

Application of Organic Fertilizer-Enriched Microbes and Biochar in Various Land Management Systems on Total N, Available P, and Available K in Pineapple Plantations

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Received 30 January 2026 Revised 20 May 2026; Accepted 21 May 2026

ABSTRACT

The decline in pineapple production in Lampung is closely related to soil degradation. This study examined the soil management system and the effects of soil management and organic fertilizer application, influenced by microbes and biochar, on the availability of nitrogen, phosphorus, and potassium in pineapple plantation soils. The study was conducted at PT Great Giant Pineapple (GGP), and soil analysis was conducted at PT GGP's R&D center. The study used a split plot design with 8 treatments and 3 replications. The main plots were soil management systems: T₁ (plow the land to a depth of 30 cm + chop the pineapple litter 1 time) and T₂ (plow the land to a depth of 40 cm + chop the pineapple litter 2 times). The subplots were organic fertilizer combined with microbes and biochar: P₁ (GGP compost 50 tons ha⁻¹), P₂ (GGP compost 40 tons ha⁻¹ + biochar 10 tons ha⁻¹), P₃ (GGP premium compost 50 tons ha⁻¹), and P₄ (GGP premium compost 50 tons ha⁻¹ + LOB microbes 40 L ha⁻¹). The results showed that T1P1 increased total soil N in plants from 6 MAP to 9 MAP by 0.03%, but this was not significant at 3 and 6 MAP. Treatment T₁P₁ increased soil available P from 3 MAP to 6 MAP by 23.77 ppm. Treatment T₁P₁ and T₂P₃ increased soil available K from 3 MAP to 6 MAP by 19.77 ppm and 11.06 ppm, respectively. T1P1 did not interact with T2P3 in increasing soil nutrients. However, T₁P₁ interacted with total N, available P, and available K. The correlation test showed a positive correlation between pH and available K in the 3rd MAP observation, between organic C and total N in the 6th MAP observation, and between organic C and available P in the 9th MAP observation. Implementing T₁P₁ addition of compost-based biochar (50 GGP ton ha⁻¹) with 30 cm tillage and 1× shredding of plant litter increased soil N, P, and K.

Keywords: Total N, available P, and available K in Soil

INTRODUCTION

Indonesia is one of the world's pineapple-producing countries. Lampung Province is Indonesia's largest pineapple producer, with annual production reaching 722,847 tons ha⁻¹ (BPS Data, 2023). One company cultivating pineapple in Lampung is PT Great Giant Pineapple (PT GGP). According to BPS data, pineapple production in Lampung decreased from 861,706 tons ha⁻¹ (2022) to 722,847 tons ha⁻¹ (2023). The decline in pineapple production is caused by land degradation from

chemical fertilizer use and intensive soil cultivation (Maula et al., 2024).

Currently, PT GGP carries out intensive land cultivation and application of chemical fertilizers throughout the year, which affects soil fertility. PT GGP's pineapple plantation has practiced intensive soil cultivation since 1979. Bhakti et al. (2017) stated that a negative impact of intensive soil cultivation is that the soil becomes prone to erosion. Erosion causes nutrient loss, increases soil compaction and penetration resistance, and decreases soil organic matter (Arsyad, 2010). Declining soil organic matter reduces microbial activity, including fungi and actinomycetes, which help decompose organic matter. According to Irfan (2014), microbes play an important role in decomposing organic matter,

providing nutrients, enhancing plant growth, and acting as enemies to plant pathogens. PT GGP addresses these problems through rehabilitation. Another rehabilitation method PT GGP uses is proper soil cultivation, including deep plowing and chopping pineapple plant litter. Deep tillage and finer shredding of pineapple litter are expected to increase nutrient availability and reduce soil compaction, thus promoting proper pineapple root development.

Efforts to increase soil microbial activity include creating non-compacted soil conditions and good soil aggregation, resulting in optimal soil aeration. Microbial activity can enhance the decomposition of organic matter in the soil, increasing nutrient availability. Increased soil microbial activity can be indicated by high levels of CO₂ in the soil or high plant respiration. Samsi et al. (2025) explained that soil respiration indicates soil organic carbon as an energy source for microorganisms. Deep plowing (>40 cm) can create a favorable environment for microbes. Deep plowing (>40 cm) can reduce the size of pineapple plant residues, thereby increasing the rate of decomposition. Deep plowing (40 cm) is thought to be better than 30 cm because it can penetrate hard layers, create better soil structure, increase aeration, and increase permeability. This study compared differences in soil tillage depth and the incorporation of pineapple plant residues by varying the amount of pineapple residues in the field. Damayanti et al. (2010) found that intensive tillage and nitrogen fertilization (100 kg N ha⁻¹) had higher respiration than no tillage.

In addition to deep tillage (40 cm), chopping pineapple litter more finely is another way to increase soil fertility. The high lignin content in pineapple litter limits nutrient availability in the soil. Therefore, adding microorganisms is expected to accelerate pineapple litter decomposition. Pineapple plants contain lignin, and its decomposition is very slow because of its complex chemical structure. Because lignin is recalcitrant (difficult to break down), microbes are added as Liquid Organic Biofertilizer (LOB) to speed up decomposition. LOB contains various microbes, including non-symbiotic nitrogen-fixing bacteria (*Azotobacter* sp. and *Azospirillum* sp.), symbiotic nitrogen-fixing bacteria (*Rhizobium* sp.), and Phosphate-Solubilizing bacteria (*Bacillus* sp. and *Pseudomonas* sp.) (Suwahyono, 2011). Balasubramanian et al. (2017) reported that *Pseudomonas* sp. and *Bacillus* sp. are phosphorus- and potassium-dissolving bacteria in the soil. The microbes applied can dissolve phosphate, including *Trichoderma*, *Azospirillum* sp., *Azotobacter* sp., *Bacillus* sp., and *Pseudomonas* sp. (Kumar et al., 2014). Nitrogen-fixing microbes include

Azotobacter and *Trichoderma*, which help convert nitrogen into ammonium or nitrate (Sapalina et al., 2022). In addition, LOB contains microbes, such as *Trichoderma*, that help break down pineapple litter (Subhan et al., 2025). It also accelerates decomposition and acts as a bioactivator, which is expected to develop and positively impact pineapple plants.

