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Comparative Effects of Organic and Inorganic Fertilization with Mycorrhizal Inoculation on the Growth and P-Uptake of Salak (*Salacca zalacca*) Seedlings in a Compost-Amended Andisol

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Abstract

The cultivation of salak (Salacca zalacca) on Andisols is constrained by low phosphorus (P) availability due to the soil's high P-fixation capacity. To evaluate strategies for enhancing P uptake, a 180-day greenhouse experiment was conducted using a factorial completely randomized design. Salak seedlings were grown in a compost-amended Andisol (2:1 v/v) and subjected to three fertilizer treatments (control [P0], liquid organic fertilizer [P1], and inorganic NPK [P2]) combined with three dosages of a Glomus-based arbuscular mycorrhizal fungi (AMF) inoculum (0 g [M0], 30 g [M1], and 60 g [M2] polybag^{-1}). The results revealed distinct treatment effects on soil, microbial, and plant parameters. In the soil, the inorganic NPK fertilizer (P2) induced significant acidification (pH 6.17), while the liquid organic fertilizer (P1) maintained a more neutral pH (7.03); however, final soil-available P was not significantly different among treatments. Biologically, the P2 treatment severely suppressed the mean mycorrhizal infection rate to 20.0%, significantly lower than the 53.3% observed under the P1 treatment. These effects directly translated to plant growth, where P1 produced significantly taller plants and greater fresh weight, and the P1M2 combination yielded the longest roots (42.43 cm). Ultimately, these improvements culminated in superior plant nutrition, with the P1 treatment facilitating the highest P uptake (0.145 g/plant), nearly double that of the P2 treatment (0.073 g/plant). The findings systematically demonstrate that an integrated approach using liquid organic fertilizer and AMF inoculation is a superior strategy for enhancing nutrient uptake efficiency and promoting vigorous growth in salak nurseries on P-fixing Andisols.

Keywords: Andisol, Arbuscular mycorrhiza, Liquid organic fertilizer, Phosphorus fixation, Salak

Introduction

Salacca zalacca (salak), a prominent horticultural commodity in Indonesia, holds significant economic and cultural value. The island of Java, in particular, is a recognized center of its cultivar diversity (Nandariyah et al., 2004). The crop's economic potential is underscored by its export performance, which grew from a value of US $1.74 million in 2013 to a peak volume of 807 tons by 2024, indicating substantial opportunities for market development (Warta Ekspor, 2014; Komalasari, et al. 2024). However, the expansion of salak cultivation is often constrained by edaphic factors, especially in mountainous regions where the predominant soil type is Andisol. From an agronomic standpoint, Andisols present a critical challenge due to their unique mineralogy. These soils are characterized by high concentrations of active aluminum (Al) and iron (Fe), primarily in the form of allophane, which exhibits a high affinity for phosphorus (P), leading to strong P-fixation and consequently low P availability for plant uptake (Dariah & Sukarman, 2014). This issue is compounded by the naturally acidic pH of these soils. In response, conventional farming practices often involve the excessive application of inorganic P fertilizers, an approach that is not only economically inefficient but also contradicts the principles of sustainable agriculture by potentially degrading long-term soil health.

The physicochemical properties of Andisols are fundamentally at odds with the specific biophysical requirements for optimal salak productivity. According to established criteria, salak cultivation demands an average annual air temperature of 18–25°C, annual rainfall between 1,000 and 2,000 mm, and well-structured soils with good to moderate drainage, a fine to medium texture, and an effective rooting depth exceeding 100 cm (Djaenudin et al. 2011; Raharjo et al. 2022). Furthermore, soil fertility parameters are critical; ideal conditions necessitate a soil pH of 5.5–7.8, an organic carbon content above 1.2%, and adequate macronutrient availability, specified as total Nitrogen >0.29%, available P_2O_5 >20 ppm, and available K_2O >29 ppm (Sari et al. 2025). The failure to meet one or more of these criteria serves as a significant limiting factor, thereby downgrading the land suitability classification and impeding the crop's productive potential.

