

† EFFECT OF ALUMINIUM ON GROWTH OF TEA (*CAMELLIA SINENSIS*) AND ITS UPTAKE OF POTASSIUM AND PHOSPHORUS

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Tea seedlings were grown for up to 10 months in the glasshouse in an acid soil, to which solutions of varying K/Al concentration ratios were given weekly. During growth, the %K in the leaf dry matter increased with the labile K concentration but was not influenced by the Al concentration in the soil. However, the largest level of Al in soil decreased plant growth and %K in the dry matter. At this level of Al in soil, plant height, number of leaves, dry matter and %K in the dry matter increased linearly with the K given to the soil. The %Al in the plant was not affected by the labile K and Al contents of the soil.

A highly significant linear relationship was observed between Al and P uptake by parts of the plant and by the whole plant, even though the soil was not treated with P as a basal nutrient. The Al/P ratios in the first mature leaf, total leaves and stems were 3.4, 3.0 and 0.8, respectively, after 6 months growth. Uptake mechanisms are proposed to explain this.

INTRODUCTION

Most plants contain not more than 200 ppm aluminium but tea, an 'aluminium accumulator', may contain as much as 20,000 ppm in mature leaves. The accumulated Al varies considerably with leaf age, maturity and genetics of the plant, rainfall, altitude and soil,¹ and it was found that the tea bush takes up Al throughout its life and stores it in the leaves. Young leaves contain only 50–100 ppm Al; this increases to between 5000 and 16,000 ppm, depending on genetic variation, in leaves about to fall. In the flush, leaf Al content increases progressively, from 50 to 1500 ppm, from the bud to the mature leaf.

Tea grows well in soil of pH < 5.0 in which ionic Al is very mobile, thus suggesting that Al is not detrimental to this plant. There seems to be no mechanism in the roots to inhibit its absorption.² The function of the large amounts of Al taken up by tea is still unknown. It has been suggested that Al prevents copper toxicity in citrus³ and manganese toxicity in *Atriplex*.⁴

The tolerance of plant species to Al is closely related to their abilities to absorb and use P in the presence of Al,^{5,6} but Ouellette & Dessureaux⁷ showed that changes in the Al tolerance of lucerne clones was not caused by the Al-P interaction. The distribution and mobility of phosphorus in the tea bush seems unaffected by the considerable range in Al content, although Al immobilises soil P as insoluble, organic and inorganic phosphate. Growing points, such as shoot and root tips, contain most of the P, but P level diminishes as the age of the leaf increases. The youngest leaves, stems and mature roots contain very little Al, which probably accounts for the lack of interference with P movement.¹

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Tolerance to aluminium is also attributed to the formation of strong aluminium-organic complexes within the plant. Most acidophilous plants contain strong organic buffer systems in the cell sap.⁸ Jones⁹ examined the complexing capacity of root macerates of mustard and suggested that complexing agents in plants may be commonly occurring organic acids, e.g., oxalic, malic and, possibly, tartaric and citric acids. De Kock & Mitchell¹⁰ showed that mustard, an aluminium-tolerant plant, absorbed the element from nutrient solutions when present as a complex, probably uncharged or with unit charge, with EDTA, nitrilotriacetic acid, or diethylenetriaminepenta-acetic acid. Rees & Sidrak⁴ showed that the Al-EDTA complex was beneficial to *Atriplex* and other Al-tolerant plants, but it was harmful to spinach and barley.

Little is quantitatively known of the effect of soil Al and K on growth and on uptake of K and P by the tea plant. The importance of this to modern intensive tea growing is evident. The glasshouse experiments described in this paper were designed to examine these effects, to derive from them the levels of Al and K which limit growth and to examine Al-P interactions within the plant.

EXPERIMENTAL

Materials

Soil, taken from the Exhaustion Land Experiments Headland at Rothamsted, North of Plot 2 (18% clay, pH 3.9, in 0.01 M-CaCl₂) had been cropped continuously with barley and given no manure since 1852. Each pot (12 cm dia., 1 litre capacity) contained 700 g soil (< 2 mm).

