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Impact of Soil Mounding on Yield Recovery and Nutrient Status of Oil Palm Cultivated on Tropical Peat Soil

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ABSTRACT

Tropical peat soils are extensively distributed across Southeast Asia and support large-scale oil palm cultivation, however their high porosity, low bulk density and poor load-bearing capacity limit root anchorage, palm stability and long-term productivity. These physical constraints contribute to impaired root development, reduced nutrient uptake efficiency and yield decline presenting major challenges for sustainable peatland management. This study evaluated the effectiveness of soil mounding as an agronomic intervention to improve yield recovery, nutrient status and root development of oil palm cultivated on tropical peat soils in Malaysia. Soil mounding was established around the palm base using elevated soil structures measuring 1 m (height) × 2 m (width) × 2 m (length) to enhance mechanical soil support, root anchorage and rhizosphere conditions. Two-way ANOVA demonstrated significant effects of treatment, year and treatment × year interaction on yield-related parameters ($p < 0.001$). Following soil mounding application, fresh fruit bunch (FFB) yield increased by 128.4%, from 9.92 to 23.30 t ha^{-1}, within 2–3 years. Average bunch weight increased by 134.9% (11.51 to 23.35 kg) while bunch number per palm increased by 200.0% (3 to 9 bunches palm^{-1}). Tukey's HSD analysis confirmed significant differences between soil-mounded palms and untreated controls ($p \leq 0.05$) indicating enhanced yield recovery following soil modification. Furthermore, soil mounding significantly improved leaf nutrient concentrations and root growth characteristics suggesting enhanced nutrient acquisition and root system establishment. Overall, soil mounding effectively mitigates key physical limitations of tropical peat soils by improving root-zone stability, nutrient utilization and reproductive performance. This approach provides a sustainable management strategy for restoring oil palm productivity and enhancing yield resilience in peatland cultivation systems.

Key words: *Oil palm, peat soil, soil mounding, nutrient status, FFB yield*

INTRODUCTION

In Malaysia, the total cultivation area of oil palm is about 5.70 million hectares (Malaysian Palm Oil Board, 2025) with 2.54 million hectares in Peninsular Malaysia followed by 1.66 million hectares in Sarawak and 1.50 million hectares in Sabah. The oil palm industry is an important part of the country's agro-economy with its significant role in GDP (Gross Domestic Product), foreign exchange and job creation, according to Basiron & Weng (2004). Of the above, it is estimated that 2.6 million ha is on tropical peat soils, which are soils with high organic matter, low bulk density, high porosity and high water-holding capacity (Paramananthan, 2013). These edaphic conditions are acceptable for planting oil palm but can cause significant problems with palm stability, anchorage in the soil, waterlogging and nutrient availability (Corley & Tinker, 2016). Palm leaning or collapse, soil instability also reports in peat soils which leads to decrease in vegetation density and continuity of the root-soil interface and hence affects water and nutrient uptake which in turn leads to yield decrease (Nursyamsi

et al., 2016). Soil mounding is widely recommended as a technique for physical amelioration of soils which can be used to enhance palm stability through providing more soil to support the palm base. Soil mounding can in addition improve mechanical stability, can better the root development due to more favorable rooting medium and leads to more root density and more root soil contact. Enhanced efficiency of nutrient uptake especially in peat soils, where lower nutrient availability is due to leaching, acidity and low base cation retention (Fairhurst & Griffiths 2014) may be achieved when there is increased root proliferation. Soil mounding can after all lead to yield recovery and to better roots development and uptake of nutrients by the oil palm grown on peat soil as evaluated in the present study.

Such soil mounding, originally used for the management of Ganoderma basal stem rot (BSR) disease has proved beneficial in the general improvement of peat soil performance and palm stabilization (Turner & Gillbanks, 2003). This is done by introducing mineral or organic soil around the base of the palm and thus increasing the bulk density which helps to reduce the subsidence rates, improve surface drainage and duration of efficient uptake of nutrients which is essential for anchor and diffusion of oxygen through soil to the root system (Samsuri *et al*., 2018; Paramananthan, 2013). A commercial trial for soil mounding to recover production losses in the lowest yielding areas of the plantation due to palm leaning and flood was undertaken in oil palm plantation on peat soils in Malaysia.