In addition to adding beneficial microbes, efforts made to improve fertilizer quality and provide nutrients include adding biochar. Biochar is a carbon-rich product obtained by burning biomass with little or no air at temperatures <700°C under limited-oxygen conditions, resulting in organic matter with a carbon concentration of 70-80% (Tambunan et al., 2014). Biochar can provide a good habitat for soil microbes to decompose organic matter, thereby increasing nutrient availability (Mautuka et al., 2022). Biochar is a useful material for increasing food security and plant diversity in areas with nutrient-poor soil, low organic matter, and water shortages. Sohi et al. (2009) found that biochar can provide a preferred habitat for microbes. Biochar can maintain the balance of carbon (C) and nitrogen (N) in the soil for a long period of time. Biochar is a useful material for increasing food security and plant diversity in areas with nutrient-poor soil, low organic matter, and water shortages. Research by Sujana (2014) found that a combination formulation of 9.28 tons of rice husk biochar per ha with a dose of chicken manure of 8.54 tons ha⁻¹ can improve soil properties and corn plant growth, such as reducing soil bulk density, increasing soil water content, total soil porosity, CEC, available K, available P, and soil organic carbon. Therefore, adding biochar and LOB, along with deep plowing (40 cm), is expected to increase macronutrients in pineapple plantation soils.

RESULTS AND DISCUSSION

Time and Place

This research was conducted from September 2023 to April 2025 at PT Great Giant Pineapple (GGP), location 32C, with coordinates 4°48'38.1"S and 105°17'04.6" E. Soil analysis was conducted at PT GGP's Research and Development Laboratory in Terbanggi Besar, Central Lampung.

Research methods

The research used a split-plot design with main-plot treatments: soil plowing to a depth of 30 cm + incorporating chopped pineapple debris once and plowing to 40 cm deep + chopping pineapple litter twice; and soil plowing to a depth of 40 cm +

incorporating chopped pineapple mulch twice. The 4 subplots were: GGP compost 50 tons ha⁻¹; GGP compost 50 tons ha⁻¹ + biochar 10 tons ha⁻¹; Premium compost GGP 50 tons ha⁻¹; and Premium compost GGP 50 tons ha⁻¹ + Liquid Organic Biofertilizer 40 L ha⁻¹. This study used a split-plot design with 8 treatments and 3 replications, resulting in 24 experimental plots (Table 1). The main plot was the soil cultivation system, while the subplots were organic fertilizer enriched with microbes and biochar.

Research Implementation

Land preparation, soil cultivation, composting application, and planting of pineapple seedlings were carried out in September–November 2023. Sampling for observation and soil analysis was carried out from January 2024 to April 2025.

Sampling

Sampling was conducted before planting, 3 Months After Planting (MAP), 6 MAP, and 9 MAP, from January to October 2024. Sampling was carried out using a shovel to a depth of 0-20 cm. In each plot, samples were taken from five points (four corners and one center) and then composited.

Observation Variables

This study observed primary and secondary variables. Primary variables included total nitrogen (N-total), available phosphorus (P-available), and soil potassium (K-available). Total N was analyzed using the *Kjeldahl method*, K-available by the *Bray and Kurt 1 method*, and available P by *atomic absorption spectroscopy* (AAS) at four observation times: baseline, 3 MAP, 6 MAP, and 9 MAP. Supporting variables include organic C and soil pH.

Organic Carbon was analyzed using the method of *Wolkley and Black*, and pH was measured with a pH meter.

Data analysis

Statistical analysis was performed using Analysis of Variance (ANOVA) at a significance level of 5%, followed by the *Duncan Multiple Range Test* (DMRT) to identify the most significant treatment.

RESULTS AND DISCUSSION

Initial Soil Conditions before Treatment Application

The total nitrogen (N-total) content in the initial observations (Table 2) was insufficient to meet pineapple plants' N requirements. This was due to low soil organic carbon content and pineapple plants' high N requirements. Acidic soil conditions, such as low pH, inhibit nitrification, which can lead to NH₄⁺ accumulation in the soil and prevent a significant decrease in total N content. Li et al. (2018) stated that in highly acidic soils, nitrification activity decreases significantly due to low sumaprate (NH₃) availability and high H⁺ concentrations. Furthermore, the initial soil phosphorus availability was very high.

However, the high phosphorus content in the soil was still insufficient to meet the nutrient requirements of pineapple plants. The high available P content in these initial observations is suspected to be due to residual phosphate fertilizer applications in the form of diammonium phosphate during the previous land management period, which is difficult to dissolve, allowing its availability to be seen. Low organic carbon content can limit soil adsorption capacity, so most phosphorus remains in dissolved

Table 1. Experimental treatment of the application of land management with Biochar and Microbe-Enriched Organic Fertilizer for N, P, and K nutrients in Ultisol soil in Central Lampung.

Treatment	Description
Main Plot	
T ₁	Soil plow to a depth of 30 cm + incorporate chopped pineapple debris once
T ₂	Soil plow to a depth of 40 cm + incorporate chopped pineapple mulch twice
Sub Plot	
P ₁	GGP compost 50 tons ha ⁻¹
P ₂	GGP compost 50 tons ha ⁻¹ + biochar 10 tons ha ⁻¹
P ₃	Premium compost GGP 50 tons ha ⁻¹
P ₄	Premium compost GGP 50 tons ha ⁻¹ + Liquid Organic Biofertilizer 40 L ha ⁻¹

Table 2. The Interaction Effect Between Land Management (T) and Biochar and Microbe-Enriched Organic Fertilizer (F) on Soil Total Nitrogen (%) at 9 MAP.

Land Management (T)	Organic Fertilizer (F)	Organic Fertilizer (F)	Organic Fertilizer (F)	Organic Fertilizer (F)	DMRT value 5%
Land Management (T)	F ₁	F ₂	F ₃	F ₄	DMRT value 5%
T ₁	0.17 b	0.08 a	0.06 a	0.06 a	3.07
	B	A	A	A	3.07
T ₂	0.06 a	0.06 a	0.06 a	0.07 a	3.07
	A	A	A	A	3.07
DMRT value 5%	5.936.216.37	5.936.216.37	5.936.216.37	5.936.216.37	

Note: Values followed by the same letter are not significantly different at the DMRT test 5% level; lowercase letters are read horizontally, capital letters are read vertically.

form and is measured as available P. High P availability can result from low P absorption due to limited plant biomass before the research was conducted (Subowo, 2013).

