig. 4. P concentration in shoots and roots of upland and lowland rice treated with Al.

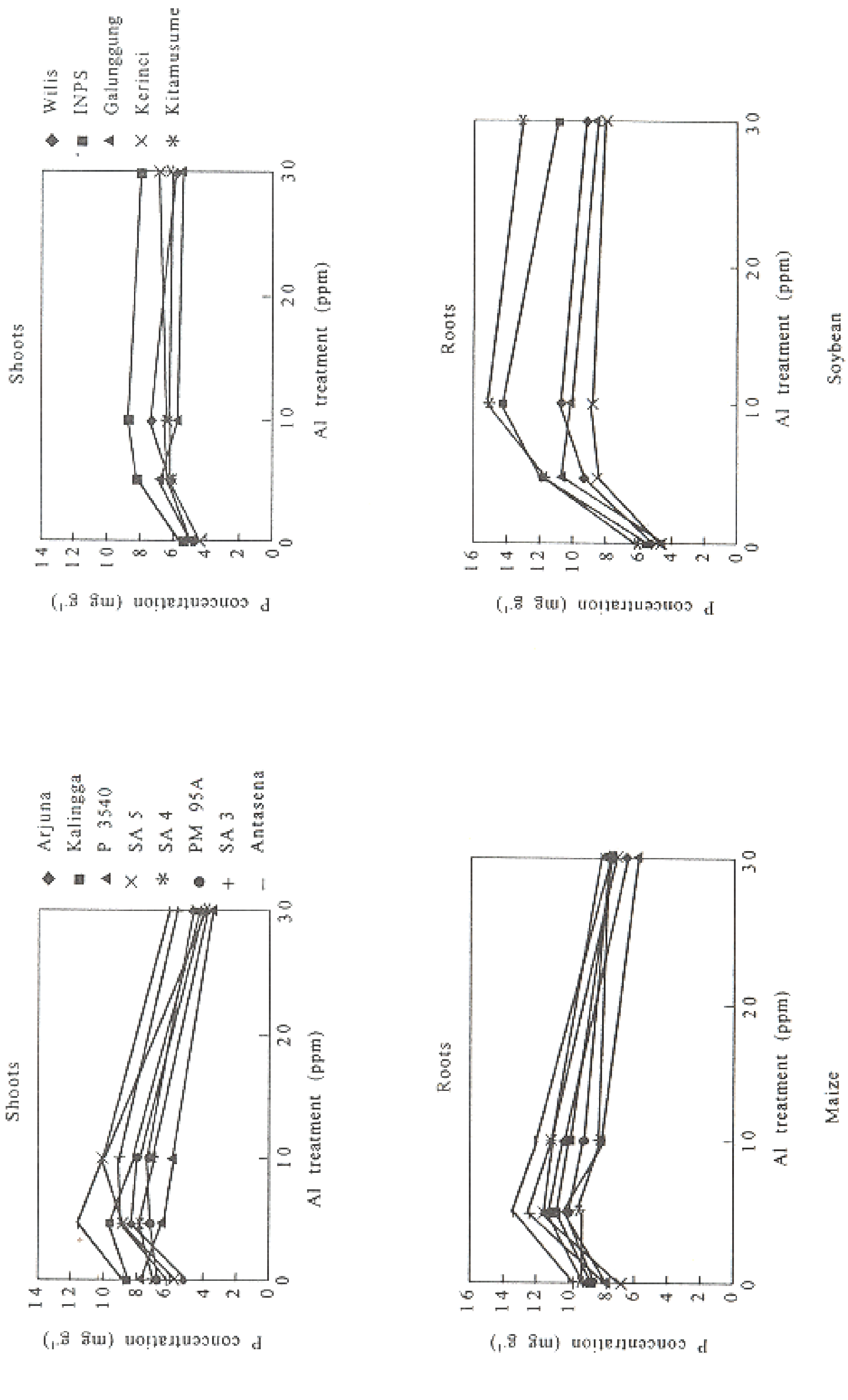

Fig. 5. P concentration in shoots and roots of maize and soybean treated with Al.