The main objective of this study was to evaluate the effectiveness of soil mounding in improving oil palm productivity, foliar nutrient status and root development under tropical peat soil conditions. Specifically, this study aimed to: (i) determine the effects of soil mounding on oil palm yield components, including fresh fruit bunch (FFB) yield, average bunch weight (ABW) and bunch number per palm; (ii) assess changes in foliar nutrient concentrations, particularly nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) following soil mounding application; and (iii) evaluate the effects of soil mounding on root development. The study also aimed to provide empirical evidence on the potential of soil mounding as an agronomic management practice to overcome the physical limitations of tropical peat soils and support sustainable oil palm production.

MATERIALS AND METHODS

Site description

The study was conducted in the Perbadanan Kemajuan Pertanian Negeri Pahang (PKPP) in Rompin, Pahang with the area of 1,710.80 ha of oil palm plantation was known as PKPP Warisan Sabak plantation (Coordinates: 2°50'24"N, 103°24'00"E). Location of the plantation picked up in **Figure 1**. The deep peat soil (Terric Histosol) is characteristic of the site ranging in depth between 150 to 250 cm. The climatic data from the past 12 years (2014- 2025) reveals that the average annual rainfall is expected to be 2200- 2300 mm with 120- 130 rainy days, with the maximum falling in the months of November- December while the minimum rainfall was observed during the months of April- May. As shown in **Figure 2**, a mini excavator was used to carry out soil mounding by moving the existing peat soil around the base of the oil palm trunks to form raised mounds.

Treatment and experimental design

A comparison of oil palm performance in peatland areas with and without soil mounding was conducted. The experiment was laid out in a comparative field test in the form of blocks; each block being treated with one treatment alone. As presented in **Table 1**, the study consisted of two treatments, namely soil mounding (T1) and no mounding (T0), with five replicates (observation blocks) assigned to each treatment. Each replicate consisted of 10 recording palms which were used for data collection throughout the study. Block selection was done to reduce site variability based on similar low yield performance (≤18 t ha-1), palm age, a high incidence

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rate of leaning (%), peat properties, water table level, field elevation and agronomic management history. For a clearer illustration of the experimental layout and arrangement of the treatments and replicates, **Figure 3** is provided.

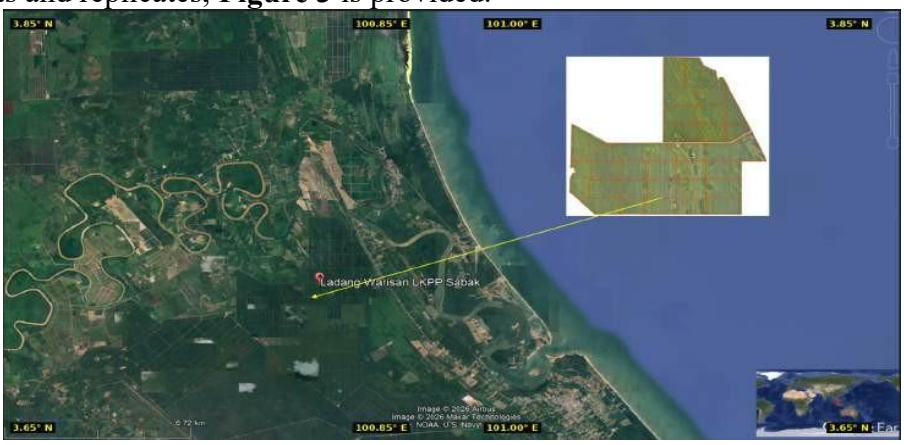


Figure 1. Location map of PKPP Warisan Sabak Plantation in Rompin District, Pahang, using ArcGIS



Figure 2. Use of a mini excavator during soil mounding operation in the oil palm block

Table 1. Experimental design

Treatment	Description	Replicates/ Blocks
T1	Mounding	5
T0	No Mounding	5

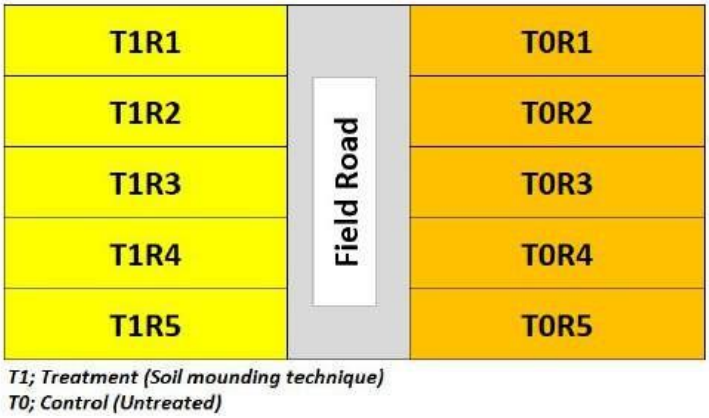


Figure 3. Treatment plot diagram

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Yield component analysis

Throughout the period 2021 to 2025 monthly secondary data (**Figure 4**) were collected from existing plantation records from the management, which is recorded monthly. The data included fresh fruit bunch (FFB) yield, average bunch weight (ABW) and bunch number per palm (BN/palm). The study consisted of five treatment blocks where soil mounding was used and five control blocks where soil mounding was not used.



