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Research Article

Mycorrhiza application improves rice morpho-physiological traits in different soil water content

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ABSTRACT

Mycorrhizal fungi are beneficial soil microorganisms that establish mutualistic associations with plant roots, significantly enhancing nutrient and water uptake under abiotic stress conditions. In West Kalimantan, limited soil water content frequently constrains rice cultivation, negatively impacting plant growth and yield. This study aimed to evaluate the effects of mycorrhizal inoculation on the morphophysiological traits of rice under varying levels of soil water content. The experiment was conducted from February to June 2022 in Mempawah Regency, West Kalimantan, using a split-split-plot randomized complete block design. The main plot factor was mycorrhizal inoculation (inoculated and uninoculated), the subplot factor was soil water content (100%, 80%, and 60%), and the sub-subplot factor was rice variety (Inpari 32 and Inpari 42). The results demonstrated that mycorrhizal inoculation significantly improved rice tolerance to moderate drought stress through adaptive morphophysiological mechanisms. This was indicated by increased phosphorus uptake efficiency and enhanced net assimilation rate, even at 60% soil water content. These physiological improvements contributed to better plant morphological development, including greater plant height (84.73 cm), dry biomass (8.36 g), number of panicles (15.83 panicles), panicle length (22.21 cm), number of grains per panicle (189.96 grains), and grain weight per clump (72.31 g).

Keywords: mutualistic associations; mycorrhizal inoculation; physiological improvements; rice tolerance

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INTRODUCTION

Rice (*Oryza sativa* L.) is the primary staple food crop in Indonesia, making its production a critical national priority to meet increasing demand. In West Kalimantan, rice consumption continues to outpace the existing production capacity. According to data from the Department of Food Crops and Horticulture (2022), the average annual rice consumption in West Kalimantan is 533,638 tonnes. In comparison, rice production in West Kalimantan in 2024 reached only 764,784 tonnes, yielding 452,440 tonnes of milled rice (BPS, 2025). The low production volume is closely related to the productivity level, with rice productivity in West Kalimantan at 3.09 tons ha^{-1}, significantly lower than the national average productivity of 5.29 tons ha^{-1} (BPS, 2025).

The low rice productivity in West Kalimantan is attributed to suboptimal soil fertility levels that hinder plant growth and development (Radian et al., 2024). Additionally, limited soil water content is a critical factor affecting the morphophysiological responses of plants, particularly during growth stages that require a consistent water supply according to the plant's needs. This condition relates to the characteristics of agricultural land in West Kalimantan, which is dominated by tidal swamplands with non-irrigated rice fields and rainfed paddies covering an area of 218,468.40 ha, along with dryland areas spanning 183,853.13 ha (BPS, 2021). Such conditions pose a high risk of fluctuations in soil water content, making crops more vulnerable to drought stress.

Optimal soil water content is essential for supporting physiological processes in rice plants, including nutrient uptake, photosynthesis, and assimilate translocation. These processes directly influence plant growth and development, ultimately determining crop production success (Cahyanti et al., 2023). However, drought stress can hinder these processes, as evidenced by reduced photosynthetic rates, decreased CO_2 and nutrient uptake, cellular damage, degradation of amyloplasts in root columella cells, and impaired hydrotropic responses. Collectively, these impacts lead to reduced yield (Barnawal et al., 2019; Chiappero et al., 2019; Etesami et al., 2015; Liu et al., 2019; Ngumbi & Kloepper, 2016). Therefore, the application of appropriate cultivation technology under limited soil water content conditions is necessary, such as the use of mycorrhizal fungi.

Mycorrhizal fungi are soil microorganisms that establish mutualistic symbiotic associations with plant roots, playing a key role in improving plant growth and productivity under various abiotic stress conditions, including drought (Begum et al., 2019; Wahab et al., 2023). These fungi develop vesicles, arbuscules, and hyphae within plant roots, as well as spores and hyphae in the rhizosphere. The hyphae form extensive mycelium networks that extend beyond the root zone, facilitating water and nutrient uptake from soil regions inaccessible to plant roots (Bowles et al., 2016).

