Effect of POME-Based Bioameliorants and Microbial Amendments on Oil Palm Seedling Growth in Different Soil Media

Santa Maria Lumbantoruan[1]*, *Marlina*[3], *Mulyadi*[1], *Erna Siaga*[2], *Sri* Nartawati[1], *Adelia* Meita Zara[2]

[1]Program of Agroecotechnology, Faculty of Agriculture, Universitas Sriwijaya, Indonesia
[2]University of Sriwijaya, Faculty of Agriculture, Department of Agronomy, Jl. Raya Palembang-Prabumulih Km 32 Indralaya, Ogan Ilir 30662, Indonesia
[3]University of Sriwijaya, Faculty of Agriculture, Department of Agroecotechnology, Jl. Raya Palembang-Prabumulih Km 32 Indralaya, Ogan Ilir 30662, Indonesia

Abstract. POME-based bioameliorants integrated with biochar and microorganisms were evaluated for improving oil palm seedling performance in marginal soils. This study evaluated the effects of POME-based bioameliorants combined with biochar and microbial amendments on seedling growth, root development, soil pH, and soil respiration in peat and mineral soils. A factorial randomized block design was used with two biochar types (rice husk and oil palm shell) and two microbial inoculants (mycorrhiza and Trichoderma sp.), all supplemented with POME. The results showed that soil pH increased to 5.07 in peat soil and 5.03 in mineral soil under the oil palm shell biochar treatment . Soil respiration increased from 2.76 to 22.85 µg CO_2–C g^{-1} soil h^{-1} in peat soil under A2M2 and from 0.44 to 34.17 µg CO_2–C g^{-1} soil h^{-1} in mineral soil. Mineral soil produced the greatest plant height (31.36 cm), whereas peat soil produced the highest fresh and dry shoot weights of 9.17 g and 4.77 g under A2M2. Overall, the combination of oil palm shell biochar + Trichoderma sp. + POME consistently produced the best biomass accumulation, root development, and seedling vigor in peat soil, demonstrating an environmentally sustainable strategy for improving oil palm nursery productivity.

1 Introduction

Oil palm (*Elaeis guineensis* Jacq.) is one of the most important plantation commodities in tropical countries, particularly in Indonesia and Malaysia, contributing significantly to economic growth, employment, and vegetable oil production worldwide. The productivity of oil palm plantations is highly dependent on the quality of seedlings during the nursery stage because vigorous seedlings possess better adaptability and growth performance after field transplantation. Therefore, improving seedling quality through sustainable and environmentally friendly approaches has become an important focus in oil palm cultivation systems.[1]

One of the major challenges in sustainable oil palm production is maintaining soil fertility and biological activity, especially in suboptimal soils such as peatlands. Peat soils are generally characterized by low nutrient availability, high acidity, poor root anchorage, and unstable biological properties, which may limit seedling growth and nutrient uptake. In contrast, mineral soils often provide better physical support and nutrient dynamics but may still experience degradation due to intensive agricultural practices. Consequently, innovative soil amendment technologies are required to improve soil quality and enhance oil palm seedling performance in different soil media.

The utilization of organic waste and beneficial microorganisms has recently attracted considerable attention as part of sustainable agricultural management. Palm Oil Mill Effluent (POME), a by-product generated from palm oil processing industries, contains substantial amounts of organic matter and plant nutrients that can potentially improve soil fertility when properly managed. However, untreated POME may also cause environmental pollution due to its high biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Therefore, integrating POME into bioameliorant formulations offers a promising alternative to convert industrial waste into value-added agricultural inputs while supporting circular bioeconomy principles.

Biochar is another important amendment widely recognized for its ability to improve soil physical, chemical, and biological properties. Biochar produced from agricultural residues such as rice husks and oil palm shells possesses high porosity and surface area, which can enhance nutrient retention, soil aeration, water holding capacity, and microbial habitat. Previous studies have demonstrated that biochar application can increase soil pH, reduce nutrient leaching, and stimulate microbial activity, thereby improving plant growth under stressful environmental conditions. Biochar produced through slow pyrolysis is formed by the thermal decomposition and carbonization of biomass biopolymers. Increasing pyrolysis temperature generally reduces biochar yield because more biopolymers are converted into bio-oil and gaseous products during thermal decomposition. Biochar produced at 450°C contains a high carbon content (91.47 wt%) with a relatively stable C/N ratio, indicating its potential to retain soil minerals, enhance soil organic carbon, and serve as a medium for CO_2 sequestration. In addition, its porous honeycomb-like structure provides a favorable habitat for soil microorganisms, promoting nutrient production, particularly nitrate, and supporting improved plant growth [2] (Fikarda et al., 2026). Oil palm shell biochar also possesses an average pore diameter of 4.93 nm and a large specific surface area (135 m^2 g^{-1}) (Dominguez et

*Corresponding author:mulyadi@fp.unsri.ac.id

al., 2020). However, although biochar application alone can improve crop productivity in low-fertility soils and contribute to climate change mitigation, integrating biochar with other soil amendments is necessary to maximize its agronomic effectiveness and economic value.

