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ALUMINIUM TOXICITY TOLERANCE OF DIFFERENT VARIETIES OF OIL PALM (*Elaeis guineensis* L. Jacq) SEEDLINGS

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ABSTRACT

Aluminium (Al) toxicity is one of the problems experienced by crops cultivated on acid soil, inhibiting root growth and nutrient absorption capability. This study evaluated the effects of different concentrations of Al-toxicity (0 μM-control; 100, 200 and 300 μM) on the physiological growth, chlorophyll content and selected nutrient uptake in roots and shoots of different varieties of oil palm seedlings, specifically the Elite Deli Dura *x BM119 AVROS* Pisifera*, Elite Deli* Dura *x Elite AVROS* Pisifera*, Ulu Remis Deli* Dura *x Dumpy AVROS and Ulu Remis Deli* Dura *x Ulu Remis* Tenera *varieties. Results showed that Al-toxicity has no significant effect on the height of shoots for all oil palm seedling varieties. The Ulu Remis Deli* Dura *x Ulu Remis* Tenera *seedlings appeared to be more tolerant, showing no significant effect on bole diameter, chlorophyll content and biomass of both shoot and roots upon Al-toxicity treatment. For selected nutrient uptake, all tested oil palm seedling varieties showed significant effects upon Al-toxicity treatment primarily from the 100 μM Al-toxicity application. The findings from this study suggested that the Elite Deli* Dura *x BM119 AVROS* Pisifera *oil palm variety exhibited the lowest tolerance towards Al-toxicity compared to the other oil palm varieties tested.*

Keywords: aluminium, oil palm, seedling, tolerance, toxicity.

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INTRODUCTION

Approximately 72% of the land area in Malaysia is from the soil order of Ultisols and Oxisols, which contain kaolinite, gibbsite, goethite, and hematite in the clay fractions (Shamshuddin and Noordin, 2011). These soils are often deep red, friable and high in iron (Fe) and aluminium oxide content. Aluminium (Al) toxicity is a major constraint that could limit plant development, eventually affecting crop yield. Research showed that there is a close relationship between exchangeable Al and root density of mature oil palms (Cristancho *et al*., 2007). The most observed symptom of Al-toxicity in plants is the inhibition of root growth. The study by Cristancho *et al*. (2011) showed that there is a significant interaction between the Al concentration and oil palm progeny on the number of leaves, root volume, lateral root growth length, magnesium (Mg) and potassium (K) content in root and shoot tissues, and calcium (Ca) and natrium (Na) content in shoot tissues. Different Al concentrations also significantly affect the morphology and physiology of oil palm varieties (Nanang *et al.*, 2014).

The physicochemical properties of soils in an oil palm agro-ecosystem will change with time. These changes are often related to the soil pH, which tends to decrease over time (Ng *et al.*, 2011). A high rate of fertilisers applied around the palm base planted on Musang series soil for seven

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years led to a marked decline in soil pH to 3.8, a reduction of almost 10% (Kee *et al*., 1995; Nelson *et al.,* 2018). Continuous decline of soil pH will increase the availability of Al in the soil and may affect the morphology and physiology of oil palm seedlings. Kochian *et al.* (2004) found that when soil pH is below 5.0, Al^{3+}, which is the most rhizotoxic Al species, is solubilised in the soil. High concentrations of Al in the soil result in a toxic Al level which affects growth performance of crops. Kochian (1995) and Yang and Horst (2015) found that Al-toxicity inhibits root growth while Krstic *et al*. (2012) showed that there is inhibition of root elongation, resulting in extensive root injury which leads to difficulties in nutrient and water uptake by the crop. Root growth in mature oil palms is reduced by 0.1 cm cm^{-3} soil due to 1 cmol of exchangeable Al kg^{-1} soil (Cristancho *et al*., 2007). Al also significantly affects the primary root growth of oil palm seedlings from different varieties (Nanang *et al*., 2014).

Many of the existing studies lack comprehensive data regarding the Al-toxicity tolerance of specific oil palm varieties. The genetic diversity present within oil palm seedlings may lead to variations in their ability to tolerate Al-toxicity. It is important to understand how distinct varieties respond to Al-toxicity to formulate targeted and effective planting management strategies. Consequently, the identification and characterisation of genotypic differences in tolerance levels can contribute significantly to the development of more resilient and productive oil palm varieties. As such, this study intended to evaluate the effects of different concentrations of Al-toxicity on the growth and chlorophyll content in oil palm seedlings and to examine the effects of nutrient uptake in roots and shoots of different varieties of oil palm seedlings due to Al-toxicity.

