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Effectiveness of Mycorrhizal Fertilizer on Soil Quality, Growth, and Yield of Upland Rice in Ultisol Soil

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Abstract

Rice production in Ultisol land is often hindered by low soil fertility, which limits the availability of nutrients and crop productivity. This research aimed to examine the effectiveness of various doses of mycorrhizal biofertilizer on improving soil quality, growth, and yield production of upland rice (Oryza sativa L.) in Ultisol soil. This experiment used mycorrhizal fertilizer (Mycogrow). The research used a Completely Randomized Design with four mycorrhizal dose treatments: M0 (control, no mycorrhiza), M1 (15 g of mycorrhiza polybag^{-1}), M2 (30 g of mycorrhiza polybag^{-1}), and M3 (45 g of mycorrhiza polybag^{-1}) with three replications, three plant samples using polybag 40 cm x 40 cm and each polybags containing 10 kg of soil for cultivating the Trisakti rice. The results showed that the application of mycorrhiza at the M3 (45 g of mycorrhiza polybag^{-1}) dose significantly improved the physical and chemical properties of the soil, such as reducing bulk density, increasing porosity, pH, soil organic matter content, and the availability of nitrogen, available phosphorous, and available potassium. During the vegetative and generative phase, the M3 (45 g of mycorrhiza polybag^{-1}) is the best treatments in increasing plant height, tiller number, flag leaf area, SPAD value, panicle number, panicle length, flowering time, and 1000-grain weight. Therefore, mycorrhiza application can be recommended as a sustainable and environmentally friendly fertilization technology.

Keyword: *Biofertilizer, dryland cultivation, soil amendment, sustainable agriculture.*

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INTRODUCTION

Upland rice is a major food commodity that plays an important role in rice supply in dryland areas. Drylands in tropical regions are dominated by acidic soils such as Ultisols, which cover approximately 45.8 million hectares or about 25% of Indonesia's total land area (Mira *et al*., 2024). Ultisols are naturally low in fertility, exhibiting acidic soil reactions (typically pH < 5.0 to 5.5), low organic carbon content, low potential phosphorus (P) and potassium (K) contents, low cation exchange capacity (CEC), low base saturation (<35%), and high aluminum (Al) saturation (Leonard *et al*., 2025). The poor nutrient condition is further exacerbated by physical constraints like high clay content and a dense solum, which can hinder root development and access to any available nutrients (Mira *et al*., 2024). Consequently, without intensive management practices such as the application of fertilizers or organic amendments, Ultisols are generally not productive for agriculture (Mulyadi *et al*., 2025).

The use of chemical fertilizers are often the easiest measure farmers can take to increase yields. Low-fertility soils do not always respond well to chemical fertilizers because the ability of plants to absorb nutrients remains limited (Handayani *et al*., 2025; Ngurah *et al*., 2025). Improving upland rice productivity requires an approach that can improve soil conditions while increasing crop growth efficiency. Biofertilizers are one option that is increasingly being used in sustainable agricultural systems. Mycorrhiza

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is a biofertilizer derived from soil fungi that live in symbiosis with plant roots. Mycorrhiza helps expand the root system so that plants can more easily utilize the nutrients available in the soil (Maulidan *et al*., 2025).

Plants that receive mycorrhizal treatment usually experience increased vegetative growth. Root development is faster, plant height is more uniform, and the number of tillers increases. The positive response of plants to mycorrhiza is also seen in the panicle formation and grain filling phases (Nazirah, 2017). The results showed that mycorrhizae were able to increase the number of grains, grain weight, and total yield per unit area of land. The differences in the results were influenced by the type of mycorrhizae used, the application dose, the age of the plants at the time of application, and the soil conditions at the cultivation site. These factors indicate that the effectiveness of mycorrhizae needs to be studied more thoroughly so that it can be widely applied in upland rice cultivation systems (Wangiyana *et al*., 2018).

Mycorrhizal fertilizers are considered to have great potential in increasing agricultural productivity on dry land (Mulyadi & Jiang, 2023; Ndruru *et al*., 2018). The use of mycorrhiza not only helps improve plant growth, but also supports efforts to improve soil quality. This technology can help farmers reduce their dependence on chemical fertilizers and maintain the balance of the soil ecosystem in the long term (Nasution, 2023). Information on the effectiveness of mycorrhiza in upland rice is still limited and needs to be developed through systematic research. Scientific studies are needed to determine the extent of mycorrhiza's influence on plant growth parameters, panicle formation, grain filling, and crop yield (Wangiyana *et al*., 2025; Mulyadi & Jiang, 2023).