In addition to biochar, beneficial microorganisms such as *Trichoderma* spp. and arbuscular mycorrhizal fungi (AMF) play important roles in promoting plant growth and soil health. *Trichoderma* functions as a plant growth-promoting fungus capable of enhancing nutrient availability, producing phytohormones, and suppressing soil-borne pathogens. Meanwhile, mycorrhizal fungi improve nutrient and water uptake through symbiotic associations with plant roots, especially under nutrient-limited conditions .[4]. The integration of biochar, POME, and microbial inoculants is therefore expected to create synergistic effects that improve root development and soil biological activity in oil palm nurseries.

Several studies have investigated the individual effects of biochar, POME, or microbial amendments on plant growth; however, information regarding their combined application as POME-based bioameliorants in contrasting soil media remains limited. Furthermore, the comparative responses of oil palm seedlings grown in mineral and peat soils under integrated bioameliorant treatments have not been extensively explored. Understanding these interactions is essential for developing adaptive and sustainable nursery management strategies suitable for different soil conditions.

Therefore, this study aimed to evaluate the effectiveness of POME-based bioameliorants combined with biochar and beneficial microorganisms in improving root growth and soil biological activity of oil palm seedlings grown in mineral and peat soil media. The findings of this study are expected to contribute to the development of sustainable oil palm nursery technologies that support environmentally friendly agricultural practices and climate-resilient plantation management.

Although previous studies have independently evaluated POME, biochar, and microbial inoculants, limited information is available regarding their synergistic effects on oil palm seedlings grown under contrasting peat and mineral soils. This study provides the first comparative evaluation of POME-based bioameliorants integrating different biochar sources and microbial inoculants across contrasting soil environments.

2 Materials And Methods

2.1 Time and Location of the Study

This research was conducted from October 2025 to February 2026 at the Agrotech Training Center (ATC), Faculty of Agriculture, Universitas Sriwijaya, Indralaya Utara District, Ogan Ilir Regency, South Sumatra, Indonesia. The study was carried out under pre-nursery conditions using two contrasting planting media, namely mineral soil and peat soil.

2.2 Materials and Equipment

The materials used in this study consisted of oil palm (Elaeis guineensis Jacq.) germinated seeds, mineral soil, peat soil, rice husk biochar, oil palm shell biochar, mycorrhiza, Trichoderma sp., and Palm Oil Mill Effluent (POME). Additional materials included polybags, water, and supporting materials for nursery maintenance.The equipment used included hoes, shovels, analytical balance, ruler, caliper, pH meter, oven, measuring cylinder, camera, and laboratory equipment for soil respiration analysis.
Experimental Design

The experiment was arranged using a factorial Randomized Block Design (RBD) with two factors. The first factor was bio ameliorant type consisting of:
A1 = Rice husk biochar (10 g)
A2 = Oil palm shell biochar (10 g)
The second factor was microbial amendment consisting of:
M1 = Mycorrhiza (5 g)
M2 = Trichoderma sp (5 g)

All treatments were combined with the application of POME as an organic liquid amendment (50 ml). Each treatment was replicated three times in mineral soil media and three times in peat soil media.

The treatment combinations were as follows: Treatment Code Description
A0M0 = control
A0M1 = Mycorrhiza + POME
A0M2 = Trichoderma + POME
A1M0 = Rice husk biochar +POME
A1M1 n= Rice husk biochar + mycorrhiza + POME,
A1M2 = Trichoderma + oil palm shell biochar+POME,
A2M0 = Oil palm shell biochar +POME
A2M1 = Oil palm shell biochar + mycorrhiza + POME,
A2M2 = Oil palm shell biochar + Trichoderma + POME

The POME used in this study was obtained from a local palm oil mill and characterized prior to application to determine its physicochemical properties. The characteristics of the POME are presented in **Table 1**.

Table 1. Physicochemical Properties of Palm Oil Mill Effluent (POME) Applied as Bioameliorant

No.	Parameter	Unit	Method	Result
1	pH	-	SNI 06-6989.11:2019	8.48
2	BOD_3	mg/L	SNI 6989.72:2009	2,818.6
3	COD	mg/L	SNI 6989.73:2019	6,541.74
4	Oil and Grease	mg/L	SNI 6989.10:2011	59.883
5	Total Lead (Pb)	mg/L	SNI 6989-84:2019	<0.030

6	Total Copper (Cu)	mg/L	SNI 6989-84:2019	0.220
7	Total Cadmium (Cd)	mg/L	SNI 6989-84:2019	<0.008
8	Total Zinc (Zn)	mg/L	SNI 6989-84:2019	0.448
9	Ammonia	mg/L	Standard Methods 24th Ed. 4500 NH_3 (2022)	300.7
10	Total Suspended Solids (TSS)	mg/L	SNI 06-6989.3:2019	3,180.00

2.3 Experimental Procedure

2.3.1 Preparation of Planting Media

Mineral soil and peat soil were collected, cleaned from debris, and air-dried before use. The planting media were then mixed with the corresponding bioameliorant treatments. Rice husk biochar and oil palm shell biochar were incorporated into the media according to the treatment combinations. The prepared media were placed into polybags for pre-nursery planting.

2.3.2 Seedling Preparation and Planting

Germinated oil palm seeds with uniform growth were selected and planted into polybags containing the repared planting media. One seedling was planted per polybag. Planting was conducted carefully to avoid root damage during transplantation.