MATERIALS AND METHODS

Study Area

This study was conducted under greenhouse-controlled conditions located at the Faculty of Plantation and Agrotechnology, UiTM Kampus Jasin, Melaka, Malaysia. The mean daily temperature was 20°C-32°C with average rainfall 2200-2400 mm yr^{-1} (Malaysian Meteorology Department, 2017).

Oil Palm Seeds Preparation

Four different oil palm varieties were used, *i.e.* Elite Deli *Dura* x BM119 AVROS *Pisifera*, Elite Deli *Dura* x Elite AVROS *Pisifera*, Ulu Remis Deli *Dura* x Dumpy AVROS and Ulu Remis Deli *Dura* x Ulu Remis *Tenera*. Their germinated seeds were collected from a local company and sown in a hydroponic system. These varieties were selected based on the major planting materials being used by plantations in Malaysia.

Preparation of Nutrient Solution

The Hoagland nutrient solution (*Table 1*) was prepared according to Nanang *et al.* (2014).

TABLE 1. NUTRIENT COMPOSITION IN 1 L OF SOLUTION

No.	Mineral salts	Molarity	Quantity
1	$Ca(NO_3)_2.4H_2O$	1	5.00 mL
2	KNO_3	1	5.00 mL
3	KH_2PO_4	1	1.00 mL
4	$MgSO_4.7H_2O$	1	2.00 mL
5	H_3BO_3	-	2.86 g
6	$MnCl_2.4H_2O$	-	1.81 g
7	$ZnSO_4.7H_2O$	-	0.22 g
8	$CuSO_4.5H_2O$	-	0.08 g
9	$H_2MoO_4.H_2O$	-	0.02 g
10	Fe EDTA	-	1.00 mL

Al Treatment

Four different Al concentrations were applied to four different varieties of oil palm seeds after transplanting to the hydroponic system. The Al concentrations applied were: Treatment 0 (control), Treatment 1 (100 µM), Treatment 2 (200 µM), and Treatment 3 (300 µM). The range of treatments was based on the findings from Christancho *et al.* (2011). Al chloride ($AlCl_3.6H_2O$) was used as the Al source. Al chloride was mixed evenly into the nutrient solution at different concentrations according to the treatments. For control treatment, the pH was set at pH 5.5 (Nanang *et al.,* 2014) which mimics the average soil pH in Malaysia, while the other Al treatments were adjusted to approximately pH 4.0 to ensure the availability of the Al. The pH adjustment was conducted by the addition of sulfuric acid (H_2SO_4) into the nutrient solution. The Al solution was monitored and replenished once a week to ensure that the concentration of Al was stable and constant.

Field Preparation

The oil palm seedlings were transplanted into a hydroponic system. Each tray containing 20 L of aerated Hoagland nutrient solution was replenished once a week. Dimensions of the hydroponic basin were 410 x 240 x 140 mm and each tray contained four different varieties of oil palm seedlings. There were 16 trays used in this study, with a total of 64 seedlings (*Figure 1*).

The treatments in this study were arranged based on a split plot design with two treatment factors. The Al stress was the first factor, and the second factor was the different oil palm varieties. There were four replications for each treatment and the arrangement is shown in *Figure 2*.

Parameters measured

A week after the treatments were applied, the seedlings' height, root length, chlorophyll value, and plant bole diameter were recorded once a week to observe the effects of Al application on the morphology and physiology of the plants. As for plant nutrient content and plant biomass, the samples were collected on the third month after the seedlings were sown. The height of the seedling was measured from the base of the seedling to the tip of the shoot weekly for a total of 90 days (Cristancho *et al.*, 2011). The root length was also measured weekly for 90 days. Only the longest root was measured for each seedling. Root length parameter is a better indicator of Al-toxicity compared to roots and leaf dry weight (Boudot *et al.*, 1994). Additionally, the bole diameter was measured once a week with a vernier calliper.

The plant nutrient content was analysed using a wet digestion method, with a 1:2 ratio of nitric acid (HNO_3) – hydrochloric acid (HCl) (Zhao *et al.*, 2023). The samples were analysed for their concentrations of selected plant nutrients, specifically P, K, Ca, and Mg, using the Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES Model DV7300). Leaf chlorophyll content was measured using