Root colonization by mycorrhizal fungi enhances plant stress tolerance by modulating various morphophysiological traits (Alqarawi et al., 2014; Hashem et al., 2015). Physiologically, mycorrhizal fungi contribute to increased chlorophyll synthesis and improved efficiency of water and nutrient uptake by the plant. This directly results in enhanced photosynthate production through more efficient photosynthesis, thereby supporting overall biomass accumulation and crop productivity (Chen et al., 2017; Muis et al., 2016; Sefrila et al., 2023). Therefore, this study aimed to analyse the role of mycorrhizal fungi on the morphophysiology of rice plants under varying levels of soil water content.

MATERIALS AND METHODS

The study was conducted in Mempawah Regency, West Kalimantan, Indonesia, with laboratory analysis carried out at the Faculty of Agriculture, Tanjungpura University. The research was conducted from February to June 2022.

Two rice varieties, Inpari 32 and Inpari 42, commonly cultivated by farmers in West Kalimantan, were used in this study. The mycorrhizal fungi inoculum, carried on a zeolite media, ±170 spores per 100 g of zeolite (mixed spores).

The inoculation process was initiated during the seedling phase by applying 20 g of the zeolite-based inoculum into each seedling hole in the nursery media. At 14 days after planting (DAP), root colonization analysis was conducted at the Plant Pathology Laboratory to confirm successful mycorrhizal establishment prior to transplanting. The success rate of rice seedlings inoculated with mycorrhizal fungus was 62% on average.

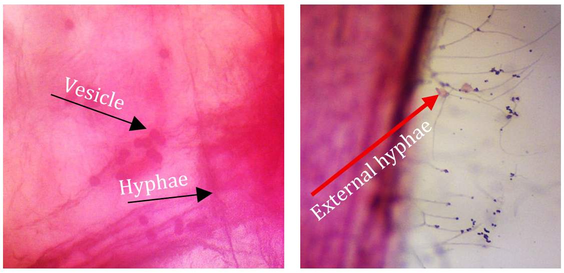

Figure 1. Cross-section of rice seedling roots infected with mycorrhizal fungi.

Alluvial soil was used as the growing media. It was sieved to a fine texture and air-dried prior to use. The initial soil water content was determined using the Gravimetric method, which showed a moisture content of 26%. Thereafter, the soil water content of the entire media was adjusted to 100% of field capacity to support the early growth phase of the plants. This 100% soil water content was maintained from planting until 10 DAP, corresponding to the seedling recovery or adaptation phase to the growing environment (Hidayat, 2016).

Three rice seedlings of each variety already inoculated were transplanted per planting hole. Planting was in a polybag sized 40 cm x 50 cm, with about 14 kg of soil media. Prior to transplanting, the mycorrhizal fungi inoculum (based on zeolite) was reapplied at a rate of 200 grams per planting hole.

The field experiment was arranged using a split-split plot randomized complete block design. Blocking was based on irrigation scheduling at 08:00, 10:00, and 12:00 (WIB). The main plots consisted of mycorrhizal fungi treatments (without and with mycorrhizal application). The subplots comprised soil water content treatments at 100%, 80%, and 60%. The sub-subplots consisted of two rice varieties of Inpari 32 and Inpari 42. Each treatment combination was replicated 3 times, resulting in 36 treatment plots. Each plot consisted of 9 rice plants, leading to a total of 324 observation units.

Soil water content management was initiated 10 DAP and maintained until the plants reached the maximum vegetative stage, 8 weeks after planting (WAP). Soil water levels were regulated by weighing the entire growing media. For the 60% and 80% soil water content treatments, irrigation was withheld until the water level decreased to the designated threshold. When the media weight fell below the target, water was added to restore the soil water content to 60% or 80% of field capacity. In the 100% soil water content treatment, no water reduction was allowed, and the weight of the growing medium was maintained at 14 kg plus the weight of plant biomass. Soil medium weight calculations were performed specifically for the 60% and 80% soil water content treatments.

$$\text{Soil water content (\%)} = \frac{\text{Percentage}}{100} \text{ x soil weight (soil water content 100\%)}$$

$$(80\%) = \frac{80}{100} \text{ x 14 kg = 11.2 kg; } (60\%) = \frac{60}{100} \text{ x 14 kg = 8.4 kg}$$

Fertilizers were applied, consisting of urea of 200 kg ha^{-1} (1.25 g per polybag), SP-36 of 100 kg ha^{-1} (0.63 g per polybag), and KCl of 50 kg ha^{-1} (0.31 g per polybag) (Agricultural Technology Assessment Center, 2019). Rice plants were harvested at physiological maturity, indicated by 90-95% of the panicles turning yellow.

