THE ROOT SYSTEM OF THE OIL PALM (*Elaeis guineensis*, Jacq.) I : A MODIFIED SOIL CORE METHOD FOR ROOT STUDY

Keywords : Soil core method; root study; *Elaeis guineensis*

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Studies were conducted on a simple technique to quantify oil palm roots using the soil core method. The modifications to existing technique involved the use of 5% sodium hexametaphosphate (Calgon), 0.5 mm mesh sieves and a microwave oven.

A 5% solution of Calgon was found to have no significant effect on the length or diameter of oil palm roots. It was effective in dispersing Rengam series soil (Typic Paleudult). After 12 hours of soaking in 5% Calgon solution, only 8% of the soil aggregates remained larger than 0.5 mm in diameter. This reduced the time of elutriation to about 10 minutes. Loss of tertiary root during the washing process was 3%. None of the secondary or primary roots passed through the 0.5 mm sieve owing to their larger diameters.

Drying did not significantly change the length or diameter of the secondary roots or the length of the tertiary roots. However, the diameter of the tertiary roots was significantly reduced. The diameter (Y) of the fresh tertiary root could be estimated from the diameter (X) of the dry root by the linear equation;

$$Y = -0.31 + 1.71X \ (r^2 = 0.94)$$

The oil palm roots could be dried in 20 minutes instead of 24 hours by using a microwave oven at low to medium power setting. The sizes of roots did not influence the time of drying when a microwave oven was used.

INTRODUCTION

Nutrient and water uptake by roots is probably the most critical agronomic factor determining the growth and yield of oil palm in Malaysia. In fact, models of nutrient absorption require an accurate assessment of the size, shape and growth rate of the root system (Silverbush and Barber, 1983; Nye and Kirk, 1987). These models are now commonly incorporated into crop simulation models and expert systems.

Despite the importance of roots, their measurement in the field has often been omitted. This is partly attributable to the labour intensive, time consuming and tedious work involved in the processes needed to quantify the root system. For example, Bohm *et al.* (1977) found that 9.5 man-days were required to collect and wash the roots from twelve 15 cm increments of a 180 cm core and measure their lengths.

Methods for extracting soil samples for root study were provided in a comprehensive survey by Bohm (1979), and modified by Floris and van Noordwijk (1984). However, these workers did not fully address the problems associated with the extraction of roots and the measurement of root parameters. Thus, there is still a need to work out a simple method to extract roots and quantify them.

The time taken to wash and sieve roots from the soil core can be reduced if the soil particles are well segregated. This has prompted the construction of a hydropneumatic elutriation system (Smucker *et al.*, 1982), while Ward *et al.* (1978) suggested the root-bag procedure. The former method requires an elaborate apparatus and a lot of water, while the latter can only handle a few small samples at a time.

Dispersion of soil particles has commonly been achieved by using sodium hexametaphosphate (Calgon), for example in particle size analysis (Blake and Hartge, 1986). Norish and Tiller (1976) found that using a 10% Calgon solution was effective in dispersing subplasticity soil. Gee and Bauder (1979) found that a 5% Calgon solution was sufficient to disperse and stabilize most highly oxidized soils. The main objections to the use of Calgon in root studies were: the discoloration of organic matter, which stained the live roots, rendering them difficult to distinguish from the dead roots; structural damage to the cell walls; and changes in the nutrient content of the roots.

However, most Malaysian soils have a low content of organic matter (Coulter, 1972; Acres *et al.*, 1975). Furthermore, root nutrient content is not a feature in most models of nutrient uptake.

It is also time-consuming to quantify fresh root parameters, especially length, and this has been the subject of numerous studies. Indirect methods of measuring root length are available, such as manual and automatic line-intercept techniques (Tennant, 1975; Wilhelm *et al.*, 1982) and the use of a sophisticated image analyser with a personal computer (Zoon and van Tienderen, 1990). These methods require careful calibration, correction for dry matter losses and/or specialized equipment which is not readily available in Malaysia.

Drying the roots before measuring them should extend the time available for completion of the work and therefore allow larger sample size and improved trial precision. Although Anderson and Ingram (1989) advised against drying the roots before recording, it has been postulated that the well lignified hypodermis of the oil palm roots (Purvis, 1956; Ruer, 1967) will prevent appreciable changes, particularly of root length.