Thirty-six-week old seedlings of *Camellia sinensis*, selected for uniformity from a large batch, were separated according to size into 'large plant' (18 cm height and with more than 8 leaves) (Experiment I) and 'small plant' (Experiment II) blocks.

A factorial combination of 100 ml K₂SO₄ (0, 2 and 4 × 10⁻⁴M-K) and Al₂(SO₄)₃ (0.00, 0.50, 1.25 and 2.50 × 10⁻⁴M-Al) solutions were given to the appropriate pots (in triplicate) on alternate days for 6 to 10 months. Nitrogen was given weekly as ammonium sulphate at the rate of 10 mg N per pot.

Sampling

The soil was sampled at 2-month intervals for 6 months from each pot with a 0.25 in (1 in = 0.025 m) auger, 6 holes per sampling, to three-quarters of the pot depth. The samples (at field capacity) from 6 replicates in experiments I and II were mixed together, without drying out, for cation and pH analyses.

The first mature leaf (the 3rd or 4th leaf from the bud) was taken from each plant at intervals of 2 months for 6 months and analysed for Al, K and P. Concurrently, plant height was measured and the leaves were counted.

After 6 months, one replicate in experiment I and all plants in experiment II were analysed as follows. The whole plant was separated from the soil, the roots were washed free from soil particles with water and the fresh weight of the leaves, stems and roots was measured. The leaves, stems and roots were then oven-dried at 100°C for 24 h and the dry weight was determined.

The remaining replicates in experiment I were given soil treatments for a further 4 months, as previously described. In addition, half the pots in one replicate were treated with 0.5 g P as inositol hexaphosphate and the other half, as sodium dihydrogen phosphate. The first mature leaf from each pot was analysed at 2-month intervals for K, Al and P. At the end of 10 months, the whole plant was separated from the soil and the fresh and dry weights were measured.

Analyses

Equilibrium K and Al in soil solution

Wet soil (10 g) was shaken with 10 ml of water at room temperature ($\sim 20^\circ\text{C}$) for 24 h, centrifuged at $12,000 \times g$ for 30 min and the supernatant solution analysed for K with an EEL (Evans Electro Selenium Ltd) flame photometer, and for Al by the aluminon method¹¹ on a spectrophotometer (Unicam SP500).

Exchangeable cations

Damp soil (1 g) was leached with 200 ml N-NH₄Cl adjusted to the pH of the soil, and the leachate collected at 3-h intervals for 24 h. The exchangeable Al and K were obtained by the method of Sivasubramaniam & Thalibudeen.¹²

Plant parts

Leaf and stem samples were oven-dried at 85°C for 24 h and ground to < 60 mesh in a 'Glencreston' hammer mill. Ground samples (0.2 g) were ashed in a muffle furnace at 450°C for 1 h,¹³ dried on a water bath with 2×10 ml 0.2 N-HCl and then dissolved in 25 ml 0.05 N-HCl. Solutions were analysed for Al and K by the methods described above, and for P by the method of Fogg & Wilkinson¹⁴ in a Technicon 'Auto Analyzer', using ascorbic acid for the reduction step.

RESULTS AND DISCUSSION

Changes in soil composition during cropping

All pots received 10 mg N as ammonium sulphate weekly during the experiment (equivalent to 750 kg/ha/year, compared with field applications of 170 to 560 kg/ha on most Ceylon estates).

Tables 1 and 2 give the amounts of Al and K (and the pH in 0.01 M-CaCl₂) in the equilibrium soil solution and on exchange sites of the soil, for the twelve treatments. Table 1 shows that, with increasing amounts of ammonium, potassium and aluminium sulphate, the pH of the soil decreased steadily from 3.95 to 3.50, as also occurred in pots not given Al. This indicates that the decrease in pH was caused by the addition of ammonium sulphate and not by aluminium sulphate. At this acidity, the hydrolysis of Al³⁺ contributes little if anything to this pH decrease. Increasing the amount of Al applied increased Al in the equilibrium solution from 0.20 to $2.50 \times 10^{-3}\text{M}$; the exchangeable Al increased only from 3.5 to 5.3 mequiv./100 g. The K concentration in the equilibrium solution increased from 1.2 to $10.0 \times 10^{-3}\text{M}$ (50 to 400 ppm) and on exchange sites from 0.10 to 3.40 mequiv. 100 g. With the three larger amounts of Al given, the concentration of K in equilibrium soil solution and on exchange sites decreased considerably, which suggests that most of the K applied was leached down the soil. The significance of this on the uptake of K by the tea seedlings is discussed later.

