Malaysian Journal of Soil Science 2024 Vol. 28: 92-104

Assessment of Plant Height and Trunk Diameter of Oil Palm as a Sole Function of Soil Textural Grains (Sand, Clay, and Silt)

Idris Sani[1,2], Teh Christopher Boon Sung[1]*, Zaibon Syaharudin[1] and Sim Choon Cheak[3]

[1]*Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*
[2]*Department of Soil Science, Faculty of Agriculture/Institute for Agricultural Research, Ahmadu Bello University, 1044 Samaru, Zaria, Nigeria*
[3]*Sime Darby Plantation Research Sdn. Bhd., 42960 Carey Island, Kuala Langat, Selangor, Malaysia*

**Correspondence*: chris@upm.edu.my

ABSTRACT

Plant height is a key indicator of healthy growth. Given the role of soil texture in productivity, the effects of sand, silt, and clay on the height and diameter of oil palm (OP) were investigated. In the four OP plantations, measurements of total and trunk heights and trunk diameters were taken from two OP clusters: tall and short. A Pro II Laser Rangefinder (ML921) was used to measure heights. Soil samples were subjected to particle distribution analysis using the pipette method. The data were processed using RStudio software. The t-test confirmed a significant difference in the heights between the clusters in all plantations, implying the accuracy of clustering. For total height, the tall cluster was greater than the short by 24.75%, 23.89%, 27.17%, and 27.51% in OP1, OP2, OP3, and OP4, respectively. Regression analysis established that soil texture accounted for 65.3%, 46.8%, 74.4%, and 69.6% of the total OP height in the fields, respectively. Sand showed a strong to moderate positive correlation with total and trunk heights, and a moderate negative correlation with trunk diameter. The clay correlated inconsistently with trunk diameter, while silt in the 0–30 cm layer showed a strong to moderate negative correlation with height. In conclusion, soil texture profoundly influences oil palm height, with sand grains exerting the greatest positive effect. Typical clay soil should be avoided during oil palm site selection, and the fields should be well-leveled to avoid erosion, which results in continuous clay deposition on the bottom slope.

Keyword: Plant height; trunk diameter, clay; sand; silt

INTRODUCTION

Globally, oil palm accounts for approximately 25 million hectare, ranking it as the 12th staple crop in terms of area coverage (Lewis *et al*., 2020). With the highest oil yield (Anaba *et al*., 2020) and increased demand (Syahza *et al*., 2021; Suh, 2023), palm oil has become a key player in the global oil industry (Wang *et al*., 2020).

Oil palm provides bedrock economic support to several tropical countries, particularly Indonesia, Malaysia, and Ghana (Ofosu-Budu and Sarpong, 2013; Anaba *et al*., 2020; Sibhatu, 2023). In Malaysia, its production stood at 19 million tonnes in 2023 (Chu, 2023), with promising potential in the food and nutrition, renewable energy, and pharmaceutical sectors (Lewis *et al*., 2020). Agronomically, the oil palm is a heavy feeder crop (Fuady *et al*., 2019) and a water-demanding crop; hence, it requires productive soil for optimum vertical growth (Obeng *et al*., 2020).

Soil texture, which is defined as the proportion of primary soil mineral grains in a given volume of soil (Brady and Weil, 2002; Rattan-Lal, 2005; Wang *et al*., 2019), is a master attribute that dynamically determines soil productivity (Obeng *et al*., 2020; Upadhyay and Raghubanshi, 2020) by influencing its hydraulic, thermal, and fertility properties (Zhang *et al*., 2008; Arora *et al*., 2011; Upadhyay and Raghubanshi, 2020). The overall effects translate into good soil health, leading to improved vertical growth and development of oil palm. In practice, each of the three mineral grains of soil (sand, silt, and clay) distinctly controls oil palm growth by determining the loss and retention of water added, adsorption and desorption of nutrients applied, and growth and expansion of the root system (Kirkham, 2005; Ho et al., 2019; Idris *et al*., 2019; Wang *et al*., 2021; Murabbi *et al*., 2022). Plant height, which gives the vertical dimensional extent of a plant from the base to the top, is one of the key indices that describes the health and vigor of a plant, thus making it a routine independent variable in growth assessment studies (Fuady *et al*., 2019; Ajeng *et al*., 2020; Bilter *et al*., 2021; Uke *et al*., 2021; Utoyo *et al*., 2022; Zainuddin *et al*., 2022).

According to Salas-Eljatib (2020), an adequate scientific understanding of height growth variables is critically required to advance the basic knowledge principles of soil science. Furthermore, discovering a clear relationship between oil palm height and the primary soil mineral particles is even more important and thought-provoking compared to the relationship between tree height and tree age conducted by Avtar *et al*. (2013) and Nishizono *et al*. (2014). Hence, it is expected that the study's findings will, in a novel way, help oil palm plantation managers and surveyors in site selection decision-making and early monitoring of growth performance and its edaphic limitation. Corley and Tinker (2016) emphasized that in-depth information about oil palm trees is always valuable for an impact-oriented management approach to be strategically implemented (Salmiyati *et al*., 2014). Therefore, this study aimed to test the hypothesis that sand contributes better to the height of oil palm than silt and clay.

MATERIALS AND METHODS

Experimental Site

The experiment was executed in four selected oil palm plantations (*Figure 1*) tagged as OP1, OP2, OP3, and OP4 situated inside the Universiti Putra Malaysia, Seri Serdang, Selangor. The fields that were established in 2011, 2012, 2012, and 2006 were planted with D × P (dura crossed to pisifera), spaced at 8.8 x 8.8 x 8.8 m.

