

# VERTICAL DISTRIBUTION OF OIL PALM (*Elaeis guineensis*) ROOTS IN SOIL AFTER ORGANIC MATTER AMENDMENTS USING BIOPORE INFILTRATION HOLES AND PILE TECHNIQUES

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## ABSTRACT

This study evaluated the effects of organic matter techniques application (surface pile and subsurface biopore infiltration holes) and organic matter types on the vertical root distribution of oil palm (*Elaeis guineensis*). The experiment used a factorial randomised block design with two factors: Application technique (pile and biopore infiltration holes) and five organic matter types (no organic matter, fresh empty fruit bunches [EFB], EFB compost, palm fronds and palm leaves). Root depth was measured at the second and fourth months after treatment. Although statistical analysis showed no significant differences ( $p > 0.05$ ), consistent biological trends were observed. Treatments using EFB compost, particularly with the pile method, indicated a tendency to promote root growth closer to the soil surface, with root depth decreasing from 6.33 to 4.17 cm. Pile applications showed faster response of root distribution than biopore infiltration holes, although biopore infiltration holes combined with EFB compost also improved root distribution. Conversely, treatments without organic inputs or with slowly decomposing materials (fresh EFB, palm fronds and palm leaves) resulted in minimal changes in root depth. These findings suggest that using EFB compost with appropriate application techniques may enhance shallow root proliferation, potentially improve nutrient uptake efficiency and support sustainable plantation management.

**Keywords:** biopore, *Elaeis guineensis*, empty fruit bunch compost, root architecture, Ultisol.

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## INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is a major plantation crop in Indonesia and Malaysia with significant economic value (Nurfatriani et al., 2022; Parveez et al., 2024; Purnomo et al., 2020). High productivity in oil palm plantations is inseparable from the role of effective and efficient fertilisation strategies. Growth and yield of oil palm vary across soil types due to differences in soil physical, chemical and biological properties (De la Peña

et al., 2024; Manorama et al., 2024). One of the key strategies to improve fertilisation efficiency is to accurately target the active root zone of the plant (Devianti et al., 2022; Joehandra et al., 2023). The application of organic matter has been shown to improve soil characteristics, including increased water holding capacity, cation exchange capacity, porosity, soil pH and enhanced activity of beneficial soil microorganisms (Nurfatriani et al., 2022; Purnomo et al., 2020). Utilisation of various organic materials such as oil palm empty fruit bunches (EFB), fronds and leaves plays an important role in this process. These materials are organic residues derived from the oil palm itself and represent a readily available source of organic matter (Zakri & Adam, 2021),

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particularly for smallholders. Their abundance and on-site availability make them a sustainable and low-cost alternative to commercial fertilisers, with high potential for use as organic amendments to improve soil fertility and plant productivity in oil palm plantations, aligning with principles of sustainable agriculture by recycling on-farm biomass. Beyond general soil improvements, the decomposition of organic matter directly influences the rhizosphere environment, creating favourable conditions for root growth. This includes releasing essential nutrients, improving soil structure which facilitates root penetration and stimulating beneficial microbial activity that can enhance nutrient availability and root signaling (Nurfatriani et al., 2022; Purnomo et al., 2020; Zakri & Adam, 2021). For oil palm, optimising root distribution, especially promoting roots closer to the soil surface, can significantly improve the efficiency of nutrient uptake from applied fertilisers and enhance gas exchange in the active root zone (Ariyanti et al., 2019; Devianti et al., 2022). Biopores are macropores in the soil formed naturally by the activity of soil fauna (e.g., worms, termites, ants) and plant roots. The presence of these pores significantly enhances soil properties by facilitating water infiltration and improving the movement of air through the soil profile (Ashabie & Masjud, 2022; Karuniastuti, 2014; Kurniadinata et al., 2016; Simanjuntak et al., 2021). When organic waste is applied to biopore infiltration holes, microbial activity is stimulated, accelerating the decomposition of organic matter into compost (Akbar et al., 2018). This compost not only improves soil fertility but also contributes directly to plant nutrition, especially when applied in the rhizosphere of oil palm (Ariyanti et al., 2019; Simanjuntak et al., 2021; Zahari et al., 2023).

