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Interactive effects of biochar and palm oil mill effluent on physiological traits and fresh fruit bunch production of oil palm

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ABSTRACT

Oil palm productivity is often limited by soil conditions and nutrient availability. The use of organic amendments such as biochar and palm oil mill effluent (POME) can be a solution to improve physiological properties and fruit yield. The objective of this study was to determine the interactive effect of biochar produced from empty fruit bunches (EFB) and varying POME application intervals on the vegetative growth and physiology of oil palms. A field experiment was conducted from October 2024 to July 2025 at the PT Perkebunan Nusantara IV oil palm plantation, located in Lagego Village, Burau District, East Luwu Regency, South Sulawesi, Indonesia. A two-factor factorial experiment was conducted with biochar EFB doses of 0, 1.85, 3.70, and 5.56 tons ha^{-1}, and POME applied without application, every two months, and every four months. The combined application of biochar and POME significantly increased LAI (6.15), chlorophyll content (a.b and total), and stomatal aperture (260.49 μm$^{2)}$ in the treatment of 5.56 tons ha^{-1} of biochar with POME applied every four months. There were no significant differences in the number of shoots, leaf production, or stomatal density. The integration of biochar with timely POME application offers a promising strategy for sustainable oil palm management through improved physiological performance and nutrient use efficiency.

Keywords: oil palm, biochar, POME, EFB, physiological traits, productivity.

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq) is a major commodity that contributes substantially to Indonesia's economy and the global vegetable oil supply. However, intensive cultivation has resulted in soil degradation and environmental issues, mainly due to excessive use of chemical fertilizers and poor waste management (Darmawan *et al*., 2021). Sustainable soil management is therefore essential to maintain productivity and reduce environmental impacts.

Biochar, produced from the pyrolysis of biomass such as empty fruit bunches (EFB), has emerged as a promising soil amendment. Its porous structure enhances cation exchange capacity, water retention, and microbial activity, thereby improving nutrient availability and root uptake efficiency in tropical soils (Nadia and Nurhanim, 2022). Palm oil mill effluent (POME), a major by-product of palm oil processing, is commonly considered a pollutant. However, it is rich in organic matter and essential nutrients, including nitrogen, phosphorus, and potassium, making it a potential organic fertilizer. Field applications of POME have shown potential to improve plant growth and leaf physiological traits while reducing environmental contamination (Krisnantia *et al*., 2024).

Physiological indicators such as chlorophyll content, leaf area index (LAI), and stomatal traits are key measures of photosynthetic capacity and plant health. While biochar and POME have been studied separately, limited research has addressed their interactive effects on oil palm physiology. Moreover, plant responses to these amendments are variable, with certain parameters showing significant improvement while others exhibit negligible change (Kamal *et al*., 2020).

This study aimed to evaluate the interactive effects of EFB-derived biochar and POME application intervals on vegetative growth and physiological responses of 7-year-old mature oil palm trees under field conditions. The findings may contribute to the development of sustainable nutrient management strategies and promote circular utilization of palm oil industry by-products.

MATERIALS AND METHODS

Experimental site

The field experiment was conducted from October 2024 to July 2025 at the oil palm plantation of PT Perkebunan Nusantara IV, located in Lagego Village, Burau Subdistrict, East Luwu Regency, South Sulawesi, Indonesia. The site was selected to its representation of large-scale commercial oil palm cultivation in Eastern Indonesia and the guaranteed availability and consistency of the key by-products (EFB and POME) used as amendments in this study. Furthermore, the selection ensures experimental homogeneity regarding crop management, providing a robust platform for evaluating the interactive effects of the treatments on mature productive trees.

Experimental design

A field-based two-factor factorial experiment was arranged using a randomized complete block design (RCBD) with three replications. The first factor was biochar (B) produced from empty fruit bunches (EFB), applied at four levels: 0 tons ha^{-1} (control), 1.85 tons ha^{-1}, 3.70 tons ha^{-1}, and 5.56 tons ha^{-1}. The second factor (L) was the application interval of palm oil mill effluent (POME), applied at a rate of 10 L $tree^{-1}$. Three levels were tested: no application (control), application every two months, and application every four months. A total of 12 treatment combinations were established, with each unit consisting of two 7-year-old productive palms (72 trees in total).