Figure 4. Fresh fruit bunches (FFB) weighed manually by field workers (a) and weighing of fresh fruit bunches (FFB) using an analogue weighing scale (b)

Foliar and root nutrient analysis

Foliar sampling was carried out at three-month intervals to determine nutrient status (nitrogen, phosphorus, potassium and magnesium) in oil palm by comparing the treatment and control treatment. The sampling process began by randomly determining a starting point within the block, followed by selecting sample palms at regular intervals specifically every 10th palm and every 10th planting row, representing approximately 1% of the total number of palms in each block was obtained (FAO, 2002; APEC, 2013). The selected palms were healthy, mature palms with normal growth and no pest infestations, diseases or physical damage that could potentially affect leaf nutrient status.

Leaf samples were collected from each recording palm using leaflets taken from frond number 17th, following the standard foliar sampling procedure for mature oil palm (Broeshart, 1956; Zakaria, 2020). For each palm, leaflets were taken from the middle portion of frond number 17th on both sides of the rachis to ensure representative sampling. The collected leaflets were combined to form a composite sample for each replicate. The samples were oven dried, ground and analysed for nutrient concentration. Nitrogen was determined using a Kjeldahl Analyzer, while phosphorus, potassium and magnesium were analysed using ICP-OES at the LKPP Corp. Laboratory, Gambang, Pahang, Malaysia.

Root sampling and analysis

Root sampling was conducted destructively by excavating the soil to a depth of 0–45 cm within the active root zone (**Figure 5**) at the end of the trial in November 2025. Sampling was carried out at each recording palm using a quadrat measuring 30 cm × 30 cm × 45 cm placed 1 m from the palm base. The collected roots were separated according to soil depths of 0–15 cm, 15–30 cm and 30–45 cm. The roots were washed free of soil and debris, oven-dried and weighed to analyse root development at each depth. Root morphology and distribution were analysed at the UPM laboratory using a root scanner with WinRHIZO software.

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Figure 5. Root sampling conducted destructively through manual soil excavation at 0–45 cm depth within the active root zone of oil palm.

Statistical analysis

IBM SPSS Statistics 27 was used for statistical analyses. Treatment differences were assessed using analysis of variance (ANOVA) at $p \leq 0.05$ for differences in fresh fruit bunch (FFB) yield, average bunch weight (ABW), bunch number per palm (BN/ palm), foliar nutrient and root density in mounded (T1) and no mounded (T0) palms. Tukey's Honestly Significant Difference (HSD) test with a value of $p \leq 0.05$ was used for mean separation besides Duncan's Multiple Range Test (DMRT) was also used.

RESULTS AND DISCUSSION

Yield components

The results presented in **Figure 6** demonstrate that soil mounding positively influenced oil palm yield performance on tropical peat soil throughout the observation period from 2021 to 2025. Before treatment implementation, both experimental areas exhibited relatively low productivity with FFB yield below 18 t ha^{-1}. The unfavourable peat soil conditions, particularly low soil bearing capacity, poor structural stability, waterlogging and a high incidence of leaning palms may have restricted root anchorage and nutrient acquisition consequently affecting overall palm productivity.

In 2021, before soil mounding implementation, the treatment block (T1) recorded an FFB yield of 9.92 t ha^{-1}, an average bunch weight (ABW) of 11.51 kg and three bunches per palm. Meanwhile, the control block (T0) recorded a higher FFB yield of 13.08 t ha^{-1}, an ABW of 13.08 kg and three bunches per palm. These findings indicated relatively poor yield performance in both areas although the treatment block exhibited lower initial productivity.