This study aims to examine the effectiveness of various doses of mycorrhizal fertilizer in improving soil quality, supporting vegetative growth, and increasing the yield of upland rice cultivated on Ultisol soil. This study was conducted to obtain measurable comparisons between application dose levels, both in terms of soil physicochemical parameters and plant physiological and agronomic responses. The findings of this study are expected to provide a scientific basis for the formulation of technical recommendations for mycorrhizal fertilization that are applicable, efficient, and easily adopted by farmers in sustainable dryland farming systems.

MATERIALS AND METHODS

Place and Time

This study was conducted at the experimental field of SMKN 1 Sultan Daulat, Subulussalam, Aceh, from March – July 2025 using Ultisol soil, which is the dominant soil type in dry areas.

Materials and Tools

The materials used in this experiment included mycorrhizal fertilizer (Mycogrow) produced by PT Agrofarm Nusa Raya (containing zeolite, 33 spores g^{-1}, 300 propagules g^{-1}, 5 species of ectomycorrhiza, and organic matter), Trisakti rice variety, ultisols soil, nitrogen fertilizer, SP-36 fertilizer, KCl fertilizer, water, polybag 40 cm x 40 cm, and pesticide. The tools used in this experiment included soil nutrient analyzer, leaf area meter, ruler, SPAD meter, analytical balance, hoe, and sprayer.

Research Design

The study used a completely randomized design (CRD) with four treatments of mycorrhizal fertilizer doses, namely: M0: No mycorrhiza application (control), M1: 15 g of mycorrhiza polybag^{-1} , M2: 30 g of mycorrhiza polybag^{-1}, and M3: 45 g of mycorrhiza polybag^{-1}.

Each treatment was repeated three times with three sample plants. This research was conducted using polybag with direct seed method and containing 10 kg of ultisols soil polybag^{-1}. The mycorrhizal fertilizer was applied to the planting holes one day before the rice seedlings were transplanted. Nitrogen fertilizer (Urea) was applied in a split dose totaling 360 kg ha^{-1} (equivalent to 4.54 g polybag^{-1}), divided into 50% basal, 30% at tillering, and 20% at panicle initiation. Potassium fertilizer (KCl) was applied at 240 kg ha^{-1} (3.02 g polybag^{-1}), split evenly between the basal application and tillering. Phosphorus fertilizer (SP-36) was applied as a basal dose at 240 kg ha^{-1} (3.02 g polybag^{-1}) in all treatments. All polybags received uniform crop management, including standard weed and pest control, throughout the experiment.

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Research Parameters

Soil Analyst

Measurements of the chemical and physical properties of the soil were carried out by collecting soil samples after the experiment from each treatment. The methods used to measure pH, soil organic matter (SOM), total nitrogen (TN), available phosphorus (AP), available potassium (AK), soil porosity, and soil bulk density were carried out using Soil Nutrient Analyzer equipment.

Vegetative Growth Parameters

(1) Plant height: Measured from the base of the stem to the tip of the highest leaf using a ruler or tape measure, conducted weekly from week 3 to week 8. (2) Number of tillers: Count all tillers that emerge from the plant clump, conducted weekly from week 3 to week 8. (3) Flag leaf area: Measured on the flag leaf (top leaf) using a Leaf Area Meter or digital imaging method (leaf area measurement software). (4) Chlorophyll content: Measured with a Soil Plant Analysis Development (SPAD) meter, observed on the flag leaf of rice plants.

Generative Growth Parameters

(1) Panicles number (PN): Counted on all panicles formed per clump when the plant enters the generative phase. (2) Panicle length (PL): Measured from the base to the tip of the panicle using a ruler. (3) Flowering age: Recorded when 50% of plants in one treatment have produced flowers/begun flowering (days after planting). (4) Weight of 1000 seeds: Calculated by weighing 1000 oven-dried seeds from each treatment using an analytical balance.