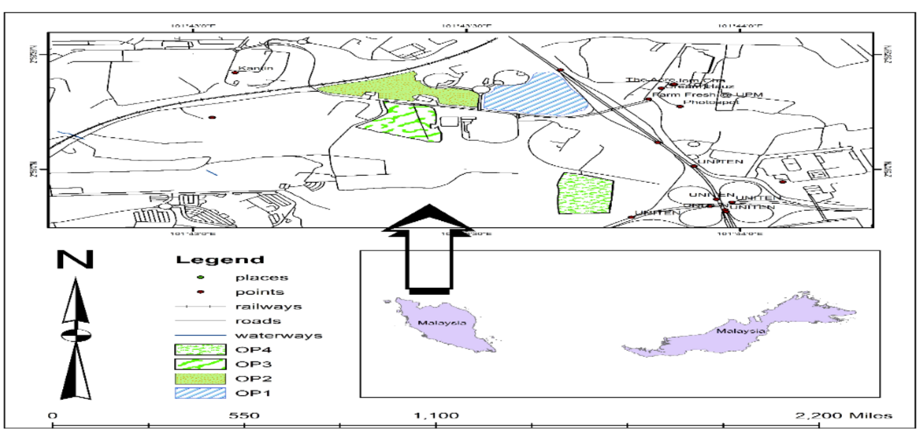


Figure 1: The study plantations

Oil Palm Clustering Design

For each oil palm plantation, the palms were visually delineated and classified into two clusters: tall and short. In each row, palms that were lower in height relative to the others were placed under a short cluster, whereas those that were normal in height formed a tall cluster. To maintain an equal number of observation replications, the number in the short cluster, which was less in all plantations, was set as the baseline. Thus, the population size (n) of the short cluster determined the population size of the tall cluster sampled for the study. In all plantations, all palms under the short cluster were measured, while an equal number of palms under the tall cluster were chosen unbiasedly using the random number technique run in Excel. However, palms that appeared unhealthy, in areas that could not permit soil sampling to the required depth (60 cm), or areas with accessibility difficulty were excluded.

Soil Sampling

A bucket auger was used to collect soil samples at 0 – 30 and 30 – 60 cm soil depths ≤ 100 cm from the palm base. In all plantations, for each cluster, 15 samples from each of the two specified depths were randomly collected. Then, three composite samples were developed by bulking five samples separately to represent each cluster and depth. The samples were air-dried, gently crushed using a porcelain mortar, and sieved using a 2-mm sieve for soil particle analysis.

Laboratory Analysis

The pipette method was employed to perform soil particle distribution analysis according to Gee and Bauder (1986), as described by Teh and Talib (2006). Twenty grams was weighed into 1000 ml, and 100 ml of 30% hydrogen peroxide (H_2O_2) was added and left for 24 h. The solution was heated and allowed to cool before adding 100 ml hydrochloric acid (0.2 N). Distilled water was then added to make the volume up to 400 ml. The system was then returned to the hotplate for 15 min. Thereafter, the solution was washed for three consecutive days. After the third wash, 50 ml Calgon 1N was added and the mixture was stirred for 15 min. A 50µm sieve was used to retain sand grains, while the slurry was transferred into a 1000 ml glass cylinder, made up to mark with distilled water, and placed in a bath until 6:39 h. A 20 ml aliquot was drawn at a depth of 10 cm and emptied into cans as clay. A metal plunger was used to agitate the system by stroking 10 times and allowing it to settle for 5 min, and another set of aliquot samples was drawn and emptied into empty cans. All cans were placed in an oven and dried at 105°C for 24 h to attain a constant weight. The weights were recorded using a sensitive electronic scale. Subsequently, % Sand, %Clay, and % Silt were computed as follows:

$$\%Sand = \left(A\ x\ \frac{100}{vol.of\ pipette}\right)\ x\ \left(\frac{100}{total\ weight}\right) \quad [1]$$

$$\%Clay = \left(B\ x\ \frac{1000}{vol.of\ pipette}\right) - Calgon\ weight\ x\ \left(\frac{100}{total\ weight}\right) \quad [2]$$

$$\%Silt = 100 - (\%Sand + \%\ Clay) \quad [3]$$

Trunk Diameter Measurement

A 5m Hua Nan Power tape was used to measure trunk circumference at the breast height (0.3m) which was divided by π value ($\frac{22}{7}$) to obtain the trunk diameter.

Plant Height Measurement

A Nikon Forestry Pro II, Laser Rangefinder/Telemeter laser model ML921 was used to measure the palm trunk and total plant heights using the three-point measurement mode. In this case, the measurement was performed at three points: Hor, Hgt, and Hgt2, representing the horizontal, base, and top, respectively. Additionally, to overcome the difficulty associated with the "hidden apex" and the inability to perfectly view the tip of the targeted fronds due to canopy overlap, different angles were tested before choosing the best angle.

Statistical Analysis

The RStudio 4.2.3 2023 version was used to perform an independent t-test using *as.factor* and *t-test* functions, while multiple regression model II results were obtained using *lim* and *summary* functions, and correlation outputs were generated using *cor* and *chart. Correlation* functions.

RESULTS

Independent T-test

The t-test results presented in Tables 1, 2, and 3 confirmed that in all the oil palm plantations, there were significant differences ($p \leq 0.05$) between the tall and short clusters in the trunk and total height, thus implying the accuracy of the clustering. In OP1, OP2, OP3, and OP4, the trunk height for the tall cluster was greater than its counterparts by 26.99%, 26.57%, 32.62%, and 33.26%, and for the total height by 24.75%, 23.89%, 27.17%, and 27.51%, respectively.