Importantly, the placement of organic materials and biopore infiltration holes can influence root distribution, particularly the development of roots closer to the soil surface. Understanding the impact of application techniques and types of organic matter on root distribution near the surface is crucial, as shallow root development can facilitate easier and more effective fertiliser application, enhance gas exchange ( $\text{CO}_2$  and  $\text{O}_2$ ) in the rhizosphere and ultimately promote better root growth and plant performance.

While previous studies have highlighted the general benefits of organic matter and the importance of root distribution for nutrient uptake, there is a limited understanding of how specific application techniques (pile [T1] versus biopore infiltration holes [T2]) interact with different types of oil palm-derived organic materials to influence shallow root proliferation in established oil palm plantations. Study into oil palm cultivation is

increasingly focusing on holistic approaches to soil health and plant-environment interactions (Manorama et al., 2024), including the role of the soil mycobiome (Azeez et al., 2024), nutrient stress responses (De la Peña et al., 2024) and the management of biomass waste as a resource (Nurmiati et al., 2024). This study can address the gap by systematically evaluating these interactions to optimise organic matter application strategies for improved root architecture, aligning with modern paradigms of sustainable oil palm management with aims to evaluate the effect of different T1 and T2 application techniques using various types of organic materials on the distribution of oil palm roots relative to the soil surface.

## MATERIALS AND METHODS

### Location of Study

The study was conducted in a 10-year-old oil palm plantation located in Kongbeng Sub-district, East Kutai District, East Kalimantan, Indonesia (coordinates: approximately  $0^{\circ}42'00''$  N,  $117^{\circ}24'00''$  E; altitude: 50-70 m above sea level). The study site is characterised by an Ultisol soil type, with a clay loam texture, pH of 4.5-5.0, and an average organic matter content of 2.5%. The average annual rainfall in the region is approximately 2,800 mm, with a relatively consistent temperature range of  $26^{\circ}\text{C}$ – $30^{\circ}\text{C}$ .

### Experimental Design

A factorial randomised complete block design (RCBD) was employed, consisting of two treatment factors. The rationale for this design was to minimise the effects of environmental variability across the plantation plot, such as differences in soil heterogeneity or topography, by grouping similar experimental units into blocks. The first factor was the application technique: T1 and T2. The second factor was the type of organic matter, with five levels: No organic matter (S0), fresh EFB (S1), EFB compost (S2), palm fronds (S3) and palm leaves (S4). Each treatment combination was replicated three times, resulting in a total of 30 experimental trees. While each replicate consisted of one tree per treatment, the total sample size across the experiment provides a basis for the observed trends. Root observations were conducted at two intervals: Second and fourth month-after-application. The samplings were separate destructive sampling events, not a single continuous measurement, to evaluate the cumulative effect of the treatments at each time point.

## Treatment of Organic Material

For the preparation of organic matter treatments, S1 and S2 were sourced directly from a nearby palm oil mill. The S2 was produced through an aerobic composting process lasting approximately 60 days, utilising natural microbial decomposition without specific microbial inoculants. During composting, the EFB piles were regularly turned to ensure aeration and for maintaining optimal moisture content. Prior to application, both types of EFB were mechanically processed using a chopper machine to achieve uniform particle size and enhance decomposition rates. In addition, S3 and S4 were collected and processed separately. The S3 and S4 used were obtained from pruning activities during fresh fruit bunch (FFB) harvesting, making them old fronds. Palm fronds were separated into rachis and leaflets prior to chopping, while palm leaves (leaflets) were chopped separately. This was done to evaluate the individual effects of each organic material on root distribution, as S3 and S4 have different physical properties and decomposition rates which can affect their unique contributions to the root environment. These processed materials were then designated as the organic amendments for treatment groups S3 and S4, respectively.

The T2 technique involved creating holes with a diameter of 10 cm and a depth of 80 cm using a soil boring tool. Two T2s were made per tree, located on the north- and south-side at 50 cm from the tip of the palm canopy. Following the preparation of T1 and T2, the respective organic matter were applied according to the designated treatments. For the T1 treatment, organic matter was placed directly on the soil surface at corresponding positions.