To address these limitations, a more sustainable approach involving biological amendments warrants investigation. The use of arbuscular mycorrhizal fungi (AMF) presents a promising alternative. AMF establish symbiotic associations with the roots of many plant species, including those of the Palmae family such as Salacca zalacca, enhancing nutrient acquisition through an extensive extraradical hyphal network. This network effectively extends the root system's absorptive area, significantly improving the uptake of diffusion-limited nutrients like phosphorus (Gianinazzi et al., 2010). The physiological importance of phosphorus cannot be overstated, as it is a fundamental constituent of ATP, DNA, and is integral to the translocation of photosynthates (Sumarni, 2012; de Bang et al. 2021). Therefore, optimizing P availability and uptake is paramount for the vigorous development of salacca seedlings, particularly within nutrient-limiting Andisol environments. This study was designed to evaluate the effects of organic manure, inorganic NPK fertilizer, and AMF inoculation on phosphorus availability in the soil and its subsequent uptake in salacca nurseries. The objective is to identify the optimal combination of fertilization and mycorrhizal application that supports sustainable growth and enhances the productivity of salacca on compost-amended Andisols.

Research Methods

The research was conducted in Greenhouse at Kemuning Village, Karanganyar Regency, Central Java using a Completely Randomized Design (CRD) with two factors arranged factorially. The growing medium consisted of Andisol soil mixed with compost in a 2:1 ratio (2 kg Andisol: 1 kg compost per polybag), with the Andisol characterized by an acidic pH of 5.67

and low available P (7.45 ppm). The first factor tested three fertilizer variants: control (P0, no fertilizer), liquid organic fertilizer (P1, applied at 120 mL per polybag through four applications of 30 mL each), and inorganic NPK fertilizer (P2, applied at 60 g per polybag through four applications of 15 g each). The second factor evaluated three mycorrhiza dosages: 0 g (M0), 30 g (M1), and 60 g (M2) per polybag, using Glomus-based inoculum. Each treatment combination was replicated three times, resulting in 27 experimental units, and each experimental units consist of one plant, therefore in total there were 27 observed plants. The growth, biomass, and nutrient uptake data shown on this research were being taken during the end of experiment through destructive method when the plants reach age 180 days after planting. Observations included plant growth parameters (height, leaf count, root length), fresh weight, P uptake, soil pH, and available P data were analyzed using ANOVA at a 95% confidence level, with significant results further tested using Duncan's Multiple Range Test (DMRT) at a 5% significance level. Correlation analysis was also performed to examine relationships between key variables. The study maintained controlled greenhouse conditions to minimize external variability, with regular monitoring of soil moisture.

Results and Discussion

Andisols, the volcanic soils used in this study, possess distinct properties impacting agricultural productivity. The diurnal temperature of the greenhouse that was used for the research ranging from 24-30^{o}C while the average relative humidity roughly 50-65%. Characterized by andic properties, andisols contain amorphous minerals that drive unique chemical behaviors (Brady and Weil, 2004). Indonesian Andisols are typically acidic (pH 3.4-6.7), high in active aluminium and iron, and exhibit exceptional phosphorus fixation due to allophane content (Dariah and Sukarman, 2014), posing significant cultivation challenges. The specific Andisol in this experiment reflected these constraints. Analysis showed an acidic pH (5.67), confirmed high allophane content (NaF pH 10.51), and consequently, very low available phosphorus (7.45 ppm). It had moderate organic matter (2.35%) with a low C/N ratio (6.85), indicating slow decomposition. Nutrient availability was further limited by low potassium (0.35 cmol(+) kg^{-1}) and nitrogen (0.2%). Collectively, these properties created a severely phosphorus-limited environment, necessitating interventions to enhance nutrient accessibility.

Table 1. Soil analysis before treatment result.

Parameter	**Result**	**Unit**	**Scoring**
pH H_2O	5,67	-	Acid*
pH NaF	10,51	-	alkali*
CEC	17,85	cmol(+)kg^{-1}	Medium*
Organic C	1,37	%	Low*
Organic Matter	2,35	%	Medium*
Total N	0,2	%	Low*
P Available	7,45	ppm	Low*
K Available	0,35	cmol(+)kg^{-1}	low*

Information : Scoring based on Balai Penelitian Tanah (2005).