Initial observations (Table 2) showed very high K availability, but it was not enough to meet pineapple plants' needs. The high K availability in these initial observations is suspected to be due to residual potassium fertilizer (K_2SO_4), which has a potassium content of up to 50%, from previous management and low plant uptake; as a result, available K in the soil remains in the high category. Available K is very high, even though the land has a very acidic pH and low organic C. Research by Jena et al. (2025) shows that organic acids such as oxalate and citric acid can dissolve K from primary minerals such as mica and feldspar.

Initial observations (Table 3) showed low organic carbon content, but it was sufficient to meet pineapple plants' organic carbon requirements. This

low organic matter content likely results from high decomposition rates in tropical climates, minimal plant litter input, and intensive land management (Subowo, 2013). Low organic carbon content indicates low cation exchange capacity (CEC), resulting in weak nutrient-binding capacity.

Total N and available K in this initial observation were within the high range but were not sufficient to meet pineapple plants' needs. Applying urea and K_2SO_4 in the field using foliar spraying will support plant growth and production. Foliar application allows nutrients to be absorbed directly by the leaves, making them more readily available to the plant and overcoming root absorption limitations caused by soil conditions or high nutrient demands during the plant's generative phase (Arsic et al., 2022). Foliar application of K_2SO_4 effectively meets increased potassium needs during the flowering and fruit-forming phases, even when soil K levels are already high (Teixeira et al., 2011). Foliar urea is rapidly

Table 3. Results of soil chemical analysis before treatment application.

Variable	Result	Result	Pineapple Plant Requirements**
Soil total Nitrogen (%)	0.25	Medium	1.2
Soil-available phosphorus (ppm)	26.81	Very High	20
Soil-available potassium (ppm)	122.88	Very High	150
Organic-C (%)	1.29	Low	1.2
pH H ₂ O	4.31	Very Acidic	4.5–5.6

Note: *Soil and Fertilizer Instrument Standards Testing Center, 2023; **Bartholomew et al., 2003.

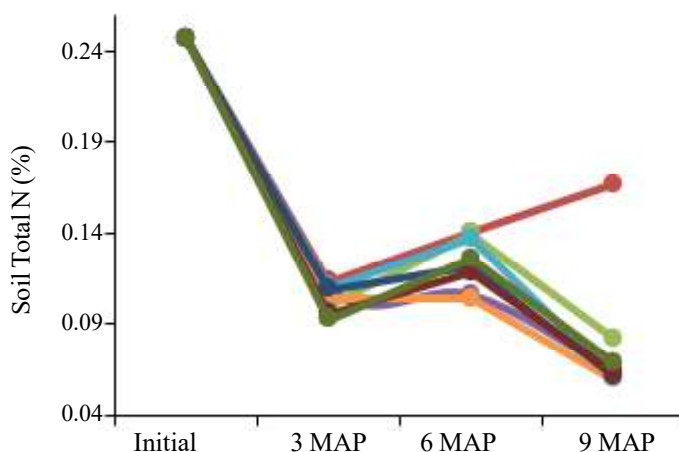


Figure 1. Dynamics of soil total N after land management and organic fertilizer application at 3 MAP, 6 MAP, and 9 MAP. —: T1P1, —: T1P2, —: T1P3, —: T1P4, —: T2P1, —: T2P2, —: T2P3, —: T2P4.

absorbed and used by plants for metabolism, helping overcome N deficiencies that may occur even when soil levels are high. Research has shown that foliar urea supports pineapple growth and yield (Patnaik and Dash, 2021).

The initial soil analysis results (Table 3) indicate that the soil pH is very acidic. This acidic condition generally occurs due to the leaching of base cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+) by high rainfall, hydrolysis of Al^{3+} , which releases H^+ ions, and a history of the use of inorganic fertilizers, especially ammonium-based ones, which can produce H^+ ions through the nitrification process (Hardjowigeno, 2015).

Total N Content of Soil

Based on the soil N-total dynamics graph (Figure 1), the percentage of total N in the soil decreased at 3 months after planting (MAP). Total N content was high at the beginning of the observation period. However, total N decreased drastically in all treatments. This decrease resulted from plant nitrogen uptake and nitrogen loss through biological and physical soil processes. At 6 MAP, pineapple plants entered the active vegetative phase, which stimulates soil microbial growth through root exudates. Utami et al. (2020) explained that during the vegetative phase of pineapple plants, the population of functional microbes in the rhizosphere increases. This is supported by a positive correlation between soil organic C and total N at 6 MAP (Table 4).

At 9 MAP (Table 2), total N content in soil treatment T_1 and organic fertilizer treatment P_1 was higher than in the other organic fertilizer treatments. In the T_2 soil treatment, all organic fertilizer treatments showed no difference. Total N content

in soil treatment P_1 and organic fertilizer treatment T_1 was higher than in the other fertilizer treatments. In organic fertilizer treatments P_2 , P_3 , and P_4 , all soil treatments were similar.

Furthermore, total soil N content at 9 MAP (Table 2) was higher in the T_1P_1 interaction treatment than in the other interaction treatments. This is because the tillage technique, using a 30 cm deep plow combined with coarse pineapple litter, improved soil structure, increased aeration, and expanded the organic matter mixing zone into deeper soil layers. Shallower plowing (30 cm) also retained more N in the topsoil, making it more readily available to plants and experiencing less loss due to leaching (Akbar et al., 2016).

Based on the soil organic carbon results, the T_1P_1 treatment was categorized as moderate, supporting microbial activity and increasing soil nitrogen. This aligns with research by Iswanto et al. (2023), which found that carbon-rich soil organic matter increases cation exchange capacity and provides a substrate for nitrogen-degrading microorganisms. Zulkarnain et al. (2013) found that applying cow manure can increase soil organic carbon. The more compost added to the soil, the greater the increase in soil organic carbon. GGP compost is also a nitrogen-rich organic material that serves as a direct source of organic nitrogen for the soil through decomposition and mineralization by soil microbes. The bamboo biochar in the compost also increases nitrogen retention because its fine pore structure can absorb nitrogen compounds. According to Farni et al. (2017), adding biochar in low doses can increase nitrogen availability by slowing nitrification and keeping nitrogen more stable in the soil.

Table 4. Results of Correlation Test between Organic Carbon and pH Soil with Total N, Available P, and Available K in Pineapple Plantations.