This paper describes investigations on the use of Calgon for segregating the soil particles and its effect on the roots. In addition, the effects of drying on oil palm roots were determined.

MATERIALS AND METHODS

Root samples were collected from two fields of oil palm which were twelve and twenty-two years old. They were planted on Rengam series soil (Typic Paleudult). These fields were respectively located in estates near Kajang and Sg. Buloh, Selangor, Malaysia.

A modified soil core auger (Chan, 1976) but with only 13 cutting edges was used to sample the roots. The auger had an internal diameter of 6.8 cm and a length of 15 cm, giving a soil core volume of 544 cm^3. Samples were collected at 15 cm intervals to a depth of 90 cm by gently knocking the top of the auger with a hammer to the desired depth.

The sampling points were randomly located in the interrows, palm circles and frond heaps. For the purpose of this paper, the data collected from the different sites in the oil palm fields were combined in the statistical analyses. The feeder roots included the tertiary and quaternary roots as no attempt was made to separate them.

The root samples collected were subjected to a series of treatments in August and October 1990 as described below.

Effect of Calgon on roots

The soil cores collected were gently washed free of soil over a 0.5 mm mesh sieve (ASTM No.35) in an 18-litre pail of water. The roots were separated into primary, secondary and feeder roots.

Each type of root was immersed in 5 cm^3 of 5% Calgon solution or distilled water for 6, 12, 18 and 24 hours. Three replicates in a complete randomized design were used. The root length and diameter were measured before and after the experiment using a Tajima Vernier caliper cum ruler.

Effect of Calgon on soil dispersion

The subsample moisture content (%) of each soil core was predetermined and expressed on an air-dried basis. The soil cores with an average moisture content of 16% (range, 14% to 20%) were placed in plastic bags and soaked in either 5% Calgon solution or distilled water. 200 cm^3 of solution were used to submerge the samples completely. The soil cores were also broken up manually to allow better absorption of the solution. The samples were soaked for 6, 12, 18 and 24 hours. Twelve replicates were used in this 2x4 split-plot experiment.

After treatment, the percentage of stable aggregates remaining in each sample was determined as an index of non-dispersion. This was carried out using a procedure for wet-sieving similar to that described by Kemper and Rosenau (1986). The major variations from the wet-sieving method were the use of a 0.5 mm mesh sieve (ASTM 35) instead of an ASTM 24 mesh sieve and the agitation of the samples, which were oscillated by hand for a minute at 30 cycles per minute with an amplitude of 1 to 2 cm. These modifications were made to conform with our method of elutriation. The aggregates remaining on the sieve were washed onto a tray, air-dried for 48 hours and weighed.

Root extraction and loss

The next step was to determine the operation time for the elutriation process and the potential loss of roots.

A completely randomized experiment was conducted with 12 replications. The soil cores were pre-soaked with 200 cm^3 of either 2.5% or 5% Calgon solution for 12 hours. The samples were then poured onto a 0.5 mm mesh sieve and gently washed in an 18-litre pail of water. The roots on the sieve were then sorted out from the coarse sand and organic debris; classified into primary, secondary and feeder roots; oven-dried and weighed. The operation time for each process of elutriation was recorded.

Any roots which passed through the sieve were regarded as lost. The loss of roots for each sample was determined by filtering the suspension through the sieve again and removing live roots, which were oven-dried and weighed. Then the soil remaining in the pail was poured onto a plastic sheet and live roots were hand-picked, oven-dried and weighed.

In the hand-extraction method, each soil core was put on a plastic sheet and manually broken into small pieces; the roots were then carefully sorted out. These roots were washed, categorized, dried and weighed. The operation time to extract the roots was recorded.

The remaining soil was then subjected to the elutriation process using 5% Calgon solution as described earlier. The live roots found were regarded as roots lost from the hand-extraction method.

Effect of drying on root parameters

Two aspects were studied: firstly, the suitability of drying before root measurements, and secondly, the optimum time of drying using an air-heated oven or a microwave oven. The air-heated oven was a Gallenkamp model OVH 410 with thermostatic and timer controls, whilst the microwave oven used was a 600 Watt National model NN5208.

In respect of the first aspect mentioned, roots washed free of soil were divided into primary, secondary and feeder roots. Their lengths and diameters were recorded using a Tajima Vernier caliper prior to oven drying at 80°C for 24 hours. The oven-dried root lengths and diameters were then measured. Thirty-six samples of each type of root were used in the experiment.