Effects of Treatment on Soil Variables

Soil pH Dynamics

The experimental treatments significantly altered soil pH (Figure 1a). While the control (pH 7.034) and liquid organic fertilizer (pH 7.03) maintained statistically similar pH levels ($p > 0.05$), the inorganic NPK fertilizer induced significant acidification, lowering the pH to 6.17. This decrease is attributed to H^+ ion release during NPK oxidation (Balittan, 2005). All treatments resulted in a higher final pH compared to the initial soil pH of 5.67, reflecting the alkalizing effect of the 2:1 soil:compost amendment. The final pH range across treatments (6.17–7.03) fell within the optimal range (6–7) for plant growth (Brady and Weil, 2007). Notably, soil pH exhibited a strong positive correlation with root length ($r = 0.7449$; Figure 1b), confirming its critical role as an indicator of soil fertility.

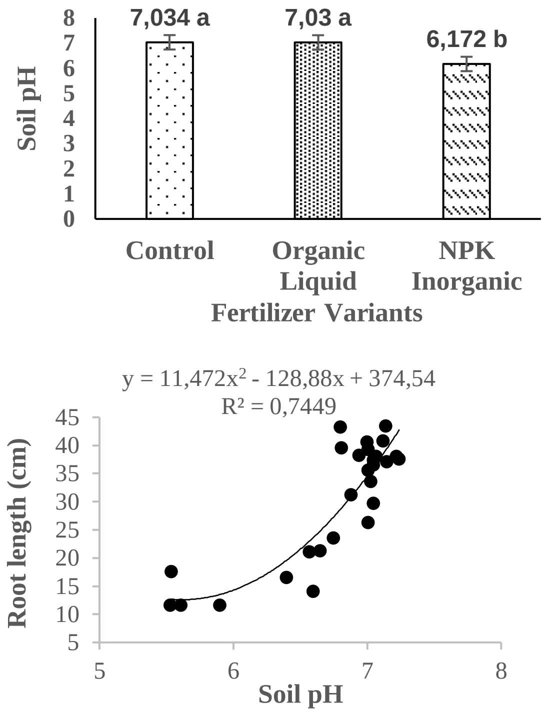


Figure 1. soil pH affected by fertilizer types (a) and Relationship soil pH and root length (b)

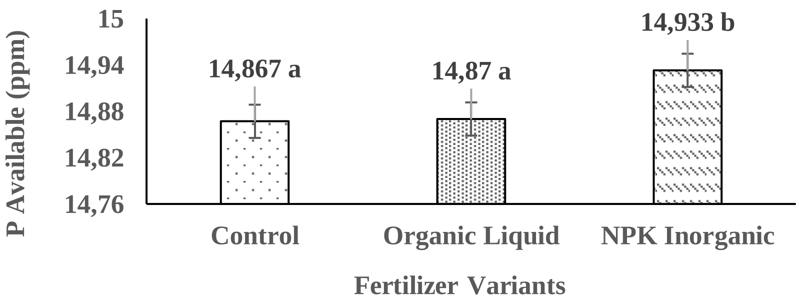


Figure 2. Effect of various fertilizer on soil P availability.

Phosphorus Availability Patterns

Phosphorus availability in the soil showed distinct patterns across treatments (Figure 2). The inorganic NPK fertilizer yielded the highest available P concentration (14.933 ppm). However, this value was only marginally higher than the control (14.867 ppm) and organic fertilizer (14.870 ppm) treatments, suggesting that while NPK provided readily soluble P, the inherent constraints of the Andisol soil strongly limited overall P release and availability. This aligns with Supadma's (2006) findings on the rapid mineral nutrient release from inorganic sources. The overall increase in available P from the initial 7.45 ppm is attributed to mineralization from the compost within the growth medium. Notably, the results confirm that P availability in Andisols remains fundamentally constrained by their inherent properties – including acidic pH, high Al oxides, and allophane content (Sanchez, 1976; Dariah and Sukarman, 2014) – despite fertilizer application. While organic treatments are known to enhance microbial activity and phosphatase production, potentially aiding organic P mineralization (Darmiyanti et al., 2006; Aziz et al., 2012), arbuscular mycorrhizal (AMF) inoculation showed no significant effect on soil P availability within this experiment. This lack of AMF effect suggests that the 90-day study period may have been insufficient for full colonization and establishment of functional hyphal networks capable of significantly enhancing P acquisition in this slow-growing palm species.

