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Persistent Mycorrhizal Colonization and Inorganic Fertilizer Effects on Morphological Traits of Liberica Coffee on Ultisol

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Abstract

Background: Liberica coffee (*Coffea liberica*) has considerable potential for cultivation on Ultisols, which are widely distributed across Indonesia. However, acidic soil pH, low cation-exchange capacity, and limited phosphorus availability restrict nutrient uptake and plant growth. Arbuscular mycorrhizal fungi can improve phosphorus uptake, water-use efficiency, and plant tolerance to environmental stress. Although mycorrhizal inoculation has been shown to promote the early growth of Liberica coffee, its long-term effectiveness under field conditions remains unclear. **Objective**: This study evaluated the interaction between mycorrhizal status and reduced inorganic fertilizer rates to support efficient and sustainable growth of Liberica coffee. **Methods:** A factorial randomized complete block design was used, consisting of two mycorrhizal treatments, namely non-inoculated (m0) and inoculated (m1), and six inorganic fertilizer rates ranging from 0, 20, 40, 60, 80, and 100% of the recommended dose. Observations included increases in plant height and stem diameter, number of leaves, number of primary branches, and mycorrhizal colonization. **Results:** Mycorrhizal status and inorganic fertilizer rate affected the morphological growth of Liberica coffee in Ultisol. Plants inoculated one year earlier maintained better growth, indicating that the mycorrhizal association remained functional after one year under field conditions. The best morphological growth of mycorrhizal plants was obtained at 60–80% of the recommended fertilizer dose, whereas non-mycorrhizal plants achieved their highest growth at 100%. **Conclusion:** Established mycorrhizal colonization remained effective in supporting Liberica coffee growth in Ultisol and enabled a 20–40% reduction in inorganic fertilizer without compromising morphological growth.

Keywords: Acidic Soils; Arbuscular Mycorrhizal Fungi; Nutrient Management; Phosphorus Uptake; Sustainable Agriculture

Cite This Article

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INTRODUCTION

Liberica coffee (Coffea liberica) is a plantation commodity with the potential for development on suboptimal lands in Indonesia. The plant exhibits relatively good adaptability to unfavourable environmental conditions, making it a viable alternative for expanding coffee cultivation areas. Ultisols, which are widely distributed across Indonesia, represent one type of soil with potential for such use. However, utilizing Ultisols for crop cultivation presents various challenges, including high soil acidity, low cation exchange capacity, and limited nutrient availability—particularly phosphorus, due to fixation by aluminium and iron (1, 2). These conditions hinder nutrient uptake, reduce fertilizer efficiency, and limit plant growth.

Efforts to improve crop productivity on Ultisols generally still rely on the application of relatively high doses of inorganic fertilizers. Although this can increase nutrient availability in the short term, the excessive use of inorganic fertilizers is inefficient and has the potential to degrade soil quality over the long term. Therefore, a nutrient management approach is needed that can enhance fertilizer use efficiency while simultaneously maintaining soil quality. One such approach is the utilization of arbuscular mycorrhizal fungi as biological agents within the plant root system.

Mycorrhizae form symbiotic relationships with roots and expand the absorption area through the development of external hyphae. This mechanism enables plants to acquire nutrients from soil zones inaccessible to roots alone—particularly phosphorus, which has low mobility in the soil (3, 4, 5, 6, 7). Beyond enhancing nutrient uptake, mycorrhizae play a role in improving soil structure (8), increasing water-use efficiency, and helping plants cope with abiotic and biotic stresses as well as heavy metal contamination (9–18). In Ultisols, which are characterized by high phosphorus fixation, the presence of mycorrhizae is crucial as it facilitates the mobilization and utilization of nutrients that were previously unavailable to the plants.

Various studies indicate that mycorrhizal plants can maintain good growth at lower inorganic fertilizer rates compared to non-mycorrhizal plants (6, 7, 19, 20, 21). This increased efficiency is attributed to the expansion of the root absorptive surface area, enhanced phosphatase activity in the rhizosphere, and improvements in nutrient mineralization and mobilization processes. Mycorrhizae can also help retain nutrients in the root zone and suppress nutrient loss through leaching (7). For certain crops, the presence of mycorrhizae allows for a 25–50% reduction in inorganic fertilizer use without compromising plant growth (4, 5, 6, 21, 22). These findings demonstrate the significant potential of mycorrhizae to reduce reliance on inorganic fertilizers within more efficient and sustainable cultivation systems.