TABLE 1—*pH values (in 0.01 M-CaCl₂) and K and Al concentrations in the equilibrium soil solutions after cropping for 2-6 months*

Treatments	2 months			4 months			6 months			
	Al, ppm	K, ppm	pH	Al, ppm	K, ppm	pH	Al, ppm	K, ppm	pH	
Al ₀	K ₀	5.5	5.0	3.68	9.4	5.3	3.54	3.0	3.6	3.52
	K ₁	5.1	74.0	3.70	9.6	145.0	3.68	4.5	105.0	3.52
	K ₂	5.4	200.00	3.70	9.2	322.5	3.70	6.0	320.0	3.52
Al ₁	K ₀	9.0	13.5	3.70	13.2	2.0	3.59	15.0	7.4	3.58
	K ₁	9.4	98.0	3.72	13.6	180.0	3.57	18.9	170.0	3.56
	K ₂	9.0	176.0	3.72	13.8	315.0	3.70	19.1	420.0	3.50
Al ₂	K ₀	18.0	7.0	3.68	29.5	1.8	3.55	27.0	4.5	3.54
	K ₁	14.3	104.0	3.68	29.5	185.0	3.52	24.0	140.0	3.44
	K ₂	14.1	132.0	3.66	25.0	355.0	3.52	33.0	380.0	3.44
Al ₃	K ₀	24.0	8.6	3.62	44.0	2.0	3.50	58.5	7.4	3.54
	K ₁	20.0	86.0	3.60	60.5	165.0	3.52	64.5	135.0	3.44
	K ₂	25.0	188.0	3.64	76.5	315.0	3.51	66.0	285.0	3.52

Values before cropping: Al = 5.4 ppm (0.20 M); K = 7.0 ppm (0.18 M); pH = 3.95 in 0.01 M-CaCl₂

TABLE 2—*Exchangeable K and Al in the soil after cropping*

Treatments	2 months		4 months		6 months		
	Al, mequiv./100 g	K, mequiv./100 g	Al, mequiv./100 g	k, mequiv./100 g	Al, mequiv./100 g	K, mequiv./100 g	
Al ₀	K ₀	3.6	0.09	3.75	0.10	3.54	0.06
	K ₁	3.6	0.80	3.30	1.06	3.36	1.73
	K ₂	3.5	1.66	3.14	1.88	3.40	3.42
Al ₁	K ₀	4.5	0.10	4.60	0.11	4.20	0.10
	K ₁	3.5	0.85	4.35	1.10	3.89	1.56
	K ₂	3.1	1.50	4.25	1.77	3.62	3.33
Al ₂	K ₀	4.9	0.14	4.95	0.11	4.39	0.06
	K ₁	4.8	0.79	4.13	0.99	3.90	1.10
	K ₂	3.7	1.27	4.05	1.65	3.93	2.23
Al ₃	K ₀	5.8	0.14	5.93	0.11	5.34	0.13
	K ₁	5.5	0.75	5.35	0.88	5.03	1.22
	K ₂	5.3	1.34	4.90	1.69	5.34	2.34

Values before cropping: exchangeable Al = 3.50 mequiv./100 g; exchangeable K = 0.09 mequiv./100 g

Elsewhere, these results are recalculated for K-Al exchange and compared with those from a laboratory experiment with this soil, to show that the long and short term K-Al exchange patterns are identical and to indicate the K selectivity of the soils.¹⁵

Effect of K and Al treatments of the soil on growth of tea seedlings

Plant heights and number of leaves were measured at 2-month intervals for 6 months and statistically analysed for the 'small' and 'large' blocks separately. Only the analyses for the significant results are given because the samplings at 2 and 4 months showed similar trends.