Root System Parameters

(1) Root length (RL): Measured after the plant is pulled out and the roots are cleaned, using a ruler or string which is then measured for length. (2) Root volume (RV): Measured using the water displacement method (placing the roots in a measuring cup filled with water and measuring the increase in water volume).

Data Analysis

The data were analyzed using analysis of variance (ANOVA) and the Least Significant Difference (LSD) test at a 5% level to determine the effect of treatment on the observed variables using the R Studio application.

RESULTS AND DISCUSSION

The Effect of Mycorrhizal Fertilizer on Soil Chemical and Physical Properties

The analysis results show that mycorrhiza application has a significant effect on the physical and chemical properties of the soil. The effect of mycorrhiza application on the physical and chemical properties of the soil is presented in Table 1. The bulk density decreased significantly with increasing mycorrhiza dose, with 45 g of mycorrhiza polybag^{-1} producing the lowest value of 1.17 g cm^{-3}. This decrease in bulk density is thought to be due to the ability of mycorrhiza to increase aggregate stability. The research by (Li *et al*., 2022) shows that mycorrhiza plays a role in increasing aggregate stability through the formation of adhesive compounds such as glomalin and the growth of external hyphal tissue that improves soil structure. These conditions increase soil pore space and support improved aeration and water movement in Ultisol soils, which are generally dense. Increased soil porosity is in line with a decrease in bulk density. The treatment with 45 g of mycorrhiza polybag^{-1} showed the highest porosity, reaching 48.92%. This high porosity is thought to be due to the activity of mycorrhiza, which is able to create macro and micro pores through hyphae development and increased root biomass. The pores formed improve the soil's ability to drain water while increasing its water holding capacity (Pauwels *et al*., 2023), so that the physical condition of the soil becomes more conducive to the growth of upland rice roots.

Based on Table 1, the chemical properties of the soil also showed a significant effect due to the application of mycorrhiza. The soil pH value increased from 5.20 in M0 to 6.12 in M3, reflecting a decrease in the acidity of Ultisol soil. This increase in pH occurred because mycorrhiza was able to reduce the concentration of H^+ and Al^{3+} ions through the mechanisms of absorption, binding, and secretion of organic acids (Alotaibi *et al*., 2021). This change in pH directly affects the increased availability of nutrients,

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especially phosphorus, which is very sensitive to fixation in acidic conditions. Soil organic matter content also increased in the mycorrhiza treatment, with the highest value of 2.04% at dose of 45 g of mycorrhiza polybag^{-1}. This increase is thought to originate from the growth of hyphal and root biomass and increased activity of decomposer microbes working synergistically with mycorrhiza. The increase in organic matter contributes to an increase in cation exchange capacity and improvement in soil structure, thereby supporting nutrient movement and absorption (Negi *et al*., 2025).

Table 1. Effects of Various Doses of Mycorrhizal Fertilizer on Physical and Chemical Properties of Soil

Treatments	Soil Parameter						
	Bulk Density	Soil Porosity	Soil pH	SOM	TN	AP	AK
M0: No mycorrhiza application	1.33 a	41.80 d	5.20 d	1.52 b	0.14 c	21.30 d	223.45 d
M1: 15 g of mycorrhiza polybag^{-1}	1.22 b	46.30 c	5.87 c	1.95 a	0.17 b	25.26 c	227.16 c
M2: 30 g of mycorrhiza polybag^{-1}	1.19 c	48.18 b	5.97 b	1.98 a	0.18 b	25.82 b	229.25 b
M3: 45 g of mycorrhiza polybag^{-1}	1.17 c	48.92 a	6.12 a	2.04 a	0.22 a	27.31 a	229.80 a

Note: - Different letters in the same column indicate significant differences in the 5% LSD test.
- SOM (soil organic matter), TN (total nitrogen), AP (available phosphorus), AK (available potassium).