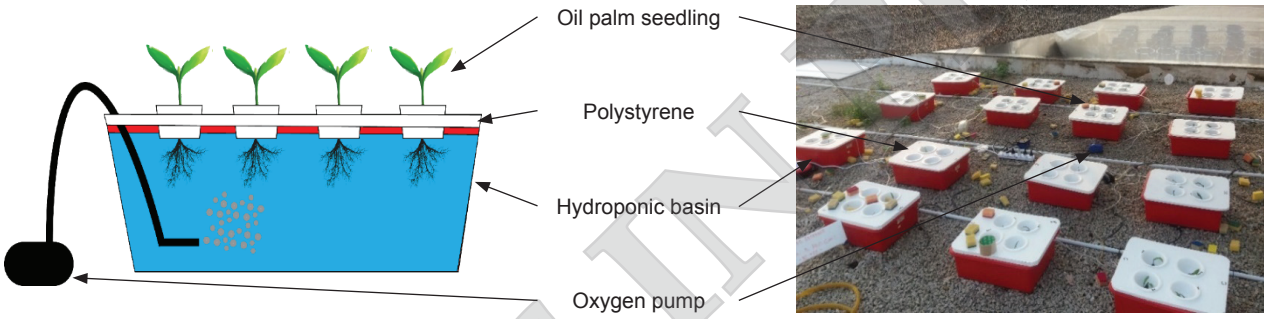
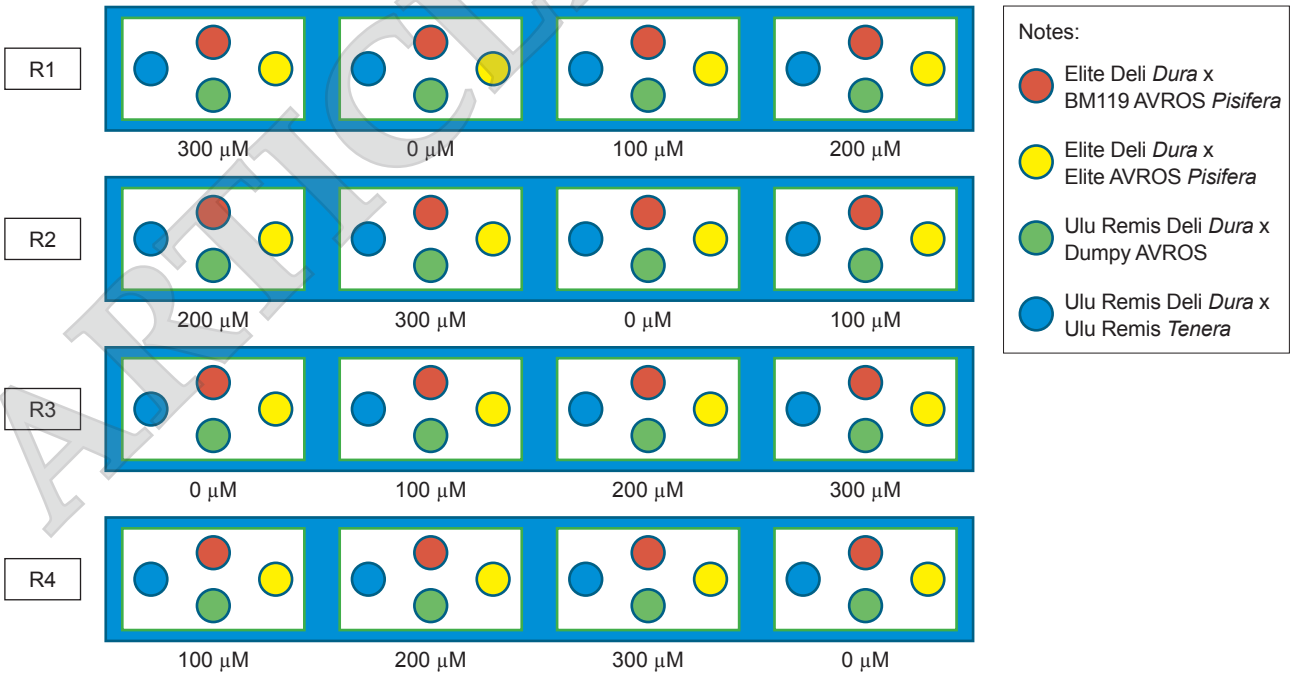


Figure 1. Preparation of the hydroponic system.



Notes: R1 to R4 indicate the replication rows. The Al concentrations (0, 100, 200 and 300 µM) applied are shown at the bottom of each row. The arrangements of four oil palm varieties are indicated in the legend on the right.

Figure 2. Split plot experimental design.

Soil Plant Analysis Development meter (SPAD) on the 90th day after initiating treatment. Finally, the biomass of the seedlings was measured after 90 days. The root and shoots were separated and weighed. The plant was then air-dried in a forced-air oven at 65°C for 48 hr. After which the dry weight of plant roots and shoots were measured and recorded.