The results of trunk diameter in Table 2 were contrary to the trend observed in trunk and plant height indices, whereby the short cluster recorded significantly higher values compared to the tall cluster in all plantations except in OP3. In OP1, OP2, and OP4, the short cluster outperformed the tall cluster by 10.7%, 14.84%, and 13.82% respectively.

Table 1: T table for Plant Height (m) Across all Oil Palm Plantations

Field	Cluster	Mean	Standard deviation	T value	Significance
OP1	Tall	12.914a	1.263892	3.321e-11	***
	Short	9.718b			
OP2	Tall	12.317a	1.885797	8.411e-08	***
	Short	9.375b			
OP3	Tall	14.169a	1.22568	2.201e-10	**
	Short	10.319b			
OP4	Tall	15.804a	1.685359	3.632e-13	***
	Short	11.457b			

Means with different letters within a group are significantly different at p ≤0.05; *** and ** indicate significance at the 99 and 99.9% confidence levels, respectively. OP = oil palm plantation.

Table 2: T table for Trunk Height (m) Across all Oil Palm Plantation

Field	Cluster	Mean	Standard deviation	T value	Significance
OP1	Tall	5.909a	0.94006	1.498e-07	***
	Short	4.314b			
OP2	Tall	4.971a	0.86299	6.792e-08	**
	Short	3.650b			
OP3	Tall	5.138a	0.40146	1.785e-11	***
	Short	3.462b			
OP4	Tall	7.087a	0.91019	2.709e-13	***
	Short	4.730b			

Means with different letters within a group are significantly different at $p \leq 0.05$; *** and ** indicate significance at the 99 and 99.9% confidence levels, respectively. OP = oil palm plantation.

Regression Analysis

The regression results (Tables 4 – 7) established that soil particle size explained 65.3%, 46.8%, 74.4%, and 69.6.3% of the causal effect of total oil palm height in OP1, OP2, OP3, and OP4, respectively. This implies that across the locations, the texture of the soil explains 64.2% of the reasons why oil palms become tall or short.

The output further indicated that, in all the fields, the contribution of sand proportion was positive, while that of clay was negative, except for the upper depths of OP2 and OP4, where the clay slope coefficients were positive. In terms of the extent of the contribution, however, the results showed inconsistency between the two depths. For instance, in OP1, the slope coefficient of sand was higher at 30 – 60 cm than at 0 – 30 by 51.6%, indicating that the positive effect of sand on the oil palm tallness is more experienced when the sand is at a lower depth. However, in OP2, a contrary result was observed, whereby the 0 – 30 sand slope value was 69.2% higher than that of 30–60 cm.

For the clay proportion, its contribution to oil palm height was consistently negative and greatly explained when recorded at a lower depth, except for OP4. The silt content described an increased oil palm height at lower depths in most of the results (75%). Meanwhile, in OP1 0 – 30, it returned NA because its estimation will reduce the precision of the model best explained by the clay and sand variables.

Table 3: T table for Trunk Diameter (Cm) Across all Oil Palm Plantations

Field	Cluster	Mean	Standard deviation	T value	Significance
OP1	Tall	74.227b	3.782036	1.071e-06	**
	Short	82.231a			
OP2	Tall	70.919b	5.047084	2.379e-08	***
	Short	81.441a			
OP3	Tall	70.732b	2.297413	2.58e-09	***
	Short	62.832a			
OP4	Tall	65.221b	4.828706	3.722e-07	**
	Short	74.233a			

Means with different letters within a group are significantly different at $p \leq 0.05$; *** and ** indicate significance at the 99 and 99.9% confidence levels, respectively. OP = oil palm plantation.

As presented above, the soil texture accounts for oil palm height. This is justifiable given the significance of soil as a medium (Quan and Liang, 2017), from which oil palm extracts water, nutrients, and exchanges gases for various metabolic processes (Morgan and Connolly, 2013; Salmiyati *et al*., 2014; Nithyatharani and Kavitha, 2018; Pressler, 2018; Bekele and Getaneh, 2022). Therefore, water and nutrient availability and their subsequent uptake potential rely heavily on soil texture (Sanchez *et al*., 2003; Schroeder *et al*., 2007; Tramontini *et al*., 2013; Chakraborty and Mistri, 2015), thus making it a key soil quality indicator (Harahap *et al*., 2019). This finding corroborates that of Anaba *et al*. (2020), who found that oil palm height was significantly affected.

Table 4: Regression Output of Soil Particle Content and Oil Palm Total Height in Field 1

Soil Particle	Depth	Intercept	Slope	Adj. R^2	Pr(>|t|)
Sand	0 – 30 cm	5.94174	0.14525	0.653	3.32e-11 ***
	30 – 60 cm	11.32	0.3001		
Clay	0 – 30cm	18.43306	- 0.14525		
	30 – 60cm	29.4719	-0.2905		
Silt	0 – 30 cm	11.32	NA		
	30 – 60 cm	8.5562	0.2905		

Table 5: Regression Output of Soil Particle Content and Oil Palm Total Height Field 2

Soil Particle	Depth	Intercept	Slope	Adj. R^2	Pr(>|t|)
Sand	0 – 30 cm	-25.9250	0.7354	0.4677	8.41e-08 ***
	30 – 60 cm	1.2288	0.2263		
Clay	0 – 30cm	-50.929	1.4708		
	30 – 60cm	21.9821	-0.2101		
Silt	0 – 30 cm	14.7681	-0.4903		
	30 – 60 cm	-2.392	0.2942		

Table 6: Regression Output of Soil Particle Content and Oil Palm Total Height Field 3