The dose of 45 g of mycorrhiza polybag^{-1} on total nitrogen, available P, and available K content in the soil was the treatment with the highest content and was significantly different from the other treatments. Total nitrogen content increased from 0.14% in M0 to 0.22% in M3. This increase is thought to be due to increased root volume and hyphal colonization, which expanded the area of nutrient absorption. Mycorrhiza also increased interaction with nitrogen-fixing microbes, resulting in more efficient mineralization (Wang *et al*., 2025). This response contributes significantly to the formation of plant vegetative networks. Phosphate availability in the 45 g of mycorrhiza polybag^{-1} treatment had the highest value and was significantly different from phosphate availability in other treatments. This increase in phosphate is thought to involve the dissolution of bound phosphate through the secretion of phosphatase enzymes and organic acids by mycorrhizae. The extensive hyphal absorption zone increases the ability of roots to obtain previously unavailable phosphate, thereby supporting ATP formation, protein synthesis, and tiller growth (Etesami *et al*., 2021). Potassium availability also increased, with the highest value in M3 at 229.80 ppm. The expansion of the mycorrhizal hyphal network increased the absorption surface area, resulting in more efficient K uptake. Potassium is necessary for osmotic regulation, stomatal opening, and photosynthate translocation, so the increase in K availability strengthened the relationship between soil quality improvement and plant generative growth (Sulaman *et al*., 2025). Increased porosity, pH, organic matter, total nitrogen, available phosphate, and available potassium create more optimal rooting conditions for upland rice.

The Effect of Mycorrhizal Fertilizer on Plant Height and Number of Tillers

The application of mycorrhizal fertilizer had a significant effect on the vegetative growth of upland rice, both in terms of plant height and tiller number in Ultisol soil. The results of the LSD test in weeks 3 to 6 showed that an increase in dose from 30 to 45 g of mycorrhiza polybag^{-1} resulted in a significant increase in plant height and tiller number compared to lower doses for both parameters. The average plant height and number of tillers resulting from mycorrhizal application are presented in Table 2 and Table 3. This shows that higher doses of mycorrhiza are able to accelerate the formation of canopy structure and increase tillering through increased nutrient uptake, particularly P and N, during the active root colonization phase at the beginning of growth. Based on Table 2, the increase in dose began to decline in plant height in week 7, as seen from the absence of significant differences between M1, M2, and M3. Based on Table 3, differences in the number of tillers from various treatments with differences in mycorrhiza doses were still visible, especially in M2 and M3, which continued to show a higher number of tillers compared to the control treatment. The eighth week showed that treatment M3 consistently produced the highest plant height and number of tillers.

The relationship between increased plant height and the number of tillers in the 45 g of mycorrhiza polybag^{-1} treatment shows that mycorrhizal fungi not only enhance vegetative growth but also promote the formation of productive organs from an early stage. Mycorrhizal colonization of roots successfully increased plant vigor and nutrient uptake efficiency in naturally nutrient-poor Ultisol soil (Liang *et al*.,

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2022). The increase in both reflects an improvement in root system function extended by external hyphae (Ilwati *et al*., 2024), so that plants are able to utilize nutrients that were previously unavailable due to P fixation by Al and Fe in Ultisol soils. This dual effect makes plants more efficient in allocating photosynthates for stem growth and tiller formation, which ultimately becomes an important basis for increasing yield components in the next generative phase.

Table 2. Effect of Mycorrhizal Fertilizer on Rice Plant Height

Treatments	Plant Height - Weeks After Planting (WAP)					
	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	8 WAP
M0: No mycorrhiza application	27.56 b	31.78 d	50.44 d	76.67 d	94.67 b	103.33 d
M1: 15 g of mycorrhiza $polybag^{-1}$	27.78 b	37.33 c	55.44 c	78.00 c	98.56 a	106.67 c
M2: 30 g of mycorrhiza $polybag^{-1}$	28.33 a	39.22 b	58.11 b	79.56 b	98.78 a	108.33 b
M3: 45 g of mycorrhiza $polybag^{-1}$	28.56 a	42.44 a	62.00 a	82.11 a	99.11 a	109.56 a

Note: Different letters in the same column indicate significant differences in the 5% LSD test.

Table 3. Effect of Mycorrhizal Fertilizer on the Number of Rice Seedlings

Treatments	Panicle Number - Weeks After Planting (WAP)					
	3 WAP	4 WAP	5 WAP	6 WAP	7 WAP	8 WAP
M0: No mycorrhiza application	7 b	15 b	26 b	32 c	38 c	34 c
M1: 15 g of mycorrhiza $polybag^{-1}$	8 ab	17 a	27 ab	35 b	39 c	35 c
M2: 30 g of mycorrhiza $polybag^{-1}$	8 a	17 a	27 ab	36 a	44 b	40 b
M3: 45 g of mycorrhiza $polybag^{-1}$	8 a	17 a	28 a	36 a	46 a	42 a

Note: Different letters in the same column indicate significant differences in the 5% LSD test.