Following soil mounding implementation in June 2022, FFB yield in T1 declined further to 7.09 t ha^{-1} compared with 14.03 t ha^{-1} in T0. A similar response was observed in ABW and bunch number with T1 recording 11.62 kg and three bunches per palm, respectively. This temporary reduction may be associated with soil disturbance during the mounding operation which could have affected the existing root system and temporarily reduced nutrient and water uptake. Nakahata *et al*. (2017) reported that soil disturbance can influence fine-root dynamics particularly during the initial period of root regeneration and establishment. Furthermore, the delayed response in FFB production is consistent with the physiological development cycle of oil palm which requires approximately 24–30 months from floral initiation to fruit bunch maturity (Corley & Tinker, 2016).

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A noticeable improvement in yield performance was observed in 2023, one year after soil mounding implementation. FFB yield in T1 increased to 15.00 t ha^{-1}, becoming comparable to the control treatment (14.97 t ha^{-1}). ABW also increased to 19.10 kg, while bunch number increased to six bunches per palm. This improvement suggests the beginning of a positive yield response following the establishment of improved root zone conditions.

The treatment effect became more pronounced in 2024, when FFB yield in T1 increased to 22.10 t ha^{-1} compared with 18.30 t ha^{-1} in T0. This improvement was accompanied by an increase in ABW to 22.70 kg and seven bunches per palm. In 2025, FFB yield in T1 reached 23.30 t ha^{-1}, compared with 20.00 t ha^{-1} in T0. ABW increased further to 23.35 kg, while bunch number reached nine bunches per palm, compared with six bunches in the control treatment. Overall, FFB yield in T1 increased by 134.9%, from 9.92 t ha^{-1} in 2021 to 23.30 t ha^{-1} in 2025. The two-way ANOVA presented in **Figure 6** indicated significant effects of treatment, year and treatment × year interaction for FFB yield ($p \leq 0.002$). Similar significant treatment and interaction effects were observed for ABW and bunch number per palm ($p \leq 0.004$).

These findings indicate that oil palm productivity responded differently between treatments over the observation period. The substantial improvement in FFB yield was associated with increases in both bunch weight and bunch number, suggesting that soil mounding contributed to the recovery of reproductive performance. The delayed yield response may be explained by the time required for root establishment, nutrient acquisition and subsequent bunch development. Overall, the findings demonstrate the potential of soil mounding as an agronomic intervention for improving oil palm yield performance under tropical peat soil conditions.

Foliar nutrient content

The foliar nutrient analysis (**Table 2**) showed changes in nitrogen, phosphorus, potassium and magnesium concentrations between T0 (no mounding) and T1 (soil mounding) from 2020 to 2025 with clear differences observed after soil mounding was implemented in June 2022. For nitrogen, T0 recorded higher concentrations of 2.54% and 2.53% in 2020 and 2021 respectively, compared with 2.51% and 2.45% in T1. Following soil mounding, nitrogen concentration in T1 increased to 2.58% in 2022 and subsequently reached 2.71% from 2023 to 2025. In contrast, T0 showed a declining trend, decreasing from 2.51% in 2022 to 2.42% in 2025. This substantial difference suggests that improved root-zone conditions following soil mounding may have enhanced nitrogen acquisition by oil palm. Nitrogen is an essential macronutrient involved in chlorophyll formation, amino acid, protein synthesis and vegetative growth thereby contributing to photosynthetic activity and overall plant productivity (Hawkesford *et al*., 2012).

A similar response was observed for phosphorus where both treatments recorded comparable concentrations of 0.153% in 2020. In 2021, T1 decreased to 0.143% compared with 0.155% in T0. However, after soil mounding, phosphorus concentration in T1 increased to 0.176% in 2022 and remained relatively stable between 0.178% and 0.180% from 2023 to 2025. Meanwhile, T0 maintained concentrations of approximately 0.155% throughout the same period. The improvement in foliar phosphorus concentration may be associated with enhanced root development and improved access to available soil nutrients. Phosphorus plays an important role in energy transfer through adenosine triphosphate (ATP), nucleic acid synthesis and root development, making it essential for plant growth and metabolic activities (Hawkesford *et al*., 2012).