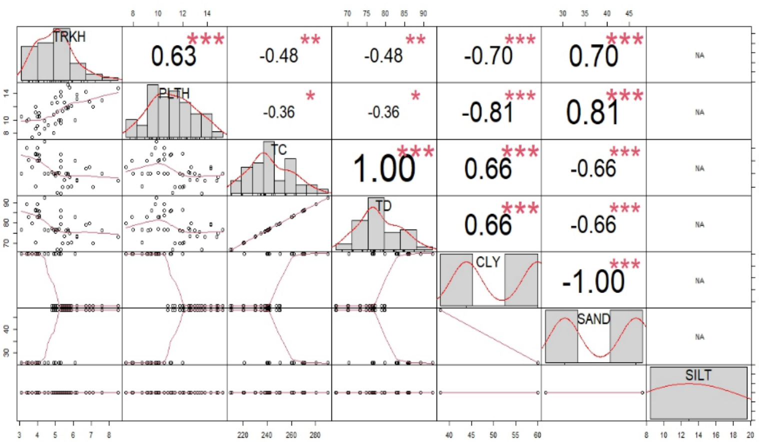
Soil Particle	Depth	Intercept	Slope	Adj. R^2	Pr(>|t|)
Sand	0 – 30 cm	4.1253	0.1674	0.744	2.20e-10 ***
	30 – 60 cm	-0.04663	0.29615		
Clay	0 – 30cm	16.9996	-0.1132		
	30 – 60cm	17.6205	-0.1328		
Silt	0 – 30 cm	8.919	0.350		
	30 – 60 cm	7.9125	0.2406		

Table 7: Regression Output of Soil Particle Content and Oil Palm Total Height Field 4

Soil Particle	Depth	Intercept	Slope	Adj. R^2	Pr(>|t|)
Sand	0 – 30 cm	-63.906	1.449	0.696	3.63e-13 ***
	30 – 60 cm	185.370	4.348		
Clay	0 – 30cm	-153.761	-4.348		
	30 – 60cm	-75.500	2.174		
Silt	0 – 30 cm	22.326	-1.087		
	30 – 60 cm	98.413	-4.348		

Correlation Analysis

Based on the Dancey and Reidy (2007) correlation rating, across all plantations, sand showed a strong to moderate positive correlation with total oil palm height and trunk height and a moderate negative correlation with trunk diameter, meaning that the higher the sand, the higher the plant and trunk height but the lesser the trunk diameter. On the other hand, clay showed a direct contrary correlation result to that of sand, except for TD, where its relationship was inconsistent. Silt content at the upper depth revealed a strong to moderate negative correlation with total plant height and trunk height, but showed a moderate positive correlation at lower depths. This means that increased silt content at lower depths is more strongly associated with increased oil palm height.



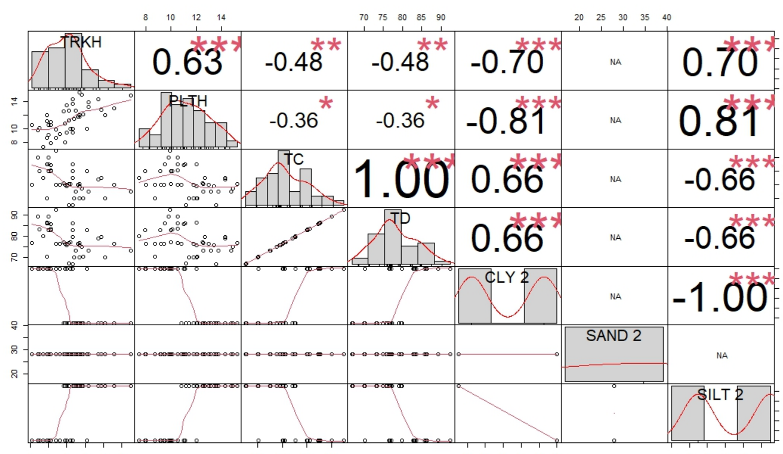
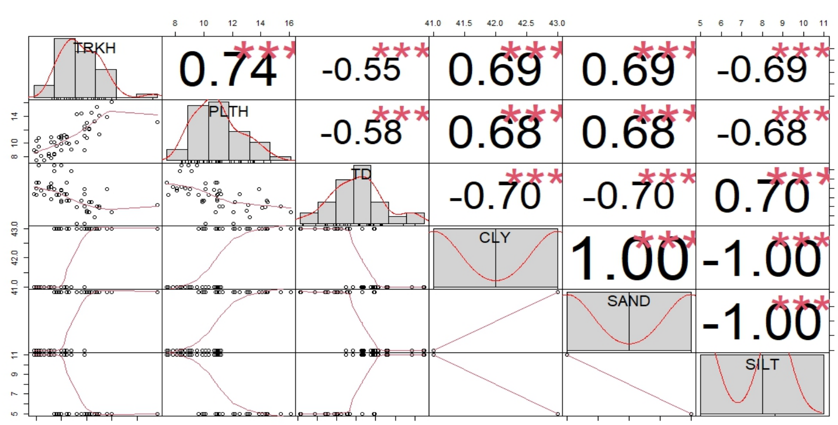


Fig. 3 and 4 Correlation chart for depth 1 and depth 2 in Plantation 1
(Note: TRKH = trunk height, PLTH = total plant height, and TD = trunk diameter)