The application procedure for organic materials (S1, S2, S3 and S4) differed according to the application technique (T1 and T2). For treatments involving organic materials, the specified mass of S1, S2 and S3 (2.5 kg) and S4 (2.0 kg) was applied to each experimental tree. For the T1 technique, the entire mass of the organic material (2.5 and 2.0 kg) was placed directly on the soil surface in a compact, circular pile at the specified distance (50 cm from the edge of the palm canopy). This placement was consistent for all organic matter types (T1S1, T1S2, T1S3 and T1S4). For the T2, the total mass of organic matter was divided equally into two portions (e.g., 1.25 kg for S2 and 1.00 kg for S4). These two portions were then filled separately into the two T2 (north and south sides) created for each treatment combination (T2S1, T2S2, T2S3, and T2S4). The S0, for both application techniques (T1S0 and T2S0), received no organic matter application. For the T2S0, the surface area designated for the T1 remained bare, and for the T2S0, the two T2s made remained empty, serving as a baseline comparison.

## Root Observation

Root observations were conducted at two intervals: The second and fourth month-after-application. During sampling, roots were collected from the soil section located between the application technique (T1 and T2) and the palm tree trunk. Specifically, an excavation pit measuring 20 (width) × 20 (length) × 30 cm (depth) was carefully made using a shovel, centered at a distance of 50 cm from the tree base towards the organic matter application point. All roots within this defined soil volume were carefully extracted, washed and then categorised by depth increments (e.g., 0–10 cm, 10–20 cm, 20–30 cm) to determine their distribution. The average depth of roots was then calculated for each treatment plot, representing the mean vertical position of the observed root mass.

## Data Analysis

The collected data were subjected to analysis of variance (ANOVA) using MINITAB statistical software version 22.1. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% significance level.

## RESULTS AND DISCUSSION

The results of variance analysis showed that T1 and T2, types of organic material and their interaction did not significantly affect the root position from the soil surface at each observation time (Table 1).

The evaluation of root depth dynamics at second and fourth month intervals revealed important differences between the T1 and T2 application techniques. As shown in Figure 1, the average root depth in the second month was 6.68 cm for T1 and 6.00 cm for T2. By the fourth month, T1 showed a shallower root depth of 5.47 cm, whereas T2 maintained a consistent root depth of 6.00 cm.

These results suggest that T1 application prompted a progressive upward movement of roots, with roots growing closer to the soil surface over time. The decomposition of surface-applied organic matter likely contributed to improved soil conditions, such as increased microbial activity, nutrient availability and soil porosity in the topsoil (Lawrence & Melgar, 2023; Romelah et al., 2017; Suvendran et al., 2025), all of which are conducive to shallow root development. Enhanced microbial activity accelerates the breakdown of organic matter, releasing readily available nutrients that attract roots. Furthermore, the incorporation of organic matter improves soil aggregation,

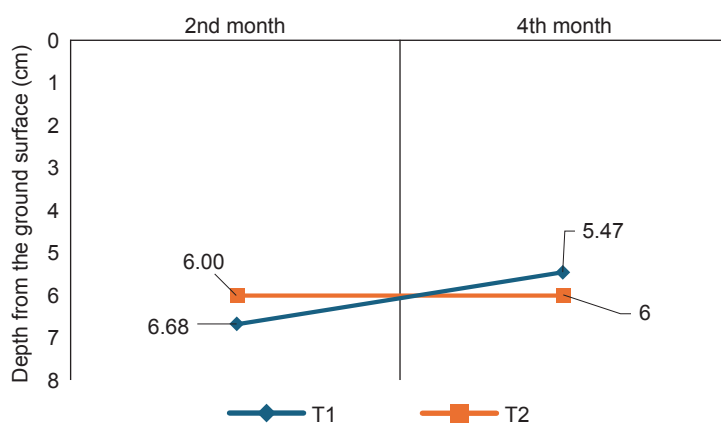


Figure 1. Mean root depth of oil palm plants under pile (T1) and biopore infiltration holes (T2), organic matter application techniques at second and fourth month observations. Positive values represent distances below the surface of the soil. Shallower root positions indicate enhanced surface-root proliferation.