Supporting Variable	Correlation Coefficient (r)	Correlation Coefficient (r)	Correlation Coefficient (r)
Supporting Variable	Soil total nitrogen (%)	Soil-available phosphorus (ppm)	Soil-available potassium (ppm)
Soil Analysis at 3 MAP			
Soil total nitrogen (%)	-	0.264 ^{ns}	0.033 ^{ns}
Soil-available phosphorus (ppm)	0.264 ^{ns}	-	0.543 ^{**}
Soil-available potassium (ppm)	0.033 ^{ns}	0.543 ^{**}	-
Organic-C (%)	0.176 ^{ns}	-0.002 ^{ns}	0.085 ^{ns}
pH	0.061 ^{ns}	0.203 ^{ns}	0.727 ^{**}
Soil Analysis at 6 MAP			
Soil total nitrogen (%)	-	0.633 ^{**}	0.146 ^{ns}
Soil-available phosphorus (ppm)	0.633 ^{**}	-	0.215 ^{ns}
Soil-available potassium (ppm)	0.146 ^{ns}	0.215 ^{ns}	-
Organic-C(%)	0.458 [*]	0.373 ^{ns}	0.002 ^{ns}
pH	-0.136 ^{ns}	-0.353 ^{ns}	-0.186 ^{ns}
Soil Analysis at 9 MAP			
Soil total nitrogen (%)	-	-0.342 ^{ns}	-0.013 ^{ns}
Soil-available phosphorus (ppm)	-0.342 ^{ns}	-	-0.042 ^{ns}
Soil-available potassium (ppm)	-0.013 ^{ns}	-0.042 ^{ns}	-
Organic-C (%)	0.182 ^{ns}	-0.655 ^{**}	0.123 ^{ns}
pH	0.138 ^{ns}	0.136 ^{ns}	-0.209 ^{ns}

Note: MAP = Months after planting; ns = not significantly different at the 5% level *= significantly different at the 5%,
 **= significantly different at the 1% level.

Soil available P content

Based on the available P dynamics graph (Figure 2), after land preparation and organic fertilizer application, the average available P in the soil fluctuated from the initial observation at 3 MAP

to 9 MAP. This is because, at 3 MAP, decomposition of organic matter from fertilizer and litter is not yet complete, so the release of organic P into the available form remains limited. However, at 6 MAP, available P increased because microbial activity reached its maximum and organic matter dissolved.

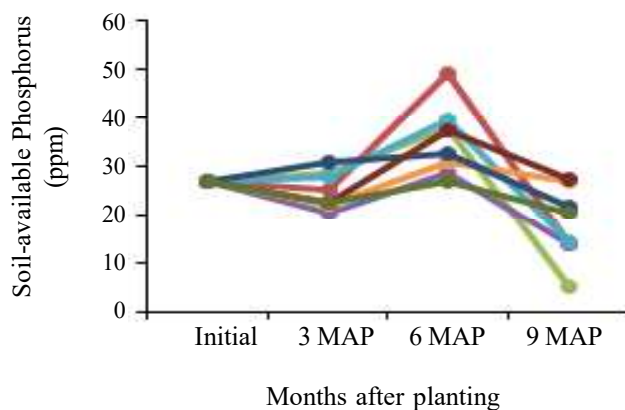


Figure 2. Dynamics of soil-available Phosphorus after land management and organic fertilizer application at 3 MAP, 6 MAP, and 9 MAP. —: T1P1, —: T1P2, —: T1P3, —: T1P4, —: T2P1, —: T2P2, —: T2P3, —: T2P4.

At 6 MAP (Table 4), available P in treatment T_1 (organic fertilizer P_1) was higher than in the other organic fertilizer treatments. In the soil treatment T_2 , organic fertilizer treatment P_3 was higher than the other organic fertilizers. In treatment T_1 , organic fertilizers P_1 , P_2 , and P_4 had higher available P than the other organic fertilizer treatments. In organic fertilizer treatment P_3 , soil treatment T_2 had higher available P than the other soil treatments. Biochar application can increase soil pH, thereby increasing available P from compounds bound to Al and Fe. Higher soil organic carbon can also increase available P. Yulnafatmawita et al. (2019) found that organic matter can increase P solubility by binding Fe and Al with organic acids. Furthermore, increasing soil organic matter can also increase the population of phosphate-solubilizing microbes. At 9 MAP, available P decreased because pineapple plants peaked in phosphorus uptake.

Furthermore, leaching and microbial re-immobilization of available P occurred because substrate availability was low. The T_1P_1 treatment had higher available P compared to other fertilizer treatments. This was because soil preparation in the T_1 treatment involved coarse shredding of pineapple litter, resulting in slower decomposition and slower release of organic acids. Organic acids function to dissolve bound phosphorus. Sari et al. (2017) found that adding organic matter and P fertilizers increased pH and available P and decreased the availability of excess Al and Fe. Phosphate-solubilizing microorganisms increased after compost addition, converting phosphorus in organic compounds into available inorganic forms. These organic acids can form chelates with Al and Fe ions, preventing

phosphorus from binding and making it more readily available to plants (Syahputra et al., 2017). The T_2P_3 interaction treatment at 6 MAP had higher available P than the other treatments. This was due to deeper tillage (40 cm) and finer shredding of pineapple litter. This increased aeration, accelerated organic matter decomposition, and expanded the mixing zone between GGP premium compost and soil. Alhadi et al. (2012) stated that tillage with deep plowing can create good pore space for water movement in the soil. Biochar serves as a nutrient buffer and provides habitat for microorganisms, while vermicompost is rich in active microbes, plant hormones (auxins, cytokinins), and readily available macro- and micronutrients. According to Lazcano and Domínguez (2011), vermicompost contains enzymes and microorganisms that can increase organic matter mineralization and release nitrogen efficiently over the long term.

Soil available K content

Based on the soil-available K dynamics graph (Figure 3), K availability decreased at 3 months after planting. Soil-available K decreased, but T_2P_2 increased significantly; this indicates that deep tillage with rapidly decomposing organic matter and biochar effectively increases potassium availability early in growth. Liang et al. (2021) reported that combining biochar and microbes maintained 25% higher available K than compost alone for up to 210 days of incubation. At 6 months after planting, almost all treatments declined. This decline was due to the intensive leaf and root formation phase, which occurs 3–6 months after planting. During this phase, plant potassium requirements increase because K supports photosynthate transport, stomatal opening, and osmotic pressure regulation. As a result, plants absorb K⁺ ions extensively, leaving lower amounts in the soil solution.