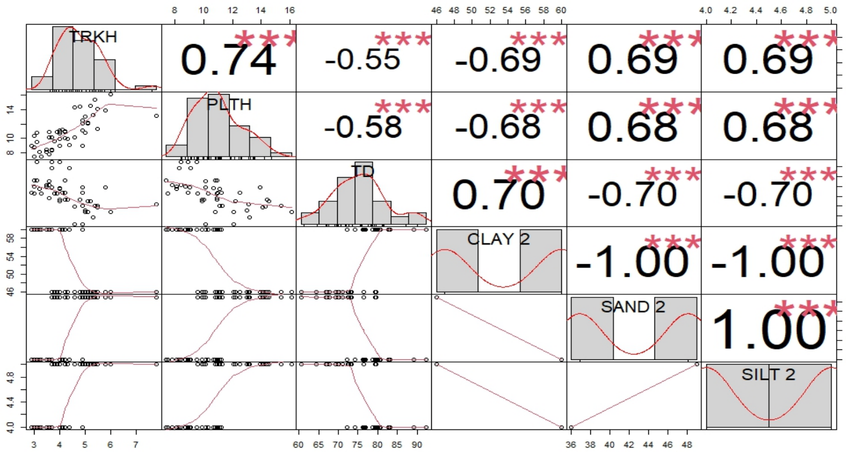


Fig. 5 and 6 Correlation chart for depth 1 and depth 2 in Plantation 2

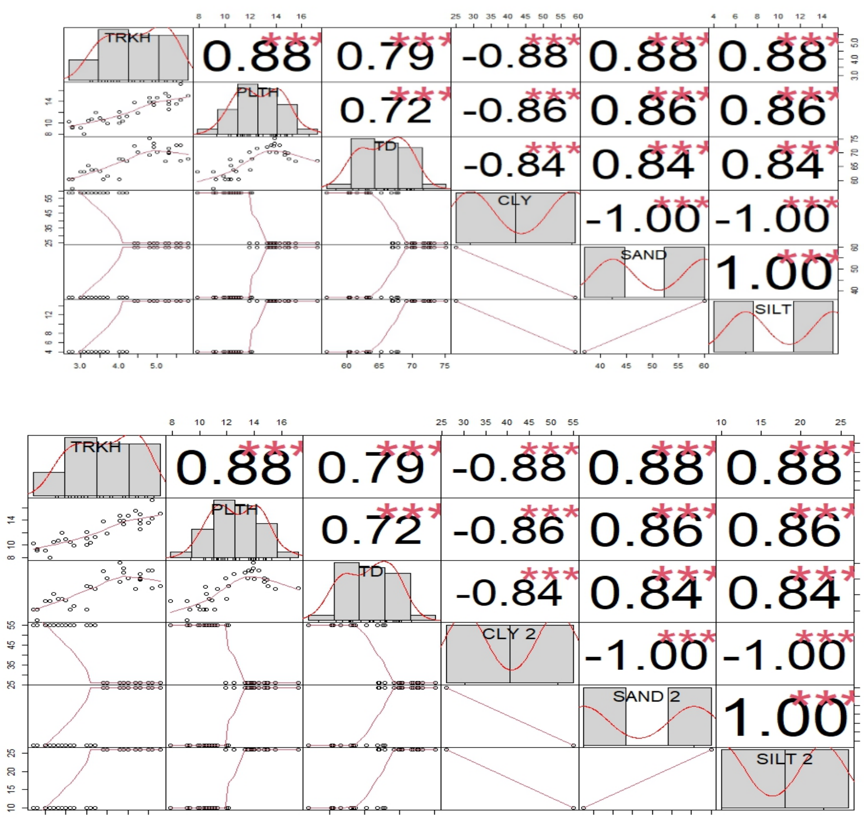
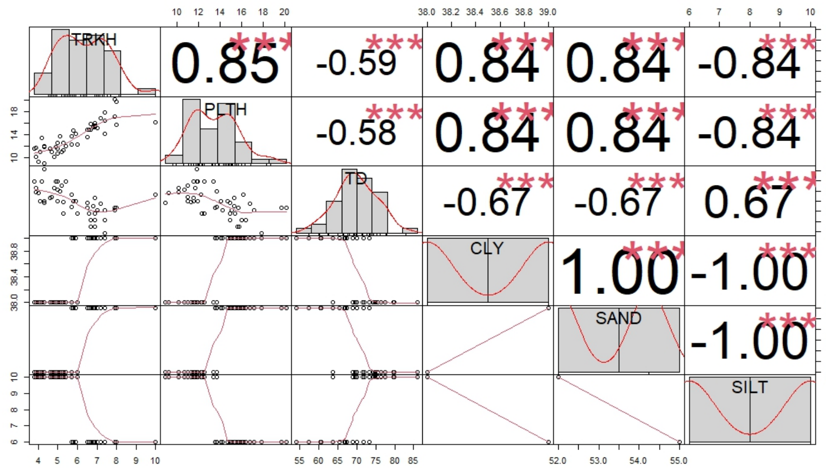


Fig. 7 and 8 Correlation chart for depth 1 and depth 2 in Plantation 3
(Note: TRKH = trunk height, PLTH = total plant height, and TD = trunk diameter)



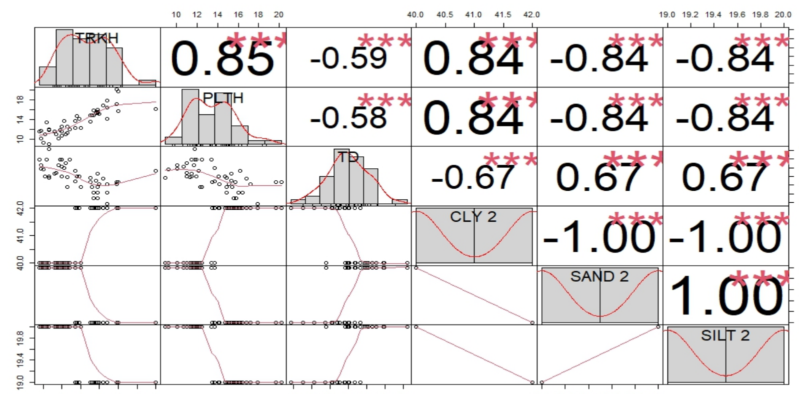


Fig. 9 and 10 Correlation chart for depths 1 and 2 in plantation 4.