In the second part, the primary, secondary and tertiary roots were either dried in an air-heated oven for 1, 2, 4, 8 or 24 hours, or in a microwave oven for 10, 20, 30, 40 or 50 min at low-medium power setting.

After treatment, the roots were placed in a plastic bag with silica gel with a cobalt indicator to prevent reabsorption of moisture while waiting to be weighed. All the roots were then placed in the air-heated oven again for 24 hours at 80°C. The roots were re-weighed and the change in moisture content was calculated.

The experiment was arranged in split-plot design with time as main plot and types of root as sub-plots. Five replications were used.

Statistical analysis

The data were analysed using the analysis of variance (ANOVA), t-test and linear regression with the MSUSTAT statistical analysis package, Version 4.10 (Lund, 1986).

RESULTS AND DISCUSSION

Root length and diameter were used to assess the effects of various treatments. The position at which to determine root diameter in the experiments was assessed by measuring the centre, proximal and distal ends of 10 each of primary and secondary roots. The results showed that the diameter at the centre of a root was similar to that at the proximal and distal ends, in the cases of both primary and secondary roots (*Table 1*). This could be due to the nature of the soil core method, which delimited the root length by the diameter of the auger so that, the change in root diameter along the shortened length was not appreciable. The results also implied a smooth cylindrical length of root.

Calgon

Table 2 indicates that soaking the roots in water and 5% Calgon solution did not significantly change the diameters of the primary and secondary roots within 24 hours. The lignified hypodermis of the primary and secondary roots (Purvis, 1956; Ruer, 1967) probably prevented root shrinkage or expansion.

The diameters of feeder roots did not change in 5% Calgon solution either, but expanded significantly in water (*Table 2*). This might be attributed to the osmotic effect of the 5% Calgon solution, which reduced water absorption by the roots.

It was also observed that the oil palm roots remained alive with minimal discolouration for the duration of the experiment.

The results therefore demonstrated that a short exposure to 5% Calgon solution had no detrimental effect on oil palm roots.

Soil segregation

The next step was to determine the effect of 5% Calgon solution on dispersing the soil particles to aid in the elutriation process.

Table 3 shows that 5% of the soil aggregates remained larger than 0.5 mm after 24 hrs of soaking in 5% Calgon solution. This compared favourably with water treatment, where 29% of the soil remained aggregated during the same period. The results confirmed the findings of Schuurman and Goedewaagen (1971) and Gee and Bauder (1979). Twelve hours of soaking in 5% Calgon solution was sufficient to disperse the soil adequately (*Table 3*).

Contrary to the observation of Anderson and Ingram (1989), the discoloration of organic matter by Calgon solution did not stain the oil palm roots sufficiently to make identification difficult. This might be ascribed to the very low organic matter content of Rengam series soil which is typical of most inland Malaysian soils (Coulter, 1972). Moreover, the dark brownish colour of the primary and secondary oil palm roots rendered the staining effect insignificant in their identification.

TABLE 1. ROOT DIAMETERS (mm) AS MEASURED ON DIFFERENT PORTIONS OF THE ROOTS

Type of root	Number of samples	Proximal end	Middle	Distal end	SE
Primary	10	6.54	6.57	6.55	0.35
Secondary	10	1.47	1.54	1.50	0.23

TABLE 2. EFFECT OF 5% CALGON AND WATER ON ROOT DIAMETER (mm)

Solution	Type of roots	Time(hr) after soaking				Mean	SE
		0	6	12	24		
Water	Primary	3.04	3.03	3.04	3.03	3.03	0.12
	Secondary	1.88	2.03	1.95	2.00	1.96	0.11
	Feeder	1.11	1.15	1.12	1.50*	1.13	0.09
5% Calgon	Primary	3.10	3.16	3.04	3.05	3.09	0.12
	Secondary	1.85	1.90	1.80	1.84	1.85	0.11
	Feeder	1.16	1.10	1.18	1.13	1.14	0.09

Significant at $\alpha = 0.05$.