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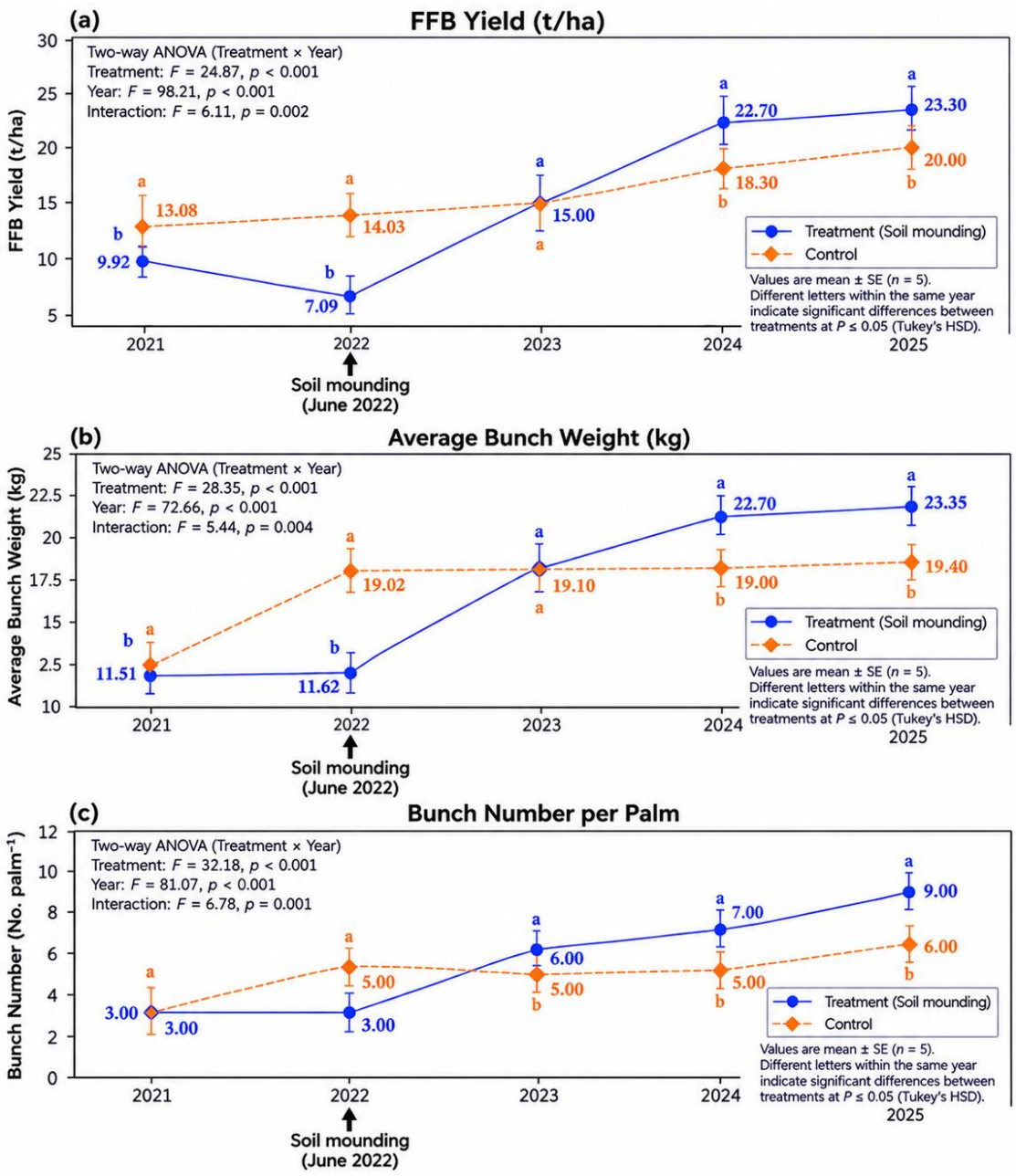


Figure 6. (a)Fresh fruit bunch (FFB) yield (t/ha), (b) the average bunch weight (kg) and (c) average bunch number per palm for the period of 2021- 2025.

For potassium, significant treatment differences were observed in most years, except 2021. In 2020, T1 recorded a higher potassium concentration (1.21%) than T0 (1.13%), while both treatments showed comparable concentrations in 2021 (0.94% and 0.97%, respectively). Following soil mounding, potassium concentration in T1 increased to 1.22% in 2022 and continued to increase to 1.24%, 1.30% and 1.31% in 2023, 2024 and 2025, respectively. Conversely, T0 showed a continuous decline from 0.94% in 2022 to 0.79% in 2025. This contrasting trend indicates an improvement in potassium nutritional status in the mounded treatment. Potassium is essential for stomatal regulation, osmotic adjustment, enzyme activation and assimilate translocation. These physiological functions are important for maintaining photosynthetic activity and supporting fruit development and yield formation in oil palm (Hawkesford *et al*., 2012; Corley & Mok, 1972).