The correlation analysis explicitly showed that the sand mineral fraction had the greatest positive influence on the increased height of oil palms, probably because of the predominance of macropores, which ease root horizontal and vertical extension for optimum nutrient and water mining. Additionally, according to Menta and Remelli (2020) and Bekele and Getaneh (2022), the presence of diverse fauna in sandier soils facilitates good soil functionality. According to the Kropff (1993) model, sand has a lower moisture accessibility threshold level than clay. The findings of Smith *et al*. (1995) conformed with these results that some crop species show better germination and growth performance when grown on sandy soil than clay.

Table 8: Soil Textural Results for the Tall Cluster Across the Two Depths in the Plantations

	OP 1		OP 2		OP3		OP 4	
	0 -30	30 – 60	0 - 30	30 - 60	0 -30	30 – 60	0 - 30	30 - 60
Sand	48	28	52	49	60	48	55	39
Clay	38	57	43	46	25	26	39	42
Silt	15	15	5	5	15	26	6	19
Texture	SC	C	SC	SC	SCL	SCL	SC	C

OP = Oil palm plantation, SC = Sandy clay, C = Clay, SCL = Sandy clay loam

Table 9: Soil Textural Results for the Short Cluster Across the Two Depths in the Plantations

	OP 1		OP 2		OP3		OP 4	
	0 -30	30 – 60	0 - 30	30 - 60	0 -30	30 – 60	0 - 30	30 - 60
Sand	26	28	48	36	37	35	52	40
Clay	60	68	41	60	59	55	38	40
Silt	14	4	11	4	4	10	10	20
Texture	C	C	SC	C	C	C	SC	C

OP = Oil palm plantation, SC = Sandy clay, C = Clay, SCL = Sandy clay loam

Tables 8 and 9 indicate that the short cluster was predominant under heavy clay conditions. The digital elevation model map showed that most of the palms in the short cluster were on the bottom slopes of the plantations. Therefore, the higher clay content may be connected with continuous clay translocation due to the influence of erosion, as observed by Idris *et al*. (2019).

CONCLUSIONS AND RECOMMENDATIONS

Based on the results and discussion presented, it can be concluded that soil texture has a profound influence on oil palm height, and sand grains have a positive effect on oil palm height, as opposed to clay particles. Given the conclusion drawn, typical clay soil should be avoided during site selection, and oil palm fields should be well-labeled where it is possible to curtail consistent erosion, which results in continuous clay deposition on the bottom slope.

ACKNOWLEDGMENT

The authors acknowledge the support of the Fundamental Research Grant Scheme (FRGS) (No. FRGS/1/2022/WAB04/UPM/02/2, from the Ministry of Higher Education of Malaysia. We are particularly grateful to Dr. Muhammad Firdaus Sulaiman for supporting us with a measuring tool.

CONFLICT OF INTEREST

The authors declare that there are no conflicts concerning the content of this paper.

AUTHORS CONTRIBUTION

All Authors have contributed tremendously.

REFERENCES

Ajeng, A.A., Abdullah, R., Malek, M.A., Chew, K.W., Ho, Y.C., Ling, T.C., Lau, B.F. and P.L. Show. 2020. The effects of biofertilizers on growth, soil fertility, and nutrients uptake of oil palm (*Elaeis guineensis*) under greenhouse conditions. *Processes*, 2020; 8(12):1681. https://doi.org/10.3390/pr8121681.

Anaba, B.D, Yemefack, M., Abossolo-Angue, M., Ntsomboh-Ntsefong, G., Bilong, E.G., Ngando Ebongue, G.F. and J.M. Bell. 2020. Soil texture and watering impact on pot recovery of soil-stripped oil palm (*Elaeis guineensis* Jacq.) seedlings. *Heliyon*. Vol. ;6(10): e05310. doi: https://doi.org/10.1016/j.heliyon.2020.e05310.

Arora, V.K.; Sing, C.B.; and A.S. Sidhu. 2011. Irrigation, tillage and mulching effects on soybean yield and water productivity in relation to soil texture. *Agric. Water Manag.* , 98, 563–568, https://doi.org/10.1016/j.agwat.2010.10.004.

Avtar, R., Takeuchi, W. and H. Sawada. 2013. Monitoring of biophysical parameters of cashew plants in Cambodia using ALOS/PALSAR data. *Environmental Monitoring and Assessment,* 185 2023-37, https://doi.org/10.1007/s10661-012-2685-y.

Bekele, M., and S. Getaneh. 2022. Function of microorganisms on soil health maintenance: A review article. *Int. J. Adv. Res. Biol. Sci*. (2022). 9(4): 82-93, doi: http://dx.doi.org/10.22192/ijarbs.2022.09.04.XXX.

Bilter, A., Agnes, S., Manurung, I., Osten M., Samosir, R.G. Nurhayati, M. and C. Manalu. 2021. Growth palm oil seedling (*Elaeis guineensis* Jacq.) via NPK fertilization and different frequency of watering. *Journal of Agronomy*, 20: 1-8, https://doi.org/10.3923/ja.2021.1.8.

Brady, N., and R. Weil. 2002. *The Nature and Properties of Soils* 13th (Ed) Prentince Hall, New Jersey. USA.

Chakraborty, K. and B. Mistri. 2015. Importance of soil texture in sustenance of agriculture: A study in Burdwan-I C. D. Block, Burdwan, West Bengal Eastern Geographer. 2015;XXI(1):475–482.

