Research Article

Decomposition of Palm Fronds (*Elaeis guineensis*) and Banana Stems Enriched with *Trichoderma* and Plant Growth Promoting Rhizobacteria (PGPR) Applied to Palm Seedlings

Kafrawi Kafrawi[1]*, Zahraeni Kumalawati[2], Sri Muliani, Darmawan Darmawan[3] and Muh. Dzulkifly Ashan[4]

[1]Department of Agricultural Production Technology, [2]Pangkep State Polytechnic of Agriculture, Indonesia.

Abstract | Palm fronds and banana stems are lignocellulosic residues that decompose slowly due to their high lignin and cellulose content. Accelerated composting using *Trichoderma harzianum* and plant growth-promoting rhizobacteria (PGPR) offers a sustainable method to convert this biomass into nutrient-rich compost. This study aimed to obtain *Trichoderma*-enriched compost from palm fronds and banana stems and to determine the optimal PGPR concentration for promoting the growth of oil palm seedlings in the pre-nursery. Preliminary research identified the type of *Trichoderma* fungus to be used and then paired with PGPR concentration treatments (P) to make compost. Furthermore, field experiments was conducted in an oil palm nursery to observe the effect of compost on the growth of oil palm seedlings, using a randomized complete block design (RCBD) with four PGPR dosage treatments (P): Control/0 mL L^{-1} (P0), 10 mL L^{-1} (P1), 20 mL L^{-1} (P2) and 30 mL L^{-1} (P3). The experimental results showed that the 20 mL L^{-1} PGPR treatment achieved the highest compost temperature (39°C), optimal C-organic content (18.31%) and the C/N ratio (19%), with improved nitrogen (0,95%), and phosphorus (3.41%). The highest potassium content was shown by the PGPR 30 mL L^{-1} treatment, at only 2.86%. The best total macronutrient content in the palm frond and banana stem compost was obtained from the PGPR 20 mL L^{-1} treatment at 7.14%. Compost enriched with PGPR 20 mL L^{-1} produced the best results for plant height growth at 70 DAP (12.64 cm), while PGPR 10 mL L^{-1} produced the best results at 84 DAP (17.15 cm) and 98 DAP (29.46 cm). Compost enriched with PGPR also improved stem diameter, number of leaves, fresh weight, and dry weight of seedlings. It is therefore recommended to apply PGPR-enriched compost at 20 mL L^{-1} to enhance organic waste decomposition and early growth performance of oil palm seedlings.

Received | August 14, 2024; **Accepted** | May 05, 2025; **Published** | March 16, 2026
***Correspondence** | Kafrawi Kafrawi, Department of Agricultural Production Technology; **Email:** kafrawidjamin@polipangkep.ac.id
Citation | Kafrawi, K., Z. Kumalawati, S. Muliani, D. Darmawan and M.D. Ashan. 2026. Decomposition of Palm Fronds (*Elaeis guineensis*) and Banana Stems Enriched with *Trichoderma* and Plant Growth Promoting Rhizobacteria (PGPR) Applied to Palm Seedlings. *Sarhad Journal of Agriculture*, 42(1): 440-453.
DOI | https://dx.doi.org/10.17582/journal.sja/2026/42.1.440.453
Keywords | Banana, Compost, Fronds, Fungi, Oil palm, PGPR, Trichoderma

Introduction

Palm oil is one of the most widely consumed and produced vegetable oils globally. In addition to its low and stable price, it is also used in various types of food, cosmetics, and renewable energy sources, such as biofuels and biodiesel. Indonesia had a total oil palm area of 16.83 million hectares, with smallholders cultivate approximately 5.89 million hectares or 35.82% (Directorate General of Plantation, 2023). This sector employs at least 2.61 million workers, highlighting its substantial socio-economic contribution.

The success of oil palm plantations begins in the nursery, where high-quality seedlings are critical for achieving optimal productivity. Two nursery systems are commonly used: the single-stage nursery and the two-stage nursery (Saputra *et al*., 2024). The most commonly used nursery is the two-stage nursery, which is carried out in small polybags. In the single-stage nursery, seeds in the form of oil palm shoots are planted directly into large polybags and maintained until they are ready for planting (Babu *et al*., 2025). Regardless of the system, the quality of seedlings is influenced by genetic factors, planting media, and nutrient availability.

Seedlings are the key to excellent performance in oil palm cultivation. Nutrient requirements vary with growth stage and macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are crucial for improving seedling vigor and quality. The amount and type of nutrients required are different for each growth stage (Setyawan *et al*., 2020; Ginting *et al*., 2021; Gusmawartati *et al*., 2025). The addition of nutrients to the planting medium in the right type and dose can enhance the growth of oil palm seedlings, resulting in high-quality seedlings (Ajeng *et al*., 2020). Oil palm nurseries require a growing medium consisting of soil and a mixture of other materials commonly used as an organic fertilizer. The composition of planting media, which combines soil with agricultural and industrial waste, has been widely used in oil palm cultivation (Hau *et al*., 2020).

However, these biomass materials have high lignin and cellulose content, which hinders their rapid decomposition. Palm fronds contain 20.13% lignin, 32.58% cellulose, and 8.37% hemicellulose (Kusmiati *et al*., 2024). Banana stems contain 9% lignin, 46% cellulose, and 38.54% hemicellulose (Nandiyanto *et al*., 2021). this high lignocellulosic composition limits microbial access and enzymatic degradation, resulting in slow composting rates and potential nutrient immobilization (Datta, 2024).

To address this issue, the use of lignocellulolytic microbial decomposers has been proposed. Fungi such as *Trichoderma*, *Aspergillus*, *Pleurotus ostreatus*, and *Rhizopus* are known to degrade complex lignocellulose structures (Kusmiati *et al*., 2024).

In addition to fungal microbes, bacterial microbes can also be used as breakers in composting, such as PGPR (plant growth-promoting rhizobacteria) bacteria (Utamy *et al*., 2025). PGPR is capable of producing growth hormones such as auxin, gibberellin, and cytokinin, as well as facilitating phosphate solubilization and nitrogen fixation (Vocciante *et al*., 2022; Tripathi *et al*., 2024; Chi *et al*., 2025; Syaiful *et al*., 2025). PGPR isolates of *Bacillus* strains isolated from Sulawesi, which were tested on shallot plants and had the best effect on the number of leaves and number of shallot bulbs (Kafrawi *et al*., 2017).

Despite the known benefits of microbial decomposers and PGPR, few studies have explored their synergistic application in accelerating the decomposition of palm fronds and banana stems for use in oil palm nurseries. Furthermore, the potential of such composts to enhance nutrient content and promote seedling performance remains underexplored. Therefore, this study aims to obtain *Trichoderma*-enriched compost from palm fronds and banana stems and to determine the optimal PGPR concentration for promoting the growth of oil palm seedlings in the pre-nursery.

Materials and Methods

Research design

This research was arranged in a randomized complete block design (RCBD). Preliminary studies were carried out to determine the type of decomposition fungi to be used in compost production, namely *Aspergillus* (K1), *Plerotus Ostreatus* (K2), *Rhizopus* (K3), and *Trichoderma* (K4). Each treatment was replicated three times, consisting of two experimental units, resulting in a total of 24 experimental units. The selected fungi were then paired with the PGPR dosage treatment (P) to make a new compost consisting of four treatments. Each treatment was replicated three times, consisting of two experimental units, for a total of 24 experimental units. Data analysis of the nutrient content of each dose of PGPR compost was composited and then tested in an oil palm nursery to see its effect on the growth of oil palm seedlings using a Randomized Complete Block Design (RCBD) with four PGPR dose treatments (P), namely Control / 0 mL L^{-1} (P0), 10 mL L^{-1} (P1), 20 mL L^{-1} (P2), 30 mL L^{-1} (P3). Each treatment was replicated five times and consisted of two units, resulting in a total of 40 experimental units.