TABLE 3. EFFECT OF SOLVENT AND TIME OF SOAKING ON SOIL SEGREGATION (% of particles > 0.5 mm)

Solution	Soaking time (hr)				Mean
	6	12	18	24	
5% Calgon	17.3	8.0	9.6	5.0	10.0
Water	53.8	54.8	39.1	29.1	44.2
Mean	35.5	31.4	24.4	17.1	

SE for type of solution treatments is 7.3.
SE for time of soaking treatments is 10.3.

TABLE 4. TIME NEEDED TO SEPARATE ROOTS FROM SOIL

Operation	Hand	Calgon 5 %	Calgon 2.5 %
Wash and sieve (min)	0	1 ± 1	5 ± 2
Extract roots (min)	59 ± 16	8 ± 2	8 ± 3
Wash roots (min)	4 ± 2	1 ± 1	2 ± 1
Total time (min)	63 ± 18	10 ± 4	15 ± 6

Note : Times taken to the nearest minute and averaged over 3 people and 12 samples (soil core of 544 cm^3).

TABLE 5. PERCENTAGE ROOT LOSS BY WEIGHT USING HAND-SEPARATION AND ELUTRIATION METHODS

Method	Type of roots	No. of samples	Average	Range	SD
Hand separation	Primary	12	0	0	0
	Secondary	12	0	0	0
	Feeder and above	12	21.1	6.3 - 41.1	10.1
Elutriation	Primary	12	0	0	0
	Secondary	12	0	0	0
	Feeder	12	3	0 – 6.7	2

Root extraction and loss

The three main processes in root elutriation after soaking in Calgon solution were washing and sieving the soil core, separating the roots from the soil and washing the roots free of soil particles. The time taken to complete the above processes is shown in *Table 4*.

By using Calgon, the operation time was reduced from 63 minutes to about 10 to 15 minutes per soil core. The 5% Calgon solution improved the speed of washing and sieving by four minutes compared with the 2.5% solution, mainly through better segregation of the soil particles. Washing the roots free of soil was also easier with 5% Calgon, resulting in a total saving of 33% of the time needed with the 2.5% solution.

The most time-consuming process in the hand separation method was the painstaking sorting of live roots from the soil, particularly the tertiary and quarternary roots. Washing the roots free of soil was also a rather lengthy process because of