Chu, M.M. 2023. Palm oil production in top Asian producers to remain tight in 2023, https://www.reuters.com/article/malaysia-palmoil-idUSKBN2TR0VP.

Corley, R.H.V., and P.B. Tinker. 2016. The Oil Palm. Print ISBN:9781405189392, Online ISBN:9781118953297, John Wiley and Sons, 2016, doi: https://doi.org/10.1002/9781118953297.

Dancey, C.P. and J. Reidy. 2007. Statistics Without Maths for Psychology. Pearson Education.

Fuady, Z., Satriawan, H. and A. Agusni. 2019. Effects of a combination of inorganic and organic fertilizers application on morphology and physiology of immature oil palm, Planta *Tropika: Jurnal Agrosains* (*Journal of Agro Science*) Vol 7 (1) doi: https://doi.org/10.18196/pt.2019.096.73-81.

Gee, G.W., and Bauder, J.W. 1986. Particle size analysis. In: A. Klute, editor, Methods of soil analysis. Part 1.2nd ed. Agron.Monogr. 9. ASA and SSSA, Madison, WI. p. 383–411.

Harahap, F.S., Sitompul, S. Rauf, A., Rahmawaty, Harahap, D.E. and H. Walida. 2019. Land suitability evaluation for oil palm plantations (*Elaeisguenensis jacq*) on Sitellu Tali Urang Julu, Pakpak Bharat District. *IOP Conf. Ser.: Earth Environ. Sci*. 260 012116.

Ho,Y.S., Bin Wasli, M.E. and P.M. Mugunthan. 2019. Evaluation of physicochemical properties of sandy-textured soils under smallholder agricultural land use practices in Sarawak, east Malaysia. *Hindawi Applied and Environmental Soil Science* Vol. 2019, Article ID 7685451, 14, https://doi.org/10.1155/2019/7685451.

Idris, S., Lawal, H., Maiyaki, M., Mahmud, A., and M. Adamu. 2019. Influence of various land use systems on selected soil productivity parameters of wetland soils. *Fudma Journal of Sciences*, Vol. 3(2), ISSN: 2616-1370, 295-301.

Kirkham, M.B. 2005. *Principles of Soil and Plant Water Relations*. ISBN: 0-12-409751-0 Elsevier Academic Press 200, Wheeler Road, 6th Floor, Burlington, MA 01803, USA 525 B Street, Suite 1900, San Diego, California 92101-4495, USA.

Kropff, M. J. 1993. Mechanisms of competition for light. In: Kropff, M.J. and H.H. van Laar (Eds). Modeling crop–weed interactions. CAB International (in association with International Rice Research Institute), Wallingford, UK, pp. 33-61.

Lewis, K., Rumpang, E., Kho, L.K.. McCalmont, J., Teh, Y.A., Gallego-Sala, A., and T.C. Hill. 2020. An assessment of oil palm plantation aboveground biomass stocks on tropical peat using destructive and non-destructive methods. *Sci. Rep.* 10, 2230 (2020). https://doi.org/10.1038/s41598-020-58982-9.

Menta, C., and S. Remelli. 2020. Soil health and arthropods: from a complex system to worthwhile investigation. *Insects*, 11(1),54, doi: https://doi.org/10.3390/insects11010054.

Morgan, J. B. and E.L. Connolly. 2013. Plant-Soil Interactions: Nutrient Uptake. *Nature Education Knowledge* 4(8):2, https://www.nature.com/scitable/knowledge/library/plant-soil-interactions-nutrient-uptake-105289112/.

Murabbi A., Abdulkadir, M., Azare I.M., Abdu, N., Nuhu, I. S. and A.I. Saminu. 2022. Suitable models for describing sulphate desorption kinetics in selected Bauchi north soils of varying parent materials in the Nigerian sudan savanna. *Agro Bali : Agricultural Journal*, Vol. 5 (3) 403-413, https://doi.org/10.37637/ab.v5i3.968403.

Nishizono, T., Kitahara, F., Iehara, T. and Y. Mitsuda. 2014. Geographical variation in age–height relationships for dominant trees in Japanese Cedar (*Cryptomeria japonica* D. Don) forests in Japan. *Journal of Forest Research* 19 305-16, http://dx.doi.org/10.1007/s10310-013-0416-z.

Nithyatharani, R., and U.S. Kavitha. 2018. Termite soil as bio-indicator of soil fertility. *International Journal for Research in Applied Science and Engineering Technology*, 6(1), 659-661. http://doi.org/10.22214/ijraset.2018.1099.

Obeng, A.S., Sadick, A., Hanyabui, E., Musah, M., Marius, M., and M.K. Acheampong. 2020. Evaluation of soil fertility status in oil palm plantations in the western region of Ghana[J]. *AIMS Agriculture and Food*, 2020, 5(4): 938-949. doi: https://doi.org/10.3934/agrfood.2020.4.938.

Ofosu-Budu K., and D. Sarpong. 2013. Oil Palm Industry Growth in Africa: A value chain and smallholders' study for Ghana. In: Elbehri A (eds), Rebuilding West African Food Potential, Rome FAO/IFAD, 349–389.

Pressler, Y. 2018. Soils are more than just a medium for plant growth. https://yaminapressler.medium.com/soils-are-more-than-just-a-medium-for-plant-growth-5345d37007d0.

Quan, M., and J. Liang. 2017. The influences of four types of soil on the growth, physiological and biochemical characteristics of *Lycoris aurea* (L' Her.) Herb. *Scientific reports*, 7, 43284. https://doi.org/10.1038/srep43284.