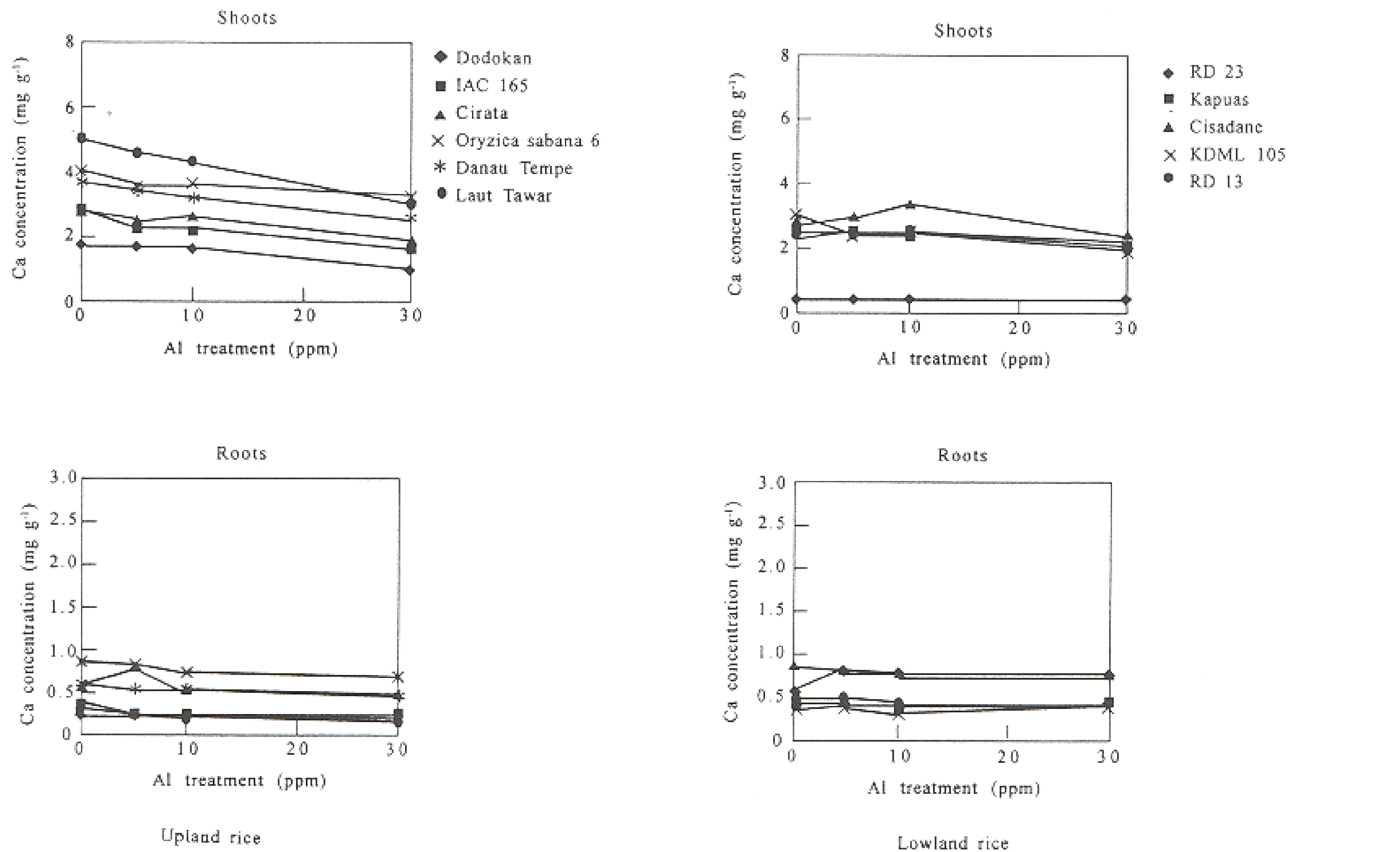

Fig. 6. Ca concentration in shoots and roots of upland and lowland rice treated with Al.