Table 2. Analysis of Variance (Anova) For Comparison of Foliar Nutrient Concentrations (%) Of Nitrogen, Phosphorus, Potassium and Magnesium Between Soil Mounding and Control Treatments 2020- 2025.

a. Nitrogen (N) concentration

Treatment	2020	2021	2022	2023	2024	2025
T0	2.54± 0.02^{a}	2.53± 0.02^{a}	2.51± 0.01^{b}	2.44± 0.01^{b}	2.44± 0.01^{b}	2.42± 0.01^{b}
T1	2.51± 0.01^{b}	2.45± 0.03^{b}	2.58± 0.02^{a}	2.71± 0.01^{a}	2.71± 0.01^{a}	2.71± 0.01^{a}
F	6.25	23.4	39.6	512.3	489.6	620.5
Sig	*	**	**	**	**	**
CV (%)	1.2	1.8	1.1	0.5	0.5	0.6
HSD	0.03	0.05	0.04	0.02	0.02	0.02

b. Phosphorus (P) concentration

Treatment	2020	2021	2022	2023	2024	2025
T0	0.153±0.002^{a}	0.155±0.002^{a}	0.155±0.004^{b}	0.155±0.003^{b}	0.155±0.003^{b}	0.155±0.002^{b}
T1	0.153±0.002^{a}	0.143±0.007^{b}	0.176±0.002^{a}	0.178±0.001^{a}	0.180±0.001^{a}	0.179±0.001^{a}
F	0.12	18.5	92.3	210.4	260.2	240.5
Sig	ns	**	**	**	**	**
CV (%)	1.5	3.2	1	0.6	0.6	0.6
HSD	0.004	0.007	0.003	0.002	0.002	0.002

c. Potassium (K) concentration

Treatment	2020	2021	2022	2023	2024	2025
T0	1.13±0.03^{b}	0.97±0.02^{a}	0.94±0.03^{b}	0.87±0.03^{b}	0.85±0.01^{b}	0.79±0.02^{b}
T1	1.21±0.02^{a}	0.94±0.03^{a}	1.22±0.03^{a}	1.24±0.03^{a}	1.30±0.01^{a}	1.31±0.02^{a}
F	18.6	1.2	85.4	150.2	310.4	420.6
Sig	**	ns	**	**	**	**
CV (%)	2.5	3.1	2	1.8	1.2	1.4

d. Magnesium (Mg) concentration

Treatment	2020	2021	2022	2023	2024	2025
T0	0.31±0.02^{a}	0.32±0.02^{a}	0.32±0.02^{a}	0.33±0.02^{b}	0.33±0.02^{b}	0.34±0.02^{b}
T1	0.31±0.02^{a}	0.25±0.02^{b}	0.32±0.01^{a}	0.43±0.02^{a}	0.52±0.02^{a}	0.53±0.02^{a}
F	0.01	22.4	0.2	140.3	310.5	330.2
Sig	ns	**	ns	**	**	**
CV (%)	4.2	5.5	3.1	3	2.8	2.7
HSD	0.03	0.04	0.03	0.04	0.05	0.05

Note: **, *, Significant at p≤ 0.01 and 0.05, respectively. T0, No mounding, T1, Soil mounding

Magnesium also showed a positive response to soil mounding particularly during the later observation period. In 2020 and 2022, both treatments recorded relatively similar concentrations of approximately 0.31–0.32%. However, T1 recorded a lower concentration of 0.25% in 2021 compared with 0.32% in T0. Following soil mounding, magnesium concentration in T1 increased substantially to 0.43% in 2023, 0.52% in 2024 and 0.53% in 2025. In comparison, T0 remained relatively stable at approximately 0.33–0.34%. The increased magnesium concentration suggests an improvement in the nutritional status of oil palm under the mounded treatment. Magnesium is a central component of the chlorophyll molecule and plays a critical role in photosynthesis, enzyme activation and carbohydrate metabolism. Consequently, adequate magnesium nutrition is important for maintaining photosynthetic efficiency and assimilate production (Hawkesford *et al*., 2012).

The consistent increases in N, P, K and Mg concentrations in T1 may be associated with improved root development following soil mounding. Sun *et al*. (2022) highlighted the importance of root-zone aeration in supporting root growth and modifying rhizosphere conditions. Similarly, Azam *et al*. (2025) reported that improved soil conditions and deeper root development contributed to enhanced water and nutrient uptake ultimately improving wheat productivity. Although these studies involved different crops and soil management

conditions, their findings support the potential relationship between root development and nutrient acquisition observed in the present study.