Effects of Fertilizer Types and Mycorrhizal Innoculation on Plants Growth Variables

Plant Height

Plant height served as a key indicator of growth in this study. Analysis of variance (ANOVA) revealed that fertilizer application had a significant effect on plant height ($p < 0.05$). However, neither mycorrhiza inoculation nor the interaction between fertilizer and mycorrhiza significantly influenced height. Duncan's Multiple Range Test (DMRT) results (Figure 3) showed that plant height under both the control and liquid organic fertilizer treatments was significantly greater than under the inorganic NPK fertilizer treatment. Among the fertilizer treatments, liquid organic fertilizer produced the tallest plants. The mean plant heights were control (P0) = 35.7 cm, liquid organic fertilizer (P1) = 37.9 cm, and inorganic NPK fertilizer (P2) = 31.1 cm.

Liquid organic fertilizer represents one variant of biofertilizer. Mahdi et al. (2010) emphasized that biofertilizers are a fundamental component of organic agriculture, crucial for sustaining long-term soil fertility. Dhamayanti et al. (2013) further noted that liquid organic fertilizer specifically serves as an effective alternative for enhancing nutrient availability and improving soil physical and chemical properties. These improved soil conditions, fostered by organic amendments, ultimately support optimal growth of plant organs, including height.

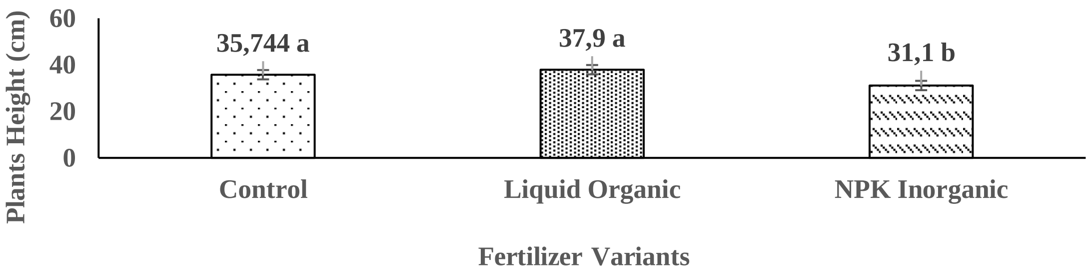
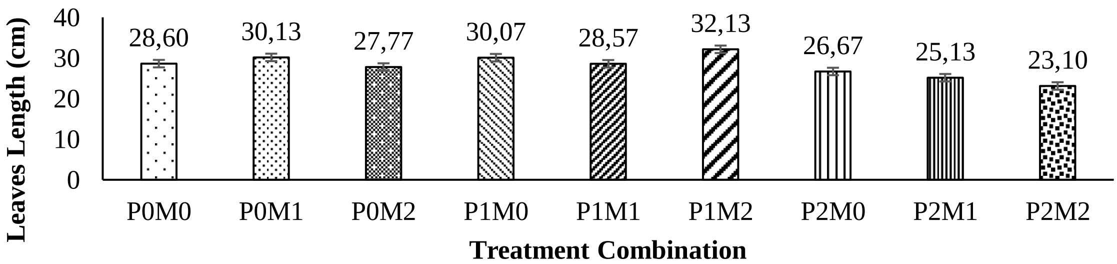


Figure 3. Effect of various fertilizer on plant heights.

Leaves Length

Leaf length, an easily observable growth indicator, is a key component of the leaf area index (LAI). It plays an important role in determining LAI due to its strong linear correlation with leaf width (Taiz and Zeiger, 2010). Analysis revealed that leaf length was not significantly affected by any fertilizer treatment, mycorrhiza inoculation dose, or their interaction (Figure 4). Nevertheless, observable trends emerged: the combination of liquid organic fertilizer with the highest mycorrhiza dose (60 g per polybag) yielded the numerically longest leaves (32.13 cm). Conversely, inorganic NPK fertilizer combined with the same high mycorrhiza dose resulted in the numerically shortest leaves (23.10 cm).