Statistical Analysis

The data obtained were analysed using SPSS version 26. Two-way ANOVA was used to analyse the variance of the treatments. The significant factors were then analysed using multiple comparison tests to compare the effects of Al-toxicity on the different oil palm seedling varieties.

RESULTS AND DISCUSSION

Effects of Different Concentrations of Al-toxicity on Growth and Chlorophyll Content of Oil Palm Seedlings

Table 2 shows the effects of different concentrations of Al-toxicity on the growth and chlorophyll content of oil palm seedlings variety Elite Deli *Dura* x BM119 AVROS *Pisifera*, Elite Deli *Dura* x Elite AVROS *Pisifera*, Ulu Remis Deli *Dura* x Dumpy AVROS and Ulu Remis Deli *Dura* x Ulu Remis *Tenera*, respectively.

The roots and chlorophyll content of oil palm seedling varieties Elite Deli *Dura* x BM119 AVROS *Pisifera* and Elite Deli *Dura* x Elite AVROS *Pisifera* were affected by all Al-toxicity treatments, leading

TABLE 2. EFFECTS OF DIFFERENT AL-TOXICITY ON DIFFERENT OIL PALM SEEDLING VARIETY

Parameters/Al-toxicity level	Treatment 0 (Control): 0 µM Al-toxicity	Treatment 1: 100 µM Al-toxicity	Treatment 2: 200 µM Al-toxicity	Treatment 3: 300 µM Al-toxicity
Elite Deli *Dura* x BM119 AVROS *Pisifera*				
Mean length of roots (cm)	19.019^{a}	13.217^{b}	14.236^{c}	15.383^{bc}
Mean height of shoots (cm)	12.406^{a}	10.452^{a}	8.297^{a}	8.505^{a}
Mean of bole diameter (mm)	1.104^{a}	0.894^{a}	0.757^{a}	0.772^{a}
Mean of SPAD value (SPAD unit)	53.500^{a}	22.500^{b}	20.500^{b}	15.400^{b}
Root biomass (g)	0.900^{a}	0.610^{b}	0.330^{c}	0.300^{c}
Shoot biomass (g)	2.130^{a}	1.840^{b}	1.670^{b}	1.620^{b}
Elite Deli *Dura* x Elite AVROS *Pisifera*				
Mean length of roots (cm)	7.136^{a}	4.586^{b}	3.553^{b}	4.574^{b}
Mean height of shoots (cm)	2.044^{a}	1.956^{a}	1.631^{a}	1.656^{a}
Mean of bole diameter (mm)	0.811^{a}	0.861^{a}	0.808^{a}	0.634^{a}
Mean of SPAD value (SPAD unit)	32.300^{a}	18.100^{b}	16.500^{b}	18.900^{b}
Root biomass (g)	0.550^{a}	0.490^{b}	0.230^{c}	0.230^{c}
Shoot biomass (g)	2.070^{a}	2.050^{b}	1.800^{c}	1.030^{c}
Ulu Remis Deli *Dura* x Dumpy AVROS *Pisifera*				
Mean length of roots (cm)	19.238^{a}	21.241^{a}	21.898^{a}	17.113^{a}
Mean height of shoots (cm)	10.157^{a}	9.651^{a}	9.047^{a}	7.802^{a}
Mean of bole diameter (mm)	1.020^{a}	0.890^{a}	0.830^{a}	0.640^{b}
Mean of SPAD value (SPAD unit)	25.800^{a}	15.900^{b}	14.300^{bc}	9.600^{c}
Root biomass (g)	0.640^{a}	0.290^{b}	0.290^{b}	0.270^{b}
Shoot biomass (g)	2.470^{a}	1.310^{b}	1.070^{b}	1.060^{b}
Ulu Remis Deli *Dura* x Ulu Remis *Tenera*				
Mean length of roots (cm)	21.856^{ab}	19.017^{ab}	16.615^{a}	14.208^{b}
Mean height of shoots (cm)	12.566^{a}	11.026^{a}	8.359^{a}	6.808^{a}
Mean of bole diameter (mm)	1.432^{a}	1.444^{a}	1.273^{a}	1.122^{a}
Mean of SPAD value (SPAD unit)	22.200^{a}	14.400^{a}	21.000^{a}	18.400^{a}
Biomass of roots (g)	0.520^{a}	0.500^{a}	0.460^{a}	0.500^{a}
Biomass of shoots (g)	2.220^{a}	1.770^{b}	1.230^{c}	1.180^{c}

Note: Different superscript letters in the same row indicate significant difference at $p \leq 0.05$

to significant effects on the biomass of roots and shoots (*Table 2*). On the other hand, the height of shoots for all varieties was not significantly affected by the application of Al-toxicity as high as 300 µM but the shoot biomass was affected. The bole diameter showed a similar pattern with the shoots, with exception of the Ulu Remis Deli *Dura* x Dumpy AVROS variety, where the highest concentration of Al-toxicity affected the bole diameter.