Research procedure

Stage of preparation

The palm fronds are collected with a dodo, and the leaves on the fronds are removed. The fronds are washed thoroughly with running water and aired. The selection of white decomposition fungi for decomposition was made by pouring each fungal suspension, namely *Aspergillus* (K_1), *Plerotus Ostreatus* (K_2), *Rhizopus* (K_3), and *Trichoderma* (K_4), into a bucket containing 500 mL of distilled water, with molasses added to a level of two tablespoons. The fungal solution was slowly poured onto the compost material, which consisted of a mixture of finely chopped palm fronds, banana stems, and bran, in a ratio of 2:2:0.5, after each treatment. If the compost material does not break when squeezed by hand, stop adding water, and the compost material is ready for incubation in a closed bucket. The compost solution is then stirred daily to even out the decomposition process and release the heat generated by decomposition.

Stages of trichoderma and PGPR

Enriched compost preparation *Trichoderma* and PGPR enriched compost was prepared according to the method of Kafrawi (2017), viz: 1). Palm fronds and banana stems were chopped into cubes and mixed evenly with chicken manure and husk in a ratio of 1:1:1:1 so that it was ready to become compost material, 2) a suspension of *Trichoderma harzianum* fungus with a concentration of 1 × 106 was prepared as much as 1000 mL and molasses was added as much as two tablespoons, 3) the suspension of *Trichoderma harzianum* fungus together with the local *Bacillus* bacterial consortium formulation of Sulawesi Island with a concentration of P2 in a ratio of 1:1, 4) the watering of the fungal and bacterial suspensions was stopped when the compost material did not break after being crushed by hand, and then the compost material was fermented for three months, 5) after fermentation, the mature enriched compost was directly applied as the main component of the planting medium to ensure that the microbial enrichment achieved during composting could optimally support early seedling growth.

Stages of planting and maintenance

Preparation of the planting media started with mixing topsoil with compost as a growing medium in polybags measuring 10 cm × 15 cm. The planting media consisted of a mixture of topsoil and palm frond compost enriched with different concentrations of PGPR in a 1:1 ratio. Seeds were planted by dipping them with the radicle pointing downwards, the plumula covered with a layer of soil that was not too hard. They were planted individually and placed in the nursery. Maintenance consists of watering and weeding. Watering was done in the morning and evening, depending on the soil's humidity. Weeding was done when weeds were growing in the polybags. The first observations were made 30 days after planting (DAP) and continued until the end of the observation, 16 weeks after planting. Parameters observed or the difference between the data at the time of observation and the first observation.

Data parameter and analysis

The parameters observed were C/N ratio of compost enriched with *Trichoderma*, compost temperature enriched with *Trichoderma* harzianum and PGPR, pH of the compost, nutrient analysis of the compost, plant height, number of leaves, stem diameter, fresh plant weight, and dry plant weight. All data underwent systematic analysis using several analytical concepts. The data were analyzed using analysis of variance with the least significant difference (LSD) test at the 95% confidence level.

Table 1: *Nutrient content of compost enriched with the weathering fungus three months after decomposition (MAD)*

Compost decomposition fungi	**Nutrient of compost (%)**		
	C-Organic	Nitrogen	**C/N**
Aspergillus (K1)	8,64	0,35	25
Plerotus Ostreatus (K2)	8,64	0,41	21
Rhizopus (K3)	9,86	0,52	19
Trichoderma (K4)	9.58	0,42	23
Standard*	Min. 5		≤ 25

**Regulation of the Minister of Agriculture No 261 - KPTS - SR.310 - M - 4 - 2019 on the minimum technical requirements for organic fertilizers, biofertilizers, and soil improvers.*

Results and Discussion

C/N ratio of compost enriched with trichoderma.

The compost, which was incubated for three months to allow for adequate decomposition, was subsequently analyzed to determine its nutrient content using a composite sampling method. Table 1 presents the results of the nutrient analysis conducted on the compost produced by applying different decomposition fungi to palm fronds and banana stems.

The C/N ratio is the most important factor in the composting process because it is driven by the activities of microorganisms, which require carbon as an energy source and nitrogen to form cells (Vocciante *et al*., 2022). The value of the C/N ratio determines the quality of the compost, as it affects the availability of nutrients and serves as an indicator of the compost's level of maturity. A higher C/N ratio indicates that the compost is not mature (Azis *et al*., 2023). The results of the C/N ratio analysis were successfully reduced in all treatments with the type of decomposition fungus used, which ranged from 19 to 25. This value meets the quality standards of solid organic fertilizer in the form of compost with a standard value of ≤ 25.

Rhizopus sp. gave the lowest reduction in C/N ratio compared to other decomposition fungi with a C/N ratio of 19. It is believed that *Rhizopus* has a superior degrading ability compared to other fungi on palm fronds. The suitability of the needs of life is achieved by using sugar or starch in palm fronds as a carbon source, resulting in a faster degradation rate of organic matter in compost with *Rhizopus* sp., which is characterized by the lowest C/N ratio. According to Hamid *et al*. (2020), the nutrient content of palm fronds and leaves is relatively low, as indicated by their high crude fiber content, but they contain a significant amount of carbohydrates in the form of soluble sugars, which accounts for approximately 22%.

Rhizopus, with the lowest C/N ratio, and *Aspergillus*, with the highest C/N ratio, were not selected as a decomposition fungus for further research. According to Shafreen *et al*. (2021), if the C/N ratio is too low, excess nitrogen (N) that is not utilized by microorganisms cannot be assimilated and is either lost through volatilization as ammonia or denitrified. Additionally, it takes several cycles of microorganisms to complete the degradation of compost materials, resulting in longer composting times and lower-quality compost results. Salangsang *et al*. (2022) state that microorganisms can break down carbon compounds for energy and utilize nitrogen for protein synthesis. If the C/N level is too high, microbes will lack N for protein synthesis, and decomposition will be slow.

The decomposition fungus selected for the follow-up study was *Trichoderma*, with a C/N ratio of 23:23. According to Abdusamatov *et al*. (2020), this microbe makes more efficient and effective use of the decomposition element nitrogen contained in palm fronds. *Trichoderma harzianum* is capable of breaking down organic matter, such as cellulose, into glucose compounds. The *Trichoderma harzianum* fungus can produce enzymes that break down cellulose into glucose and also acts as an environmentally friendly biofungicide, as it does not pollute the environment but can restore the natural balance and fertility of the soil.

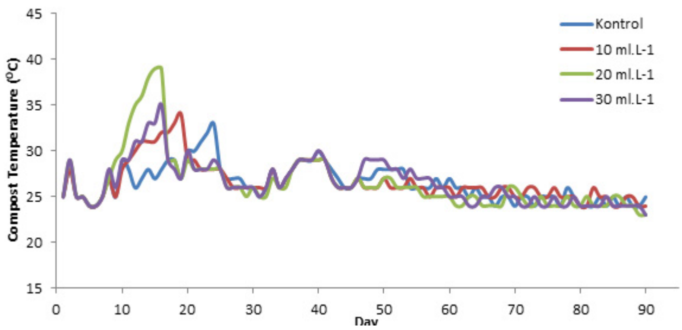

Figure 1: *Temperature variation of Trichoderma-enriched compost and different doses of PGPR during the decomposition process at 3 MAD.*

Compost temperature enriched with trichoderma harzianum and PGPR

The next stage of research involves combining the use of *Trichoderma* and PGPR as compost enrichment materials. The treatment of PGPR doses on the decomposition process shows different compost temperatures during the incubation period until the compost is mature. Temperature variations are visible in Figure 1.

Figure 1 illustrates that the temperature fluctuates, and the maximum temperature achieved in the composting process for the P2 treatment is 39°C. As a comparison, the minimum compost temperature achieved at the end of the experiment by PGPR doses P2 water and P3 is 23°C. The results showed that in each sample treatment, the temperature was significantly higher in the second week, indicating that the composting rate was faster due to the activity of decomposing organic matter by microorganisms.