The Effect of Mycorrhizal Fertilizer on Flag Leaf Area and SPAD of Rice Plants

The application of mycorrhizal fertilizer had a significant effect on the flag leaf area and chlorophyll content of upland rice plants in Ultisol soil. Graphs of rice flag leaf area and chlorophyll content of upland rice are presented in figure 1A-B. Figure 1A shows a gradual increase with increasing mycorrhizal doses, where treatment M3 produced the highest flag leaf area (9.06 cm^2) and was significantly different from the other treatments. The increase in flag leaf area with the application of various doses of mycorrhiza indicates an improvement in photosynthetic capacity, as the flag leaf is the main organ that contributes to photosynthate accumulation during the panicle filling phase. Mycorrhizal hyphae that expand the root absorption area increase the supply of P and N, two important elements that play a role in the formation of leaf surface area. Figure 1B shows that chlorophyll content measured by SPAD values increased in line with increasing mycorrhiza doses. Treatment M3 produced the highest chlorophyll content (39.07), followed by M2 and M1, while M0 showed the lowest value (35.70). This indicates that mycorrhiza increases the nitrogen and magnesium nutrient status of leaves, two major components of chlorophyll (Asadi *et al*., 2022). Increased chlorophyll reflects high photosynthetic efficiency in plants, which directly affects biomass formation and productivity in the generative phase (Mao *et al*., 2022). The effectiveness of mycorrhiza in increasing chlorophyll is consistent with its main function of increasing nutrient availability and improving the metabolic balance of plants in highly alkaline acidic soils such as Ultisols.

The relationship between vegetative growth and physiological responses in plants is clearly evident in the correlation between plant height, number of tillers, flag leaf area, and chlorophyll content. Plants that grow taller and produce more tillers in treatments with mycorrhizae, particularly M3, have a more developed root system, enabling them to absorb nutrients more efficiently. This condition encourages the formation of larger flag leaves and an increase in chlorophyll content, as the absorption of nitrogen, phosphorus, and potassium is more optimal. Larger leaf area provides higher photosynthetic capacity, while increased chlorophyll content strengthens the physiological quality of the leaves (Yan *et al*., 2021). This combined response indicates that mycorrhizal colonization strengthens the vegetative phase while providing physiological benefits in the generative phase, which ultimately supports the yield potential of upland rice on Ultisol soils.

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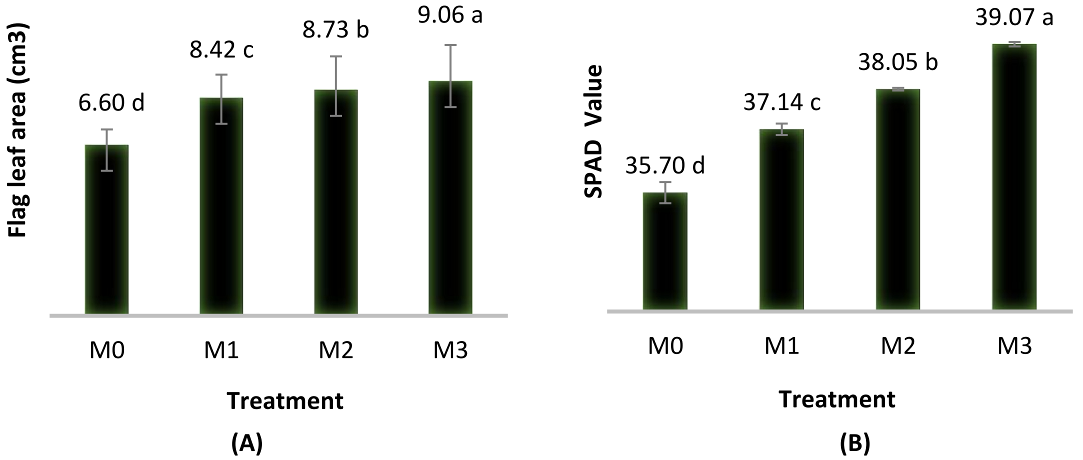

Figure 1. Effects of Mycorrhizal Fertilizer on (A) Flag Leaf Area of Rice Plants and (B) SPAD Chlorophyll Content of Rice Leaves. Note: Different Letters in the Same Column Indicate Significant Differences At the 5% LSD test.