The lack of significant treatment effects may be partly attributed to high light intensity in the greenhouse. Intense light can induce etiolation symptoms in leaves (Vandenbussche et al., 2005), potentially masking treatment responses. While this study found no significant treatment effect on leaf length in salak, research on cereal crops by Amujoyegbe et al. (2007) suggests that combined organic and inorganic fertilizer strategies can improve LAI and reduce production costs, highlighting a potential area for future investigation in perennial palms.



Information : P0 = Control; P1 = Liquid organic fertilizer; P2 = NPK inorganic fertilizer. M0 = Mycorrhiza 0 $g.polybag^{-1}$; M1 = Mycorrhiza 30 $g.polybag^{-1}$; M2 = Mycorrhiza 60 $g.polybag^{-1}$

Figure 4. Effect of various fertilizer and mycorrhiza dosage on leaves length.

Roots Length

Fertilizer type, mycorrhiza dosage, and their interactions significantly influenced root length ($p < 0.05$, Table 2). The longest roots (42.43 cm) occurred under liquid organic fertilizer combined with the highest mycorrhiza dose (60 g $polybag^{-1}$), while the shortest roots (14.00 cm) were observed with inorganic NPK fertilizer without mycorrhiza (0 g $polybag^{-1}$).

Table 2. Root length affected by various fertilizer and mycorrhizal dosage treatment.

Fertilizer Variants	**Mycorrhiza dosage (g.polybag^{-1})**			**Means**
	0	**30**	**60**	
Control	29 c	36,57 d	38,73 de	34,77a
Liquid organic fertilizer	36,67 d	38,27 de	42,43 e	39,12 b
NPK inorganic fertilizer	14,00 a	20,67 b	14,73 a	16,47 c
Means	26,56 a	31,84 b	31,96 b	30,12

Information : Number followed by the same index letter are not significantly based on 5% DMR test level.

Roots serve as the primary plant organ for anchorage and acquisition of water/nutrients (Gregory, 2006). Their elongation is modulated by factors including plant growth regulators (PGRs) and microbial consortia – components present in liquid organic fertilizers. When applied to soil, liquid organic fertilizers enhance nutrient distribution homogeneity compared to granular NPK fertilizers. Crucially, nutrient absorption efficiency depends strongly on root morphology (length and volume). Root distribution correlates positively with soil phosphorus (P) availability (Takahashi and Katoh, 2024), which is itself influenced by tillage, rhizosphere pH, fertilizer type, and planting duration (Andraski & Bundy, 2003; Vu et al., 2009; Niu et al., 2013).

The dose-responsive increase in root length with mycorrhizal inoculation (Figure 5) demonstrates AMF's role in nutrient acquisition. This aligns with Gregory's (2006) model where mycorrhizal hyphae extend the root absorption zone. The relationship between root length and P uptake followed the exponential equation $y = 0{,}0466e^{0{,}0289x}$. (r= 0.4453), confirming morphological dependence. Fertilizer type also mediated mycorrhizal efficacy: inorganic NPK reduced colonization (consistent with suppressed infection in high-fertility soils), whereas organic treatments increased infection rates up to 83.23% (Novriani, 2010), explaining the superior root development under organic+AMF combinations.

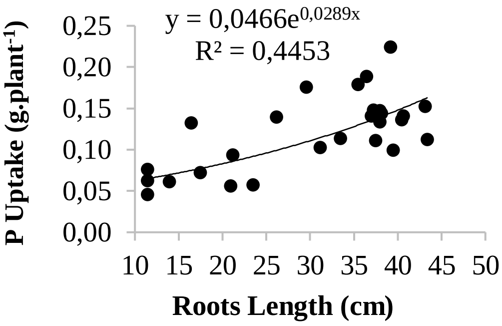


Figure 5. Relation between roots length and P uptake.

Plants Fresh Weigth

Plant fresh weight serves as a growth indicator reflecting the cumulative water and nutrient uptake utilized for metabolism and structural development, integrating contributions from leaves, stem, and root tissues (Dwidjoseputro, 1994). Duncan's Multiple Range Test (DMRT) results (Figure 6) revealed distinct treatment effects: plants receiving control (no fertilizer) and liquid organic fertilizer treatments showed statistically comparable fresh weights.

In contrast, plants treated with inorganic NPK fertilizer exhibited significantly lower fresh weight relative to both other treatments.