The increase in temperature typically began at the start of the composting process, reaching a maximum between days 10 and 25, and then decreased until the end of the process. The increase in temperature on day 10 was due to the release of microbial nutrients from the organic matter in the palm fronds and banana stalks, resulting in intense growth and activity of microbial decomposers. Along with the intensive decomposition of organic matter, a significant amount of heat was released, increasing the temperature of the compost pile. The microbial activity then decreases, accompanied by a decrease in pile temperature, until the end of the composting process. The temperature achieved in the 20 mL L^{-1} treatment is due to the microbial population receiving balanced nutrition from the compost pile, which enables them to support microbial activity, resulting in a higher temperature than in the other treatments. According to Ho *et al*. (2022), the optimal temperature range for good composting activity is between 30 °C and 60 °C. Therefore, the results obtained indicate the occurrence of a good composting process. The composting process will go well if the compost temperature is suitable for the growth of microorganisms (Abdusamatov *et al*., 2020)

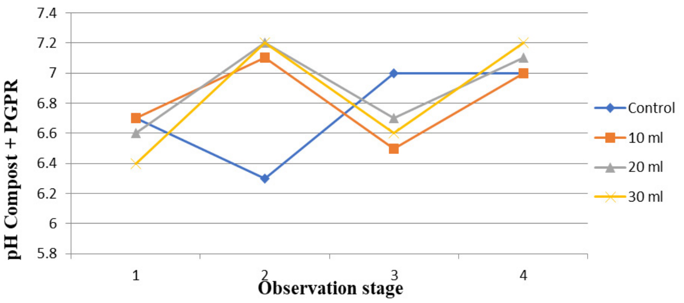

Figure 2: *PH of compost from palm fronds and banana stems enriched with Trichoderma and different doses of PGPR during the decomposition process at 3 MAD.*

pH of the compost

The composting process can take place over a wide pH range. The decomposition process is characterized by an increase in the pH of the compost during the incubation period, as illustrated in Figure 2. Theoptimum pH for the composting process is between 6.5 and 7.5. If the pH is too acidic or too alkaline, oxygen consumption will increase, and this will have dire consequences for the environment; if the pH is too alkaline, the nitrogen element in the compost material will be converted into ammonia, whereas if the pH is too acidic, some microorganisms will die (Sadeli *et al*., 2022). Figure 2 shows the initial condition of the compost pile, which had a relatively low pH. During the decomposition process and upon entering the second observation, there was an increase in the pH of the composter at all PGPR doses, except for the control treatment, which experienced a decrease in pH by 0.4 points. Sutton *et al*. (2020) state that the addition of PGPR microorganisms causes an increase in the activity of microorganisms that break down organic nitrogen into ammonia. Ammonia increases pH due to its alkaline nature. The lack of addition of PGPR microorganisms in the control, which relies solely on indigenous microorganisms, results in low microbial activity, leading to a decrease in the pH of the composter.

In the third observation, the opposite condition occurred. All the compost piles treated with PGPR experienced a decrease in pH. In contrast, the control treatment experienced an increase in pH that persisted throughout the experiment, with a final pH of 7. This was caused by the activity of indigenous microorganisms from the compost pile that took longer to multiply their population and were able to influence the decomposition process. While the PGPR-treated compost pile initially started at a relatively high pH condition in the second observation, the pH level decreased in the third observation. This is in line with the statement of Saypariya *et al*. (2024), who noted that the pH value decreased slightly with increasing days of composting. The process of acid release, whether temporary or local, will cause a decrease in pH. The pH condition of the palm frond and banana stem compost produced in all PGPR dosage treatments and the control met the MOA standard, which is between 4 - 9 (Figure 2). The maximum pH range for most bacteria is between 6 - 7.5. For fungi, it is 5-8. Based on this description, the optimum pH condition is 7 or in the range of 5 to 8 (Mawad *et al*., 2020). Therefore, the pH achieved at the end of composting indicates that the process is progressing well.

Nutrient analysis of compost

Table 2 presents a comparative analysis of the nutrient composition of compost treated with *Trichoderma* in combination with varying doses of Plant Growth Promoting Rhizobacteria (PGPR).

Table 2 shows that composters from all PGPR dose treatments showed a decrease in C/N ratio compared to the control. The decrease in the C/N ratio followed a linear curve, i.e., the higher the PGPR dose, the higher the C/N ratio of the composters. The pH of the composters increased with increasing PGPR dose. Meng *et al*. (2021) state that, in general, the C/N

Table 2: *Compost content of palm fronds and banana stems enriched with Trichoderma harzianum and different doses of PGPR at the age of 3 MAD.*

Dose of PGPR	Moisture (%)	pH	C/N	C-Organic(%)	Macro-nutrient (%)			Total macro-nutrient
					Nitrogen (N)	Phosfor (P_2O_5)	Potassium (K_2O)	
Control	8.52	7	23	13.77	0.59	2.69	2.33	2,33
10 mL. L[1]	7.22	7	18	15.34	0.85	3.22	2.85	6,92
20 mL. L[1]	6.79	7.1	19	18.31	0.95	3.41	2.78	7,14
30 mL. L[1]	5.44	7.2	20	16.19	0.79	2.98	2.86	6,63
Standard*	10 - 25	4 - 9	≤ 25	Min. 15	------- Total macro-nutrient Min 2 -------			

** Regulation of the Minister of Agriculture No 261 - KPTS - SR.310 - M - 4 - 2019 on the minimum technical requirements for organic fertilizers, biofertilizers, and soil improvers.*

ratio and pH of the compost in all treatments met the standards for organic fertilizers, namely a C/N ratio of ≤ 25 and a pH range of 4-9. Microbes can grow well in media rich in carbon, which serves as their habitat and energy source. Allaily *et al.* (2022) state that the increase in pH in each compost bin is caused by the breakdown of protein into ammonia (NH_3). pH changes in compost begin with a slightly acidic pH due to the formation of simple organic acids, followed by a rise in pH during further incubation as a result of protein breakdown and the release of ammonia.

Compost nutrient levels increased in all PGPR treatments, including organic carbon, nitrogen, phosphorus, and potassium. However, it is slightly different from the linear curve of the C/N ratio and pH of the compost, where the nutrient content of the compost tends to increase with increasing doses of PGPR. However, at the end of the experiment, the nutrient content began to peak at the highest PGPR dose. This is due to the excessive PGPR population at high doses (P3), resulting in insufficient compost substrate as an energy source to support PGPR activity. A high C/N ratio of 20 in compost causes the nutrient content of the compost to become flat. According to Nemet *et al.* (2021), microorganisms need carbon and nitrogen for their metabolic activities. When the C/N ratio is high, the biological activity of microbes decreases, and several cycles are required to degrade organic matter, thereby extending the time required for organic matter decomposition and producing lower-quality products.

Furthermore, if the C/N ratio is too low, excess nitrogen that is not utilized by microorganisms cannot be assimilated and is lost through volatilization as ammonia or denitrification (Meng *et al.*, 2021). The highest PGPR dose resulted in the highest C/N ratio and caused low microbial activity. This results in low nutrient levels, affecting the overall production of macronutrients by both PGPR and the control group. However, the moisture content is too low. In this case, the decomposition efficiency decreases because there is insufficient water to dissolve the organic matter, which serves as an energy source for microorganisms (Abdurahman *et al.*, 2021).

Table 3: *Average height increase (cm) of oil palm seedlings at 70, 84, and 98 DAP*

PGPR	Height of oil palm seedlings at maturity		
	70 DAP	84 DAP	**98 DAP**
P0 (Control)	12.00[a]	15.85[a]	26.66
P1 (10 ml.L^{-1})	11.95[a]	17.15[a]	29.46
P2 (20 ml.L^{-1})	12.64[a]	16.14[a]	28.30
P3 (30 ml.L^{-1})	8.00[b]	11.28[b]	23.32
$LSD_{0,05}$	3.35	4.23	ns

Note: Mean values followed by different letters indicate significant differences between treatments in the LSD test at p < 0.05.