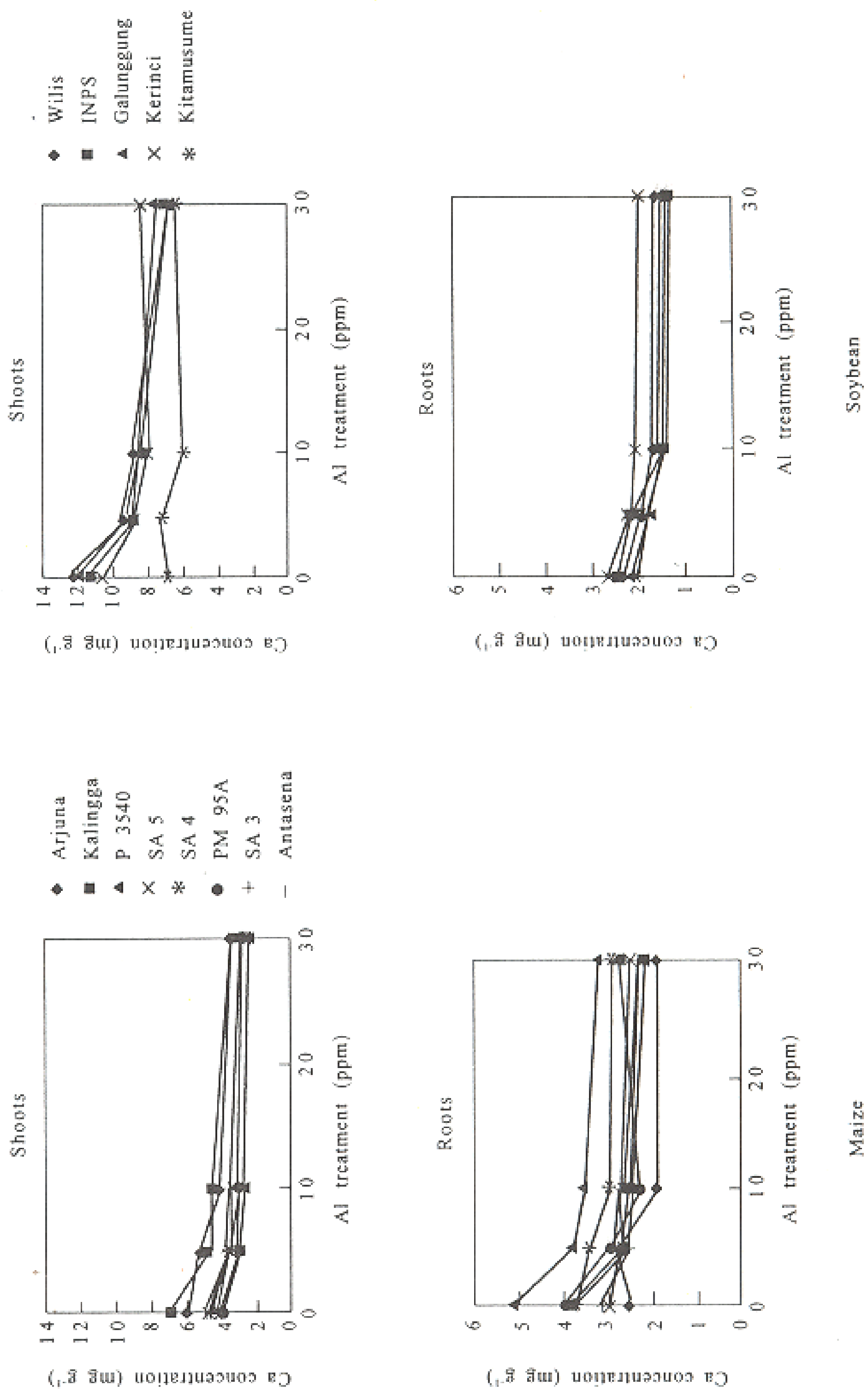

Fig. 7. Ca concentration in shoots and roots of maize and soybean treated with Al.

CONCLUSIONS

Relative growth in shoots and roots of upland rice, lowland rice, maize, and soybean generally decreased with an increase of Al level. However, the low Al level (5 ppm) sometimes stimulated the growth of shoots and roots of some varieties in these species.