Effects of Nutrient Uptake in Root and Shoot of Different Varieties of Oil Palm Seedlings to Al-toxicity

A similar pattern in nutrient uptake, specifically P, K, Ca, and Mg was observed in both roots and shoots of the oil palm seedlings (*Table 3*). For all oil palm varieties, the uptake of selected nutrients by both roots and shoots was significantly different among treatments. The uptake of P in shoots and roots was affected by a minimum of 100 µM Al-toxicity application for all oil palm seedling varieties. Upon increment of Al-toxicity level to 200 and 300 µM, the uptake of P in both roots and shoots fluctuated in all seedling varieties. The application of 100 µM Al-toxicity had a significant effect on the uptake of K, Ca and Mg in the seedling's roots and shoots, for all oil palm varieties.

These findings revealed that the uptake of nutrients specifically P, K, Ca, and Mg was affected by Al-toxicity at as low as 100 µM level.

DISCUSSION

The overall results indicated reduction in root growth at 100, 200 and 300 µM Al-toxicity for Elite Deli *Dura* x BM119 AVROS *Pisifera* seedlings (*Table 2* and *3*). A reduction was also observed for Elite Deli *Dura* x Elite AVROS *Pisifera* and Ulu Remis Deli *Dura* x Ulu Remis *Tenera* seedlings. The decrease in root length may be due to a reduction in cell division and elongation activity. Cristancho *et al.* (2010) also reported a reduction in total root length in Nigerian *Dura* x Nigerian *Dura* and Deli *Dura* x AVROS *Pisifera* oil palm progenies. In addition, Nanang *et al.* (2014) similarly observed a reduction in primary root length in oil palm varieties toward Al stress conditions. Li *et al*. (2008) found that exposure of the root tips of several wheat varieties to Al led to a reduction in mitotic activities in the root. In plants, the presence of Al ions in the soil solution is much more destructive than H ions, even at the same concentration (Krstic *et al*., 2012)

The relationship between the pectin group and Al in root cells could be the reason for the reduction in root growth (Klimashevskii and Dedov, 1975; Yang and Horst, 2015). A reduction in cell division was attributed to the decrease in the root length of oil palm seedlings treated with high Al concentrations (Nanang *et al*., 2014). Inhibition of root growth was also due to the binding of Al ions to the pectin and other cell wall parts, which caused changes in cell characteristics such as extensibility, enzyme activities and cell porosity. On the other hand, despite high Al concentrations, Ulu Remis Deli *Dura* x Dumpy AVROS seedlings exposed to 100 µM of Al exhibited increased root length. Cristancho *et al*. (2011) also observed a positive effect of Al exposure to the root volume of Nigerian *Dura* x Nigerian *Dura* oil palm progeny at 100 µM of Al. In other plants such as *Melastoma malabathrichum* L., addition of Al into its water culture solution increased the root growth (Osaki *et al*., 1997; Watanabe *et al.,* 2005). This plant is known as an Al-accumulation shrub. However, results in the present study indicate that the application of 100 µM of Al does not affect the mean height of the shoot and mean length of roots of three oil palm seedlings (Elite Deli *Dura* x BM119 AVROS *Pisifera*, Elite Deli *Dura* x Elite AVROS *Pisifera* and Ulu Remis Deli *Dura* x Ulu Remis *Tenera*). Apart from the Ulu Remis Deli *Dura* x Dumpy AVROS variety, the oil palm seedling varieties tested in this study showed retardation in shoot growth at 200 and 300 µM Al concentrations.

In response to Al alleviation, retarded shoot growth and chlorosis on the leaves have been observed in oil palm seedlings, which may be due to the reduction of some essential nutrient elements such as P (Cristancho *et al*., 2009). Al effects on foliar resembled effects from P deficiency, such as overall stunting, smaller size, dark green colour and delayed maturity (Rout *et al*., 2001). Apart from that, a reduction of 31.8% in height was observed in oil palm seedlings exposed to 200 µM Al (Cristancho *et al*., 2011). In this study, we observed a negative effect on the bole diameter size of Ulu Remis Deli *Dura* x Dumpy AVROS oil palm seedlings treated with 300 µM Al. Most of the oil palm varieties tested showed a reduction in bole diameter size. Cristancho *et al*. (2011) reported that oil palm seedlings exhibited a 28.9% reduction in bole diameter size when subjected to 200 µM Al. Currently, there are not many studies examining the effects of high Al concentrations on bole diameter size.