Phosphorus uptake by rice plants was analysed at the Soil Chemistry and Fertility Laboratory at 8 WAP. Phosphorus uptake was determined using the Bray I extraction method and quantified with a spectrophotometer. Plant height and dry weight were also measured at 8 WAP. Plant height was recorded from the base of the stem to the tip of the longest leaf using a measuring tape. The dry weight was obtained from a single destructive sample, which was oven-dried at 100°C for 48 hours. The net assimilation rate (NAR) was calculated based on dry weight and leaf area measurements taken at 2, 4, 6, and 8 WAP. The NAR was determined using the following formula (Sudhakar et al., 2016):

$$\text{NAR} = \left(\frac{W_2 - W_1}{t_2 - t_1}\right) \text{x} \left(\frac{\log_e A_2 - \log_e A_1}{A_2 - A_1}\right)$$

Note: W_2 and W_1 plant dry weights at times t_1 and t_2, $\log_e A_2$ and $\log_e A_1$ are the natural logs of leaf areas A_1 and A_2 at times t_1 and t_2.

The number of grains per panicle was determined by counting all grains formed on each panicle, followed by calculating the average for each sample. Grain weight per clump was measured by weighing the dry grains harvested from each sample using a digital scale.

The data on phosphorus uptake and net assimilation rate were tabulated and presented as vertical bar charts. Morphological data of rice plants were analyzed using analysis of variance (ANOVA). Post-hoc tests were carried out on the source of variations showing a significant effect using the Honestly Significant Difference (HSD) test with a confidence level of 95%.

RESULTS AND DISCUSSION

The use of Inpari 32 and Inpari 42 varieties did not exhibit a significant effect on any of the morphological observations (Table 1). Nevertheless, the results indicated that there was almost no significant interaction effect between mycorrhizal fungi treatment and soil water content, except for grain weight per clump (Table 1). This suggests that the plant response to mycorrhizal is relatively stable across different soil water content conditions. The positive impact of mycorrhizal fungi in supporting rice growth and yield is related to their role as a biofertilizer, which aids root absorption of water and nutrients, enhances nutrient availability, stimulates plant growth hormone production, increases photosynthetic rate, and improves osmotic pressure in cells subjected to salinity and drought stress (Tuhuteru et al., 2024; Utari & Rachmawati, 2022).

Optimal soil water content availability is a crucial factor required by plants to support their physiological processes, as it directly affects plant development and biomass productivity (Cahyanti et al., 2023). Physiologically, limited water uptake from the soil reduces the efficiency of CO_2 absorption, which is essential for photosynthesis. Water deficit conditions compel plants to regulate stomatal closure tightly to minimise water loss through transpiration, thereby reducing photosynthetic efficiency and impacting plant growth and productivity (Caferri & Bassi, 2022). Meanwhile, no significant effect was observed from the use of Inpari 32 and Inpari 42 varieties on the morphological parameters of rice plants. This may be attributed to the similarity in genetic characteristics and adaptation of both varieties to the growing environment, resulting in uniform morphological responses to the treatments (Darwati & Noerwan, 2019).

Table 1. Analysis of variance for plant height, dry weight, number of panicles, panicle length, number of grains per panicle, and grain weight per hill on mycorrhizal fungi and soil water content treatments across different varieties.

Source	df	Plant height	Dry weight	Number of panicles	Panicle length	Number of grains per panicle	Grain weight per hill
Main plot							
Block	2	0.19ns	0.76ns	0.26ns	0.02ns	0.97ns	2.54ns
Mycorrhiza (M)	1	45.86*	48.65*	536.93*	41.04*	45.23*	379.51*
Error (a)	2						
Subplot							
Soil water content (A)	2	11.18*	64.41*	15.41*	6.74*	7.40*	30.79*
MxA	2	1.03ns	0.69ns	3.54ns	0.85ns	0.79ns	16.82*
Error (b)	8						
Sub-sub plot							
Variety (V)	1	0.11ns	0.02ns	3.93ns	0.51ns	1.89ns	0.54ns
MxV	1	3.41ns	1.76ns	0.01ns	0.31ns	2.40ns	0.00ns
AxV	2	0.43ns	1.29ns	0.66ns	1.98ns	1.21ns	0.60ns
MxAxV	2	0.55ns	3.79ns	3.88ns	1.87ns	3.79ns	3.47ns
Error (c)	12						
Total	35						