According to total Al_{RG50} values, Al tolerance of the species tested was in the order of barley < maize < soybean < lowland rice < upland rice. For maize varieties, the Al tolerance was in the order of Arjuna < Kalingga < P 3540 < SA 5 < SA 4 < PM 95A < SA 3 < Antasena; for soybean was Wilis < INPS < Galunggung < Kerinci < Kitamusume; for lowland rice was RD 23 < Kapuas < Cisadane < KDML 105 < IR 66 < RD 13, and for upland rice was Dodokan < IAC 165 < Cirata < Oryzica sabana 6 < Danau Tempe < Laut Tawar. Based on the rank of Al tolerance, rice was the useful crop to be planted in acid soils. Antasena (maize), Kitamusume (soybean), RD 13 (lowland rice), and Laut Tawar (upland rice) were also recommended for acid soils.

Concentration of P and C in shoots and roots commonly decreased with an increase of Al level. However, sometimes the low Al level (5 ppm) stimulated absorption of P and Ca, which increased P and Ca concentration in shoots and roots.

REFERENCES

Baligar, V.C., I. Anghinoni, G.V.E. Pitta, H.L. Santos, E. Cunha Filho, and R.E. Schaffert. 1995. Aluminum effects on plant and nutrient uptake parameters of soil and solution grown sorghum genotypes. J. Plant Nut. 18 (11): 2325-2338.

Clark, R.B. 1977. Effect of aluminum on growth and mineral elements of Al-tolerant and Al-intolerant corn. Plant Soil 47: 653-662.

Farid Jan. 1991. Aluminum effects on growth, nutrient net uptake and transport in 3 rice (*Oryza sativa*) cultivars with different sensitivity to aluminum. Physiologia Plantarum 83: 441-448.

Foy, C.D., R.L. Chaney, and M.C. White. 1978. The physiology of metal toxicity in plants. Annu. Rev. Plant Physiol. 29: 511-566.

Huang, J.W., D.L. Grunes, and L.V. Kochian. 1992. Aluminum effects on the kinetic of calcium uptake into cells of the wheat root apex. Quantification of calcium fluxes using a calcium-selective vibrating microelectrode. Planta 188: 414-421.

Kinraide, T.B. 1993. Aluminum enhancement of plant growth in acid rooting media. A case of reciprocal alleviation of toxicity by two toxic cations. Physiol. Plant 88: 619-625.

Klotz, F. and W.J. Horst. 1988. Genotypic differences in aluminum tolerance of soybean (*Glycine max* L.) as affected by ammonium and nitrate-nitrogen nutrition. J. Plant Physiol. 132: 702-707.

Kruger, E. and E. Sucoff. 1989. Aluminum and the hydraulic conductivity of *Quercus rubra* L. root systems. J. Exp. Bot. 40: 659-665

Marschner, H. 1997. Mineral nutrition of higher plants. Second edition. Academic Press, Harcourt Brace & Company, Publishers, London.

Osaki, M., T. Watanabe, and T. Tadano. 1997. Beneficial effect of aluminum on growth of plants adapted to low pH soils. Soil Sci. Plant Nutr. 43 (3): 551-563.

Pintro, J., J. Barloy, and Fallavier. 1996. Aluminum effects on the growth and mineral composition of corn plants cultivated in nutrient solution at low aluminum activity. J. Plant Nut. 19 (5): 729-741.

Rengel, Z. 1992. Role of calcium in aluminum toxicity. New Phytol. 121: 499-514.

Spehar, C.R. 1994. Aluminum tolerance of soya bean genotypes in short terms experiments. Euphytica 76: 73-80.

Taylor, G.J. and C.D. Foy. 1985. Mechanisms of aluminum tolerance in *Triticum aestivum* L. (wheat) III. Long-term pH changes induced in nutrient solutions by winter cultivars differing in tolerance to aluminum. J. Plant Nutr. 8: 613-628.

Taylor, G.J. 1988. Mechanisms of aluminum tolerance in *Triticum aestivum* (wheat). V. Nitrogen nutrition, plant induced pH, and tolerance to aluminum; correlation without causality? Can. J. Bot. 66: 694-699.

Watanabe, T., M. Osaki, and T. Tadano. 1997. Aluminum-induced growth stimulation in relation to calcium, magnesium, and silicate nutrition in *Melastoma malabathricum* L. Soil Sci. Plant Nutr. 43(4): 827-837.