All varieties showed negative effects on chlorophyll content upon exposure to Al-toxicity. The chlorophyll content reduction was observed even at 100 µM Al concentration. The decrease in chlorophyll content from 200 µM Al exposure might be due to a significant reduction in root and shoot nitrogen (N) and Mg (Cristancho *et al*., 2011). In maize plants, chlorophyll content was severely affected upon exposure to 200 µM Al (Mihailovic *et al*., 2008). The reduction in chlorophyll content may reduce net photosynthesis due to its vital function in the photosynthesis process.

TABLE 3. EFFECTS OF DIFFERENT AL CONCENTRATIONS ON NUTRIENT UPTAKE IN ROOTS AND SHOOTS OF DIFFERENT OIL PALM SEEDLING VARIETIES

Parameters/Al-toxicity level	Treatment 0 (Control): 0 µM Al-toxicity	Treatment 1: 100 µM Al-toxicity	Treatment 2: 200 µM Al-toxicity	Treatment 3: 300 µM Al-toxicity
Elite Deli *Dura* x BM119 AVROS *Pisifera*				
P in root (mg/kg)	18 916.67^{a}	19 813.33^{b}	13 850.00^{c}	21 390.00^{d}
K in root (mg/kg)	45 556.67^{a}	46 546.67^{a}	28 536.67^{b}	32 400.33^{c}
Ca in root (mg/kg)	5 352.33^{a}	6 510.00^{b}	5 080.33^{c}	5 213.33^{d}
Mg in root (mg/kg)	23 275.22^{a}	24 290.00^{b}	15 822.33^{c}	19 667.89^{a}
P in shoot (mg/kg)	16 556.67^{a}	26 273.33^{b}	7 462.333^{c}	13 426.67^{d}
K in shoot (mg/kg)	20 650.00^{a}	16 846.67^{b}	15 136.67^{c}	20 840.00^{a}
Ca in shoot (mg/kg)	5 352.33^{a}	6 510.00^{b}	5 080.33^{c}	5 213.33^{d}
Mg in shoot (mg/kg)	2 548.00^{a}	2 482.33^{ac}	2 326.67^{b}	2 459.00^{c}
Elite Deli *Dura* x Elite AVROS *Pisifera*				
P in root (mg/kg)	14 020.00^{a}	7 725.67^{b}	8 903.33^{c}	12 823.33^{d}
K in root (mg/kg)	159 086.70^{a}	18 030.00^{b}	20 373.33^{c}	25 743.33^{d}
Ca in root (mg/kg)	8 889.00^{a}	5 341.667^{b}	5 277.33^{b}	8 596.33^{c}
Mg in root (mg/kg)	4 721.67^{a}	2 486.00^{b}	2 497.33^{b}	3 741.67^{c}
P in shoot (mg/kg)	15 856.67^{a}	28 563.33^{b}	16 980.00^{c}	20 610.00^{d}
K in shoot (mg/kg)	25 213.33^{a}	39 663.33^{b}	40 700.00^{b}	40 686.67^{b}
Ca in shoot (mg/kg)	8 112.00^{a}	7 372.67^{b}	6 980.33^{c}	11 470.00^{d}
Mg in shoot (mg/kg)	3 035.67^{a}	6 664.00^{b}	5 963.33^{c}	5 789.00^{c}
Ulu Remis Deli *Dura* x Dumpy AVROS *Pisifera*				
P in root (mg/kg)	8 733.67^{c}	7 317.67^{d}	13 620.00^{a}	9 563.00^{b}
K in root (mg/kg)	16 723.33^{a}	15 596.67^{d}	16 040^{c}	16 593.33^{b}
Ca in root (mg/kg)	4 820.667^{ab}	4 994.667^{b}	4 791^{b}	5 452.333^{a}
Mg in root (mg/kg)	2 555^{a}	2 123^{b}	2 374.667^{b}	2 125^{c}
P in shoot (mg/kg)	19 136.67^{c}	25 903.33^{a}	15 883.33^{d}	25 446.67^{b}
K in shoot (mg/kg)	36 960^{a}	28 850^{b}	3 7530^{b}	53 506.67^{b}
Ca in shoot (mg/kg)	9 750^{a}	7 683.667^{b}	8 883^{c}	10 483.33^{d}
Mg in shoot (mg/kg)	4 976^{a}	5 804.667^{b}	5 000.667^{c}	7 025.667^{c}
Ulu Remis Deli *Dura* x Ulu Remis *Tenera*				
P in root (mg/kg)	20 733.33^{a}	23 200.00^{b}	27 003.33^{c}	14 686.67^{d}
K in root (mg/kg)	37 066.67^{a}	19 486.67^{b}	31 056.67^{c}	20 453.33^{b}
Ca in root (mg/kg)	6 529.67^{a}	4 448.00^{b}	10 326.67^{c}	4 771.67^{d}
Mg in root (mg/kg)	4 049.33^{a}	2 872.33^{b}	4 935.33^{c}	2 732.33^{d}
P in shoot (mg/kg)	22 183.33^{a}	21 376.67^{b}	30 386.67^{c}	18 990.00^{d}
K in shoot (mg/kg)	47 910.00^{a}	38 466.67^{b}	46 243.33^{a}	43 853.33^{c}
Ca in shoot (mg/kg)	11 886.67^{a}	16 943.33^{b}	13 056.67^{c}	8 411.00^{d}
Mg in shoot (mg/kg)	7 213.00^{a}	6 002.67^{b}	6 815.67^{c}	5 783.67^{a}