The Effect of Mycorrhizal Fertilizer on the Number and Length of Panicles

The application of mycorrhizal fertilizer has a significant effect on the number and length of panicles. The differences in the effects of mycorrhizal application at various doses on the number and length of panicles are presented in figure 2A-B. Figure 2A shows that the 45 g polybag^{-1} mycorrhizal dose treatment produced the highest number of panicles and was significantly different from other treatments but not significantly different from the 30 g of mycorrhiza polybag^{-1} dose. Higher mycorrhizal doses improve root system function through external hyphal colonization, thereby increasing the efficiency of nitrogen, phosphorus, and potassium absorption. Better nutrient availability in the late vegetative phase and approaching generative phase strengthens panicle primordium formation, which ultimately leads to an increase in the number of panicles formed (Zhang *et al*., 2025).

Figure 2B shows that the application of 45 g of mycorrhiza polybag^{-1} resulted in the highest panicle length and was significantly different from the panicle length in other treatments. The increase in panicle length was closely related to the high photosynthetic capacity, which was previously reflected in the flag leaf area and chlorophyll content. Plants treated with mycorrhiza have a higher carbon assimilation capacity, resulting in more optimal biomass accumulation in the panicle (Basiru & Hijri, 2024). This condition allows the panicle to grow longer and potentially hold more grains. More intensive nutrient uptake through mycorrhizal colonization supports plant structure formation from the early to generative phases. The close relationship between vegetative growth and improved panicle structure shows that mycorrhiza acts as a trigger for increased upland rice productivity in Ultisol soils, which typically have low nutrient availability and high acidity levels.

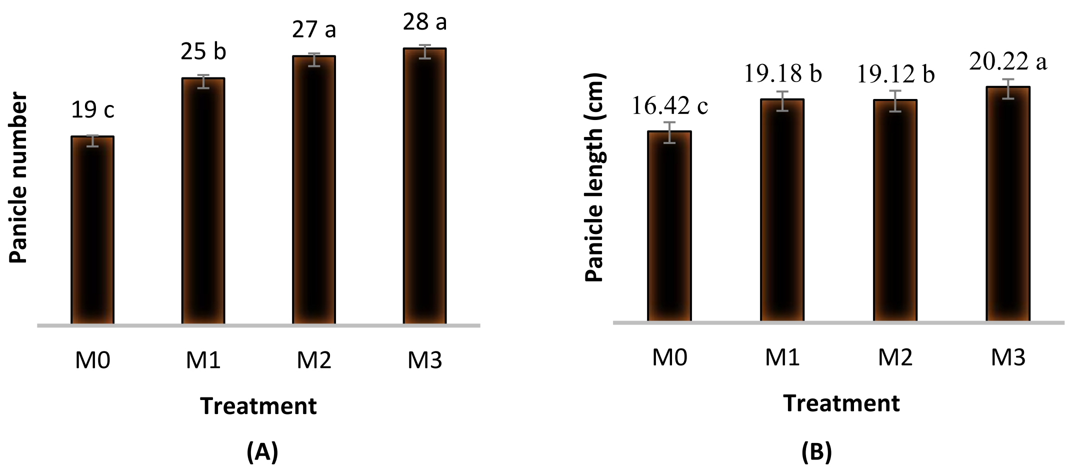

Figure 2. Effects of Mycorrhizal Fertilizer on (A) Panicle Number of Rice and (B) the Panicle Length of Rice. Note: Different Letters in the Same Column Indicate Significant Differences At the 5% LSD test.