Preparation of organic amendments

Biochar was produced from air-dried from oil palm empty fruit bunches (OPEFB) by slow pyrolysis at 300–400 °C for 3.5 hours using a modified metal drum. The resulting biochar was quenched and enriched with *actinomycetes* bacteria 10^{-8} prior to application. POME was fermented anaerobically in a 500 L closed container by mixing 425 liters of raw effluent with enzyme solution 5% (25 L) and molasses 10% (50L) for 30 days under ambient conditions.

Field application

Application discs were manually prepared as circular trenches (1 m distance from trunk, 30 cm deep) around each experimental tree. Biochar was applied once (one month after disc preparation) by evenly spreading the material within the trench according to the designated dosage. POME was applied repeatedly according to the designated intervals by pouring the fermented solution into the disc (Figure 1).

Data collection and analysis

The parameters observed included the number of spear leaves, LAI, chlorophyll index a,b and total (measured using a CCM-200+ device), stomatal characters (stomatal number, stomatal

Figure 1. Application trench for biochar and POME around the oil palm tree (1 m from the trunk and 30 cm deep)

aperture area, stomatal density) measured under a microscope, and leaf nutrient content (N, P, K).

Data were analyzed using ANOVA based on the factorial RCBD model. Tukey's HSD test was applied to separate the means when significant differences ($p \leq 0.05$) were detected.

RESULT AND DISCUSSION

Number of spear leaves

Figure 2 shows the number of spear leaves on oil palms did not different significantly between treatments ($p > 0.05$), but the trend pattern showed a positive response to the combination of 3.70 t ha^{-1} biochar with POME application every two months, which resulted in the highest number of spear leaves (28 leaves). These findings indicate that more intensive POME application frequency plays a role in increasing new leaf formation, possibly through increased availability of macro nutrients such as nitrogen (N) and potassium (K). as discussed elsewhere Sakiah and Mardiana (2018) noted that every 100 tons of POME contains an average of 55 kg of N and 85 kg of K, which contribute to vegetative growth. POME application improves soil chemical properties such as organic C, pH, total N, and available K (Ratnasari *et al*., 2024). The application of a high biochar dose (5.56 t ha^{-1}) showed no significant effect on the number of spear leaves. as discussed by Sianipar *et al.* (2025) shows that biochar application, while improving the physical and chemical properties of the soil, has a gradual effect on oil palm growth, including biomass and nutrient uptake. This indicates that growth responses such as leaf number may take longer to show significant changes. Regular application of POME, especially at optimal biochar doses, can strengthen nutrient supply and support the vegetative growth of oil palms more effectively.

Frond production

Frond production (Figure 3) did not show statistically significant differences between treatments ($p > 0.05$). Nevertheless, the application of 3.70 t ha^{-1} biochar without POME resulted in the highest number of fronds production, indicating that biochar, even without additional nutrient input, can improve vegetative growth through enhancement of soil physical properties such as aeration and water-holding capacity (Yosephine *et al*., 2020). Biochar is also known as a habitat for microorganisms that are beneficial in increasing the availability of important macro nutrients such as nitrogen and phosphorus, which support the formation and growth of leaves and plant fronds. In addition, biochar increases air retention in the soil, reduces nutrient leaching, and improves soil aggregate structure, which overall results in more fertile soil conditions for vegetative plant growth (Rivandi *et al*., 2024). A review of biochar's agronomic impacts notes that its porous structure and high surface area directly increase soil water retention and reduce bulk density, thereby improving root-zone aeration and supporting greater shoot growth without extra nutrient inputs (Kocsis *et al*., 2022).