The K and Al treatments had no significant effect on plant heights of the 'large' plants. There were qualitative indications that increasing the K concentration increased the plant height, while increasing the Al₃ concentration to Al₂ decreased the height; with 'small' plants, these effects were statistically significant (Table 3). Also at the Al₃ concentration, increasing K concentrations greatly increased plant height.

TABLE 3 — *Effect of K and Al treatments on the height (cm) of 'small' plants after 6 months cropping*

	Al ₀	Al ₁	Al ₂	Al ₃	Mean	S.E.	L.S.D.	
							P = 0.05	P = 0.01
K ₀	32.0	36.7	44.7	21.0	33.6	± 2.43	6.8	9.5
K ₁	53.7	47.0	45.3	25.3	42.8			
K ₂	34.7	37.0	34.7	35.7	35.5			
Mean	40.1	40.2	41.6	27.3		± 4.85	13.5	19.0
						± 2.80	7.8	11.0

TABLE 4 — *Effect of Al and K treatments on the number of leaves of 'small' plants after 6 months*

	Al ₀	Al ₁	Al ₂	Al ₃	Mean	S.E.	L.S.D.
							(P = 0.05)
K ₀	11.7	14.0	18.0	11.7	13.9	± 1.09	3.1
K ₁	15.0	19.3	20.3	11.7	16.6		
K ₂	15.7	14.7	13.3	12.3	13.9		
Mean	14.1	15.9	17.3	11.9		± 2.18	6.1
						± 1.26	3.5

In neither block of plants was any difference in the number of leaves observed with increases in K concentration. Al concentrations above Al₂ treatment, (1.0×10^{-4} M-Al in the equilibrium soil solution) usually produced fewer leaves in 'large' and 'small' plants, but the effect was only significant ($P = 0.05$) in the latter (Table 4). This effect is similar to that observed with plant height.

After 6 months, the dry matter weights of all 'small' plants and only one replicate (12 plants) of the 'large' plants were recorded. Table 5 shows that the dry matter content of the 'small' plants increased significantly from K₀ to K₁ but the decrease from K₁ to K₂ treatment was not significant.

The largest amount of soil aluminium, Al₃, decreased the dry matter yield highly significantly ($P = 0.001$). At this level of Al, increasing the soil K concentrations increased the dry matter yield significantly, i.e. with this amount of exchangeable and solution aluminium, the tea plant responded almost quantitatively to K treatment. Qualitatively the dry matter yield of the 'large' plants was not affected by the K treatments but Al₀ treatments more than Al₁ decreased the dry matter value.

The growth indices, i.e. number of leaves and height and dry matter content of the plant, show that for 'small' and 'large' plants, increasing soil K concentrations significantly increased growth. Smaller concentrations of Al ($0.2-1.0 \times 10^{-3}$ M in the equilibrium soil solution) did not affect the growth of the plant. The largest concentration investigated (2.0×10^{-3} M-Al in the soil solution) retarded plant growth and, at this concentration, increasing K concentrations had a beneficial effect.

TABLE 5 — *Effect of K and Al treatments on the total oven-dry weight (g) of 'small' plants*

	Al ₀	Al ₁	Al ₂	Al ₃	Mean	S.E.	L.S.D.		
							P = 0.05	P = 0.01	P = 0.001
K ₀	4.67	6.70	7.00	2.60	5.24	±0.65	1.8	2.6	3.5
K ₁	7.97	9.00	9.73	3.70	7.60				
K ₂	5.77	5.97	6.47	4.23	5.60				
Mean	6.13	7.22	7.73	3.51		±1.30	3.6	5.1	6.9
						±0.75	2.1	3.0	4.0

TABLE 6 — *% K in the first mature leaf after six months cropping of 'large' plants*