2.3.3 Observed Parameters

The observed variables included:Plant height (cm),Number of leaves (leaves),Le, Stem diameter (mm), Soil pH,Leaf greenness level,Root length (cm),Shoot fresh weight (g),Shoot dry weight (g)
Root fresh weight (g),Root dry weight (g),Soil respiration (CO_2 mg day^{-1} 150 g^{-1} soil),All growth observations were conducted during the pre-nursery period, while destructive observations were performed at the end of the experiment.

2.4 Data Analysis

The obtained data were analyzed using analysis of variance (ANOVA) at the 5% significance level. When significant differences among treatments were detected, the means were further compared using Duncan's Multiple Range Test (DMRT) at the 5% level. Statistical analysis was performed to evaluate the effects of bioameliorants and microbial amendments on oil palm seedling growth in mineral and peat soil media.

3 Results and Discussion

The results showed that the application of POME-based bioameliorants and microbial amendments produced different responses to changes in soil pH in peat soil and mineral soil media. Figure 1 shows that soil pH values in mineral soil were generally higher and more stable compared to peat soil. This indicates that the inherent characteristics of the soil media strongly influenced the effectiveness of the treatments in improving soil chemical properties, particularly soil acidity.

In peat soil media, soil pH values ranged from 3.67 to 5.07. Treatment A2M0 produced the highest pH value of 5.07, whereas treatment A2M1 showed the lowest pH value of 3.67. This finding suggests that the increase in pH under treatment A2M0 indicated that the treatment combination was able to improve peat soil conditions, although not significantly. POME-based bioameliorants were presumed to supply decomposed organic matter that released basic cations such as Ca^{2+}, Mg^{2+}, and K^{+}, thereby reducing the concentration of H^{+} ions in the soil. In addition, microbial activity from microbial amendments likely accelerated organic matter decomposition, resulting in improved soil buffering capacity and enhanced soil pH.

Conversely, the low pH value observed in treatment A2M1 indicates that treatment effectiveness was strongly influenced by the interaction between the type of ameliorant and soil microbial activity. Under this treatment, the decomposition of organic matter may not have proceeded optimally, causing organic acids in peat soil to remain dominant. Peat soil naturally contains high concentrations of organic acids, such as humic and fulvic acids, which maintain low soil pH when mineralization processes are not functioning effectively. In mineral soil media, soil pH values ranged from 4.10 to 5.03. Treatment A2M0 also produced the highest pH value in this medium at 5.03, while the lowest pH value was observed under treatment A0M1 at 4.10. This condition suggests that mineral soil possessed a better buffering capacity than peat soil, resulting in more stable pH changes. The presence of clay minerals and base cations in mineral soil allowed the soil to resist changes in acidity even after the application of organic matter and microbial treatments. Therefore, increases or decreases in pH in mineral soil were not as extreme as those observed in peat soil. Interestingly, treatment A2M0 produced the highest pH values in both soil media. This indicates that the treatment combination was the most effective in improving soil chemical properties in both peat and mineral soils. This indicates that the treatment combination was the most effective in improving soil chemical properties in both peat and mineral soils. The treatment likely created a better balance between the organic carbon source from POME and soil microbial activity, allowing organic matter decomposition to proceed more steadily and resulting in more optimal soil pH improvement. The results also demonstrated that peat soil showed a greater response to pH changes than mineral soil. This condition indicates that peat soil was more responsive to bioameliorant application due to its initially higher acidity level. With the application of treatments, soil

These findings are consistent with the study of [3] reported that the application of Palm Oil Mill Effluent (POME) to marginal soils increased soil pH through enhanced organic matter content and soil microbial activity. The study explained that organic matter decomposition produced humic compounds and basic cations that reduced soil acidity. In addition, [5] stated that microbial inoculation in acidic soils could improve soil pH through accelerated organic matter biodegradation and enhanced soil enzymatic activity.

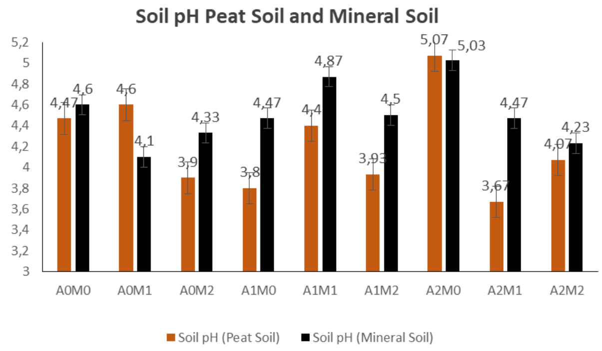


Fig. 1. Comparison of Soil pH in Peat Soil and Mineral Soil Under Different Treatments

transformation and the release of base cations capable of improving soil pH. In contrast, pH changes in mineral soil tended to be smaller because the soil conditions were relatively stable from the beginning.

Another study [6] also showed that the application of organic matter to acidic soils increased cation exchange capacity and reduced Al and Fe toxicity, thereby creating more favorable conditions for plant growth. The results indicate that soil pH changes were strongly influenced by soil type and treatment combinations. Peat soil exhibited more dynamic pH changes due to its high organic matter content and initially high acidity level, whereas mineral soil showed more stable pH conditions because of its greater soil buffering capacity. These findings suggest that the application of POME-based bioameliorants andmicrobial amendments has strong potential to improve soil chemical quality, particularly in peatlands characterized by low fertility and high acidity.