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The Effect of Mycorrhizal Fertilizer on Flowering Time and 1000-Grain Weight

The application of mycorrhizal fertilizer has a significant effect on the flowering time and 1000-grain weight of upland rice. The differences in the effects of mycorrhizal application at various doses on the flowering time of upland rice and 1000-grain weight are presented in figure 3A-B. Figure 3A shows that the 45 g of mycorrhiza polybag^{-1} treatment resulted in the fastest flowering time and was significantly different from the other treatments, although it was not significantly different from the 30 g of mycorrhiza polybag^{-1} dose. This acceleration indicates that the higher the mycorrhiza dose, the more effective the colonization of external hyphae is in facilitating the absorption of essential nutrients, especially phosphorus, which plays an important role in regulating meristem differentiation and the transition of plants to the reproductive phase (Guigard *et al*., 2023). More optimal nutrient availability since the end of the vegetative phase accelerates the formation of early panicles, allowing plants to enter the flowering phase more quickly.

Figure 3B shows that the weight of 1000 grain treated with a dose of 45 g of mycorrhiza polybag^{-1} produced the highest seed weight and was significantly different from other treatments. This increase in seed weight is closely related to the higher photosynthetic capacity of plants in treatments with higher mycorrhiza doses, as reflected in larger flag leaf area and higher chlorophyll (SPAD) values. These conditions allow for more intensive accumulation of photosynthates during the seed filling phase, resulting in optimal endosperm formation (Lu *et al*., 2025). Better biomass accumulation in seeds under the influence of mycorrhiza results in fuller grains, thereby significantly increasing the weight of 1000 grain. The achievement of faster flowering and higher seed weight in the M3 treatment reinforces the results in growth variables, particularly plant height, number of tillers, flag leaf area, and chlorophyll content.

Mycorrhizal fertilization increases the absorption of nitrogen, phosphorus, and potassium from the early stages, supporting the formation of a more robust plant structure and increasing photosynthetic capacity throughout growth. The synergistic relationship between better vegetative vigor and more efficient grain filling shows that mycorrhiza not only affects yield formation but also optimizes all stages of growth (Das *et al*., 2022). This combination of physiological responses indicates that a dose of 45 g of mycorrhiza per polybag is the most effective treatment for increasing upland rice productivity in Ultisol soils, which are generally nutrient-poor and acidic.

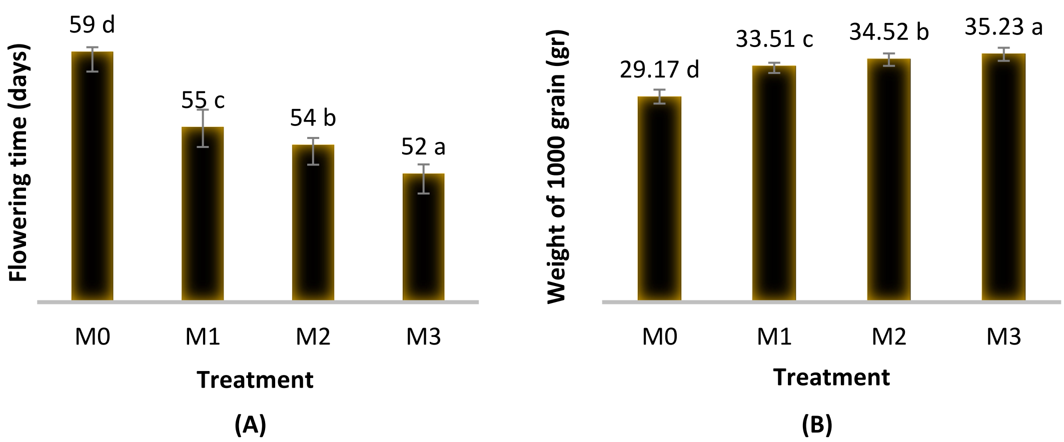

Figure 3. Effects of Mycorrhizal Fertilizer on (A) flowering time of rice plants and (B) weight of 1000 grain. Note: Different letters in the same column indicate significant differences at the 5% LSD level.