Rattan-Lal, M.K. S. 2005. *Principles of Soil Physics*. Marcel Dekker, Inc. New York Basel, ISBN: 0-8247-5324-0 (Print Edition).

Salas-Eljatib, C. 2020. Height growth–rate at a given height: A mathematical perspective for forest productivity, *Ecological Modelling*, Vol. 431, 2020, 109198, ISSN 0304-3800, https://doi.org/10.1016/j.ecolmodel.2020.109198.

Salmiyati, Heryansyahb, A., Ida Idayuc, I., and E. Supriyanto. 2014. oil palm plantations management effects on productivity fresh fruit bunch (FFB), 2013 4th International Conference on Agriculture and Animal Science (CAAS 2013)., APCBEE Procedia 8 (2014) 282 – 286, ScienceDirect. doi: https://doi.org/10.1016/j.apcbee.2014.03.041.

Sanchez, P.A., Palm C.A., and S.W. Buol. 2003. Fertility capability soil classification: a tool to help assess soil quality in the tropics. *Geoderma.* Vol. 114 (3-4) :157–185. https://doi.org/10.1016/S0016-7061(03)00040-5.

Schroeder, B.L., Hubert, J.W., Hubert C., Hubert F.G., Panitz, J.H., Wood, A.W., and P.W. Moody. 2007. Recognizing differences in soil type to guide nutrient inputs on-farm - a case study from Bundaberg. *Proc. Aust. Soc. Sugar Cane Technol.* 2007;29:138–148.

Sibhatu, K.T. 2023. Oil palm boom: Its socioeconomic use and abuse. *Front. Sustain. Food Syst*., 23 Jun. 2023, Sec. *Land, Livelihoods and Food Security* Vol. 7 - 2023 | https://doi.org/10.3389/fsufs.2023.1083022.

Smith, M., Brandt T., and J. Stone. 1995. Effect of soil texture and cicrotopography on germination and seedling growth in *Boltonia decurrens* (asteraceae), a threatened floodplain species. *Wetlands.* 1995;15(4):392–396, doi: https://doi.org/10.1007/BF03160894.

Suh, M. 2023. World palm oil supply forecast: review and update. *Oil Palm Industry Economic Journal* Vol. 23 (2) Sep. 2023 p. 61-69, DOI: https://doi.org/10.21894/opiej.2023.07.

Syahza, A., Bakce, D., Irianti, M., Asmit, B. and B. Nasrul. 2021. Development of superior plantation commodities based on sustainable development. *International Journal of Sustainable Development and Planning* Vol. 16, No. 4, pp. 683-692.

Teh, C.B.S. and J. Talib. 2006. Soil Physics Analyses, Vol. 1. Universiti Putra Malaysia Press.

Tramontini, S., van Leeuwen C., Domec J.C., Destrac-Irvine A., Basteau C., Vitali M., Mosbach-Schulz O., and C. Lovisolo. 2013. impact of soil texture and water availability on the hydraulic control of plant and grape-berry development. *Plant Soil*. 2013;368:215–230, doi: https://doi.org/10.1007/s11104-012-1507-x.

Uke, A., Nakazono-Nagaoka, E., Chuah, J., Zain, N.A., Amir, H., Sudesh, K., Zainal Abidin, N.H.A, Hashim, Z., and A. Kosugi. 2021. Effect of decomposing oil palm trunk fibers on plant growth and soil microbial community composition. *Journal of Environmental Management*, Vol. 295, 113050, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2021.113050.

Upadhyay, S., and A.S. Raghubanshi. 2020. Urban Ecology, Chapter 16 - *Determinants of soil carbon dynamics in urban ecosystems,* Editor(s): Pramit Verma, Pardeep Singh, Rishikesh Singh, A.S. Raghubanshi, Urban Ecology, Elsevier, 299-314, ISBN 9780128207307, https://doi.org/10.1016/B978-0-12-820730-7.00016-1.

Utoyo, B., Hartono, J.S.S., Usodri, K.S., and W. Yuliana. 2022. Growth response of oil palm seedlings (*Elaeis guineensis* jacq.) at several intervals of kno_3 fertilization in main nursery. *IOP Conf. Series: Earth and Environmental Science* 1012 (2022) 012041, doi: https://doi.org/10.1088/1755-1315/1012/1/012041.

Wang, D., Wang, Z., Zhang, J., Zhou, B., Lv, T., and W. Li. 2021. effects of soil texture on soil leaching and cotton (G*ossypium hirsutum* l.) growth under combined irrigation and drainage. *Water*. 2021; 13(24):3614. https://doi.org/10.3390/w13243614.

Wang, F.J.; Wang, Z.; Zhang, J.; and W.H. Li. 2019. Combined effect of different amounts of irrigation and mulch films on physiological indexes and yield of drip-irrigated maize (Zea mays L.). *Water 2019, 11(3), 472; https://doi.org/10.3390/w11030472.*

Wang, L., Lee, M., Ye, B. and G.H. Yue. 2020. Genes, pathways and networks responding to drought stress in oil palm roots. *Sci Rep* 10, 21303 (2020). https://doi.org/10.1038/s41598-020-78297-z.

Zainuddin, N., Keni, M.F., Syed Ibrahim, S.A., and M.M. Masri. 2022. Effect of integrated biofertilizers with chemical fertilizers on the oil palm growth and soil microbial diversity. *Biocatalysis and Agricultural Biotechnology*, Vol. 39, https://doi.org/10.1016/j.bcab.2021.102237.

Zhang, Y.L.; Li, H.E.; and X.C. Zhang. 2008. Effects of soil texture on soil water movement and transport on slope land. *J. Irrig. Drain*. 2008, 27, 27–30, Corpus ID: 131706066.