The improvement in foliar nutrient status also provides a possible explanation for the subsequent improvement in oil palm yield components. Adequate N, P, K and Mg supply supports photosynthesis, assimilate production, root activity and reproductive development which collectively contribute to bunch formation and fruit development. In the present study, the higher foliar nutrient concentrations observed in T1 from 2022 onwards coincided with subsequent improvements in average bunch weight, bunch number per palm and fresh fruit bunch (FFB) yield during the later observation years. This delayed agronomic response is consistent with the relatively long bunch formation cycle of oil palm which requires approximately 24–30 months (Corley & Tinker, 2016). Therefore, the improvement in foliar nutrient status following soil mounding may have contributed to the recovery of yield performance over the subsequent years.

Root development

Soil mounding significantly influenced oil palm root development on tropical peat soil, particularly in terms of root extension, proliferation and branching characteristics. As presented in **Table 3**, significant differences between the control treatment (T0: no mounding) and mounded treatment (T1: soil mounding) were observed following the implementation of soil mounding in June 2022. Root length was significantly higher in T1 (963.10 cm) compared with T0 (805.12 cm). This indicates greater root extension under the mounded condition suggesting that the raised soil surface may have provided more favourable conditions for root development. Similarly, the number of root tips was significantly higher in T1 (3,014.47) than in T0 (2,208.95). The greater number of root tips indicates increased fine-root proliferation which may enhance the capacity of oil palm to explore the surrounding soil for water and nutrients. Root branching also showed a significant response to soil mounding. The number of forks increased to 4,755.87 in T1 compared with 3,766.25 in T0. In addition, T1 recorded a significantly higher number of root crossings (437.80) than T0 (310.98). The greater number of forks and crossings suggests a more extensively developed root network under the mounded condition. These root architectural characteristics are important for increasing soil exploration and potentially improving the acquisition of water and nutrients. Similar findings were reported by Azam *et al*. (2025), who demonstrated that greater root development and deeper soil exploration contributed to improved water and nutrient uptake. Although their study focused on wheat rather than oil palm, the findings support the functional relationship between root development and resource acquisition.

In contrast, projected area, surface area, estimated volume, measured volume, average estimated diameter, average measured diameter and number of nodules showed no significant differences between treatments. The projected area was 80.74 cm^2 in T1 compared with 73.97 cm^2 in T0, while surface area was 253.66 and 232.37 cm^2, respectively. Similarly, estimated root volume was 7.63 cm^3 in T1 and 7.01 cm^3 in T0, whereas measured volume was 14.38 and 12.67 cm^3, respectively. Average estimated diameter and average measured diameter were 1.15 and 0.90 mm, and 1.03 and 0.78 mm, respectively. No root nodules were detected in either treatment. The absence of significant differences in these parameters suggests that the response to soil mounding was more pronounced in root extension and branching than in root thickness and overall root volume. This indicates that soil mounding may have promoted the development of a more extensive root system rather than substantially increasing individual root size.

The root distribution patterns at different soil depths (0–15 cm, 15–30 cm and 30–45 cm) obtained through root scanning analysis using WinRHIZO software, are presented in **Figure 7**. At the upper soil layer (0–15 cm), T0 exhibited a relatively sparse and scattered root

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distribution, whereas T1 showed a denser and more concentrated arrangement of roots. A similar pattern was observed at the intermediate depth (15–30 cm), where T1 demonstrated a more extensive root distribution compared with T0. At the deeper soil layer (30–45 cm), root presence in T0 was considerably limited, while T1 exhibited more noticeable root development. These observations suggest that soil mounding promoted more extensive vertical and horizontal root distribution within the peat soil profile particularly at deeper soil layers.

Table 3. Analysis of Variance (Anova) for comparison of root distribution with difference soil depth between T1 (Soil Mounding) and T0 (Control) treatments 2022- 2025.

Parameter	T0	T1	F	Sig	CV (%)
Length (cm)	805.12 ± 62.10^{b}	963.10 ± 55.32^{a}	8.45	*	7.8
Projected area (cm²)	80.74 ± 5.12^{a}	73.97 ± 6.03^{a}	1.12	ns	6.9
Surface area (cm²)	253.66 ± 14.88^{a}	232.37 ± 16.21^{a}	1.54	ns	6.2
Volume estimated (cm³)	7.63 ± 0.52^{a}	7.01 ± 0.61^{a}	0.98	ns	7.4
Volume measured (cm³)	14.38 ± 1.02^{a}	12.67 ± 1.15^{a}	1.33	ns	8.1
Ave diameter estimated (mm)	1.15 ± 0.06^{a}	0.90 ± 0.07^{a}	2.21	ns	6.5
Ave diameter measured (mm)	1.03 ± 0.05^{a}	0.78 ± 0.06^{a}	2.64	ns	7.2
Number of tips	2208.95 ± 142.33^{b}	3014.47 ± 168.25^{a}	9.12	*	7.6
Number of forks	3766.25 ± 221.54^{b}	4755.87 ± 248.11^{a}	7.88	*	6.9
Number of crossings	310.98 ± 21.44^{b}	437.80 ± 24.66^{a}	8.01	*	7.3
Number of nodules	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	–	ns	–