The results in figure 2 showed that the application of POME-based bioameliorants and microbial amendments had a significant effect on soil respiration in both peat soil and mineral soil media. Before Treatment application (BT), the initial soil respiration in peat soil was 2.76 µg CO_2–C g^{-1} soil h^{-1}, whereas the initial soil respiration in mineral soil was only 0.44 µg CO_2–C g^{-1} soil h^{-1}. The difference in initial respiration values indicated that peat soil initially had higher biological activity than mineral soil. This condition was closely related to the high organic matter and organic carbon content in peat soil, which served as the primary energy source for soil microorganisms. In contrast, the low initial respiration in mineral soil indicated that organic matter content and microbial activity were still relatively low before treatment application.

After the application of POME-based bioameliorants and microbial amendments, soil respiration increased significantly in both soil media. In peat soil, soil respiration increased to 7.77–22.85 µg CO_2–C g^{-1} soil h^{-1}. The highest value was obtained in treatment A2M2 at 22.85 µg CO_2–C g^{-1} soil h^{-1}, representing approximately an eight-fold increase compared to the initial respiration of peat soil. Meanwhile, in mineral soil, soil respiration increased more drastically to 2.28–34.17 µg CO_2–C g^{-1} soil h^{-1}. Treatment A0M0 produced the highest respiration value of 34.17 µg CO_2–C g^{-1} soil h^{-1}, which was nearly 77 times higher than the initial respiration of mineral so

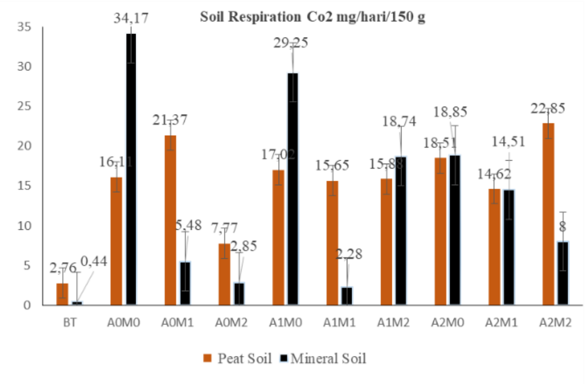


Fig. 2. Comparison of Soil Respiration in Peat Soil and Mineral Soil Under Different Treatments

The increase in soil respiration after treatment indicated that POME-based bioameliorants provided an easily available organic carbon source that could be readily utilized by soil microorganisms, thereby significantly increasing microbial metabolic activity. POME contains dissolved organic matter and simple carbon compounds that can serve as respiratory substrates for soil microorganisms. In addition, the applied microbial amendments were presumed to accelerate organic matter decomposition and increase soil enzymatic activity, resulting in higher soil respiration rates.

Interestingly, the pattern of soil respiration increase differed between peat soil and mineral soil media. In peat soil, the increase in respiration tended to be more stable across almost all treatments. This indicates that peat soil microorganisms had adapted to conditions wit high organic matter content, causing the response to POME addition to occur more gradually. Furthermore, organic matter in peat soil is mostly present in complex forms, resulting in slower decomposition processes and more stable increases in soil respiration.

In contrast, mineral soil exhibited very high increases in respiration under several treatments, particularly A0M0 and A1M0. This finding suggests that, this condition indicates that microorganisms in mineral soil responded very rapidly to the addition of new carbon sources from POME because the soil initially contained low organic matter levels. When sufficient carbon sources became available, microbial metabolism increased immediately, causing soil respiration to rise drastically. However, under several other treatments such as A1M1 and A0M2, soil respiration values remained relatively low. This may have been caused by differences in the effectiveness of microbial combinations in utilizing available organic substrates or by competition among microorganisms in the soil.

The results of this study indicate that soil respiration can be used as an important indicator for evaluating soil biological activity after bioameliorant application. Higher soil respiration reflects greater microbial activity in decomposing organic matter and facilitating nutrient cycling within the soil. However, excessively high respiration may also indicate accelerated carbon loss in the form of CO_2, especially in soils with high organic

This finding suggests that microorganisms in mineral soil responded rapidly to the addition of new carbon sources from POME because the soil initially contained relatively low organic matter levels. [7] reported that the application of liquid organic matter and biofertilizers increased soil respiration through enhanced microbial biomass and organic carbon decomposition activity. The study showed that soils with low organic matter content generally exhibited more drastic increases in respiration following the addition of organic carbon sources. In addition, [8] stated that soil respiration is strongly influenced by the availability of easily decomposable organic carbon, which serves as the primary energy source for soil microorganisms.

Another study [9] on peat soils demonstrated that increased soil respiration following organic matter application was closely associated with enhanced decomposer activity and organic carbon mineralization. The study also explained that peat soils exhibit more stable respiration patterns than mineral soils due to their high content of complex organic carbon. Furthermore, [10] reported that the application of liquid organic waste in agricultural soils increased soil enzymatic activity, microbial biomass, and soil respiration as a result of greater substrate carbon availability for microorganisms.