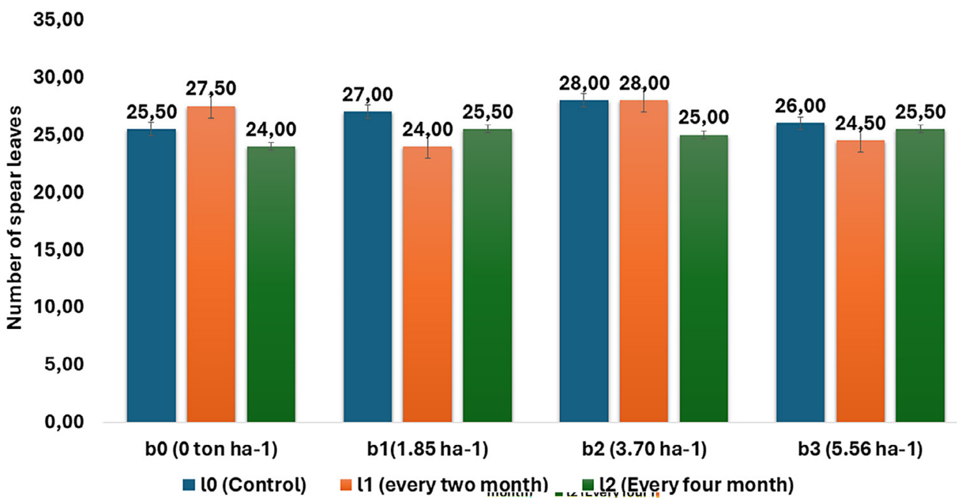

Figure 2. Effect of biochar and POME on a Number of spear leaves

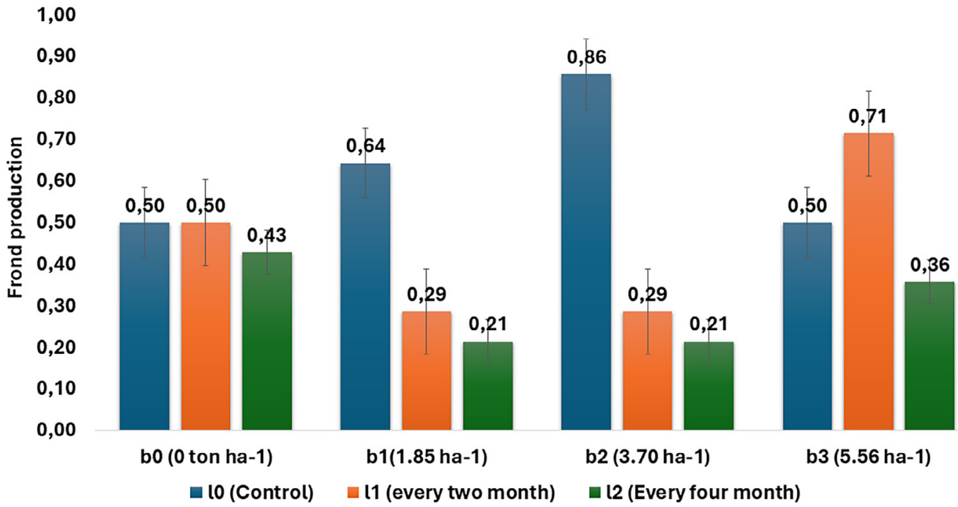

Figure 3. Effect of biochar and POME on frond production

Stomatal density and stomatal number

Stomatal density and stomatal number (Figure 4) was not significantly affected by either biochar or POME application ($p > 0.05$). The highest mean stomatal density (565.6 stomata μm^2) and stomatal number (111.0 μm^2) was both observed in the treatment without biochar and with POME application every four months, whereas the lowest value was recorded in the control treatment (0 ton ha^{-1}