Notes: Means followed by different superscript letters within the same row are significantly different according to Duncan Multiple Range Test at $p \leq 0.05$.

The improved root distribution under T1 may be associated with more favourable physical conditions within the mounded root zone. The raised soil surface potentially improved soil aeration and drainage, creating a more suitable environment for root penetration and development. This is particularly relevant in tropical peat soils where high moisture content and poor soil bearing capacity can restrict root development and anchorage. Sun *et al*. (2022) highlighted the importance of root-zone aeration in supporting root growth and influencing rhizosphere conditions. Therefore, improved aeration under the mounded condition may have contributed to the greater root extension and branching observed in the present study. Overall, the findings demonstrate that soil mounding was associated with improved oil palm root development particularly in terms of root length, number of tips, forks and crossings. The more extensive root distribution observed across the three soil depths further suggests that mounding may have enhanced root exploration within the peat soil profile. These improvements indicate that soil mounding can be considered a potential agronomic practice to promote root development and improve the capacity of oil palm to explore soil resources under tropical peat soil conditions.

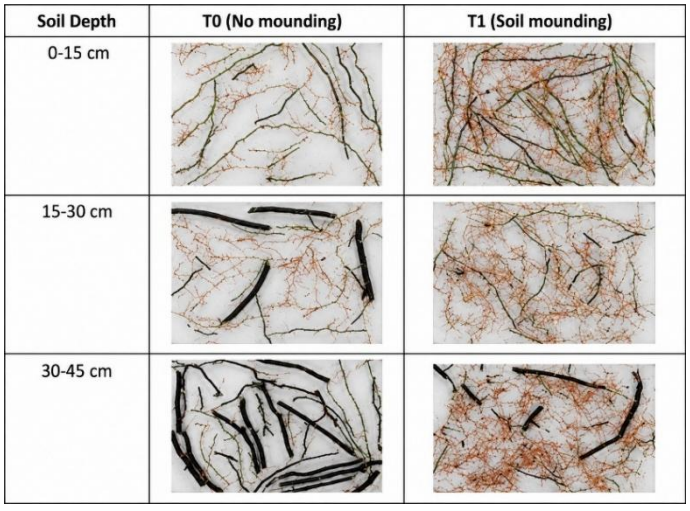


Figure 7. Illustration of root distribution at different soil depth was analysed using a root scanner with WinRHIZO software.

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CONCLUSION

Overall, soil mounding demonstrated a positive effect on oil palm productivity, foliar nutrient status and root development under tropical peat soil conditions. Although an initial reduction in fresh fruit bunch (FFB) yield was observed following the implementation of soil mounding in June 2022, this response may have been associated with temporary root disturbance during the soil modification process. Nevertheless, subsequent improvements in root development particularly root length, number of tips, forks and crossings indicated enhanced root proliferation and branching under the mounded treatment. The more extensive root distribution observed across the sampled soil profile further suggested improved root exploration within the peat soil. These changes were accompanied by higher foliar concentrations of nitrogen (N), phosphorus (P), potassium (K) and magnesium (Mg) reflecting an improvement in the nutritional status of the palm. The improved root development and foliar nutrient status may have contributed to better vegetative performance and the subsequent increase in average bunch weight, bunch number per palm and overall FFB yield. Notably, the FFB yield response became more evident in the later years which is consistent with the physiological bunch formation cycle of oil palm requiring approximately 24–30 months from inflorescence development to bunch maturity. This highlights the importance of evaluating the effectiveness of soil mounding over an extended period rather than relying solely on short-term yield responses.

Therefore, soil mounding can be considered a promising agronomic management practice for addressing the physical limitations of tropical peat soils. By improving root-zone conditions and supporting root development and nutrient status, this practice has the potential to enhance long-term oil palm productivity and facilitate yield recovery on peat soils.

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