Plant height

Plant growth is influenced by both genotypic and environmental factors, among which the growing medium plays a critical role. As an essential component of the plant's environment, the medium affects nutrient availability, water retention, and root development. Table 3 presents the average height growth of oil palm *(Elaeis guineensis*) seedlings. Figure 3 illustrates the progressive increase in plant height of oil palm seedlings at 70, 84, and 98 days after palnting (DAP). The data trend shows an increasing pattern, indicating active vegetative growth. The increase in height reflects the efficacy of compost treatments enriched with different biological agents (e.g., *Trichoderma* and PGPR) in promoting elongation growth.

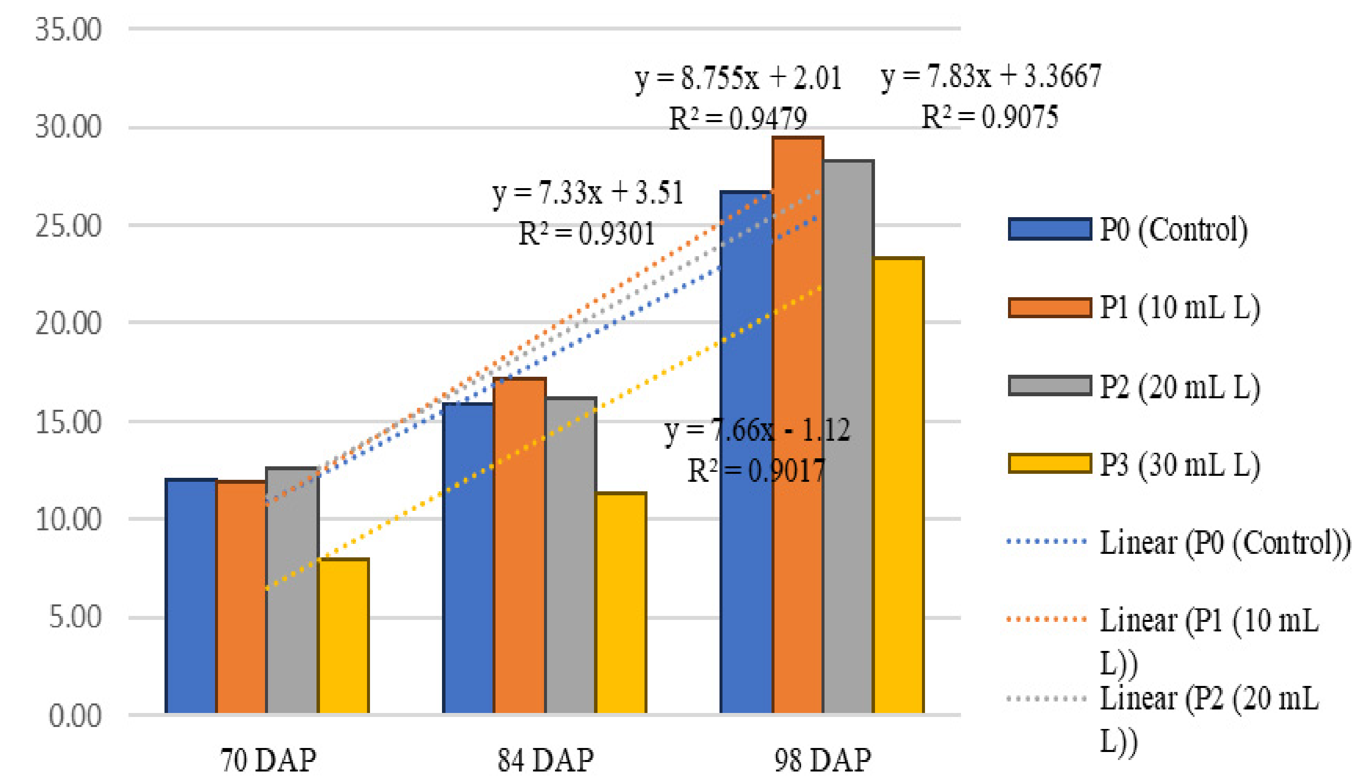

Figure 3: *Average height increase (cm) of oil palm seedlings at 70, 84, and 98 DAP.*

The trendline (regression curve) shows a positive linear regression, implying that plant height increases consistently over time. This regression model quantifies growth rate and helps predict future height development under similar conditions. A steeper slope indicates a more responsive treatment group, indicating a higher efficiency of compost treatment in supporting early plant development.

The growing medium is one of the key factors that must be considered, as it significantly affects the growth and development of plants to achieve optimal results (Supriatna *et al*., 2022). Proper management during seedling propagation is critical to the growth and development of oil palm plants. The provision of appropriate growing media and essential nutrients supports optimal seedling development (Lubis *et al*., 2023). The increase in plant height at 70 DAP indicates that the application of oil palm frond compost and banana stem enriched with PGPR as a growing medium mixture for oil palm seedlings at dose P2 resulted in better plant height growth compared to other treatments. However, this difference was not significant compared to the P1 dose treatment. In further growth at 84 DAP, the best plant height increase was observed in the lower treatment, dose P1, at 17. 15 cm, but still not significantly different from the P2 dose treatment. At the final observation at 98 DAP, the P1 dose consistently showed a better trend in plant height increase compared to the P2 dose treatment and even compared to the control and P3.

The bacterial population density in the medium applied with PGPR dose P2 was higher compared to dose P1, resulting in higher bacterial activity in dose P2, which in turn led to the production of compounds beneficial to the growth of oil palm seedlings. This was evidenced by the best increase in plant height at the beginning of the observation (70 DAP) obtained from the P2 treatment. The activity of microorganisms from the high bacterial population in the P2 dose treatment is reduced in its influence on the height increase of oil palm seedlings. A high bacterial population requires a high availability of compost litter as a sufficient energy source for bacteria. Conversely, at the same media concentration with a lower bacterial population density (P1), bacterial activity is more stable due to the availability of energy from oil palm frond compost, thereby supporting better oil palm seedling growth, as observed during further observations at 84 DAP. Nguyen *et al*. (2021) stated that the source of nutrition for bacteria is litter; bacteria will experience 'starvation' when food sources are reduced, which causes fluctuations in the number of bacterial cells.

The diversity of microbial isolates, such as bacteria, in the production and expression of various secondary metabolites, is significantly influenced by physical and chemical factors in the environment, which serve as a source of nutrition for bacteria (Alami *et al*., 2024). Soil microorganisms play a complex role, ranging from mineralization, nitrogen fixation, nitrification and denitrification, phosphate solubilization, antibiosis, siderophore production, plant growth regulation, and induction of plant resistance (Pattnaik *et al*., 2021). Microorganisms decompose organic matter applied to the soil and use it as an energy source (Datta, 2024).

At 98 DAP, the highest increase in oil palm seedling height was still obtained from the P1 dose treatment. This indicates that the P1 dose has a more pronounced effect on subsequent seedling growth, particularly in terms of plant height. According to Grover *et al.* (2021), the administration of PGPR can increase root length, the number of roots, the number of leaves, and plant height. The results of the observations showed that although the highest oil palm seedling height was obtained from the P1 dose, this result was not significantly different from the P2 dose, as indicated by the analysis of variance. Meanwhile, the P3 dose was considered less effective in increasing seedling height because the organic material in the compost media did not meet the energy nutrient needs of bacteria.

Number of leaves

Figure 4 shows the average number of leaves increase of oil palm seedlings at 70,84, amd 98 days after palnting (DAP). This figure shows the development of leaf numbers in oil palm seedlings at the same three growth stages. Leaf number is an important indicator of photosynthetic capacity and overall plant vigor. The increasing trend in number of leaves indicates an optimal physiological response to the compost treatments. The linear regression pattern indicates that the increase remained consistent or tapered over time. The regression curve facilitates interpretation of treatment effects on leaf production rate. If the data aligns with a linear model, it indicates that leaf production has not yet saturated and the seedlings are in an active vegetative phase.

Based on the results of the experiments on the application of palm frond compost fertilizer and banana stems enriched with different doses of PGPR to oil palm seedlings, it was found that leaf formation in the experimental plants varied between treatment doses P1 and P2. However, the analysis of variance showed no significant effect. However, a trend was observed, where at 70 DAP, treatment P2 produced the highest average number of leaves, with 2.00 leaves, followed by treatment P1, with 1.90 leaves. Conversely, at 84 DAP, the highest average number of leaves was obtained from the P1 dose with 2.50 leaves, while the P2 dose yielded only 2.30 leaves.