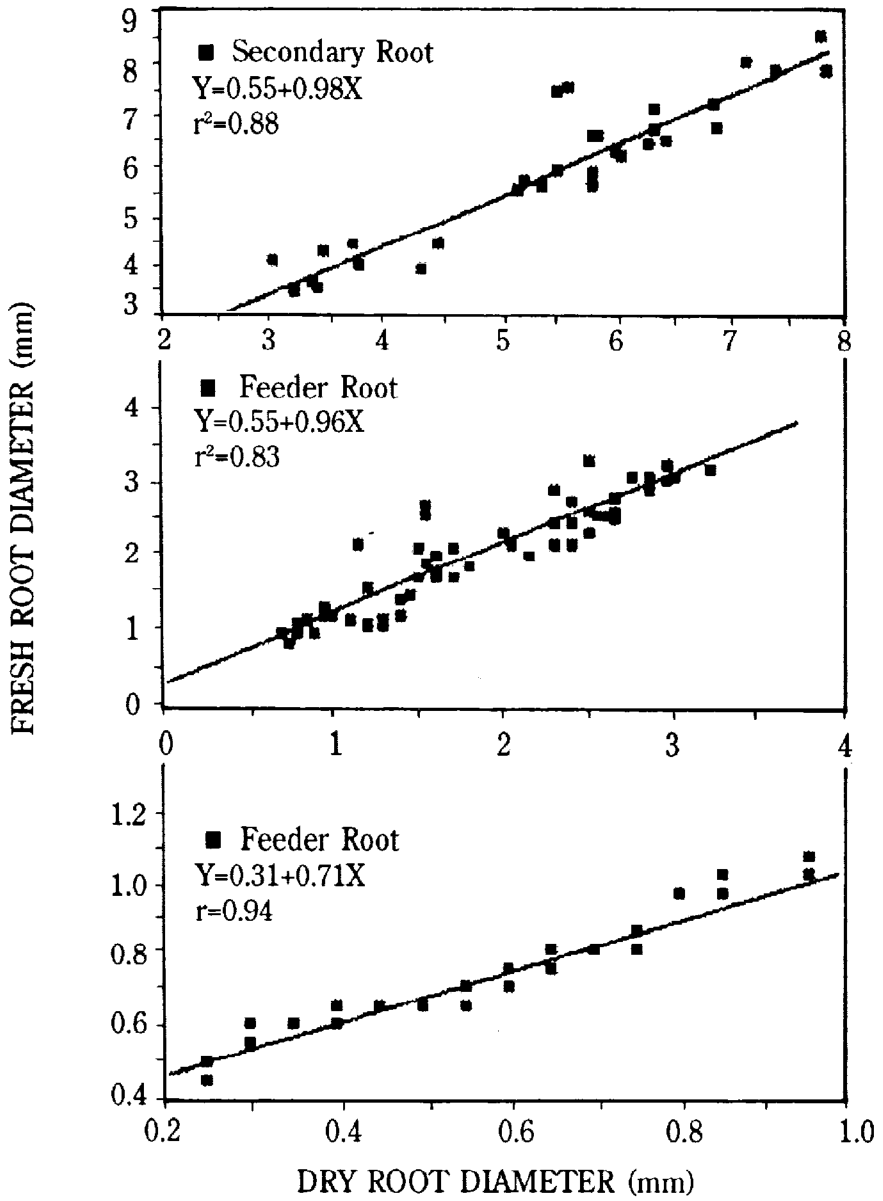

Figure 1. Relationship Between Fresh Root Diameter and Dry Root Diameter of Oil Palm.

TABLE 6. DISTRIBUTION OF DIAMETERS (mm) OF OIL PALM ROOTS

Type of roots	Number of samples	Average (mm)	Range (mm)	SD
Primary	32	5.84	3.45-8.50	1.49
Secondary	54	2.04	0.85-3.30	0.74
Feeder	60	0.71	0.30-1.05	0.14

the clay sticking to the root surfaces. The total time taken was 63 min per soil core, which was six times longer than the process using 5% Calgon solution.

Anderson and Ingram (1984) reported that loss of roots from various species during the process of elutriation ranged from 10% to 20 %. In the present experiment a similar sieve size of 0.5 mm mesh (ASTM 35) was used. No primary or secondary roots passed through the sieve although there was a loss of 3% of feeder roots (*Table 5*). Only three out of 12 soil cores showed any losses of roots: these ranged from 0.4% to 7.7% of the total weight of the feeder roots.

The above results could be attributed to the diameters of the various categories of oil palm roots (*Table 6*). The smallest diameters of primary and secondary roots were bigger than the 0.5 mm mesh of the sieve used. On the other hand, approximately 6.7% of the tertiary plus quarternary roots were smaller than 0.5 mm diameter. These roots were generally broken during the washing and sieving process and were therefore likely to pass through the sieve. Another probable source of loss of root during elutriation was careless complete submergence of the sieve in the pail of water resulting in the overflow of smaller roots. It was however noted that root losses were generally less than 6.7 %. This could be partially attributed to the wiry nature of feeder roots which were entangled in the sieve during elutriation.

Table 5 shows that root loss from the hand-separation method was high, at 21.1%. This was mainly from tertiary and quarternary roots which were overlooked during the sorting process. The loss of roots was higher in the upper soil levels where more feeder roots were found which rendered them more tedious to extract.

The present study showed that the hand-separation method should not be used because it is time-consuming and gives imprecise quantification of roots owing to high loss of root.

Drying of root

It has been commonly recommended that root parameters should be recorded prior to drying (Anderson and Ingram, 1989). However, it was postulated that the lignified oil palm roots should undergo minimal change in their parameters after drying.

This was confirmed for the primary and secondary roots, which showed no statistical differences in root length or diameter after drying (*Table 7*). The tertiary root length did not differ significantly after drying either. However, the diameter of the feeder roots was reduced (*Table 7*). This can be mainly ascribed to their non-suberized cell walls. ***Figure 1*** shows that the diameter (Y) of the fresh feeder root could be estimated from the diameter (X) of the dry feeder root by the linear equation,

$$Y = -0.31 + 1.71 X \text{ ; with an } r^2 = 0.94.$$

Although changes during drying in the diameters of the primary and secondary roots were statistically insignificant, there was a trend for root diameters to be reduced as shown in ***Figure 1***. Hence, the diameters of the fresh primary and secondary roots could also be estimated from their respective diameters of the dry roots using the linear equations.