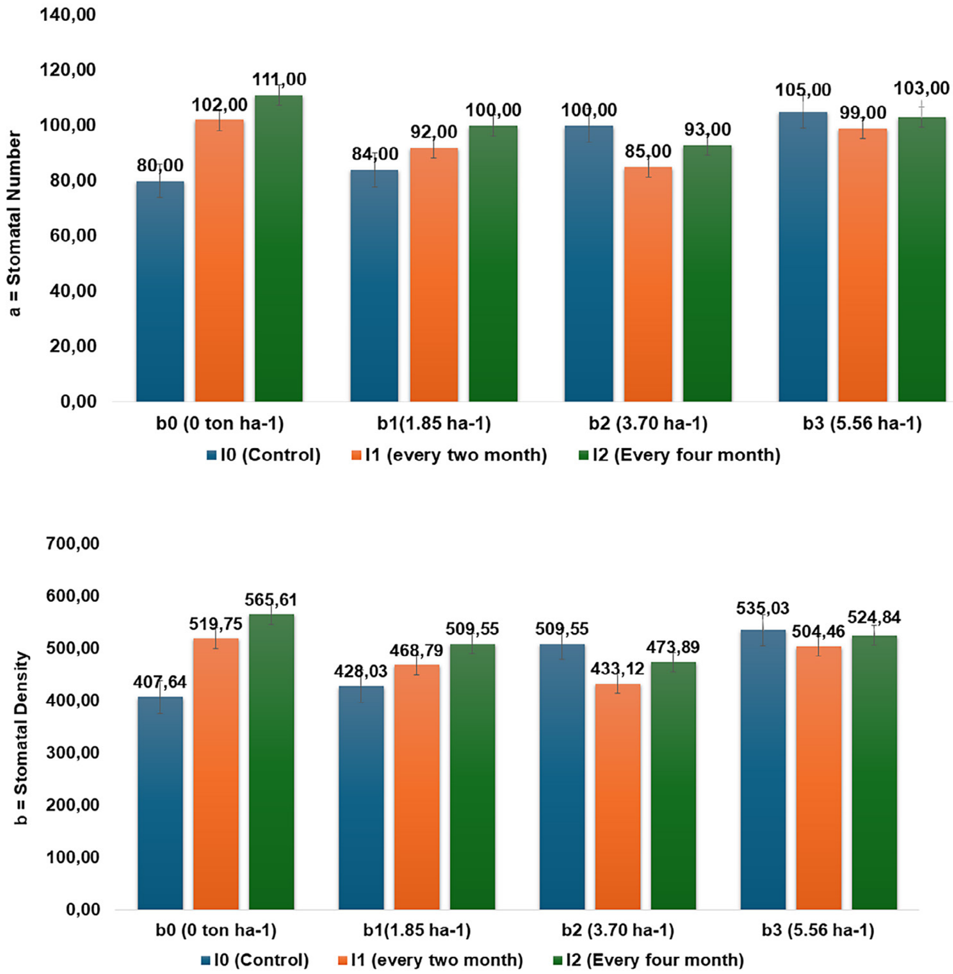

Figure 4. Effect of biochar and POME on (a) stomatal number, (b) stomatal density

biochar without POME application). In contrast, stomatal number and density were not significantly affected by either biochar or POME application. This is consistent with the understanding that stomatal density is genetically regulated and relatively stable in mature palms (Behera *et al*., 2022). Husna *et al*. (2023) also reported that changes in stomatal density are more pronounced during the seedling stage than in mature, productive palms.

Stomatal aperature area

Results shown in Table 1 that the application of palm oil mill effluent (POME) has a significant effect on the stomatal aperature area of oil palm plants. The highest average stomatal aperature area in the treatment of POME every 4 months (L2) was 260.49 μm², which was significantly different from the treatment without POME.

POME application had a significant effect on stomatal aperture area, with the widest openings observed at four-month application intervals. Wider stomatal apertures enhance gas exchange and transpiration efficiency, which improves CO_2 diffusion into mesophyll cells and supports higher net photosynthetic rates. These findings align with Muir (2020), who emphasized that stomatal aperture size is a key determinant of gas exchange efficiency and plant productivity. Increased stomatal opening also enhances transpiration cooling, which helps prevent leaf overheating under high light intensity and maintains optimal photosynthetic enzyme activity (Lawson and Matthews, 2020). as discussed by Franks *et al*. (2017) further highlighted that stomatal regulation maintains a balance between CO_2 uptake and water loss, influencing overall water use efficiency. The results of this study can be interpreted that POME treatment is able to stimulate physiological responses in plants in the form of wider stomatal opening to optimize CO_2 absorption, increase leaf cooling, and indirectly support biomass accumulation and oil palm productivity.

Table 1. Effect of biochar and POME on the stomatal aperature area

Palm oil mill effluent (POME) application interval		CV (L) HSD
L0 (Control)	202.92 b	54.87
L1 (every two months)	213.59 a	
L2 (every four months)	260.49 a	

Note: *the means followed by different letters within the same column indicate significant differences according to Tukey's HSD test at $p \leq 0.05$.

Leaf area index

Table 2 provides a summary of the results indicated that leaf area index (LAI) was significantly influenced by POME application ($p < 0.05$), whereas biochar and the interaction between biochar and POME showed no significant effects ($p > 0.05$). The treatment produced the highest mean LAI value (6.15). where POME was applied every four months (L2), while the lowest value was observed in the control treatment without POME application.

Table 2. Effect of biochar and POME on the leaf area index

Palm oil mill effluent (POME) application interval		CV (L) HSD
L0 (Control)	5.20 b	0.90
L1 (application of effluent once every two months)	6.03 ab	
L2 (application of effluent once every four months)	6.15 b	

Note: *the means followed by different letters within the same column indicate significant differences according to Tukey's HSD test at $p \leq 0.05$.