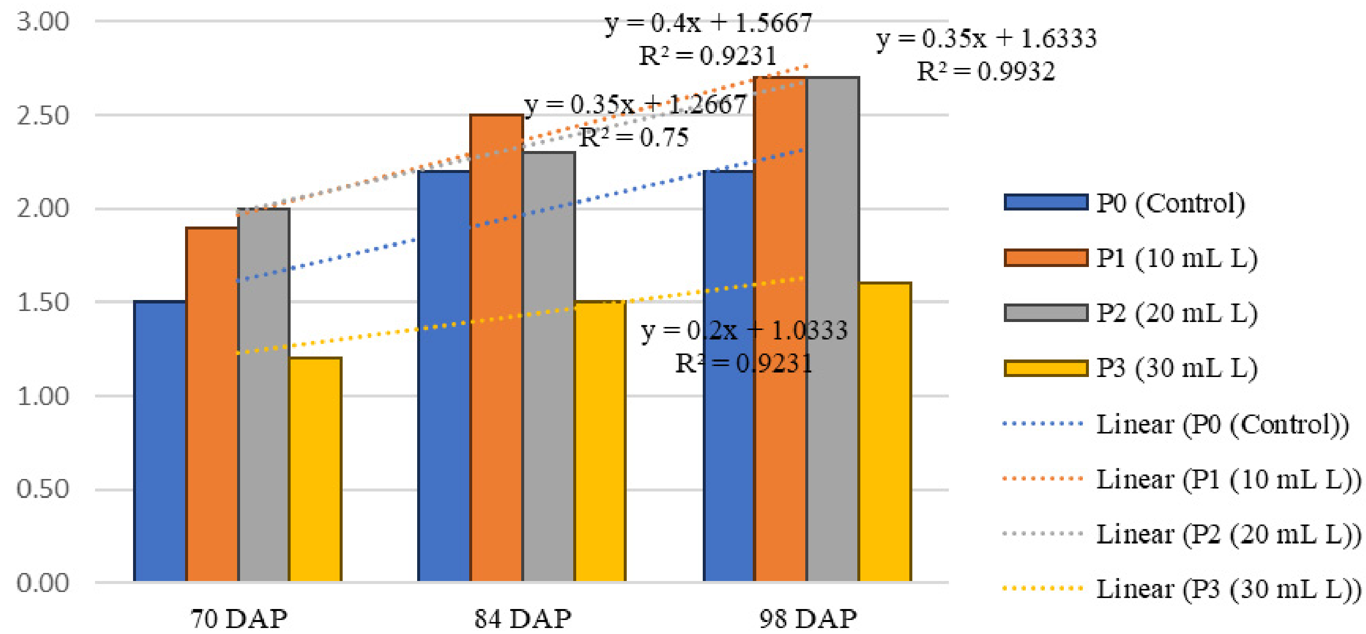

Figure 4: *Average number of leaves increase of oil palm seedlings at 70, 84, and 98 DAP.*

Further growth, at 98 HST, resulted in an average of 2.7 leaves obtained from two concentrations of PGPR application, namely doses P1 and P2. Along with the growth of oil palm seedlings, plants can produce exudates from their roots. According to More *et al.* (2019), during photosynthesis, plants produce compounds that are essential for growth and secondary metabolites in the form of exudates, which are released into the root zone. Exudates include low-molecular-weight compounds, such as sugars, amino acids, and aromatic compounds, that are released from cells into the intercellular space and surrounding soil.

Soil microbial populations form communities that establish associative relationships with plants, for example, through the use of non-symbiotic higher plant root exudates as an energy source by heterotrophic nitrogen (N)-fixing bacteria (Hu *et al.*, 2021). The presence of free-living nitrogen-fixing bacteria in the root zone is beneficial to plants, as it helps them meet their nitrogen needs. The dose range of P1 and P2 in oil palm frond and banana stem compost is the optimal concentration range to achieve the nitrogen balance needed for oil palm seedling growth. Plants need nutrients to grow and develop, which are utilized in the plant's metabolic processes. Each nutrient absorbed by plants has a unique function that no other element can replace. Nitrogen is a macronutrient that is an integral part of chlorophyll and plays a role in photosynthesis (Yousuf *et al.*, 2020). If plants have enough nitrogen, this can be indicated by the functioning of photosynthesis, greener leaves, and better vegetative growth. Furthermore, Mardegan *et al.* (2022) explained that low nitrogen levels in the soil can be increased through the application of fertilizers. Thus, increasing the dose of nitrogen fertilizer can increase the number of leaves.

Compost of oil palm fronds and banana stems enriched with PGPR at a dose of P2 was more effective in supporting the growth of oil palm seedlings, especially in terms of organic carbon content (18.31%) and C/N ratio (19%), as shown in Table 2. Li *et al.* (2021) explained that the optimal C/N ratio ensures an abundant energy supply for microorganisms, allowing them to reproduce rapidly. Compost products from oil palm fronds and banana stem enriched with *Trichoderma harzianum*, and PGPR have met the total macronutrient content standard of at least 2%, as shown by the P2 dose treatment of 7.14. Therefore, the dose of P2 in the compost of oil palm fronds and banana stems will stimulate the growth of oil palm seedlings at the next growth stage in the leading nursery.

The application of PGPR, a consortium of active bacteria that colonize plant roots, plays a crucial role in enhancing leaf number, crop yield, and soil fertility (Khan *et al.*, 2020). The positive effects of PGPR on plant growth through media application were also reported PGPR. Applications at 300 mL and 350 mL did not show significant differences in plant height and leaf number, but significant differences were observed in leaf width, root length, and fresh plant weight. An increase in leaf number is one of the plant growth parameters that can be directly observed (Putra & Ibnusina, 2023). This study provides information that the application of PGPR at the appropriate concentration (in this study, P1 and P2) can influence the increase in leaf number. However, as oil palm is a perennial plant with slow vegetative growth compared to annual plants, observing seedlings at 98 days after planting (DAP) is insufficient to describe the overall effect of PGPR fully. This study is expected to provide information on the initial growth of seedlings. Zhang *et al.* (2024) report that the effect of PGPR is quite beneficial in promoting plant growth, with PGPR-treated plants exhibiting better growth than non-PGPR-treated plants.

Table 4: *Average stem diameter (cm), plant fresh weight (g), and plant dry weight (g) of oil palm seedlings at 98 DAP*

PGPR	Stem diameter (cm)	Fresh plant weight (g)	Dry plant weight (g)
P0 (Control)	5.42[ab]	4.09[ab]	0.62[ab]
P1 (10 $ml.L^{-1}$)	5.75[a]	4.52[a]	0.67[ab]
P2 (20 $ml.L^{-1}$)	5.99[a]	4.52[a]	0.82[a]
P3 (30 $ml.L^{-1}$)	4.74[b]	3.57[b]	0.51[b]
$LSD_{0,05}$	0.74	0.73	0.20

Note: Mean values followed by different letters indicate significant differences between treatments in the LSD test at $p < 0.05$.

Stem diameter, Fresh plant weight, and dry plant weight

Table 4 presents the analysis of average stem diameter, fresh weight, and dry weight of plants at 98 days after planting (DAP), using compost enriched with *Trichoderma* and different doses of Plant Growth-Promoting Rhizobacteria (PGPR).