The results showed close relationships between fresh root length and diameter and dry root length and diameter respectively. Drying should extend the period available for recording the root parameters and therefore allow more samples to be collected.

Consequently, the scope of research could be expanded and the trial precision be increased.

Microwave versus air-heated oven

It has been demonstrated that drying had little effect on root length and diameter. Conventionally, drying of root samples has been carried out using an air-heated oven at 60°C to 75°C (Schuurman and Goedewaagen, 1971). However, in recent years, drying using microwave oven has been reported to reduce the drying time of various materials, such as cocoa beans (Tiong, 1990).

Table 8 shows that the use of the microwave oven reduced the time required to dry the root samples to less than 1% change in moisture content, by comparison with an air-heated oven. Approximately 20 min were sufficient to dry the primary, secondary and tertiary roots. On the other hand, the air-heated oven took about 24 hr

TABLE 7. EFFECT OF MICROWAVE DRYING ON MEAN ROOT LENGTH AND DIAMETER PER SOIL CORE

	Length (cm)				Diameter (mm)			
Type of roots	df	Fresh	Dry	SE	df	Fresh	Dry	SE
Primary	35	9.34	9.52	1.25	35	5.84	5.40	0.37
Secondary	35	18.15	17.81	2.21	35	2.06	1.86	0.14
Feeder	59	40.51	40.34	5.46	59	0.71	0.56*	0.03

Note : *Significantly different at $\alpha = 0.05$

TABLE 8. EFFECT OF METHOD AND TIME OF DRYING ON PERCENTAGE CHANGE IN MOISTURE CONTENT OF OIL PALM ROOTS

Method	Time of drying (min)	% Moisture Changes Type of roots: Primary	Secondary	Feeder	Mean
Oven	60	45.7	1.85	2.42	16.6[a]
	120	36.2	1.59	2.48	13.4[a]
	240	30.8	3.23	2.20	12.1[a]
	480	15.1	-0.26	-0.69	4.7[b]
	1440	0.3	-0.50	-0.53	-0.3[b]
	Mean	**25.6[a]**	**1.19[b]**	**1.73[b]**	**9.3**
Microwave	10	1.8	1.87	1.32	1.7[a]
	20	0.4	0.32	0.03	0.2[b]
	30	0.4	0.44	0.72	0.0[b]
	40	0.2	1.03	-0.12	0.4[b]
	50	0.7	0.68	0.94	0.8[ab]
	Mean	**0.7[a]**	**0.87[a]**	**0.31[a]**	**0.6**

Note : Figures with the same superscript letter are not significantly different at $\alpha = 0.05$

to dry the larger primary roots and 8 hr to dry the secondary and tertiary roots. The poorer drying efficiency of the air-heated oven was ascribed to the surface crusting effect during the drying process (Copson, 1975) which hindered the inner water from evaporating. This effect was more pronounced with samples of larger diameter and hence the primary roots would take longer to dry as found in the experiment.

It was also interesting to note that for the air-heated oven, the percentage moisture change (Y) was logarithmically related to the time of drying (X) for primary roots as given below:

$$Y = 106 - 34 \log (X); \text{ with } r^2 = 0.98 \text{ and } Sy.x = 2.65$$

This indicated that the moisture trapped in the inner part of the root samples was more difficult to vaporize. This further supported the hypothesis of the surface crusting effect.

The results also showed that there was no interaction between the time of drying and the type of roots for microwave oven treatments. Hence, the various categories of oil palm roots could be similarly dried using the microwave oven.

CONCLUSIONS

The results showed that by modifying the soil core method to study the oil palm root system with the use of sodium hexametaphosphate (Calgon) in a 5% solution, 0.5 mm mesh sieve and a microwave oven, the time of elutriation was reduced from 63 min to 10 min and of root drying from 24 hr to 20 minutes.

Soil samples should be soaked in 5% Calgon solution for at least 12 hr prior to elutriation to segregate the soil particles. A 0.5 mm mesh sieve (ASTM 35) is adequate to prevent loss of most tertiary and quarternary roots. Root drying may be carried out prior to measurements in order to extend the time-frame for completion of work and hence allow for increased numbers of samples in the experiment. This should improve the precision and scope of experiments. Drying should be done using a microwave oven at low to medium power setting for 20 minutes.