Overall, the results indicate that the application of POME-based bioameliorants and microbial amendments effectively increased soil respiration in both peat and mineral soils. The differences in respiration responses between the two media indicate that the inherent characteristics of the soil strongly influenced microbial activity in utilizing the applied organic matter. Peat soil exhibited more stable respiration due to its initially high organic matter content, whereas mineral soil showed more drastic increases in respiration because of the rapid microbial response to the addition of new carbon sources from POME.

Table 2. Growth Performance of Oil Palm Seedlings in Peat Soil and Mineral Soil Under Different POME-Based Bioameliorant and Microbial Amendment Treatment

Parameter/ Treatments	Peat Soil			
	Plant Height (cm)	Leaf Greennes s index	Number of Leaves	Stem Diameter (cm)
A0M0	25.95a	55.56a	5.00a	7.65a
A0M1	27.88a	51.18a	5.08a	8.14a
A0M2	26.58a	51.99a	4.83a	7.75a
A1M0	26.12a	51.62a	5.00a	7.58a
A1M1	27.72a	53.08a	4.67a	7.43a
A1M2	25.72a	50.13a	4.67a	7.93a
A2M0	24.28a	51.52a	4.67a	7.20a
A2M1	26.47a	50.63a	4.83a	7.60a
A2M2	27.93a	52.33a	5.17a	8.02a

Parameter/ Treatments	Mineral Soil			
	Plant Height (cm)	Leaf Greennes s index	Number of Leaves	Stem Diameter (cm)
A0M0	27.36a	50.49a	4.67a	7.09a
A0M1	28.33a	49.15a	4.89a	7.29a
A0M2	26.73a	52.78a	4.78a	6.83a
A1M0	29.53a	54.03a	5.00a	7.90a
A1M1	25.23a	46.22a	4.22a	7.43a
A1M2	29.09a	52.62a	4.78a	7.66a
A2M0	31.36a	57.71a	4.56a	7.84a
A2M1	22.76a	44.27a	4.33a	6.68a
A2M2	27.10a	51.22a	4.78a	6.80a

The results showed that the application of POME-based bioameliorants and microbial amendments produced different responses on the growth of oil palm seedlings grown in peat and mineral soil media. These differences were observed across all growth parameters measured, including plant height, leaf greenness level, number of leaves, and stem diameter. The interaction between soil characteristics and treatment combinations was presumed to be the main factor influencing the growth performance of oil palm seedlings.

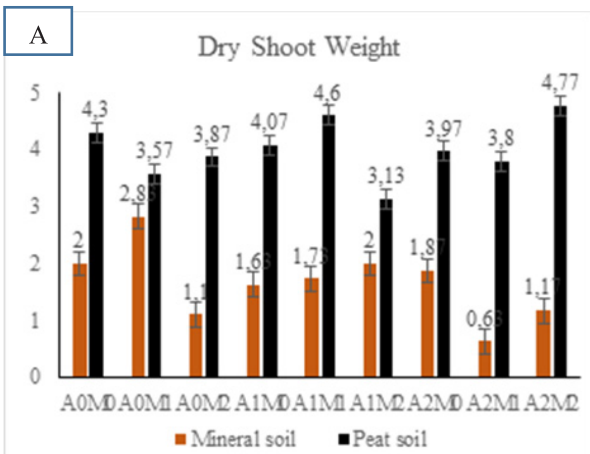
For the plant height parameter, treatment A2M0 in mineral soil produced the highest plant height, reaching 31.36 cm, whereas the highest value in peat soil was recorded under treatment A2M2 at 27.93 cm. The superior growth observed in mineral soil indicates that this medium had a better capacity to supply nutrients and support root development. The more stable structure of mineral soil allows roots to absorb water and nutrients more efficiently compared to peat soil, which is generally acidic and prone to nutrient leaching. Meanwhile, the increased plant height under treatment A2M2 in peat soil suggests that the combination of POME-based bioameliorants and microbial amendments was able to improve the chemical properties of peat soil, thereby enhancing plant growth. These findings are consistent with the study of [11] reported that Plant Growth Promoting Rhizobacteria (PGPR) in oil palm nurseries enhanced plant growth through increased nitrogen fixation, phosphate solubilization, and the production of growth hormones such as indole-3-acetic acid (IAA). Furthermore that soil microorganisms play an important role in improving nutrient use efficiency in oil palm seedlings, resulting in more optimal vegetative growth[12]

In the leaf greenness level parameter, treatment A2M0 in mineral soil produced the highest value of 57.71, while the highest value in peat soil was observed under treatment A0M0 with 55.56. Leaf greenness is closely related to chlorophyll content and nitrogen availability within plant tissues. Mineral soil was presumed to provide more available nitrogen, thereby supporting chlorophyll formation more effectively. In addition, the application of POME-based bioameliorants likely enhanced soil microbial activity, which contributed to nitrogen mineralization processes. Plant growth-promoting microorganisms can improve nitrogen uptake efficiency and chlorophyll synthesis, resulting in greener leaves and enhanced photosynthetic activity. A more recent study demonstrated that the combination of organic fertilizers and biofertilizers in oil palm nurseries improved plant physiological quality, including leaf chlorophyll content and photosynthetic efficiency [13].