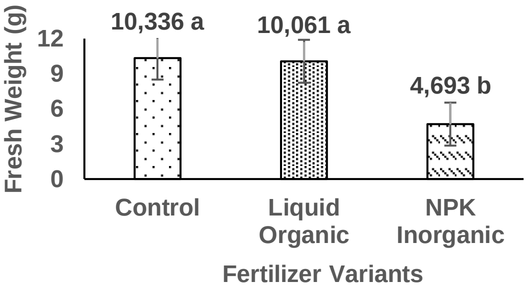


Figure 6. Effect of various fertilizer on plants fresh weight.

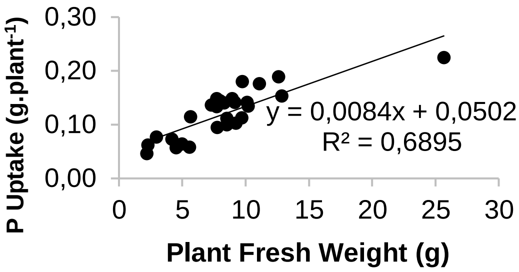


Figure 7. Relation between plants fresh weight with P uptake.

Mean plant fresh weights differed significantly among treatments: the control yielded 10.336 g, liquid organic fertilizer 10.061 g, and inorganic NPK fertilizer only 4.693 g (Figure 6). Fresh weight exhibited a strong positive correlation with phosphorus uptake ($r = 0.689$; Figure 7), following the linear regression equation $y = 0.0084x + 0.0502$. This aligns with Hammond et al. (2009), who identified P uptake efficiency—governed by root morphology—as a primary determinant of biomass production. The superior fresh weight under organic fertilization demonstrates its significant role in enhancing plant biomass. As Damayanti et al. (2013) established, liquid organic amendments improve critical soil properties (chemical, physical, and biological). These improvements stimulate root development, leading to more efficient nutrient acquisition and ultimately optimizing overall plant growth.

Mycorrhiza Infection Rate

The mycorrhizal infection rate, indicating successful root colonization by symbiotic fungi (Declerck et al., 2005), varied significantly among fertilizer treatments ($p < 0.05$, Table 3). Root staining analysis revealed that fertilizer type had a significant effect on infection percentage, while the mycorrhiza inoculation dose itself (0, 30, or 60 g per polybag) did not significantly influence colonization success. Plants under liquid organic fertilizer achieved the highest mean infection rate (53.3%), followed closely by the unfertilized control (46.7%). In stark contrast, inorganic NPK fertilizer severely suppressed mycorrhizal symbiosis, yielding a significantly lower infection rate of only 20.0%. This suppression aligns with Novriani's (2010) finding that high mineral nutrient availability from inorganic sources inhibits fungal colonization. Crucially, increasing the mycorrhizal inoculum dose (0 g: 37.8%, 30 g: 46.7%, 60 g: 35.6%) failed to enhance infection rates significantly, regardless of fertilizer treatment. This indicates that soil chemical conditions (driven primarily by fertilizer type) exerted a stronger influence on colonization success than the quantity of inoculant applied within this experimental system.

Table 3. Fertilizer types and mycorrhiza dosage effects on mycorrhiza infection rate (%).

Fertilizer Variants	**Mycorrhiza Dosage (g.polybag^{-1})**			**Means**
	0	**30**	**60**	
Control	46,67	53,33	40,00	46,67a
Liquid organic fertilizer	53,33	60,00	46,67	53,3 b
NPK anorganik fertilizer	13,33	26,67	20,00	20,00 c
Means	37,78 a	46,67 a	35,56 a	30,12