Note: Different superscript letters in the same row indicate significant difference at $p \leq 0.05$

Of the four different oil palm varieties tested, the root biomass of three varieties (Elite Deli *Dura* x BM119 AVROS *Pisifera*, Elite Deli *Dura* x Elite AVROS *Pisifera*, Ulu Remis Deli *Dura* x Dumpy AVROS) were affected due to Al-toxicity treatments. Root biomass was observed in Ulu Remis Deli *Dura* x Ulu Remis *Tenera* seedlings, treated with up to 200 µM Al. This positive effect can be correlated with the availability of P in the root. Increasing P availability in the root cell protects the cell membrane against Al toxic actions (Batista *et al*., 2009). Decreasing root and shoot biomass was correlated with the reduction of root and shoot growth. A reduction in root biomass was also reported in red spruce trees exposed to Al-toxicity (Graefe *et al*., 2008; Raynal *et al*., 1990). It is well

known that the most significant effect of Al-toxicity in plants is on the root growth and development which will eventually affect the root biomass. On the other hand, shoot biomass of the Ulu Remis Deli *Dura* x Dumpy AVROS variety was found to be the most affected. Similarly, 57.5% reduction in the shoot dry weight was observed in a Nigerian *Dura* x Nigerian *Dura* oil palm progeny (Christancho *et al*., 2011). Reduction in the shoot's dry mass of corn plants was also observed when the plants were treated with 100 mg kg^{-1} Al (Batista *et al*., 2009). In the present study, K content in the roots of Elite Deli *Dura* x BM119 AVROS *Pisifera* seedlings decreased upon exposure to Al concentrations of 200 and 300 µM.

Similarly, reduction trends in root K content had been observed previously in Angola *Dura*, Nigerian *Dura* and Deli *Dura* x AVROS *Pisifera* oil palm seedlings at 200 µM Al exposure (Cristancho *et al*., 2011) and in various oil palm seedlings treated with 225 ppm Al (Nanang *et al*., 2014). K deficiency symptoms such as necrosis of old oil palm fronds were observed after treatment with high concentrations of Al for about five to six months. In contrast, increased K content in the roots of Elite Deli *Dura* x Elite AVROS *Pisifera* and Ulu Remis Deli *Dura* x Ulu Remis *Tenera* seedlings were observed. Increased K content was also observed in the shoots of Elite Deli *Dura* x Elite AVROS *Pisifera* oil palm seedlings. Increased K content was also observed in Al-treated Deli *Dura* x Dumpy AVROS *Pisifera* (Cristancho *et al*., 2011) and five oil palm progenies (Nanang *et al*., 2014). Al-tolerant maize genotypes are able to accumulate high concentrations of K when exposed to high Al concentrations (Giannakoula *et al*., 2008). Al can block the inward K channels in the root hair (Cristancho *et al*., 2011). This was in line with a study by Liu and Luan (2001) on Al inhibition of K uptake and root elongation.