Furthermore, because potassium is mobile, some of the K released from organic matter may also be lost through leaching. In the 9 MAP observation, available K increased in almost all treatments. The largest increase occurred in treatment T_2P_1 . This is due to continued organic matter decomposition, which begins only 6 months post-planting and releases K into the soil. The increase in available K also reflects more stable soil pH conditions and higher organic carbon content in several treatments. Organic carbon increases soil cation exchange capacity (CEC) and supports soil microbial populations involved in nutrient cycling. Handayanto (2020) reinforces this, stating that organic matter acts not only as a nutrient source

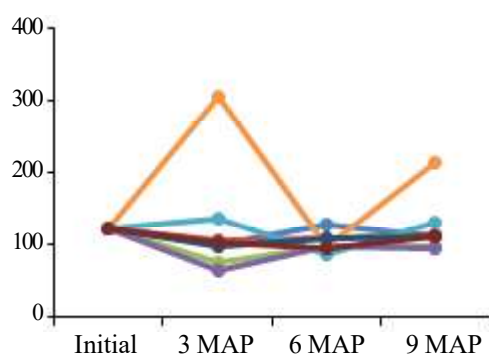


Figure 3. Dynamics of soil-available Potassium after land management and organic fertilizer application at 3 MAP, 6 MAP, and 9 MAP. —: T_1P_1 , —: T_1P_2 , —: T_1P_3 , —: T_1P_4 , —: T_2P_1 , —: T_2P_2 , —: T_2P_3 , —: T_2P_4 .

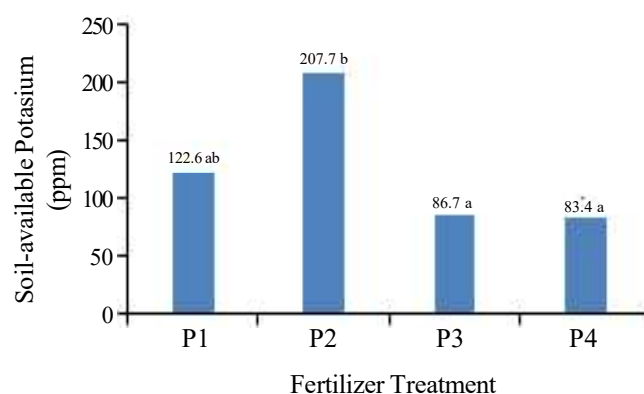


Figure 4. The effect of applying microbe-enriched organic fertilizer and biochar (P) on soil available K at the 3 MAP observation.

but also as a buffering agent for nutrient availability by increasing CEC and pH stability.

At 3 MAP (Figure 4), K availability was highest in the P_2 treatment compared with the other treatments. This is because biochar was added at a higher dose than in the other treatments. This biochar contains potassium in a soluble form, has high porosity, and a negative charge that can increase K retention in the soil. Biochar has a high potassium (K) content in the form of mineral ash such as K_2CO_3 and KCl or other K salts that are readily soluble in the soil and readily available to plants (Lehmann and Joseph, 2015). In addition, biochar acts as a buffer that retains K around the root zone, so it is not easily washed away by rainwater or irrigation (Laird et al., 2010). Compost in P_2 provides organic matter and organic acids that help

dissolve K previously absorbed in soil minerals (Sundari et al., 2017).

Soil available K content at 6 MAP (Table 5) was higher in the T_1P_1 and T_2P_3 interaction treatments than in the other interaction treatments. This is because, in the T_1P_1 treatment, T_1P_1 tillage T_1 is considered effective in improving soil aeration and structure. According to Utomo et al. (2016), moderate tillage increases soil porosity and water infiltration without disrupting the stable subsoil structure. Thus, soil conditions better support root growth and nutrient uptake. Shredding pineapple litter once provides enough organic residue for decomposition. GGP compost has a fairly high potassium content in a form that dissolves easily and is available to plants. Manure, including cow dung compost, can increase the availability of

Table 5. The Effect of Interaction Between Land Management (T) and Biochar and Microbe-Enriched Organic Fertilizer (F) on Soil-available P (ppm) at 6 MAP.

Land Management (T)	Organic Fertilizer (F)	Organic Fertilizer (F)	Organic Fertilizer (F)	Organic Fertilizer (F)	DMRT value 5%	DMRT value 5%
Land Management (T)	F ₁	F ₂	F ₃	F ₄	DMRT value 5%	DMRT value 5%
T ₁	49.08 c	37.81 b	28.76 a	39.42 b	39.42 b	5.00
	B	B	A	B	B	5.00
T ₂	31.00 b	32.53 b	37.47 c	26.78 a	26.78 a	5.00
	A	A	B	A	A	5.00
DMRT value 5%	3.553.713.81	3.553.713.81	3.553.713.81	3.553.713.81	3.553.713.81	

Note: Values followed by the same letter are not significantly different at the DMRT test 5% level; lowercase letters are read horizontally, capital letters are read vertically.

potassium that is dissolved and can be absorbed by plants. This available potassium includes water-soluble and exchangeable forms, both of which plants can easily use (Bihari et al., 2018). The organic carbon content in treatment T_1P_1 is relatively high at 6 MAP, reflecting compost's role in improving soil chemical properties, increasing the soil's ability to absorb and release nutrients, and stimulating soil microbial activity. Furthermore, bamboo biochar in compost helps maintain the stability and efficiency of nutrient release, especially K. Biochar has a porous structure and high surface area, increasing the soil's cation exchange capacity (CEC) (Lehman and Joseph, 2015). This supports the soil's ability to store and release K ions slowly and efficiently.

Soil available K content at 6 MAP (Table 5) was highest under the T_2P_3 treatment compared with other treatments. This is because land preparation used deeper plowing (40 cm) and shredded pineapple litter twice, creating a looser, more open soil environment. This supports aeration, root penetration, and soil microbial activity, which plays a crucial role in nutrient mobilization, including potassium. A more open soil structure also increases water percolation and organic matter decomposition, resulting in more effective K release from organic fertilizers (Rahman et al., 2020). Biochar can improve soil physical and chemical properties, particularly by increasing cation exchange capacity (CEC), so K released from organic matter is less likely to leach and remains in the soil solution in a readily available form.