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REFERENCES

ACRES, B O; BOWER, R P; BURROUGH, P A; FOLLAND, C J; KALSI, M S; THOMAS, P and WRIGHT, P S.(1975). The soils of Sabah Vol. 5 (References and appendices). *Land Resources Division,* Ministry of Overseas Development, Surrey, England: pp. 135.

ANDERSON, J M and INGRAM, J S I (1989). Tropical soil biology and fertility : *A handbook of methods,* pp.59-69. CAB International, United Kingdom.

BLAKE, G R and HARTGE, K H (1986). Particle density. In : A. Klute (ed). Methods of Soil Analysis. Part 1. *Physical and Mineralogical Methods. 2nd Ed. Agronomy 9,* pp. 383-411.

BOHM, W (1979). Methods of studying root systems. Springer-Verlag, Berlin : p. 188.

BOHM, W; MADUAKOR, H and TAYLOR, H M (1977). Comparison of five methods for characterising soybean rooting density and development. *Agron. J. 69,* pp. 415-419.

CHAN, K W (1976). A rapid method for studying the root distribution of oil palm and its application. In : D.A. Earp and W. Newall (Eds.). *Proc. Int. Devt. In Oil Palm.* ISP, Kuala Lumpur, pp. 131-166.

COPSON, D A (1975). Microwave heating. 2nd Ed. AVI. Publ. Co. Inc. Connecticut, USA : p. 615.

COULTER, J K (1972). Soils of Malaysia : A review of investigations on their fertility and management. *Soils and Fertilizers. 35 (5)*, pp. 475-498.

FLORIS, J and VAN NOORDWIJK, M (1984). Improved methods for the extraction of soil samples for root research. *Plant and Soil 77*, pp. 369-372.

GEE, G W and BAUDER, J W (1979). Particle size analysis by hydrometer : A simplified method for routine textural analysis and a sensitivity test of measurement parameters. *Soil Sci. Soc. Am. J. 43*, pp. 1004-1007.

KEMPER, W D and ROSENAU, R C (1986). Aggregate stability and size distribution. In : A. Klute (Ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd Ed. *Agronomy 9*, pp.425-442.

LUND, R E (1986). A user's guide to MSUSTAT statistical analysis package. Version 3.20. Montana State University, U.S.A.: p. 165.

NORRISH, K and TILLER, K G (1976). Subplasticity in Australian soils. 5. Factors involved and techniques of dispersion. *Aust. J. Soil Res. 14*, pp. 273-289.

NYE, P H and KIRK, G J D (1987). The mechanism of rock phosphate solubilisation in the rhizosphere. *Plant and Soil 100*, pp. 127-134.

PURVIS, C (1956). The root system of the oil palm, its distribution, morphology and anatomy. *J. WAIFOR 1*, pp. 60-82.

RUER, P (1967). Repartition en surface du systeme radiculare du palmier a huile. *Oleagineux 22*, pp. 535-537.

SCHUURMAN, J J and GOEDEWAAGEN, M A J (1971). Methods for the examination of root systems and roots. Centre for Agricultural Publishing and Documentation, Wageningen, Netherlands: 86 p.

SILVERBUSH, M and BARBER, S A (1983). Sensitivity of simulated phosphorus uptake to parameters used by a mechanistic mathematical model. *Plant and Soil 74*, pp.93-100.

SMUCKER, A J M; McBURNEY, S C and SRIVASTURA, A K (1982). Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. *Agron. J. 74*, pp.500-503.

TENNANT, D (1975). A test of a modified line intersect method of estimating root length. *J. Ecology 63*, pp. 995-1001.

TIONG, M I (1990). Moisture determination of cocoa beans by microwave oven. *Pertanika 13(1)*, pp. 67-72.

WARD, K J; KLEPPER, B; PICKMAN, R W and ALLMARAS, R R (1978). Quantitative estimation of living wheat root lengths in soil cores. *Agron. J. 70*, pp. 675-677.

WILHELM, W W; NORMAN, J M and NEWEL, R L (1982). Semi automated x-y plotter-based method of measuring root length. *Agron. J. 74*, pp. 149-152.

ZOON, F C and VAN TIENDEREN, P H (1990). A rapid quantitative measurement of root length and root branching by microcomputer image analysis. *Plant and Soil 126*, pp. 301-308.