For the number of leaves parameter, peat soil showed a relatively better response compared to mineral soil. Treatment A2M2 in peat soil produced the highest number of leaves at 5.17 leaves, while in mineral soil the highest value reached only 5.00 leaves under treatment A1M0. The higher number of leaves in peat soil was likely associated with its high organic matter content and greater moisture retention capacity. These conditions supported vegetative tissue formation and maintained water availability during plant growth. Furthermore, the combination of bioameliorants and microbial amendments was presumed to increase soil biological activity, making nutrients more readily available to plants. The application of PGPR and Trichoderma sp. in oil palm seedlings tended to increase leaf number and vegetative growth compared to untreated controls. [14] explained that rhizomicrobiome engineering in marginal soils enhanced microbial\ activity and nutrient uptake efficiency, thereby improving vegetative plant growth.

Regarding the stem diameter parameter, treatment A0M1 in peat soil produced the highest value of 8.14 mm, while the highest value in mineral soil was obtained under treatment A1M0 at 7.90 mm. Stem diameter reflects the plant's capacity for cell division and enlargement, which is strongly influenced by water and nutrient availability. Peat soil, with its higher water-holding capacity, likely provided a more stable environment for stem development. In addition, organic matter derived from POME may improve soil structure and root system development, resulting in more effective nutrient uptake. The application of ameliorants and beneficial bacteria in peat soils increased nitrogen-fixing bacterial activity and improved soil fertility, thereby supporting plant growth. Similarly.

Based on Figure A, peat soil generally produced higher fresh shoot weight values compared to mineral soil under almost all treatments. Treatment A2M2 showed the highest fresh shoot weight value in peat soil, while in mineral soil the highest value was observed under treatment A1M1. The greater fresh shoot biomass observed in peat soil was likely associated with its high organic matter content, which enhanced water retention, nutrient availability, and biomass accumulationn.



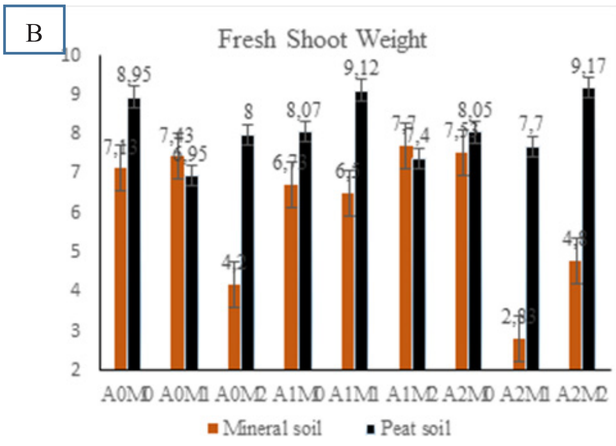
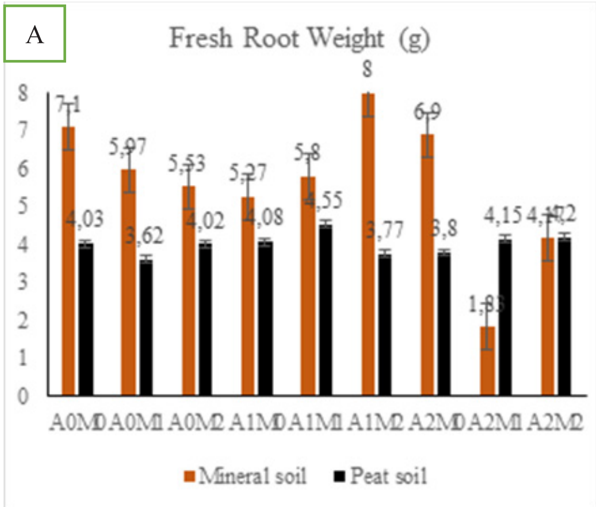


Fig. 3. Comparison of (A) Fresh Shoot Weight and (B) Dry Shoot Weight of Oil Palm Seedlings in Peat Soil and Mineral Soil Under Different POME-Based Bioameliorant and Microbial Amendment Treatments The results showed that the application of POME-based bioameliorants and microbial amendments affected the fresh shoot weight and dry shoot weight of oil palm seedlings grown in peat soil and mineral soil media.

Fig. 4. Morphological responses of oil palm seedlings under different POME-based bioameliorant and microbial amendment treatments

Based on Figure 4, oil palm seedlings grown in peat soil generally exhibited greener leaves, broader canopy development, and more vigorous shoot appearance compared with seedlings grown in mineral soil. This morphological response was consistent with the fresh shoot weight data presented in Figure 3, where peat soil produced higher fresh shoot biomass under most treatment combinations. The highest fresh shoot weight in peat soil was observed under treatment A2M2 at 9.17 g, followed by A1M1 at 9.12 g and A0M0 at 8.95 g, whereas mineral soil produced relatively lower biomass with the highest value recorded under treatment A1M2 at 7.70 g.