TABLE 1. ROOT POSITION FROM SOIL SURFACE

Item	Root depth from soil surface (cm)	
	2nd month	4th month
<b>Application techniques (T)</b>		
Pile (T1)	7.68	7.47
Biopore infiltration holes (T2)	8.00	7.00
<b>Organic pile (S)</b>		
No organic material (S0)	8.33	7.67
Fresh EFB (S1)	6.67	4.67
EFB compost (S2)	6.33	4.17
Palm fronds (S3)	8.67	5.67
Palm leaves (S4)	7.65	6.50
<b>Interaction (TxS)</b>		
T1S0	9.00	7.00
T1S1	7.67	4.33
T1S2	7.33	4.00
T1S3	9.00	5.00
T1S4	7.67	7.00
T2S0	9.33	8.33
T2S1	9.00	5.00
T2S2	9.00	4.33
T2S3	9.67	6.33
T2S4	9.00	6.00

increases porosity and aeration, which are crucial for oxygen supply to roots, facilitating their proliferation in shallower soil layers (Ho et al., 2022; Yahya et al., 2010).

This early response to organic matter placed directly on the soil surface reflects a faster influence on the rhizosphere microenvironment compared to subsurface amendments. The ability of the T1 technique to elicit a quicker response in root distribution near the surface makes it a potentially

valuable strategy for immediate nutritional benefits, particularly in situations requiring rapid nutrient availability for young or stressed oil palm plants.

In contrast, roots in T2 remained at a stable depth throughout the observation period. This indicates that, within the initial four months, T2 had not significantly altered the vertical distribution of roots. However, this technique’s long-term benefits for soil health, such as improving water infiltration and soil porosity, are crucial for enhancing root system resilience against environmental stressors like drought or intermittent flooding (Andriyani & Fadila, 2024; Edy et al. 2020). The decomposition of organic matter within T2 is a slower process. Microbial communities must first colonise the material, which then gradually decomposes, releasing nutrients and improving soil porosity over time (Intara et al., 2018; Jourdan & Rey, 1997). Consequently, the T2 may exhibit delayed but potentially more profound impacts on root proliferation in the long term.

From an agronomic perspective, the T1 technique demonstrates an advantage for short-term root stimulation near the soil surface. This shallow rooting may enhance fertiliser uptake efficiency, reduce nutrient leaching and contribute to improved early plant growth performance (Safitri et al., 2018a). However, T2 may offer superior long-term benefits by promoting deeper and more stable rhizosphere improvements, thus enhancing root system resilience against environmental stressors such as drought or compaction (Edy et al., 2020). It is important to note that although no statistically significant differences were detected between treatments during this period, the observed biological trends underline critical differences in the mechanism and timing of root response.

The radar chart (Figure 2) presents a clear comparative visualisation of root depth dynamics under different organic matter treatments at the

second and fourth months of observation. Overall, a contraction of the radar plot from the second to the fourth month across most treatments indicates a consistent biological trend of roots proliferating toward the soil surface over time.

Among the treatments, S2 demonstrated the most substantial shift towards shallower root depth, with roots moving from an initial depth of approximately 6.33 cm at 2nd-month to 4.17 cm at the 4th-month, representing a decrease of approximately 34%. This pattern suggests that the decomposition of S2 significantly improved the soil microenvironment, enhancing nutrient availability, soil aeration and microbial activity, which collectively favoured shallower root growth (Yahya et al., 2010; Zuraidah et al., 2015). This finding is consistent with recent studies that highlight the role of nutrient availability in shaping root architecture; for instance, De la Peña et al. (2024) demonstrated that oil palm seedlings respond to nitrogen scarcity by altering their root systems, suggesting that improved nutrient supply from S2 application would encourage proliferation in nutrient-rich topsoil layers. The effectiveness of S2 can be attributed to its advanced decomposition state, which means a lower C/N ratio and a higher proportion of readily available macro and micronutrients compared to fresh materials (Yahya et al., 2010; Zahari et al., 2023). This provides an immediate nutrient boost and fosters a more active microbial community, crucial for nutrient cycling and creating a favourable rhizosphere for root development (Ho et al., 2022). This is further supported by studies exploring the beneficial microbial communities in oil palm residues (Nurmiati et al., 2024) and those that use microbial inoculants like *Trichoderma* to manage EFB waste (Nurmiati et al., 2024), reinforcing the biological

link between waste management and soil health. While we did not directly measure soil microbes, our results align with these findings by showing a clear biological response from the plant to the organic amendments.

Similarly, S1 induced a notable shift, reducing root depth from 6.67 to 4.67 cm over the same period. This indicates that even less-decomposed organic matter, when applied appropriately, can contribute to positive changes in root architecture. Although less decomposed than S2, S1 still contains substantial amounts of organic carbon, cellulose and lignin, which upon gradual decomposition contribute to improving soil structure and providing a slow-release nutrient source (Liew et al., 2010; Zakri & Adam, 2021).