Table 4 shows that the best average stem diameter growth and the best dry weight of plants were shown

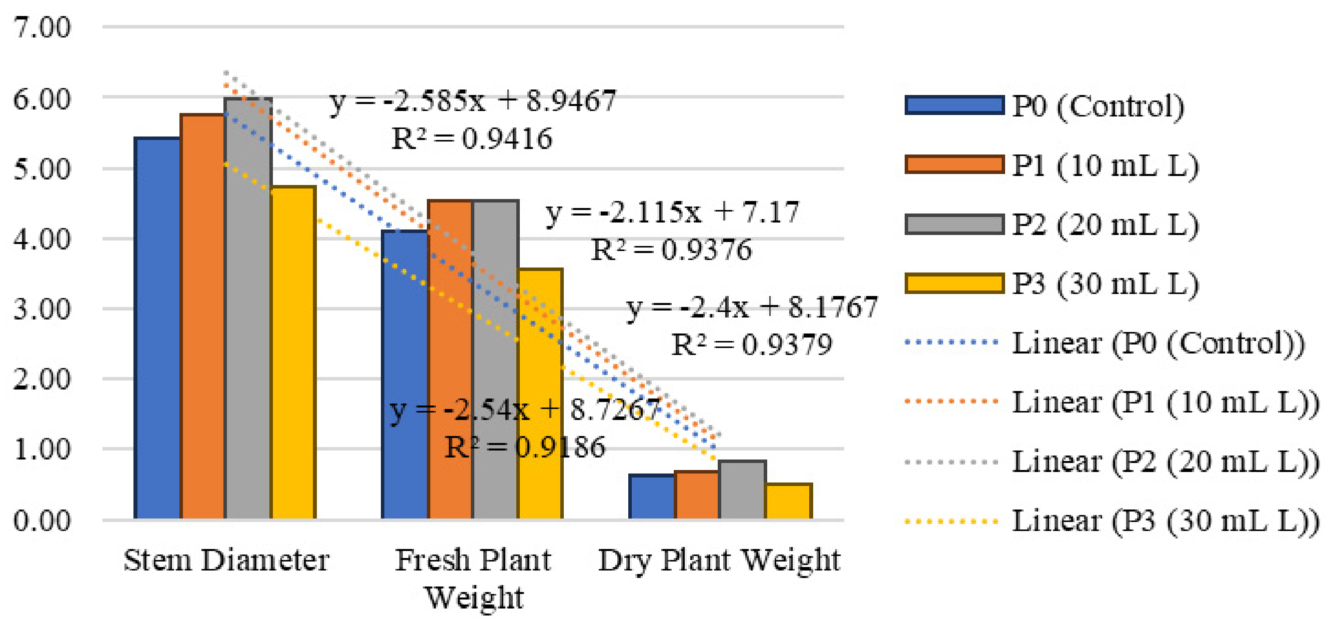

Figure 5: *Average stem diameter, fresh weight, and dry weight of oil palm seedlings at 98 DAP.*

by the treatment with a PGPR dose of 20 mL L^{-1} (P2), which was 5,99 cm and 0,82 g, which was not significantly different from the control treatment (P0) and a dose of 10 mL L^{-1} (P1), but significantly different from a dose of 30 mL L^{-1} (P3). As for the fresh weight parameter of plants, the best doses were shown by 10 mL L^{-1} (P1) and 20 mL L^{-1} (P2) with the same average fresh weight value of plants, which was 4,52 g, which was not significantly different from the control treatment (P0) and a dose of 10 mL L^{-1} (P1), but significantly different from a dose of 30 mL L^{-1} (P3).

Figure 5 illustrates the association between sctructural growth (stem diameter) and biomass accumulation (fresh and dry weight) of oil palm seedlings at 98 days after planting (DAP). In plant growth studies, these variables are physiologically interrelated-stem diameter generally reflects the plant's ability to transport water and assimilates, which directly contributes to biomass formation. The regression analysis (Figure 5) reveals a strong positive linear relationship between stem diameter and biomass parameters (fresh and dry weight) of oil palm seedlings at 98 DAP. Stem diameter accounts for a substantial proportion of the variation in fresh weight, as indicated by the high coefficient of determination (R^2), indicating that thicker stems are consistently associated with greater water and nutrient storage capacity, thus increasing total biomass accumulation. Similarly, dry weight shows a significant positive correlation with stem diameter, reflecting the structural and physiological resilience of seedlings with larger diameters. The regression slope indicates that increases in stem diameter result in proportional gains in fresh and dry biomass.

The stem is an area of accumulation of plant growth, especially in younger plants. The presence of more nutrients can encourage vegetative plant growth, including the formation of chlorophyll, which in turn provides a measure of increasing stem diameter (Widiyanto *et al*., 2024). Sufficient phosphorus and potassium nutrient content at a PGPR treatment dose of 20 mL L^{-1} (P2) affects stem diameter growth. This is in line with Hapsoh *et al*. (2020), which states that phosphorus and potassium elements play a crucial role in enlarging the diameter of plant stems, particularly in their function as connecting tissue between roots and leaves during the process of nutrient absorption.

The administration of PGPR doses that cause an increase in both fresh and dry weight of plants indicates that PGPR plays a role in enhancing the growth of oil palm seedlings. Astuti *et al*. (2023) explained that dry weight indicates an increase in oil palm seedling biomass. Biomass is formed through photosynthesis and respiration, which are sources of carbon frameworks that comprise organic compounds. The increase in dry weight indicates an increase in effective photosynthesis and respiration capacity, resulting in an increase in the organic material that makes up the plant body. Several research studies also report an increase in both fresh and dry weight of plants with the increase in PGPR treatment dose (Astuti *et al*., 2023; Abidin *et al*., 2025; Ambata *et al*., 2025).

Conclusions and Recommendations

The highest compost temperature resulting from the PGPR treatment was achieved with 20 mL L^{-1}, while the optimum compost pH was obtained with 10 mL L^{-1}. The 20 mL L^{-1} treatment produced the best results, particularly in terms of C-organic content (18.31%) and C/N ratio (19%). The highest nitrogen and phosphorus nutrient contents were observed in the 20 mL L^{-1} PGPR concentration treatment at 0.95% and 3.41%, respectively. The highest potassium content was shown by the 30 mL L^{-1} PGPR concentration treatment at 2.86%. The best total macronutrient content of the oil palm frond and banana stem compost was obtained from the 20 mL L^{-1} PGPR treatment (7.14). Palm frond and banana stem compost fertilizer enriched with 20 mL L^{-1} PGPR gave the best results for plant height growth at 70 DAP (12.64 cm), with a concentration of 10 mL L^{-1} at 84 and 98 DAP (17.15 and 29.46 cm). The oil palm seedlings that had the most leaves, the largest stem diameter, and the best fresh and dry weight at the end of the experiment were those treated with oil palm frond compost. Banana stems with a PGPR concentration of 20 mL L^{-1}, which each amounted to 2.7 leaves, 5.99 cm, 4.52 g, and 0.82 g.

Acknowledgements

Thanks are extended to the Ministry of Higher Education, Science and Technology of the Republic of Indonesia and the Director of the Pangkajene Islands State Agricultural Polytechnic for facilitating and publishing this research.

Novelty Statement

A "compost" product from palm frond waste and banana stems fermented with the addition of Trichoderma harzianum fungus and a consortium of local Sulawesi Bacillus bacteria as a plant growth promoter.

Author's Contribution

Kafrawi Kafrawi: Formal analysis, investigation, data curation, original draft, visualisation.
Zahraeni Kumalawati: Conceptualisation, methodology, validation, formal analysis, source, data curation, visualisation, funding acquisition.
Sri Muliani and Muh. Dzulkifly Ashan: Conceptualisation, validation.
Darmawan Darmawan: Conceptualisation, methodology.

Generative AI or AI assisted technology statement
The authors declare that no genrative AI was used in the creation of this manuscript.

Conflict of interest
The authors have no conflict of interest.

References

Abdurahman. M.H., A.Z. Abdullah and N.F. Shoparwe. 2021. A comprehensive review on sonocatalytic, photocatalytic, and sonophotocatalytic processes for the degradation of antibiotics in water: Synergistic mechanism and degradation pathway. Chem. Eng. J., 413: 127412. https://doi.org/10.1016/j.cej.2020.127412

Abdusamatov, S., J. Alimov, V. Shurigin and K. Davranov. 2020. Trichoderma harzianum 857 is an Effective Destructor of Cellulose-Containing Raw Materials. Environ Sci.: Ind J. Res., 16 (3): 113. https://doi.org/10.37532/tses.2020.16(3).113

Abidin, A.Z., U.K. Rusmarini and E.N. Kristalisasi. 2025. Pengaruh pemberian biochar dan volume PGPR terhadap pertumbuhan bibit kelapa sawit di pre nursery. Agroforetech., 3 (1): 220-224.ISSN 2986-6718.