Furthermore, vermicompost increases nutrient-solubilizing microbial activity, which can help release potassium from the mineral and organic fractions of the soil (Wang et al., 2020). Organic matter also acts as a chelating agent. It improves soil aggregation, indirectly maintaining the stability of available K. Biochar and vermicompost can increase soil organic carbon and CEC, so more of the potassium released from organic matter decomposition is retained in colloidal complexes and remains available to plants. Biochar also forms stable potassium complexes. Vermicompost in GGP premium compost is a good source of potassium and is rich in active microorganisms that can mineralize organic matter. Inah et al. (2022) stated that adding vermicompost increases the availability of K, Ca, and Mg in the soil. Microbial activity in vermicompost produces organic acids during decomposition, which can dissolve K from the insoluble fraction (Wang et al., 2020).

Soil organic matter

At 3 MAP (Table 6), treatment T_1 (organic fertilizer P_3) had higher organic carbon than the other organic fertilizer treatments. Treatment T_2 (organic fertilizer P_2) had higher organic carbon than the other organic fertilizer treatments. Organic fertilizer treatments P_3 and P_4 with soil treatment T_1 had higher organic carbon than T_2 . The minimum soil cultivation system can maintain soil moisture and a more stable soil temperature than intensive soil cultivation. This condition strongly supports soil microbial activity and increases microbial biomass

Table 6. The Interaction Effect Between Land Management (T) and Biochar and Microbe-Enriched Organic Fertilizer (F) on Soil-available K (ppm) at 6 MAP.

Land Management (T)	Organic Fertilizer (F)	Organic Fertilizer (F)	Organic Fertilizer (F)	Organic Fertilizer (F)	DMRT value 5%
Land Management (T)	F ₁	F ₂	F ₃	F ₄	DMRT value 5%
T ₁	127.13 b	107.67 a	97.84 a	98.47 a	20.85
	B	B	B	B	20.85
T ₂	86.29 a	96.82 ab	109.31 b	96.04 ab	20.85
	A	B	B	B	20.85
DMRT value 5%	12.9913.5913.96	12.9913.5913.96	12.9913.5913.96	12.9913.5913.96	

Note: Values followed by the same letter are not significantly different at the DMRT test 5% level; lowercase letters are read horizontally, capital letters are read vertically.

while reducing carbon loss as CO_2 (Moeskops et al., 2010). Biochar in P_3 has a porous structure and high cation exchange capacity, allowing it to store carbon in a more stable, non-degradable form (Lehmann and Joseph, 2015). In addition, vermicompost in the P_3 treatment can accelerate soil microbial activity, helping decompose organic matter. The microbes in vermicompost produce enzymes such as cellulase and ligninase, which help decompose organic residues and accelerate the formation of organic carbon in the form of young humus within 2–3 months. Wang et al. (2020) explain that biochar and vermicompost can increase microbial biomass and activated carbon fractions at the start of their application.

Rahman et al. (2020) explain that carbon accumulation at the beginning of the growing season is due more to slow mineralization than to increased activated carbon input. Sitorus and Sembiring (2012) found that compost application significantly increases soil organic carbon content at the time of application, but increased microbial activity causes decomposition and mineralization of organic carbon; over time, organic carbon content decreases and some carbon is released as CO_2 . Biochar has stable carbon properties and resists microbial decomposition, significantly increasing soil organic carbon content. Biochar also increases soil organic carbon (C-organic), especially in the surface layer, contributing to the formation of complex organic compounds such as humic and fulvic acids, which enhance soil aggregation and stability (Sonari et al., 2023). At 3 MAP (Table 6), the P_2 and P_4 treatments with T_1 showed higher organic C content than T_2 . This is because shallower tillage increases the concentration of organic matter, biochar, and microbes at the soil surface. Biochar plays a crucial

role in increasing soil organic C content because it resists decomposition. Biochar can persist in the soil for a long time and also provides a habitat for decomposing microbes, slowing carbon loss through mineralization (Lehmann and Joseph, 2015). Therefore, treatment P_1 is more optimal because the biochar remains in the top layer, which is rich in litter input.

Soil pH

The soil pH in the P_2 , P_3 , and P_4 treatments was higher than in P_1 (Figure 5). This was due to the addition of biochar to the P_2 treatment. The P_3 treatment had a higher soil pH due to the application of vermicompost. The P_4 treatment had a higher pH because it received LOB microbes containing nutrient-solubilizing microorganisms such as *Bacillus*, *Pseudomonas*, and *Trichoderma*, which can mobilize phosphate and increase the availability of base cations through mineral weathering.

Biochar's ability to increase pH comes from its base-cation content (Ca^{2+} , K^+ , Mg^{2+} , and Na^+) and its ability to neutralize H^+ ions in the soil. Furthermore, biochar has a high cation exchange capacity and a large pore surface area, allowing it to retain nutrients and increase the soil's pH buffering capacity. However, biochar's effect on increasing pH is often slow and gradual, resulting in a pH increase of 6 MAP (Lehmann and Joseph, 2015). Adding vermicompost containing humic acid and active microorganisms can also gradually increase soil pH by releasing alkaline cations through mineralization. Vermicompost also contains free aluminum-binding compounds, which slowly reduce ions that cause soil acidity. Research by Aminah et al. (2022) shows that vermicompost application can increase soil pH by around 0.3–0.5 within 2–3

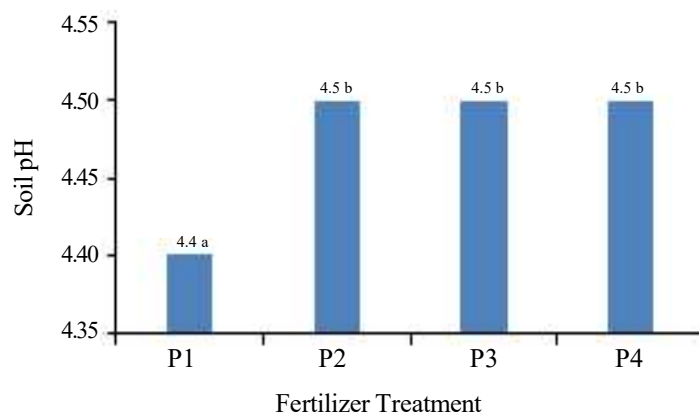


Figure 5. The effect of applying microbe-enriched organic fertilizers and biochar (P) on soil pH at 6 MAP observations.