The higher shoot biomass observed in peat soil was closely associated with its high organic matter content and greater water-holding capacity, which supported continuous cell expansion and vegetative tissue formation. The application of POME-based bioameliorants likely supplied additional organic substrates and essential nutrients that enhanced photosynthetic activity and biomass accumulation. The superior performance of treatment A2M2 also suggests that the integration of oil palm shell biochar, Trichoderma sp., and POME created synergistic interactions that improved soil biological activity, nutrient retention, and phytohormone production. In Figure B, a similar pattern was also observed for the dry shoot weight parameter. Peat soil produced higher dry shoot weight values than mineral soil. Treatment A2M2 resulted in the highest dry shoot weight value, whereas treatment A1M2 produced the lowest value. This result indicates that, the increase in dry shoot weight indicates that POME-based bioameliorants and microbial amendments enhanced photosynthetic efficiency and nutrient uptake, leading to greater dry matter accumulation in



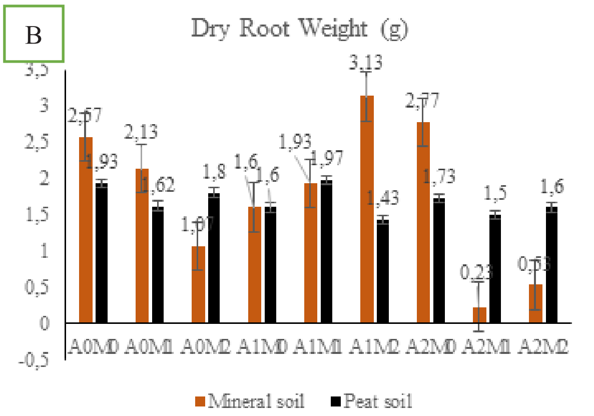


Fig. 5. Comparison of (A) Fresh Root Weight, (B) Dry Root Weight, and (C) Root Length of Oil Palm Seedlings in Peat Soil and Mineral Soil Under Different POME-Based Bioameliorant and Microbial Amendment Treatment

The results presented in Figure 5 showed that the application of POME-based bioameliorants andmicrobial amendments affected fresh root weight, dry root weight, and root length of oil palm seedlings in both peat soil and mineral soil media. In general, mineral soil produced higher fresh root weight and dry root weight values compared to peat soil, while root length varied depending on the treatment applied. In Figure 5A, treatment A1M2 produced the highest fresh root weight in mineral soil, whereas peat soil generally showed lower fresh root biomass. This condition indicates that mineral soil provided a more favorable environment for root development due to better soil structure and aeration. The availability of organic carbon from POME and microbial activity likely enhanced nutrient absorption and root metabolic activity, resulting in greater fresh root biomass.

A similar trend was observed in Figure 5B for dry root weight. Treatments with higher fresh root weight generally also produced higher dry root weight values. This indicates that the increase in root biomass was not only caused by water accumulation but also reflected greater accumulation of photosynthetic products in root tissues. The increase in dry shoot weight suggests that improved nutrient availability and microbial activity stimulated root growth and enhanced dry matter accumulation in the roo

Fig. 6 . Root Morphology of Oil Palm Seedlings Under Different POME-Based Bioameliorant and Microbial Amendment Treatments in (A) Mineral soil and (B) Peat soil Media

Figure 6 shows the root morphology of oil palm seedlings grown under different POME-based bioameliorant and microbial amendment treatments in peat soil and mineral soil media.
The visual root appearance in Figure 6 is closely related to the quantitative data presented in Figure 5, particularly fresh root weight, dry root weight, and root length parameters.

In Figure 6A (peat soil), the root systems generally appeared denser, more fibrous, and more extensively branched. This observation is consistent with the data in Figure 4C, where several treatments in peat soil showed relatively high root length values. The more developed root morphology also corresponded with higher fresh root weight and dry root weight values shown in Figure 6A and Figure 6B. The high organic matter content in peat soil combined with POME-based bioameliorants likely improved microbial activity and nutrient availability, thereby stimulating root elongation and root branching.

Meanwhile, in Figure 6B (mineral soil), several treatments showed root systems that were relatively more compact with lower branching intensity. However, certain treatments still exhibited strong root development, which corresponded to the higher fresh root weight values observed in Figure 5A. This condition indicates that although root morphology in mineral soil appeared less fibrous than in peat soil, the roots were still able to accumulate biomass effectively due to better soil aeration and root penetration.

The relationship between Figure 5 and Figure 6 demonstrates that increased root length was generally followed by higher fresh and dry root biomass. Longer and more branched roots increased the root absorption area, allowing plants to absorb water and nutrients more efficiently.The application of POME-based bioameliorants and microbial amendments not only improved root biomass quantitatively but also enhanced root architecture visually, particularly in peat soil media [15].

4 Conclusion

The application of POME-based bioameliorants integrated with biochar and beneficial microbial amendments significantly influenced the growth performance, root development, soil pH, and soil biological activity of oil palm seedlings grown in contrasting soil media. The responses varied according to soil characteristics and treatment combinations, indicating a strong interaction between organic amendments, microbial inoculants, and soil type.

Mineral soil generally promoted superior plant height, root biomass accumulation, and soil respiration, reflecting its favorable physical structure, aeration, and nutrient availability. In contrast, peat soil supported greater shoot biomass production and leaf development due to its high organic matter content and water-holding capacity. The incorporation of POME, biochar, and microbial amendments improved soil quality by enhancing soil pH and stimulating microbial activity, as evidenced by the substantial increase in soil respiration.