The Effect of Mycorrhizal Fertilizer on Rice Root Length and Root Volume

The results on root length show that the application of mycorrhizal fertilizer has a significant effect on the length and volume of upland rice roots (figure 4A-B). Figure 4A presents data on rice root length, where treatment M3 produced the highest root length, namely 39.67 cm, and was significantly different from all other treatments. This increase illustrates that higher doses of mycorrhiza are capable of forming more extensive external hyphal colonization, thereby enlarging the root exploration area in utilizing the pore space of Ultisol soil, which is generally dense and has high Al saturation (Yunedi & Perdana, 2023). Root-hypha interaction enhances the development of primary and lateral roots, which ultimately contributes to an increase in overall root length (Grondin *et al*., 2024). Figure 4B shows root volume, which exhibits a similar response pattern, where the 45 g of mycorrhiza polybag^{-1} (M3) dose of mycorrhiza

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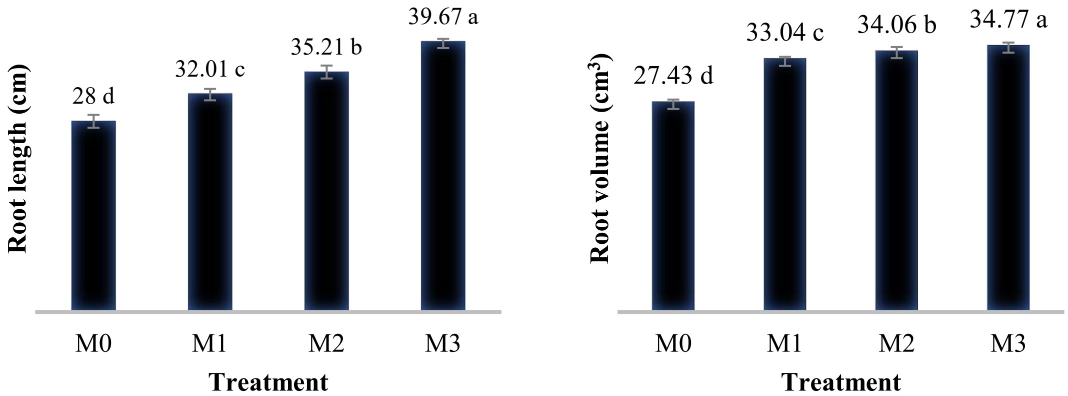
treatment produced the highest root volume and was significantly different from the other treatments. This increase in volume reflects the formation of a more branched root system and greater accumulation of active tissue.

External mycorrhizal hyphae play a direct role in expanding the absorption of water and nutrients, mainly phosphorus, nitrogen, and micronutrients such as Zn and Cu, which are very important in cell wall synthesis, root respiration, and tissue expansion. Thicker and denser roots enable plants to have more stable absorption capacity even when growing in media with limited aeration such as Ultisol. The longest and highest root volume in the M3 treatment reinforces the physiological link between the root system and the growth response of the upper part of the plant. Longer roots increase nutrient exploration, while greater volume increases the root's ability to store carbohydrates and support the supply of metabolites to the plant canopy (Fujii, 2024). The positive response in root length and volume indicates that mycorrhizae help plants overcome nutrient limitations and high acidity conditions. More intensive hyphal colonization in the M3 treatment not only increased vegetative growth but also facilitated the formation of yield components, indicating that this dose is the most optimal treatment for supporting upland rice productivity.



(A) **(B)**

Figure 4. Effects of Mycorrhizal Fertilizer on (A) rice plant root length and (B) rice plant root volume. Note: Different letters in the same column indicate significant differences at the 5% LSD level.

CONCLUSION

Based on the results of the study, it can be concluded that the application of mycorrhizal fertilizer is proven to be effective in improving soil quality, growth, and upland rice production on Ultisol soil. The most optimal effect was observed at 45 g of mycorrhiza polybag^{-1}, characterized by improvements in soil physical properties such as a decrease in bulk density and an increase in porosity, as well as improvements in soil chemical properties in the form of an increase in pH, organic matter content, and availability of Nitrogen, Phosphorus, and Potassium nutrients. A positive response was also reflected in the vegetative growth of plants with an increase in plant height, number of tillers, flag leaf area, and chlorophyll content, which supports higher photosynthetic capacity. In the generative phase, this treatment was able to increase the number and length of panicles, accelerate flowering age, and increase the weight of 1000 grain. Additionally, the root system developed better with increased root length and volume. Therefore, the use of mycorrhizal fertilizer at a dose of 45 g polybag^{-1} can be recommended as a sustainable and environmentally friendly fertilization technology to enhance the productivity of upland rice in dryland areas with acidic soil conditions such as Ultisols.

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