Note: *: significant effect, ns: non-significant effect

Phosphorus uptake

The laboratory analysis showed that the rice varieties used (Inpari 32 and Inpari 42) without mycorrhizal fungi inoculation exhibited a trend of increasing phosphorus uptake in response to increasing soil water content up to 100% field capacity (Figure 2). This is related to edaphic drought conditions, which reduce phosphorus diffusivity in the soil due to increased phosphorus immobilisation caused by drought (Bitterlich et al., 2024; Sharma et al., 2021). Moreover, under water-deficit conditions, plants reduce their transpiration rate to conserve water, which can inhibit the uptake of essential nutrients, while prioritising the absorption of specific nutrients critical for survival (Reisig, 2023). Water availability plays a vital role in providing a medium for dissolved chemicals and forming nutrient solutions that are exchangeable and available for plant uptake (Huntley, 2023).

Phosphorus uptake by rice plants inoculated with mycorrhizal fungi reached the highest values at 80% soil water content (0.157 g for Inpari 32 and 0.145 g for Inpari 42). Interestingly, at 60% soil water content, phosphorus uptake remained higher compared to the 100% soil water content condition (Figure 2). This indicates that the presence of mycorrhiza can enhance phosphorus uptake efficiency, even under drought stress. Mycorrhiza assists plants in absorbing nutrients and water through the expansion of their hyphal network and the production of phosphatase enzymes that mobilise phosphorus from unavailable to available forms (Liu et al., 2019; Plassard et al., 2019; Simamora et al., 2015). The efficacy of this symbiosis tends to increase under drought stress conditions, as Pauwels et al. (2023), reported that water deficit can stimulate enhanced mycorrhizal activity in supporting plant nutrition.

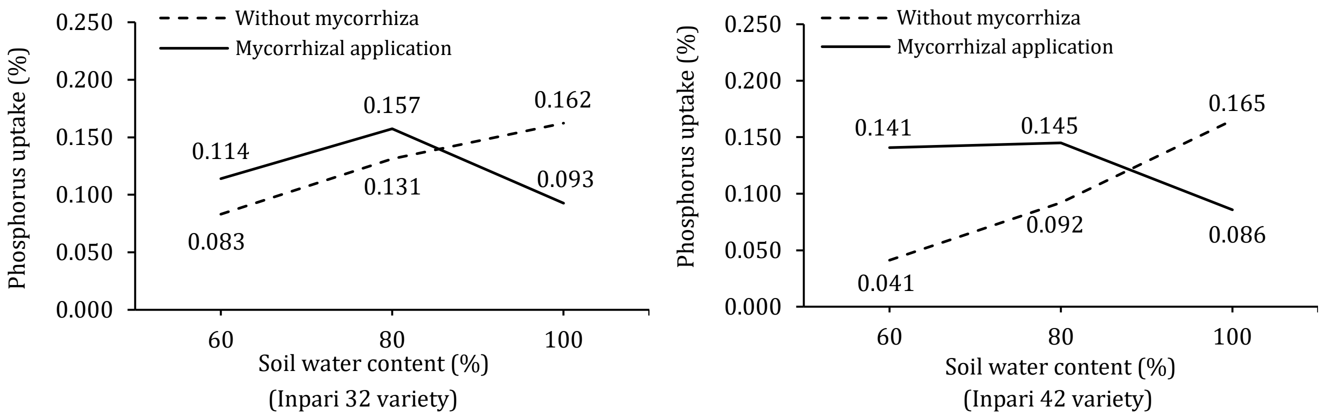

Figure 2. Phosphorus nutrient uptake as influenced by mycorrhizal fungi under various soil water content levels.

Net assimilation rate

Net assimilation rate is a measure of a plant's ability to produce dry matter or carbohydrates per unit leaf area over time, reflecting the photosynthetic efficiency of the plant (Sudhakar et al., 2016). The mycorrhizal fungi infection was able to increase the net assimilation rate of rice plants, even under conditions of 60% soil water content, outperforming plants with 100% soil water content that lacked mycorrhizal fungi (Figure 3). This is related to the role of mycorrhizal fungi in enhancing water and nutrient uptake, as well as improving photosynthetic efficiency (Begum et al., 2019).