In contrast, treatments S0 and S4 showed minimal changes in root depth, maintaining deeper root positions close to 7.67–8.33 and 6.50–6.67 cm, respectively. These results highlight the limited effect of slow decomposing materials or the absence of organic amendments in altering root distribution within a short-term window. The application of S3 also led to moderate improvement, with root depth shifting from 8.67 to 5.67 cm, a decrease of approximately 35%.

Although S3 and S4 contain higher lignin and cellulose compared to EFB, which causes them to decompose more slowly (Jourdan & Rey, 1997; Zakri & Adam, 2021), their long-term contribution to soil organic matter content and structural stability remains significant. This slower decomposition rate means a more gradual release of nutrients and less immediate impact on soil physical properties, explaining the moderate improvement observed in root depth. However, their long-term contribution to soil organic matter content and structural stability remains significant.

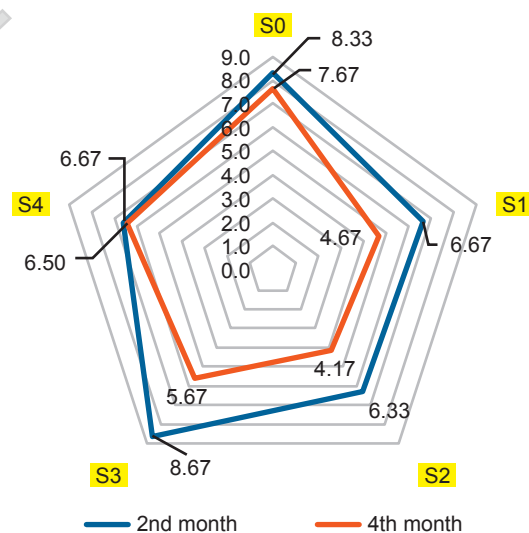


Figure 2. Effect of organic matter types on oil palm root depth from the ground surface (in cm) at second and fourth month observations. Shallower root positions represent improved root proliferation near the surface, beneficial for efficient nutrient uptake.

The role of the soil mycobiome is particularly relevant here, as highlighted by Azeez et al. (2024), who found distinct fungal communities in the root and soil environments of oil palm. This suggests that the type of organic matter applied may differentially influence these microbial communities, which in turn could affect root proliferation and overall soil health over a longer period. Although S3 may decompose more slowly compared to EFB, they still contribute meaningfully to root growth dynamics when applied properly (Jourdan & Rey, 1997). S3 with their higher lignin and cellulose content compared to EFB, decompose more slowly (Jourdan & Rey, 1997; Zakri & Adam, 2021).

Thus, the radar chart effectively demonstrates that the type and decomposition stage of organic matter are critical factors influencing root depth dynamics. Well-decomposed materials, such as old EFB, create a more favourable rhizospheric environment that encourages root proliferation near the surface (Liew et al., 2010), ultimately improving nutrient uptake efficiency and supporting sustainable oil palm management (Liew et al., 2012; Yahya et al. 2010).

**Root Distribution Patterns Visualised Through Radar Chart Analysis**

The radar chart in *Figure 3* offers a comprehensive visual comparison of root depth variations across treatment combinations at two different observation times. Overall, a contraction in the radar area from the second to the fourth month indicates a general trend of roots growing closer to the soil surface over time.

Among all treatment combinations, pile application combined with EFB compost (T1S2)

and biopore infiltration holes application with EFB compost (T2S2) exhibited the most pronounced reduction in root depth, with final root depths as close as 4.00–4.33 cm from the soil surface, indicating significant movement towards shallower proliferation. This highlights the crucial role of partially decomposed organic matter in facilitating enhanced surface root proliferation. The readily available nutrients and improved physical conditions (e.g., increased porosity and water holding capacity) resulting from the decomposition of S2 create a more hospitable environment for root growth near the soil surface, where nutrient cycling is typically most active. Conversely, biopore infiltration holes without organic matter (T2S0) maintained the deepest root systems throughout the study period, underscoring the necessity of organic input to stimulate beneficial changes in root distribution. The radar chart also revealed that while T1 techniques generally stimulated faster surface rooting, T2 could achieve comparable biological improvements when paired with the right organic materials. These findings demonstrate that both application method and organic matter quality synergistically affect root architecture and have significant implications for improving fertiliser use efficiency in oil palm plantations (Safitri et al., 2018b).