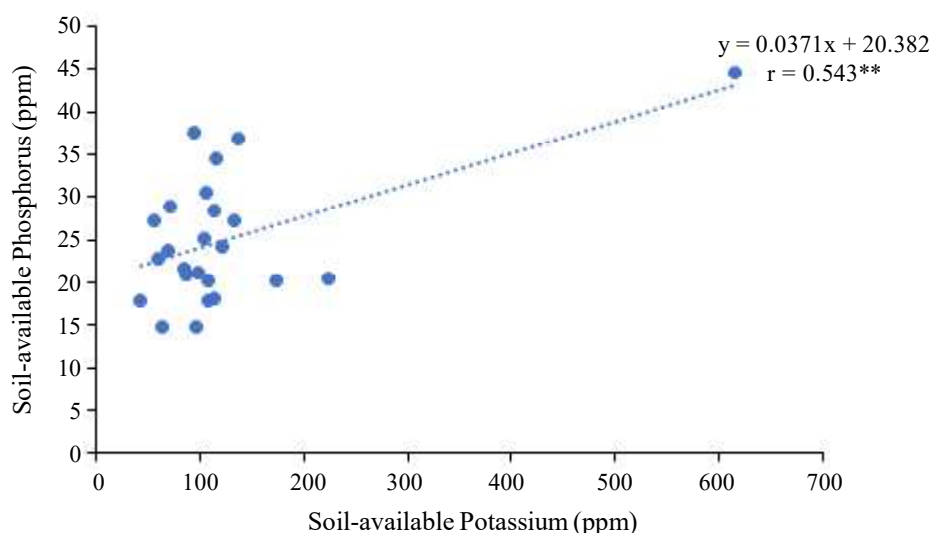


Figure 6. The correlation between soil-available P and soil-available K at 3 MAP.

months after application. In addition to vermicompost, adding LOB microbes introduces nutrient-solubilizing microorganisms such as *Bacillus*, *Pseudomonas*, and *Trichoderma*, which can mobilize phosphate and increase base-cation availability through mineral weathering. Furthermore, some soil microbes can reduce soil acidity through nitrogen fixation and neutralization of organic acids, especially when sufficient organic matter and carbon sulfate are available. This effect tends to stabilize soil pH, rather than increase it sharply (Aminah et al., 2022).

Correlation between organic C and pH with total N, available P, and available K

The 3 MAP correlation analysis results (Figure 6) show a positive and highly significant correlation between available P and available K in the soil. This indicates that higher available P in the soil is associated with higher available K, driven by organic matter inputs—organismal activity releases various nutrients, including phosphorus and potassium. Phosphorus, initially bound in organic forms such as phytate or in inorganic compounds like Al-P and Fe-P, is released as available orthophosphate. At the same time, potassium is released from primary clay minerals such as mica and feldspar into the soil solution (Asril et al., 2023). In addition, organic acids and enzymes produced by microbial activity can increase the dissolution of bound phosphate and release potassium from clay minerals, so high microbial activity can simultaneously increase the availability of both elements (Baloc et al., 2023). P and K availability in the same soil layer can be very high because both are influenced by phosphate-solubilizing microorganisms and the decomposition

of organic matter, which also releases potassium (Ashofie and Prasetya, 2019). In addition, the correlation results in 3 MAP (Figure 8) show that soil pH also has a positive and very significant correlation with K availability. This indicates that higher soil pH is associated with higher K availability. Subowo (2011) explains that increasing soil pH reduces the saturation of H^+ and Al^{3+} ions. These ions compete with K^+ ions in the cation exchange complex, so increasing pH can increase K^+ release into the soil solution and make it more available to plants. Applying organic materials such as biochar, which is alkaline and has a high cation exchange capacity (CEC), can also increase soil pH. Biochar can neutralize soil acidity and provide cation bases, including K^+ . In Wei et al. (2025), the combined application of biochar and compost significantly increased soil pH and K availability. This is because it adsorbs H^+ ions and enhances soil microbial activity. Higher soil pH also creates better conditions for soil microorganisms, which mineralize organic matter and accelerate nutrient release, including potassium.

The correlation analysis of 6 MAP observations (Figure 7) showed a highly significant, positive correlation between total nitrogen and available P. This indicates that higher soil total N content is associated with greater increases in available P. This increase is due to high soil organic matter application, which leads to microbial mineralization that releases nitrogen as ammonium and nitrate, as well as phosphorus, into the soil. Satria et al. (2023) found that total soil N content is positively correlated with available P through nutrient release from mineralized organic matter. Research by Sugianto et al. (2018)

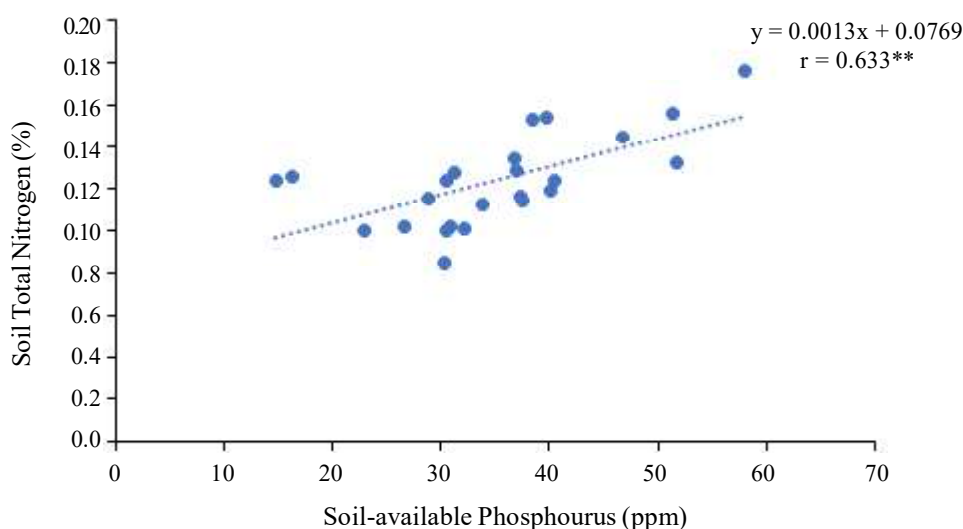


Figure 7. The correlation between soil total Nitrogen and available soil P at 6 MAP.

explained that root and microbial activity in the rhizosphere influences phosphorus availability through changes in pH, root exudates, and phosphatase enzyme production. When nitrogen supplies are sufficient, plants tend to increase the exudation of organic compounds from their roots, contributing to increased solubilization of previously unavailable P.