Ajeng, A.A., R. Abdullah, M.A. Malek, K.W. Chew, Y.C. Ho, T.C. Ling, B.F. Lau and P.L. Show. 2020. The effects of biofertilizers on growth, soil fertility, and nutrient uptake of oil palm (Elaeis guineensis) under greenhouse conditions. Proce., 8(12): 1–16. https://doi.org/10.3390/pr8121681

Alami, M.M., S. Guo, Z. Mei, G. Yang and X. Wang. 2024. Environmental Factors Affecting Secondary Metabolism in Medicinal Plants: Exploring Accelerating Factors. Med. Plant Biol., 3(1): 0–0. https://doi.org/10.48130/mpb-0024-0016

Allaily, A., M.A. Yaman, Z.P. Aprilia, N.S. Asminaya and Z. Zulfan. 2022. Quality of Organic

Fertilizer Due to Material Combination with Bio-activator. ITAPS., 404–410. https://doi.org/10.2991/absr.k.220309.079

Ambata, H.T.A., M.N.A. Eyong, M.A.B. Bedine, Y.O.Y. Youassi, M.B. Jiogue, F.J.N. Dikongue, S.N. Tchameni and M.L. Sameza. 2025. Evaluating Trichoderma viride for enhancing oil palm growth and biochemical defense against fusarium wilt caused by Fusarium oxysporum f. sp. elaeidis. Folia Microbiol., 27. https://doi.org/10.1007/s12223-025-01273-5.

Astuti, Y.T.M., M.C. Simanjuntak, D.P. Putra, I. Iqrar and I. Ekawati. 2023. The application of plant growth promoting rhizobacteria and organic matters from black soldier fly larva culture, Calliandra, cocopeat in the pre-nursery oil palm seedling. E3S Web of Confer., 432 (00038): 1-8. https://doi.org/10.1051/e3sconf/202343200038.

Azis, F.A., M. Choo, H. Suhaimi and P.E. Abas. 2023. The Effect of Initial Carbon to Nitrogen Ratio on Kitchen Waste Composting Maturity. Sustain. (Switzerland)., 15(7): 1–18. https://doi.org/10.3390/su15076191

Babu, B.K., R.K. Mathur, K. Suresh, G. Ravichandran, B. Susanthi, G.B. Patil, N. Ruthweek and M. Mahesh. 2025. Efficient regeneration protocol for producing true-to-type oil palm (Elaeis guineensis (Jacq.) through somatic embryogenesis from the immature male inflorescence. Heliyon., 11(1): e41479. https://doi.org/10.1016/j.heliyon.2024.e41479

Chi, N.T.Y., N.L.K. Minh and Q.V.C. Thi. 2025. Isolation and characterization of plant growth-promoting rhizobacteria from wild rice (Oryza rufipogon) in the Mekong Delta, Vietnam. Biodiversit., 26 (3): 1221-1228. https://doi.org/10.13057/biodiv/d260321.

Datta, R. 2024. Enzymatic degradation of cellulose in soil: A review. Heliyon., 10(1): e24022. https://doi.org/10.1016/j.heliyon.2024.e24022

Directorate General of Plantation. 2023. Palm Oil. (https://ditjenbun.pertanian.go.id/).

Ginting, E.N., S. Rahutomo, R. Farrasati and I. Pradiko. 2021. Distribution of macronutrients (N, P, K, Mg) from single-nutrient and compound fertilizers application in oil palm seedlings (*Elaeis guineensis* Jacq.). Agric. Sci., 6(1): 10. https://doi.org/10.22146/ ipas.60205

Grover, M., S. Bodhankar, A. Sharma, P. Sharma, J. Singh and L. Nain. 2021. PGPR Mediated Alterations in Root Traits: Way Toward Sustainable Crop Production. Front. Sustain. Food Syst., 4: 1–28. https://doi.org/10.3389/fsufs.2020.618230

Gusmawartati, A.A.R. Effendi, E. Ariani and I.R. Dini. 2025. Optimizing oil palm seedling growth (Elaeis guineensis Jacq.) in the leading nursery using NPK fertilizer and Mycorrhizal biofertilizer. J Trop Plant Agron., 7 (1): 82–90. https://doi.org/10.36378/ juatika.v7i1.3904.

Hamid, N.A.A., N.H. Mustaffer, M. Maulidiani, A. Mediani, I.S. Ismail, C.L. Tham, K. Shadid and F. Abas. 2020. Quality evaluation of the physical properties, phytochemicals, biological activities, and proximate analysis of nine Saudi date palm fruit varieties. J. Saudi Soc. Agric. Sci., 19(2): 151–160. https://doi.org/10.1016/j.jssas.2018.08.004

Hapsoh, I.R. Dini, Wawan and A.H. Sianipar. 2020. The growth of oil palm seedlings using a combination medium of organic oil palm empty fruit bunch and NPK fertilizer at the main nursery. J. Trop. Soils., 25 (2): 61–69. https://doi.org/10.5400/jts.2020.v25i2.61-69.

Hau, L.J., R. Shamsuddin, A.K.A. May, A. Saenong, A.M. Lazim, M. Narasimha and A. Low. 2020. Mixed Composting of Palm Oil Empty Fruit Bunch (EFB) and Palm Oil Mill Effluent (POME) with Various Organics: An Analysis on Final Macronutrient Content and Physical Properties. Waste Biomass Valoriza., 11(10): 5539–5548. https://doi.org/10.1007/s12649-020-00993-8

Ho, T.T.K., V.T. Tra, T.H. Le, N.K.Q. Nguyen, C.S. Tran, P.T. Nguyen, T.D.H. Vo, V.N. Thai and X.T. Bui. 2022. Compost to improve sustainable soil cultivation and crop productivity. Case Stud. Chem. Environ. Eng., 6: 100211. https://doi.org/10.1016/ j.cscee.2022.100211

Hu, H.Y., H. Li, M.M. Hao, Y.N. Ren, M.K. Zhang, R.Y. Liu, Y. Zhang, G. Li, J.S. Chen, T.Y. Ning and Y. Kuzyakov. 2021. Nitrogen fixation and crop productivity enhancements co-driven by intercrop root exudates and key rhizosphere bacteria. J. Appl. Ecol., 58(10): 2243–2255. https://doi.org/10.1111/1365-2664.13964

Kafrawi, K., Z. Kumalawati and N. Nildayanti. 2017. Formulation of red onion Plant Growth

Promoting Rhizobacteria (PGPR) as a stimulant for the growth of red onion (Allium ascalonicum). (Patent No. S15201707227). Pangkep State Polytechnic Agric. https://pdkii ndonesia.dgip.go.id /detail/ e3b0c44298fc1c149afbf4c89 96fb92427ae4 1e464 9b934ca49599 1b7852b855.