Photosynthetic efficiency in this study was closely associated with phosphorus uptake mediated by mycorrhizal fungi. The correlation coefficient between phosphorus uptake and net assimilation rate was 0.86 for Inpari 32 and 0.97 for Inpari 42. This suggests that increased photosynthetic efficiency is significantly influenced by the plant's ability to absorb phosphorus. According to Malhotra et al. (2018), phosphorus plays a crucial role in ATP production, which provides the energy necessary for photosynthesis. Furthermore, Iqbal et al. (2023) reported that limited phosphorus availability can reduce the photosynthetic rate in plants, leading to decreased carbon fixation, growth, and productivity.

Plant height

The HSD test indicated that the mycorrhizal fungi significantly increased rice plant height compared to plants without mycorrhizal fungi. Furthermore, the 100% soil water content treatment resulted in significantly greater plant height than the 80% and 60% soil water content treatments (Table 2). Plant height is the outcome of accumulated physiological processes influenced by water and nutrient uptake, which, in turn, affect cell division and cell enlargement activities (Jing et al., 2024).

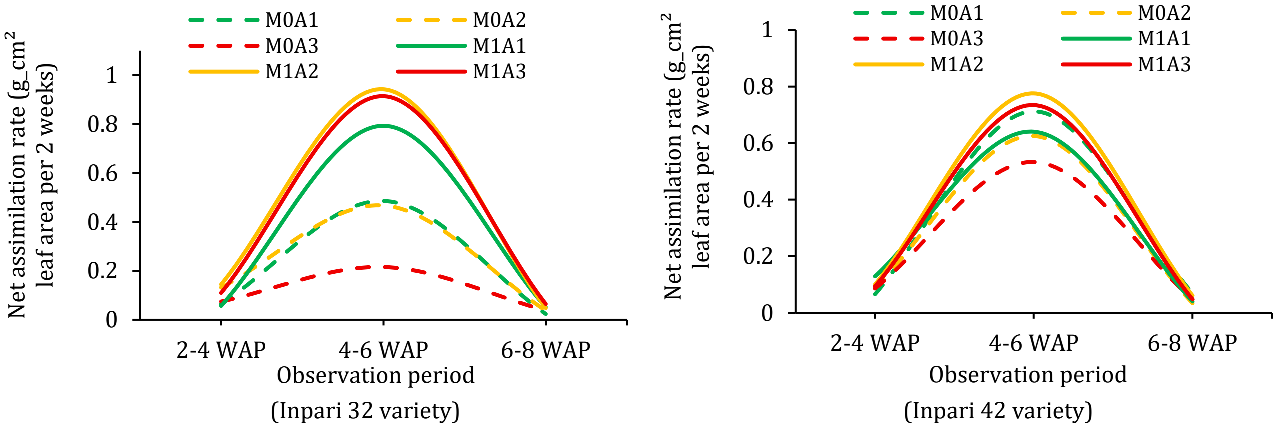

Figure 3. Net assimilation rate affected by mycorrhizal fungi under different levels of soil water content. M0 (without mycorrhizal fungi); M1 (application of mycorrhizal fungi); A1 (soil water content at 100%); A2 (soil water content at 80%); A3 (soil water content at 60%).

According to Manan & Al-Machfudz (2015), soil water availability is closely related to nutrient absorption by plants during metabolic processes. Plants respond to water availability by enhancing vegetative growth, such as increasing plant height. These findings are consistent with those of Kiuk et al. (2022), who reported that the application of mycorrhizal fungi significantly supports increased plant height.

Table 2. Average of plant height, dry weight, number of panicles, panicle length, and number of grains per panicle under mycorrhizal fungi treatment and soil water content levels.

Treatments	Average				
	Plant height (cm)	Dry weight (g)	Number of panicles	Panicle length (cm)	Number of grains per panicle
Mycorrhiza					
Without mycorrhiza	76.45b	7.26b	8.31b	16.66b	154.63b
Application mycorrhiza	84.73a	8.36a	15.83a	22.21a	189.96a
HSD 0.05	5.26	0.68	1.40	3.72	22.60
Soil water content (%)					
100	86.65a	8.57a	13.33a	21.43a	190.86a
80	78.11b	7.61c	12.72b	19.56b	168.61b
60	77.01b	7.25c	10.17c	17.32c	157.42c
HSD 0.05	1.82	0.10	0.50	0.92	7.30

Note: Numbers followed by the same letter in a column are not significantly different based on the HSD test at 0.05 level.