	Al ₀	Al ₁	Al ₂	Al ₃	Mean	S.E.	L.S.D.		
							P = 0.05	P = 0.01	P = 0.001
K ₀	0.56	0.57	0.66	0.92	0.68	±0.10	0.28	0.40	0.53
K ₁	1.72	1.51	1.50	1.57	1.58				
K ₂	1.63	2.00	1.64	1.88	1.79				
Mean	1.30	1.36	1.27	1.46		±0.19	0.53	0.75	1.00
						±0.11	0.31	0.43	0.58

Uptake of potassium and aluminium by tea seedlings

The % K and % Al (on a dry matter basis) in the first mature leaves were, measured for 'large' and 'small' plants at 2-month intervals for 6 months. Table 6 shows that the soil Al concentration did not affect the leaf K concentration in 'large' and 'small' plants. At the highest Al concentration, increasing the K concentration in the soil solution increased the % K in the leaf, similar to the dry matter yield at 6 months. Plotting % K in the leaf against the molar K/Al ratio in the equilibrium soil solution (Fig. 1) shows that at K/Al ratios in the soil solution below a critical value, plant performance, as measured by the K concentration in the leaf, was adversely and acutely affected by increasing soil Al concentration and favourably by increasing K. The critical K/Al ratio in the equilibrium soil solution in these experiments was between 1.5 to 3.0.

The %Al in the first mature leaf of 'large' and 'small' plants did not vary with increasing soil Al concentration (Fig 2). This suggests that the tea plant has some mechanism for controlling Al uptake even when concentrations in the soil are high, contrary to the suggestion of Chenery² that tea has no mechanism in the roots to inhibit absorption of Al.

Interaction between aluminium and phosphorus uptake

Plant tolerance to soil Al has been attributed to the Al-P interaction⁵ and to the formation of organic complexes in the plant.⁹

During cropping, phosphate was not given to the soil and the P concentration in the first mature leaf decreased with Al concentration (Fig. 3). The uptakes of Al and P by 'small' plants after 6 months cropping were measured. Their inter-relationship is shown in Fig. 3; the correlation is highly significant (P = 0.001). The regression coefficient ($b = 2.97 \pm 0.27$) suggests that 3 moles of Al are associated with one mole of P. At the pH of the soil (3.5–4.0), a univalent cation, containing (Al³⁺) only, is probably a co-ordination complex of Al³⁺ with organic anions. De Kock & Mitchell¹⁰ demonstrated that plants easily absorb Al-organic complexes with univalent charge or no charge.

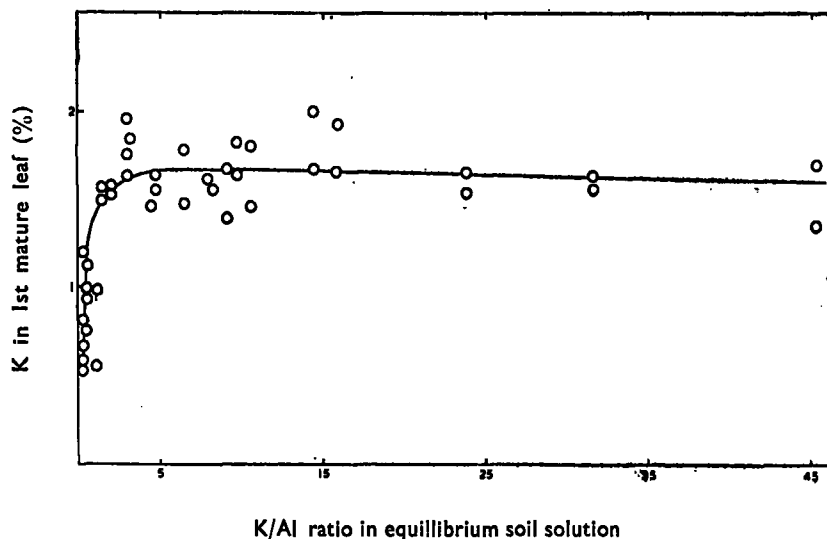


FIG. 1—Effect of the K/Al ratio in the equilibrium soil solution on % K in the 1st mature leaf