Khan, N., A.M.D. Bano and A. Babar. 2020. Impacts of plant growth promoters and plant growth regulators on rainfed agriculture. In PLoS ONE., 15(4). https://doi.org/10.1371/journal.pone.0231426

Kusmiati, R., Y. Syaputri, Abun and R. Safitri. 2024. Pretreatment and fermentation of lignocellulose from oil palm fronds as a potential source of fiber for ruminant feed: a review. J. Sustain. Agric. Environ., 3(3): 1–18. https://doi.org/10.1002/sae2.70003

Li, J., C. Sang, J. Yang, L. Qu, Z. Xia and H. Sun. 2021. Stoichiometric imbalance and microbial community regulate microbial elements use efficiencies under nitrogen addition. Soil Biol. Biochemi., 156: 108207. https://doi.org/10.1016/j.soilbio.2021.108207

Lubis, E.J., A. Rauf and S. Sarifuddin. 2023. Effectiveness of Fertilization Techniques on Growth Two Varieties of Palm Oil Seeds (Elaeis guineensis Jacq.) in Main Nursery. J. Soc. Res., 2(8): 2759–2772. https://doi.org/10.55324/josr.v2i8.1333

Mardegan, S.F., A.F. Castro, S.S. Noirtin, F. Chaves, R. Sandro, M.S. Avelar, F. Alexandre, O. Teixeira, F. Chaves, R. Sandro, M.S. Avelar and F. Alexandre. 2022. Soil Science and Plant Nutrition Organic farming enhances soil carbon and nitrogen dynamics in oil palm crops from Southeast Amazon. Soil Sci. Plant Nutr., 68(1): 104–113. https://doi.org/10.1080/00380768.2022.2031285

Mawad, A.M.M., A. El-Latif Hesham, N.M.H. Yousef, A.A.M. Shoreit, N. Gathergood and V.K. Gupta. 2020. Role of Bacterial-Fungal Consortium for Enhancement in the Degradation of Industrial Dyes. Curr. Genom., 21(4): 283–294. https://doi.org/10.2174/1389202921999200505082901

Meng, L., W. Li, S. Zhang, X. Zhang, Y. Zhao and L. Chen. 2021. Improving sewage sludge compost process and quality by carbon sources addition. Scient. Repor., 11(1): 1–8. https://doi.org/10.1038/s41598-020-79443-3

More, S., S. Shinde and M. Kasture. 2019. Root exudates a key factor for soil and plant: An overview. J. Pharm. Innov., 8(6): 449–459.

Nandiyanto, A.B.D., N.N. Azizah and S. Rahmadianti. 2021. Isotherm study of banana stem waste adsorbents to reduce the concentration of textile dying waste. J. Eng. Res., 9: 1–15. https://doi.org/10.36909/jer.ASSEEE.16063

Nemet, F., K. Perić and Z. Lončarić. 2021. Microbiological activities in the composting process : A review. Columella : J. Agric. Environ. Sci., 8(2): 41–53. https://doi.org/10.18380/szie.colum.2021.8.2.41

Nguyen, J., J. Lara-Gutiérrez and R. Stocker. 2021. Environmental fluctuations and their effects on microbial communities, populations, and individuals. FEMS Microbiol. Rev., 45(4): 1–16. https://doi.org/10.1093/femsre/fuaa068

Pattnaik, S., B. Mohapatra and A. Gupta. 2021. Plant Growth-Promoting Microbe Mediated Uptake of Essential Nutrients (Fe, P, K) for Crop Stress Management: Microbe–Soil–Plant Continuum. Front. Agron., 3: 1–20. https://doi.org/10.3389/fagro.2021.689972

Putra, Y.W. and F. Ibnusina. 2023. Application of Plant Growth Promoting Rhizobacteria (PGPR) Dosage on Growth and Production of Lettuce (*Lactuca sativa L* .). 25(1): 9–12.

Sadeli, A., A. Wulandari, L. Sinuraya, E. Mirwandhono and L. Hakim. 2022. The comparative of activator effect and fermentation time on nutrient quality, physical quality (temperature, pH) in compost. Inter. Conf. Agric. Environ. Food Sec., 977(1): 1–7. https://doi.org/10.1088/1755-1315/977/1/012130

Salangsang, M.C.D., M. Sekine, S. Akizuki, H.D. Sakai, N. Kurosawa and T. Toda. 2022. Effect of carbon to nitrogen ratio of food waste and short resting period on microbial accumulation during anaerobic digestion. Biomass Bioener., 162: 106481. https://doi.org/10.1016/j.biombioe.2022.106481

Saypariya, C.D., D. Singh, A.K. Dikshit and M.B. Dangi. 2024. Composting of organic fraction of municipal solid waste in a three-stage biodegradable composter. Heliyon., 10(17): e37444. https://doi.org/10.1016/j.heliyon.2024.e37444

Setyawan, H., S.M. Rohmiyati and J.H. Purba. 2020. Application of Cow Manure, Urea, and

NPK Fertilizer Combination on the Growth of Palm Oil (Elaeis Guineensis Jacq) in Pre-Nursery. Agric. J., 3(1): 74–83. https://doi.org/10.37637/ab.v3i1.419

Shafreen, M., K. Vishwakarma, N. Shrivastava and N. Kumar. 2021. Physiology and Distribution of Nitrogen in Soils. In Soil Nitrogen Ecol., 5: 3–31. https://doi.org/10.1007/978-3-030-71206-8_1

Supriatna, J., M.R. Setiawati, R. Sudirja, C. Suherman and X. Bonneau. 2022. Composting for a More Sustainable Palm Oil Waste Management: A Systematic Literature Review. Scient. World J., 2022(1): 1–20. https://doi.org/10.1155/2022/5073059

Sutton, M.A., N. van Dijk, P.E. Levy, M.R. Jones, I.D. Leith, L.J. Sheppard, S. Leeson, Y. Sim Tang, A. Stephens, C.F. Braban, U. Dragosits, C.M. Howard, M. Vieno, D. Fowler, P. Corbett, M.I. Naikoo, S. Munzi, C.J. Ellis, S. Chatterjee and P.A. Wolseley. 2020. Alkaline air: changing perspectives on nitrogen and air pollution in an ammonia-rich world. Philosophical Transactions of the Royal Society A: Mathematical, Physical Eng. Sci., 378(2183): 20190315. https://doi.org/10.1098/rsta.2019.0315

Saputra, R.T.Y., E. HD and M. Yanita. 2024. Analysis of Oil Palm Seedling Farming Bussiness (Case Study of Tridian Nursery and Sumber Makmur). AJARCDE., 8(2). https://doi.org/10.29165/ajarcde.v8i2.410

Syaiful, S.A., K. Mantja, F. Faisal, I. Irmayanti, P.I. Khaerani and M.F. Anshori. 2025. Synergistic effects of hormonal priming and Trichoderma asperellum on the morphological and physiological traits of true shallot seeds. Sar. J. Agric., 41(2): 796-806.

Tripathi, A., V.K. Pandey, D. Jain, G. Singh, N.S. Brar, A. Taufeeq, I. Pandey, K.K. Dash, A.V. Samrot and S. Rustagi. 2024. An updated review on significance of PGPR-induced plant signalling and stress management in advancing sustainable agriculture. J. Agric. Food Res., 16(101169). https://doi.org/10.1016/j.jafr.2024.101169.

Utamy, R.F., A. Ako, S. Baba, S.G. Zulkharnaim, L. Alhamd, A.U.N. Indrawirawan and P.I. Khaerani. 2025. Effects of plant growth-promoting rhizobacteria and seedling density on morphologic characteristics and nutrient content of corn fodder. Sarhad J. Agric., 41(1): 209-219.

Vocciante, M., M. Grifoni, D. Fusini, G. Petruzzelli and E. Franchi. 2022. The Role of Plant Growth-Promoting Rhizobacteria (PGPR) in Mitigating Plant's Environmental Stresses. Appl. Sci., 12(3). https://doi.org/10.3390/app12031231

Widiyanto, S., I. Wardati, A. Salim and A. Madjid. 2024. Pengaruh PGPR akar kelapa sawit dan Trichoderma sp. terhadap pertumbuhan bibit kelapa sawit (Elaeis guineensis Jacq.) varietas DxP Simalungun. J. Ilmu Pertan., 1 (1): 21-28. ISSN 3046-7535.

Yousuf, A., T. Sheikh, S. Bashir and A. Ahmad. 2020. Low nitrogen stress regulates chlorophyll fluorescence in coordination with photosynthesis and Rubisco efficiency of rice. Physiol. Molecul. Biol. Plant. 26(1): 83–94. https://doi.org/10.1007/s12298-019-00721-0

Zhang, T., Q. Jian, X. Yao, L. Guan, L. Li and F. Liu. 2024. Heliyon Plant growth-promoting rhizobacteria (PGPR) improve the growth and quality of several crops. Heliyon., 10(10): e31553. https://doi.org/10.1016/j.heliyon.2024.e31553.