Research by Kartika et al. (23) demonstrates that inoculation with mycorrhizae and plant growth-promoting bacteria enhances the early growth and adaptation of Liberica coffee in Ultisols. However, that research was limited to the initial growth phase, leaving the persistence of colonization and the effects of mycorrhizae during subsequent field growth unexplored. Furthermore, most prior studies were conducted during the nursery stage or involved the simultaneous application of inoculants and fertilizers. Information remains limited regarding the ability of mycorrhizae—established in the roots during the early phase—to persist and contribute to the growth and fertilizer-use efficiency of perennial crops.

Studying mycorrhizal persistence in Liberica coffee is important because the established symbiosis has the potential to endure as long as the plant's root system remains active. This persistence allows mycorrhizae to continue supporting nutrient uptake during the advanced vegetative phase and offers the possibility of reducing inorganic fertilizer dosages. However, the extent to which fertilizer application can be

reduced while still maintaining plant growth remains uncertain, particularly for Liberica coffee cultivated directly on Ultisol soils.

Based on these conditions, this study aims to evaluate the effects of mycorrhizal status and varying dosages of inorganic fertilizer on the growth of Liberica coffee during the advanced growth phase on Ultisol soil. The study also seeks to determine the extent to which inorganic fertilizer application can be reduced while still maintaining plant growth. Its novelty lies in evaluating the persistence of colonization and the effects of mycorrhizae—applied initially during the nursery stage—on the fertilization efficiency of established Liberica coffee plants in the field. The findings are expected to provide a scientific basis for developing more efficient and sustainable mycorrhiza-based fertilization technologies for suboptimal lands.

METHODS

Study design and setting

The research was conducted from June to July 2026 at the Teaching and Research Farm of the Faculty of Agriculture, University of Jambi (Jambi Luar Kota District, Muaro Jambi Regency), on Ultisol. The experiment employed 2 × 6 factorial Randomized Block Design. The first factor was mycorrhizal inoculation status: without inoculation (m0) and with inoculation starting from the seedling stage (m1). The second factor was the inorganic fertilizer dosage: 0, 20, 40, 60, 80, and 100% of the recommended dosage. There were 12 treatment combinations, each replicated three times, resulting in a total of 36 experimental units.

Population, samples and sampling

A total of 144 Liberica coffee plants were used, with four plants per experimental unit. Two plants were randomly selected from each experimental unit as sample plants, resulting in 72 plants being observed. The values from these two plants were averaged to represent a single experimental unit. The independent variables consisted of mycorrhizal inoculation status and inorganic fertilizer dosage, while the dependent variables included increases in plant height, stem diameter, number of leaves, total leaf area, number of primary branches, and percentage of root colonization.

Instruments and criteria

Plant height was measured using a tape measure and stem diameter using a vernier caliper, while the number of leaves and primary branches was determined by direct counting. Total leaf area was calculated using the formula: leaf length × leaf width × a constant. The increase in each variable was calculated as the difference between the final and initial values. Root colonization was observed using the method of Kormanik and McGraw (24), while the percentage of colonization was calculated based on the method of Giovannetti and Mosse (25).

Procedure and data collection

The plants used were inoculated with *Glomus* sp. 1a and *Glomus* sp. 3c (from the collection of Kartika et al. [26]) at a rate of 10 g per polybag, starting from the seedling stage. Inorganic fertilizers—specifically urea, SP-36, KCl, and kieserite—were applied according to treatment levels at full recommended dosages of 50, 40, 40, and 15 g per plant, respectively [27]. Growth observations were conducted over eight weeks, while root samples were collected at the end of the study to determine the percentage of mycorrhizal colonization.

Statistical analysis

The observational data are presented in the form of a graph, complete with standard deviations.

RESULTS

Increase in Coffee Plant Height

The height increase of Liberica coffee plants over eight weeks is presented in Figure 1. In plants without mycorrhizal inoculation, the height increase tended to rise with increasing inorganic fertilizer dosages, reaching a maximum at the 100% recommended dosage. Conversely, mycorrhiza-inoculated plants exhibited the greatest height increase at the 60% recommended dosage, followed by a slight decline at the 80% and 100% dosages.

At a fertilizer dosage of 60%, the height increase of mycorrhiza-inoculated plants was greater than that of non-inoculated plants at the same dosage. Descriptively, mycorrhiza-inoculated plants receiving 60–80% of the recommended fertilizer dosage exhibited height increases comparable to or greater than those of non-inoculated plants receiving the 100% dosage.