The relationships between the uptake of Al and P by all leaves and stems, separately, were statistically analysed (Fig. 3). In both cases, the correlation between the Al and P contents is very significant ($P = 0.001$). The regression coefficients are 3.42 ± 0.41 and 0.80 ± 0.10 for the Al-P interaction in the leaves and stems, respectively, indicating that the distribution of Al and P changes within the plant during growth. These results suggest that the active uptake of Al by tea is possibly as an inorganic complex of molar Al/P ratio of 1. It may be that Al accumulates in the leaf through a 'phosphate pump' cycling between root and leaf. but because of the limited number of plants available it was not possible to test this hypothesis.

After 6 months cropping, either inositol hexaphosphate (Na salt) or sodium dihydrogen phosphate was given to 'large' plants. The % P and % Al in the first mature leaf were measured after cropping for 8 months and the analyses qualitatively compared (Table 7). The inositol hexaphosphate had no effect on P and Al uptake, but NaH_2PO_4 increased the concentration of Al and P in the leaf. This result supports the mechanism suggested above for accumulation of Al in the tea plant.

TABLE 7 — % Al and % P in leaves at 10 months after addition of inositol phosphate and NaH_2PO_4 to the soil at 6 months

Al or P, %	No P added	Inositol hexaphosphate	NaH_2PO_4
P	0.043	0.054	0.074
Al	0.047	0.048	0.275

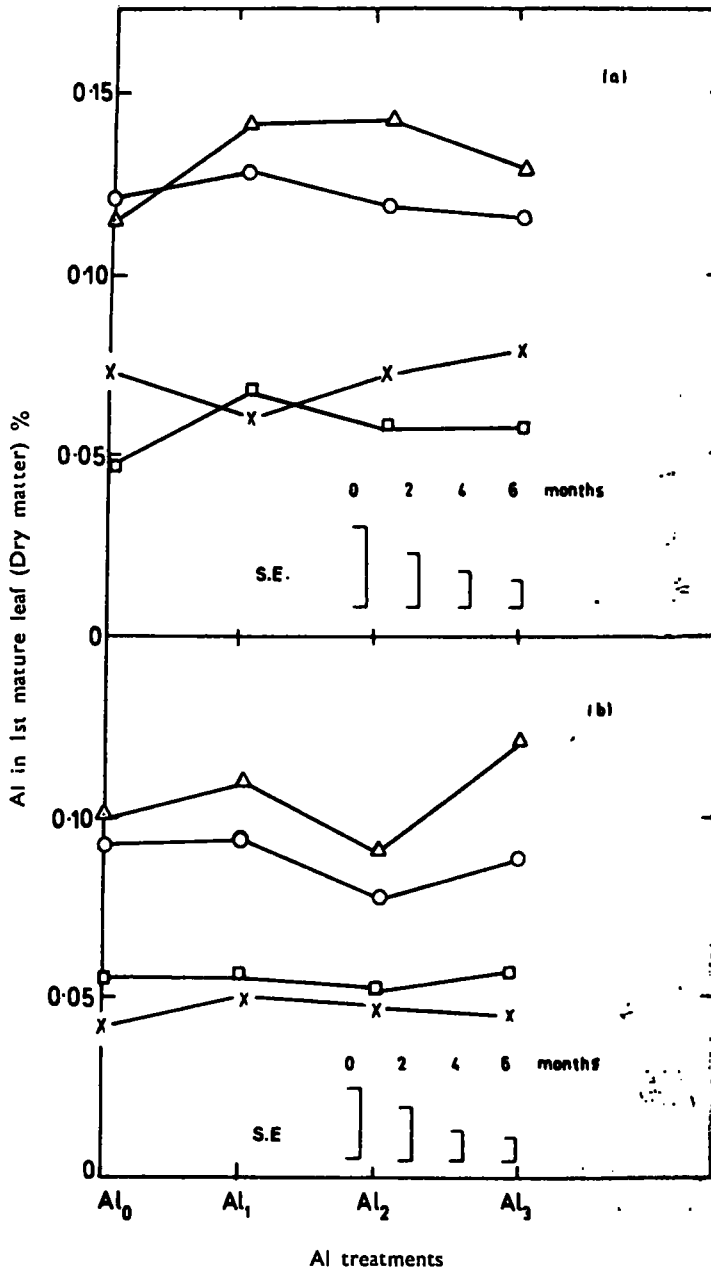


FIG. 2—% Al in the 1st mature leaf vs Al treatments for (a) 'large' and (b) 'small' plants