The leaf area index (LAI) was significantly affected by POME application, with the highest mean LAI (6.15). The optimal LAI value for achieving high productivity is in the range of 5–6, which indicates a sufficiently dense yet efficient canopy that reflects more optimal leaf expansion, increases the plant's ability to capture light, supports biomass production, and optimizes photosynthetic efficiency in light absorption (Breure, 2010). The strong correlation between LAI and the normalized difference vegetation index (NDVI), as shown by remote-sensing studies, further confirms that a high LAI reflects healthy canopy conditions and strong yield potential (Yuniasih *et al*., 2022). Increased LAI represents optimal leaf expansion, improving light capture efficiency, biomass accumulation, and overall photosynthetic performance. Other researchers Salmiyati *et al*., (2025) emphasized that LAI is identified as the main physiological parameter that is closely correlated with fresh fruit bunch (FFB) productivity, due to its ability to represent the efficiency of converting solar radiation into biomass through canopy photosynthetic activity.

Chlorophyll index

Figure 5 shows the interaction between EFB biochar doses and frequency of POME application on chlorophyll a, b, and total chlorophyll content in palm oil leaves. The intersecting lines indicate a significant interaction, meaning that the effect of biochar depends on the frequency of POME application. The highest chlorophyll a concentration was recorded in the b1 × l2 treatment (1.85 tons ha^{-1} biochar with POME applied every four months) 501.92 μmol m², suggesting that a

Figure 5. Interaction effect of biochar and POME on (a) chlorophyll a, (b) chlorophyll b, (c) chlorophyll total

moderate biochar dose combined with a balanced POME application schedule optimizes chlorophyll synthesis. In contrast, the b2 × l1 (3.70 ton ha^{-1} biochar with POME applied every two months) combination resulted in the lowest chlorophyll levels 385.38 µmol m², possibly due to excessive nutrient accumulation leading to physiological stress.

A similar trend was observed for chlorophyll b and total chlorophyll, with the b1 × l2 treatment consistently producing superior results. This outcome reflects a synergistic interaction between biochar-induced soil improvement and the sustained nutrient input provided by POME. Biochar, with its porous structure and high surface area, enhances soil water and nutrient retention by increasing cation exchange capacity (CEC), thereby reducing nutrient leaching from the root zone (Khan *et al*., 2024). Concurrently, POME serves as a nutrient-rich organic fertilizer, supplying essential macronutrients such as nitrogen and potassium—critical for chlorophyll synthesis and photosynthetic metabolism (Ramadhan *et al*., 2019).

The combined application of biochar and POME fosters an optimal rhizosphere environment: biochar acts as a reservoir for water and nutrients, while POME replenishes essential elements—collectively enhancing photosynthetic efficiency and plant productivity. Maulana *et al*. (2025) reported that oil palm empty fruit bunch (OPEFB) biochar contains stable carbon and functional groups such as O–H and C=O, which contribute to improved nutrient retention and availability. Moreover, Nio and Banyo (2011) emphasized that leaf chlorophyll content serves as an early physiological indicator of plant stress, such as water deficiency. A decline in chlorophyll reflects metabolic disruption, whereas elevated chlorophyll levels indicate a more stable and healthy physiological state.

Macronutrient composition of leaf tissue (N, P, K)

Leaf tissue analysis for N, P, and K further supports these results. Nitrogen is essential for protein and chlorophyll biosynthesis, phosphorus is involved in ATP-driven energy transfer, and potassium regulates stomatal conductance and assimilate transport. Optimal concentrations of these nutrients explain the observed increases in shoot production, leaf expansion, photosynthetic efficiency, and stomatal aperture area, which together contribute to improved vegetative and physiological performance (Sianipar *et al*., 2025; Sholeh, 2016).

CONCLUSIONS

Palm oil mill effluent (POME) positively influenced the vegetative and physiological performance of 7 yeras old mature oil palms, although not all parameters exhibited statistically significant responses. Morphological traits, including the number of spear leaves and frond production, remained relatively stable, reflecting the growth characteristics of mature palms in a physiologically steady phase. In contrast, physiological parameters such as leaf area index, chlorophyll content, and stomatal aperture showed distinct responses, particularly under the treatment of 5.56 ton ha^{-1} biochar combined with POME applied every four months.

These results demonstrate the interactive effects of biochar and POME in enhancing photosynthetic capacity, nutrient availability, and soil physical properties, thereby contributing to improved physiological efficiency and sustainable oil palm production systems.

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