Although the results of the ANOVA indicated no statistically significant differences ( $p>0.05$ ) among treatments, clear biological trends were observed in root distribution patterns. Root depths consistently tend to be shallower under specific treatment combinations, particularly those involving decomposed organic materials (Ho et al., 2022; Suvendran et al., 2025) and pile application techniques.

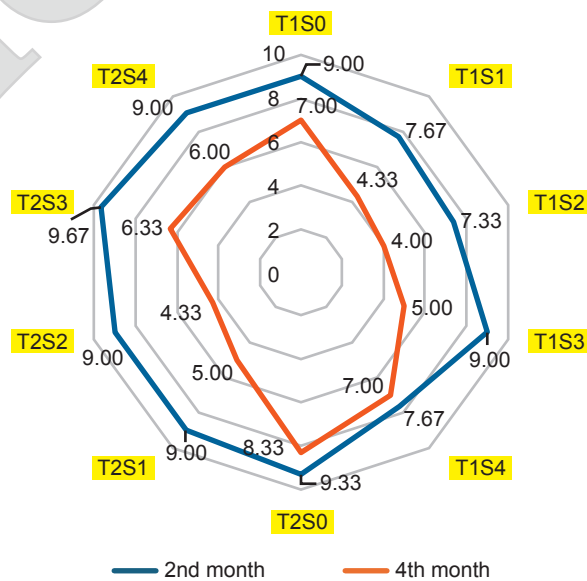


Figure 3. Radar chart showing root depth (cm) from the soil surface at the second (blue line) and fourth months (orange line) for different application techniques and organic matter combinations. A reduced distance from the center represents shallower root growth.

These trends suggest that, while variability within replicates may have masked statistical significance at the conventional 5% level, the treatments exerted biologically meaningful effects on root development. Similar observations have been noted in field-based agricultural studies, where environmental variability and soil heterogeneity often limit the detection of statistical differences despite the presence of clear agronomic responses (Patzold et al., 2008).

It is important to recognise that in field experiments, biological relevance and agronomic impact are as crucial as statistical thresholds. The evident tendency of roots to proliferate closer to the soil surface under certain organic matter and application technique combinations supports the practical significance of these treatments for enhancing nutrient uptake efficiency and sustainable plantation management. Thus, while the statistical analysis did not confirm treatment effects at the  $p < 0.05$  level, the observed biological patterns provide valuable insights into the influence of organic amendment strategies on oil palm root architecture. Future studies with increased replication and longer observation periods are recommended to verify and reinforce these promising biological trends under varied field conditions.

## CONCLUSION

This study investigated the influence of different organic matter types and application techniques on the vertical distribution of oil palm roots. Although statistical analysis did not reveal significant differences ( $p > 0.05$ ), consistent biological trends were observed, particularly with the use of S2 and the T1 application technique. S2 effectively promoted shallower root development. The T1 application method demonstrated a faster initial effect on surface root proliferation within four months, while T2 combined with decomposed organic matter also showed substantial improvements, suggesting potential long-term benefits. These findings, visually supported by radar chart analyses, emphasise that the quality and decomposition stage of organic matter are critical factors influencing root architecture. The strategic use of well-decomposed organic matter, especially with suitable application techniques, holds practical significance for enhancing nutrient uptake efficiency, reducing fertiliser losses and supporting the sustainability of oil palm cultivation systems by promoting the circular economy of oil palm biomass. Future study with longer observation periods and additional soil parameters is recommended to further validate these promising biological trends under diverse field conditions.

These findings suggest that while our study did not directly measure nutrient uptake efficiency, the observed shallow root proliferation serves as a strong indicator of a biological mechanism that could potentially enhance nutrient absorption. The strategic use of well-decomposed organic matter and suitable application techniques holds significant potential for sustainable plantation management by promoting the circular economy of oil palm biomass. We acknowledge the limitations of this study, particularly the sample size and the short observation period. Therefore, we recommend that future studies be conducted with increased replication and longer observation periods to statistically validate these findings. Additionally, incorporating measurements of nutrient uptake and an evaluation of root types would provide a more comprehensive understanding of the treatment effects.

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