○ — 0; △ 2; × 4, □ 6 months

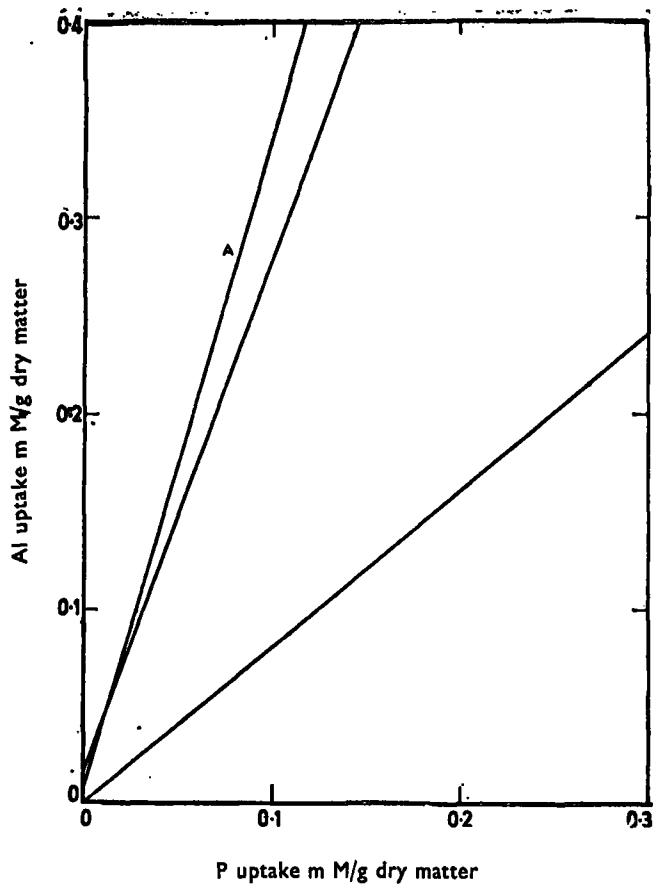


FIG. 3—Relationship between Al and P uptake in (A) first mature leaf ($b = 3.424 \pm 0.405$, $r^2 = 0.68^{***}$), (B) all leaves and stems (2.789 ± 0.77 , 0.76^{***}) and (C) stems (0.800 ± 0.101 , 0.65^{***}) after 6 months cropping

The tea plant contains appreciable amounts of organic acids, e.g. oxalic acid,¹⁶ and polyphenols,¹⁷ distributed in varying amounts in different plant parts. Chenery¹ qualitatively compared the distribution of Al and P in tea plants and concluded, that there is no Al-P interaction in the plant. However, Jones⁹ showed that Al^{3+} forms strong complexes with organic acids, such as oxalic acid, in the mustard plant. Roberts¹⁸ isolated 23 flavonols and identified quercetin, myricetin and kaempferol in tea. These flavonols, with free 5- or 3- hydroxyl groups, form strong complexes with Al^{3+} .¹⁹

A possible mechanism for the uptake of Al-P by tea may be that at a soil pH 3.9, complex cations of Al^{3+} and $H_2PO_4^-$ ions with an Al/P ratio of 1 form less charged ions, or even neutral molecules, (with or without soil organic acids), which move passively into the plant. Such Al-P ions or molecules move to the leaves, where they are synthesised into large complex molecules with organic acids, polyphenols, carbohydrates or nucleoproteins, depending on the distribution of these within the tea plant. Some P then returns to the roots and helps in moving more Al from the roots to the leaves, which results in an increase in the amounts of Al in the leaves relative to P, as the plant grows.

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