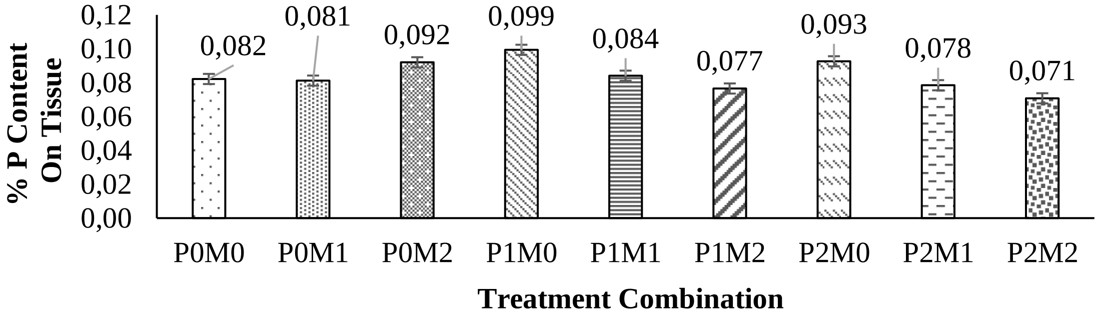
Information : Number followed by the same index letter are not significantly based on 5% DMR test level.

The highest mycorrhizal infection rate (60%) was achieved with liquid organic fertilizer combined with 30 g polybag^{-1} of arbuscular mycorrhizal fungi (AMF). Conversely, the lowest infection rate (13.33%) occurred under inorganic NPK fertilizer without AMF inoculation (0 g polybag^{-1}). Correlation analysis revealed a moderate positive relationship between infection rate and root length (*r* = 0.580). This aligns with the observation that high nutrient availability from inorganic fertilizer suppressed colonization, while organic fertilizer enhanced it – consistent with findings that organic amendments stimulate both mycorrhizal infection and microbial activity (Novriani, 2010; Montalba et al., 2010).

AMF form obligates symbiotic relationships with higher plants, extending their root systems to improve nutrient acquisition (Delvian, 2006). Crucially, AMF colonization exhibits nutrient-dependent regulation: infection increases under low-nutrient conditions but decreases when mineral nutrients (particularly phosphorus) are abundant (Smith & Read, 2008). The measurable infection in control treatments (0 g AMF inoculum) confirms the presence of indigenous AMF populations in the experimental soil. Successful colonization is further influenced by host root architecture (Gregory, 2006). The slow colonization observed may reflect the thick cortical tissues characteristic of perennial palm roots, requiring extended timeframes for functional hyphal networks to establish – a factor potentially limiting AMF efficacy within this 90-day nursery study.

Phosporus (P) on Plants Tissue and P uptake on Plants

P content in plant tissues based on the results of analysis of variance test showed no significant effect between treatments various fertilizer and mycorrhiza dosage, as well as the interaction of both treatments (Figure 8). The highest P content of plant tissues is aplication of liquid organic fertilizer with 0 g.polybag^{-1} mycorrhizal dose, with a P content 0.099% plant $^{-1}$.



Information : P0 = Control, P1 = Liquid organic fertilizer, P2 = NPK inorganic fertilizer, M0 = Mycorrhiza doses 0 $g.polybag^{-1}$, M1 = Mycorrhiza doses 30 $g.polybag^{-1}$, M2 = Mycorrhiza doses 60 $g.polybag^{-1}$

Figure 8. Effect on treatment combination on leaves P content.

Analysis of variance result showed that fertilizer variants have significant effect on the P uptake value, whereas addition of mycorrhizae and interaction between the treatments did not show the significant effect. DMR test results Figure 9 shows that there is a real difference between control treatment and liquid organic fertilizer with the use of inorganic fertilizers. The highest value of P uptake indicated in the treatment of liquid organic fertilizer, which amounted to 0,145 grams of plant $^{-1}$ and the lowest rate is 0.073 g plant $^{-1}$ in inorganic NPK fertilizer treatment.

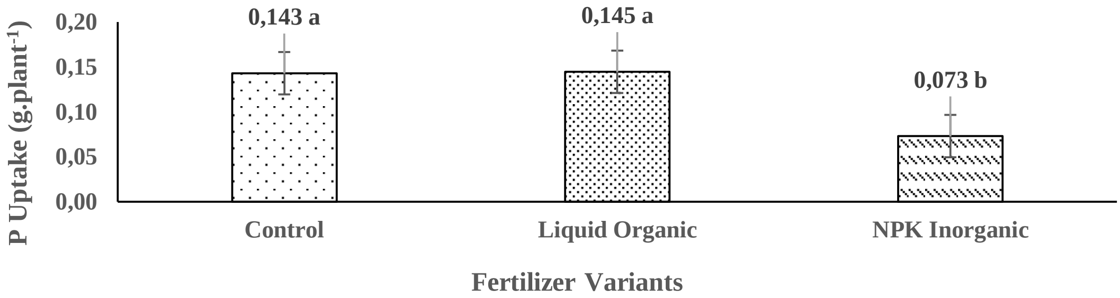


Figure 9. Effect of fertilizer variants treatment on plants P uptake.