Among the tested treatments, the combination of oil palm shell biochar, Trichoderma sp., and POME (A2M2) showed the most consistent positive effects on biomass accumulation, root morphology, and overall seedling vigor, particularly in peat soil. Improved root architecture, characterized by greater root length and branching, was associated with enhanced nutrient and water uptake, contributing to better seedling growth. These findings are consistent with previous research showing that the combination of *Trichoderma asperellum* and palm kernel shell biochar (T-mix) was the most effective treatment for improving the root health of oil palm seedlings.

The integration of POME-based bioameliorants, biochar, and beneficial microorganisms represents a promising and environmentally sustainable strategy for improving oil palm seedling performance and soil fertility in both peat and mineral soils. This approach not only enhances nursery productivity but also promotes the beneficial utilization of palm oil industry waste, supporting sustainable agriculture, circular bioeconomy principles, and climate-resilient oil palm cultivation. The positive effects of biochar, microbial inoculants, and organic amendments on oil palm growth and soil quality are consistent with previous studies highlighting their role in improving nutrient retention,

Acknowledgements

The authors gratefully acknowledge PT Bumitama Gunajaya Agro Group (BGA Group) for providing the oil palm shell biochar used in this study. The authors sincerely appreciate the company's valuable support, which contributed to the successful implementation of this research.

References

[1] A. Kushairi, M. Ong-Abdullah, B. Nambiappan, E. Hishamuddin, M. N. I. Z. Bidin, R. Ghazali, and G. K. A. Parveez, "Oil palm economic performance in Malaysia and R&D progress in 2018," Journal of Oil Palm Research, vol. 31, no. 2, pp. 165–194, 2019.

[2] A. Fikarda, M. R. Rahman, Y. Bindar, and L. D. Kasmiarno, "Sustainable biochar production from palm kernel shell through slow pyrolysis: A life cycle assessment of its application as an eco-friendly fertilizer," Engineering Chemistry, vol. 13, pp. 69–82, 2026.

[3] M. Khalid, Z. A. Rahman, M. H. Musa, and M. H. A. Husni, "Application of palm oil mill effluent (POME) improves soil properties and growth performance of crops in marginal soils," Agronomy, vol. 10, no. 8, Art. no. 1125, 2020.

[4] S. M. Lumbantoruan and S. Anggraini, "Biofertilizer formulation in stimulating corn growth in drought stress peatland," Jurnal Agroqua: Media Informasi Agronomi dan Budidaya Perairan, vol. 19, no. 2, pp. 345–353, 2021.

[5] L. Xu, Y. Wang, H. Chen, and F. Zhao, "Microbial inoculation improves soil pH and enzymatic activity in acidic soils," Applied Soil Ecology, vol. 170, Art. no. 104264, 2022.

[6] S. M. Shaheen, A. El-Naggar, J. Wang, N. E. Hassan, N. K. Niazi, H. Wang, et al., "Biochar as an (im)mobilizing agent for the potentially toxic elements in contaminated soils," in *Biochar from Biomass and Waste*. Amsterdam, The Netherlands: Elsevier, pp. 255–274, 2019.

[7] Y. Li, J. Zhang, H. Wang, and Z. Xu, "Combined application of biofertilizer and liquid organic matter improves soil biological activity and plant biomass production," Journal of Soil Science and Plant Nutrition, vol. 21, pp. 2684–2696, 2021.

[8] N. Fierer, S. A. Wood, and C. P. Bueno de Mesquita, "How microbes can, and cannot, be used to assess soil health," Soil Biology and Biochemistry, vol. 153, Art. no. 108111, 2020.

[9] V. Krashevska, D. Sandmann, F. Marian, M. Maraun, and S. Scheu, "Organic matter decomposition and soil respiration in tropical peat soils under different management systems," Soil Biology and Biochemistry, vol. 165, Art. no. 108520, 2022.

[10] X. Zhang, Q. Li, A. Zhu, W. Liang, J. Zhang, and Y. Steinberger, "Effects of liquid organic waste application on soil microbial biomass, enzyme activity, and respiration," Ecological Indicators, vol. 104, pp. 452–460, 2019.

[11] S. Peng, Y. Chen, X. Li, and W. Zhang, "Plant growth-promoting rhizobacteria enhance nutrient uptake and vegetative growth of oil palm seedlings," Rhizosphere, vol. 25, Art. no. 100642, 2023.

[12] Y. Ding, J. Wang, Y. Liu, and S. Chen, "Soil microbial communities improve nutrient use efficiency and vegetative growth in oil palm seedlings," Applied Soil Ecology, vol. 184, Art. no. 104721, 2023.

[13] A. Adileksana, Y. Nuraini, and E. Handayanto, "The effect of organic fertilizer and biofertilizer on chlorophyll content and growth of oil palm seedlings," IOP Conference Series: Earth and Environmental Science, vol. 418, Art. no. 012045, 2020.

[14] T. Simarmata, B. N. Fitriatin, and T. Turmuktini, "Rhizomicrobiome engineering in marginal soils to improve nutrient efficiency and sustainable crop productivity," Sustainability, vol. 17, no. 2, Art. no. 845, 2025.

[15] S. Anandan, A. Ali, A. Selvarajoo, and C. V. Supramaniam, "Trichoderma combined with palm kernel shell biochar promotes root health and rhizosphere biodiversity in young oil palm seedlings infected with Ganoderma boninense," Frontiers in Microbiomes, vol. 5, Art. no. 1742803, 2026.