Furthermore, the 6 MAP observations (Figure 8) show a highly significant positive correlation between soil organic C and total N. This indicates a significant positive relationship between soil organic C levels and total N content. Increases in organic C tend to be followed by increases in total N. Organic C is the primary source of soil organic matter, which releases nitrogen through mineralization as it decomposes. During mineralization, soil

microorganisms decompose this organic matter and produce inorganic compounds such as NH_4^+ (ammonium) and NO_3^- (nitrate), which plants can use. Therefore, higher organic C means a larger organic N reserve and greater mineralization potential. This aligns with Lehmann and Kleber (2011), who stated that organic matter plays a crucial role in the gradual release of N through soil microbial activity. This aligns with research by Ranesa et al. (2024), which showed a very strong correlation between organic C and available N in soil, where organic matter directly increases N availability through active mineralization processes. Increasing organic C also improves soil structure, cation exchange capacity (CEC), and water retention, which indirectly supports nitrogen stability in the soil.

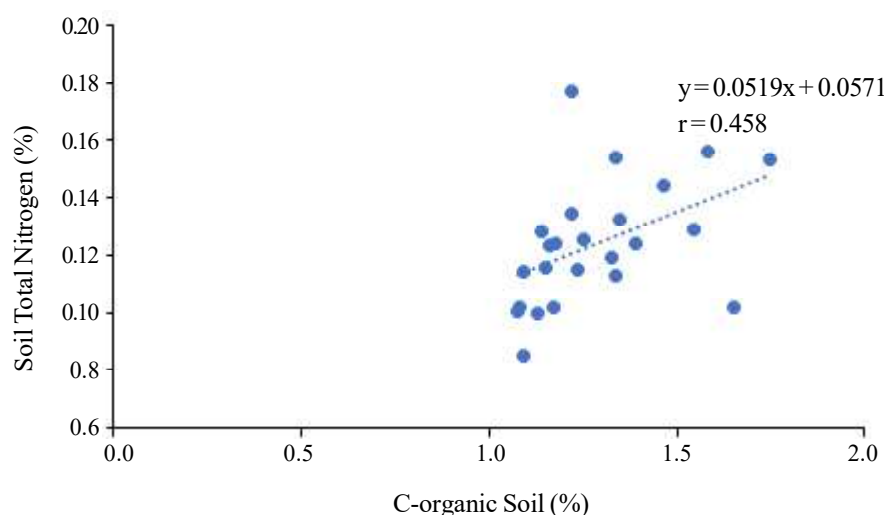


Figure 8. The correlation between soil total Nitrogen and C-Organic soil at 6 MAP.

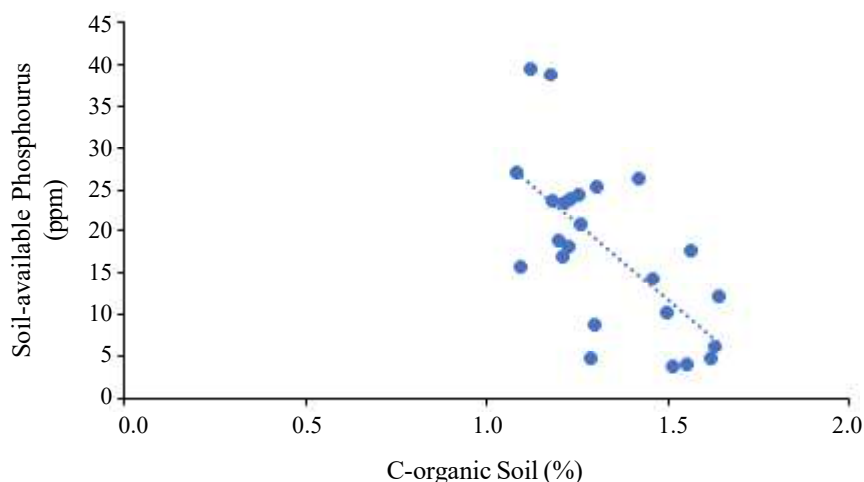


Figure 9. The correlation between soil available P and soil organic C at 9 MAP.

The observed correlation of 9 MAPs (Figure 9) shows a significant negative relationship between soil organic C content and available P. This indicates that higher organic C content is associated with lower available P concentrations. The main cause of the decrease in available P at high organic C is phosphorus immobilization by soil microorganisms. As active organic matter decomposes, microbes require large amounts of phosphorus for cell synthesis. Hence, they absorb inorganic phosphate from the soil and convert it into organic forms in microbial biomass, which is temporarily unavailable to plants. Purbalisa et al. (2020) found that increasing soil organic C with fresh organic matter increases microbial population and activity, resulting in increased CO_2 production and nutrient uptake, including phosphorus, by microbes. This can reduce phosphorus availability to plants in the initial period after organic matter application. Thus, although increasing soil organic matter is generally expected to increase nutrient availability, in the final phase (9 MAP) P availability decreases due to microbial immobilization and phosphate uptake by biochar or compost that has not yet fully decomposed.

CONCLUSIONS

The conclusions obtained based on the research conducted, namely:

Land cultivation with a plow (40 cm) + shredding of pineapple plant litter 2 times had no significant effect on increasing total N, available P, and available K in pineapple plantations. Land cultivation with deep plowing (30 cm) + chopping pineapple plant litter once significantly increased total soil N at 9 MAP.

Application of organic fertilizer enriched with microbes and biochar (GGP premium compost 50 tons ha^{-1} + LOB) had no significant effect on total N, available P, or available K in pineapple plantations. Applying GGP compost at 50 tons ha^{-1} significantly increased total N at 9 MAP, and applying GGP compost at 40 tons ha^{-1} + biochar at 10 tons ha^{-1} significantly increased available K at 3 MAP.

Deep plowing (40 cm) + chopping pineapple plant litter twice did not interact with the application of organic fertilizer enriched with microbes and biochar to increase total N, available P, and available K in pineapple plantations. Deep plowing (30 cm) and GGP compost (50 tons ha^{-1}) interacted to increase total N in the soil at 9 MAP.

If a similar study is conducted on mixed fertilizer dosage, the author suggests observing at the beginning of planting, when the mixed fertilizer is still available, so its effect on all research variables can be observed more effectively.

ACKNOWLEDGMENTS

The author would like to express his gratitude to the Department of Soil Science, Faculty of Agriculture, University of Lampung, and PT Great Giant Pineapple for facilitating this research activity.

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