Phosphorus (P) uptake in both roots and shoots of Ulu Remis Deli *Dura* x Ulu Remis *Tenera* seedlings appeared to increase at 200 µM Al level. For other varieties however, a negative effect in P absorption was observed at as low as 100 µM Al. Shoot P content in Elite Deli *Dura* x BM119 AVROS *Pisifera*, Elite Deli *Dura* x Elite AVROS *Pisifera* and Ulu Remis Deli *Dura* x Dumpy AVROS varieties showed decreasing pattern at 200 µM Al. The root P content for Elite Deli *Dura* x Elite AVROS *Pisifera* and Elite Deli *Dura* x BM119 AVROS *Pisifera* decreased from exposure to 100 µM and 200 µM, respectively. On the other hand, root P content increased in Ulu Remis Deli *Dura* x Dumpy AVROS seedlings subjected to 200 µM Al. These observations are in line with a report by Cumming *et al*. (1986) on red spruce, where the P concentrations increased in roots but decreased in shoots. Al-toxicity may lead to the fixation of P into a less available form in the soil and in plant root (Fleming *et al*., 1974). Depending on the concentration, Al may function as an inducer or inhibitor of Ca inflow (Cristancho *et al*., 2011). In this study, the patterns in shoot and root Ca contents upon exposure to the different Al concentrations were inconsistent.

Decreased Ca content in roots of oil palm seedlings is most probably due to the destruction of the roots. Cristancho *et al*. (2011) also reported a 31.8% reduction in root Ca content in Nigerian *Dura* x Nigerian *Dura* oil palm seedlings on Al exposure. The presence of Al also inhibited the uptake of Ca in Al sensitive wheat varieties (Huang *et al*., 1992). High Al concentrations in soil also inhibits Ca uptake in garlic crops (Liu *et al*., 1993). In this study, Mg content in the roots of oil palm seedling also decreased from exposure to the lowest Al concentration used here 100 µM, but the shoot Mg content increased in all oil palm varieties. Cristancho *et al*. (2011) also reported a reduction in root Mg content in oil palm seedlings treated with Al with decreased shoot Mg content observed in the Nigerian *Dura* oil palm progeny. Several studies have reported that the reduction in uptake of most nutrient elements was due to a major destruction of the roots of oil palm seedlings and other plants in high Al concentrations. The reduction of nutrient uptake could be the declining effects in plant roots traits, especially the length of lateral roots, total root volume and root tips (Cristancho *et al*., 2009; 2010; 2011; Li *et al*., 2008). Pteridophyta families also exhibited imbalanced nutrient uptake especially in Ca, Mg, P, and K, due to the accumulation of Al (Olivares *et al*., 2009).

Apart from that, inconsistencies in nutrient absorption may also be due to effects of high Al concentrations on water uptake and movement in plants. Water plays an essential role in transporting nutrients throughout the plant. For example, the stomata of *Arabidopsis* plants closed after 9 hr of exposure to 100 µM Al (Sivaguru *et al*., 2003). The transpiration rate in wheat also decreased after exposure to 148 µM Al for 28 days (Ohki, 1986).

CONCLUSION

Different oil palm varieties show different responses towards high Al concentrations, suggesting differences in the levels of Al tolerated. The most affected part of oil palm seedlings exposed to high concentration of Al was the roots. The Elite Deli *Dura* x BM119 AVROS *Pisifera* seedlings appeared to have a low tolerance to high Al concentrations as compared to the other three varieties. In terms of shoot growth, Elite Deli *Dura* x Elite AVROS *Pisifera* and Ulu Remis Deli *Dura* x Dumpy AVROS varieties showed a high tolerant level towards Al esposure. Besides that, Elite Deli

Dura x Elite AVROS *Pisifera* demonstrated a steady bole diameter growth as compared to the other three varieties. On the other hand, the Ulu Remis Deli *Dura* x Ulu Remis *Tenera* variety exhibited the highest chlorophyll content. The Ulu Remis Deli *Dura* x Ulu Remis *Tenera* and Elite Deli *Dura* x Elite AVROS *Pisifera* varieties produced the highest root and shoot biomass growth respectively. In terms of root and shoot nutrient contents, Ulu Remis Deli *Dura* x Dumpy AVROS roots and Elite Deli *Dura* x Elite AVROS *Pisifera* shoots contained high amounts of K while Ulu Remis Deli *Dura* x Ulu Remis *Tenera* shoots and roots contained high amounts of P. High Ca contents were observed in the Elite Deli *Dura* x BM119 AVROS *Pisifera* roots and shoots, Ulu Remis Deli *Dura* x Dumpy AVROS roots and Ulu Remis Deli *Dura* x Ulu Remis *Tenera* shoots. Finally, Mg content was relatively higher in the roots and shoots of Elite Deli *Dura* x BM119 AVROS *Pisifera* and Ulu Remis Deli *Dura* x Dumpy AVROS seedlings as well as in Elite Deli *Dura* x Elite AVROS *Pisifera* shoots. From this study, the Elite Deli *Dura* x BM119 AVROS *Pisifera* oil palm seedlings exhibited the lowest tolerance towards high Al concentrations as compared to the other three oil palm varieties tested.

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