Dry weight

The HSD test showed that rice plants inoculated with mycorrhizal fungi produced significantly higher dry biomass compared to plants without mycorrhizal inoculation. Furthermore, dry biomass accumulation under 100% soil water content was significantly higher than that under 80% and 60% soil water content conditions (Table 2).

According to Wangiyana et al. (2023), mycorrhizal fungi can enhance the dry weight of rice plants by supporting more optimal tiller development. This improvement is associated with the enhanced capacity of plants to absorb water and nutrients, facilitated by the presence of mycorrhiza. The increased efficiency of nutrient and water uptake subsequently supports more optimal metabolic processes, thereby improving photosynthetic efficiency and dry biomass accumulation (Astiko et al., 2019).

Photosynthesis itself contributes approximately 90–95% to the formation of plant dry matter (He et al., 2021).

Number of panicles

The formation of panicles in rice plants inoculated with mycorrhizal fungi was significantly higher compared to plants without mycorrhizal inoculation. Additionally, plants grown under 100% soil water content produced more panicles than those under 80% and 60% soil water content conditions (Table 2). Physiologically, panicle formation in rice is the result of an effective photosynthetic process, which is supported by transpiration activity and stomatal conductance. These processes collectively influence the plant's ability to generate tillers and subsequently form panicles (Subarjo et al., 2024).

The number of panicles formed in this study was also consistent with the observed net assimilation rate, where mycorrhizal inoculated plants exhibited higher photosynthetic efficiency. Meanwhile, non-mycorrhizal plants, the highest photosynthetic efficiency was observed under conditions of 100% soil water content (Figure 3). This is in line with Maisura et al. (2020), who stated that the net assimilation rate reflects the average photosynthetic efficiency of leaves, which ultimately contributes to the formation of panicles and grains.

Panicle length and number of grains per panicle

Panicles produced by mycorrhizal-inoculated plants were significantly longer compared to rice plants without mycorrhizal fungi. This was also followed by an increase in the number of grains per panicle, which was significantly higher in mycorrhizal inoculated plants compared to non-inoculated plants. Panicle length and the number of grains formed were significantly greater under 100% soil water content than under 80% and 60% soil water content conditions (Table 2).

According to Bachtiar et al. (2016), phosphorus is essential for flower, fruit, and seed formation. Therefore, the greater the plant's phosphorus uptake, the longer the panicle and the higher the number of grains formed. In this study, panicle length and the number of grains produced were consistent with the level of phosphorus uptake by the plants (Figure 2).

Grain weight per hill

The HSD test for grain weight per hill showed that mycorrhizal inoculated rice plants produced significantly higher grain weight across all soil water content conditions (100%, 80%, and 60%) compared to plants without mycorrhiza. Moreover, under 100% soil water content, mycorrhizal inoculated plants produced significantly higher grain weight per hill than those under 80% and 60% soil water content (Table 3). Grain weight per hill in this study showed a strong relationship with the number of panicles and the number of grains per panicle. Correlation analysis revealed a coefficient of 0.97, indicating that the number of panicles and grains per panicle influenced 97% of the grain weight per hill.

Table 3. Average of grain weight per hill for the interaction between mycorrhizal fungi treatment and soil water content.

Mycorrhiza	Soil water content (%)			Average
	100	80	60	
Without mycorrhiza	26.84d	22.39d	18.64d	22.62b
Application mycorrhiza	100.91a	69.53b	46.48c	72.31a
Average	63.87a	45.96b	32.56c	
HSD 0.05	Interaction (8.45)	Mycorrhiza (10.97)	Soil water content (3.30)	

Note: Numbers followed by the same letter are not significantly different based on the HSD test at 0.05 level.

CONCLUSIONS

The inoculation of mycorrhizal fungi in rice plants was found to enhance plant physiological processes, particularly phosphorus uptake efficiency, even under 60% soil water content, and to improve the net assimilation rate in the Inpari 32 and Inpari 42 rice varieties. These physiological enhancements contributed to improved morphological characteristics, including increased plant height (84.73 cm), dry biomass (8.36 g), number of panicles (15.83 panicles), panicle length (22.21 cm), number of grains per panicle (189.96 grains), and grain weight per clump (72.31 g).

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