Phosphorus (P) is a crucial macronutrient in plants, typically constituting 0.2–0.4% of plant tissue (2000–4000 ppm) (Suhariyono and Yurizon, 2005). In young oil palms, P concentrations range slightly lower, at 0.19–0.21% (Reuters and Robinson, 1985). P is essential for biochemical processes, serving as a structural component of ATP, RNA, and DNA, and facilitating energy transfer and sugar metabolism (de Bang et al., 2021). Despite high soil P availability, inorganic fertilizer treatments often result in reduced P uptake due to stunted root systems (Gregory, 2006). While NPK fertilizers rapidly increase N, P, and K availability, excessive ammonium (from N fertilization) can inhibit root elongation, damage root hairs, and impair overall nutrient absorption (Ingestad, 1973; Wijayani, 2000). Despite high soil P availability, inorganic fertilizer treatments often result in reduced P uptake due to stunted root systems (Gregory, 2006). While NPK fertilizers rapidly increase N, P, and K availability, excessive ammonium (from N fertilization) can inhibit root elongation, damage root hairs, and impair overall nutrient absorption (Ingestad, 1973; Wijayani, 2000).

Mycorrhizal colonization is enhanced in low-nutrient soils, as plants depend on fungal networks for P acquisition (Delvian, 2006). However, under high P availability, mycorrhizal activity declines. Critically, even in slow-growth conditions, mycorrhizae remain functional in P uptake (Smith et al., 2003). Excessive soil nutrient concentrations can create hypertonic conditions, where external osmotic pressure exceeds cellular levels. This may induce plasmolysis—efflux of water from plant cells—rendering nutrients inaccessible and exacerbating stress (Wijayani and Widodo, 2005).

Delvian (2006) noted that mycorrhizal colonization tends to increase in growth media with low nutrient availability, as plants rely more heavily on symbiotic fungi to access essential nutrients. Conversely, when nutrient levels—particularly phosphorus—are sufficient, the functional role of mycorrhizae in nutrient uptake diminishes. Wijayani and widodo (2005) also metioned that higher concentration nutrient concentration will likely to make nutrients solution in soil to be more concentrated more than osmotic pressure inside the plats cell, concentrated nutrient solution could not absorbed by the plants and more likely the liquid content in the plant cell extracted into nutrient solution on the outside which is called as plasmolisis. Based opinion of Smith et al. (2003), in response to low growth does not mean mycorrhizal no role in the absorption of P.

Conclusion

This study concludes that an integrated approach combining liquid organic fertilizer with arbuscular mycorrhizal fungi (AMF) is the most effective strategy for improving the growth and phosphorus nutrition of *Salacca zalacca* seedlings on P-fixing Andisols. While inorganic NPK fertilizer marginally increased soil P availability, its application was counterproductive, leading to soil acidification, significant suppression of mycorrhizal colonization, and ultimately, reduced plant biomass and P uptake. In contrast, the organic fertilization strategy not only enhanced key growth parameters, including root development and biomass accumulation, but also fostered a robust symbiotic relationship. The highest mycorrhizal infection rate (60.0%) was achieved with the liquid organic fertilizer combined with a 30 g AMF inoculum (P1M1), indicating optimal conditions for symbiotic establishment. However, the greatest root elongation (42.43 cm) was observed with the liquid organic fertilizer and a 60 g AMF inoculum (P1M2). This suggests that while a moderate inoculum dose is most efficient for colonization, a higher dose may provide a greater initial stimulus for root morphological development. These findings underscore the critical role of integrating organic inputs with microbial bio-effectors for sustainable nutrient management in P-limited agroecosystems. Future research should focus on validating these greenhouse results through long-term field trials, quantifying the contribution of indigenous versus inoculated AMF communities, and conducting a thorough economic analysis to assess the scalability of this organic-mycorrhizal strategy for commercial salak production.

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