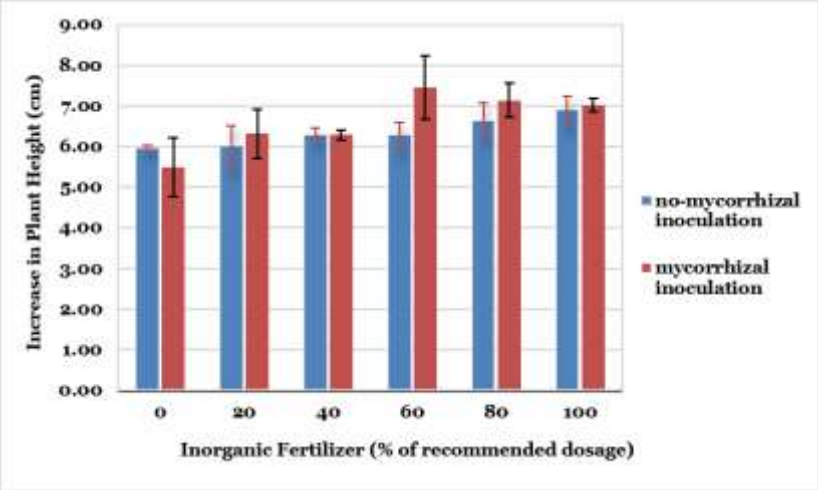

Figure 1. Height increase of Liberica coffee plants without and with mycorrhizal inoculation at various inorganic fertilizer dosages on Ultisol soil

Increase in Diameter

The increase in Liberica coffee stem diameter exhibited different response patterns depending on the mycorrhizal inoculation status (Figure 2). In non-inoculated plants, the increase in stem diameter tended to rise gradually with increasing fertilizer dosage, reaching its highest value at the dosage of 100% of the recommended rate.

In mycorrhiza-inoculated plants, the increase in stem diameter rose up to a fertilizer dosage of 80% of the recommended amount, then declined slightly at the 100% dosage. At dosages of 60% and 80%, the increase in stem diameter for inoculated plants was greater than that of non-inoculated plants at the same dosage levels. The values observed at the 60–80% dosages were also comparable to or higher than those of non-inoculated plants at the 100% dosage.

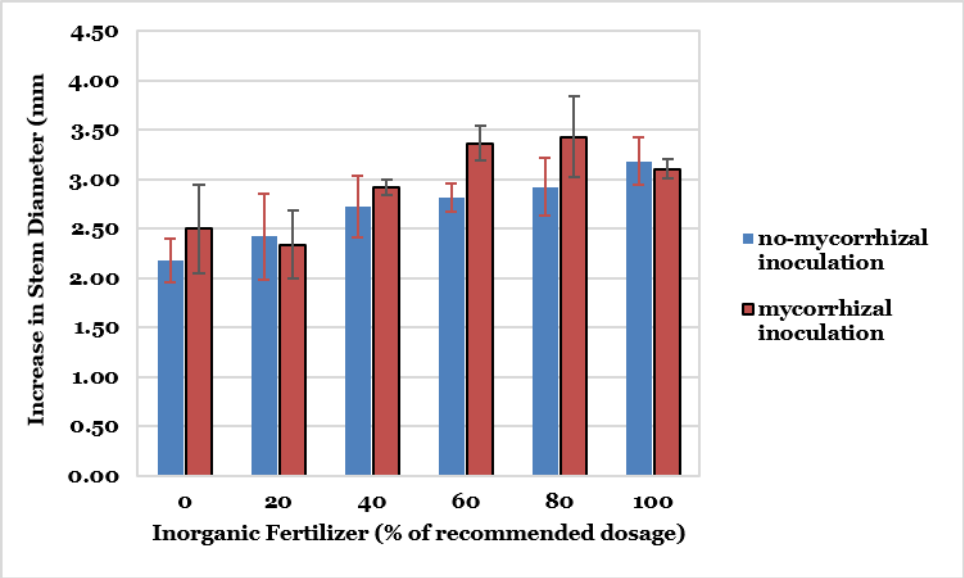

Figure 2. Increase in stem diameter of Liberica coffee plants without and with mycorrhizal inoculation at various inorganic fertilizer dosages on Ultisol soil

Increase in the Number of Leaves

The increase in the number of Liberica coffee leaves is presented in Figure 3. In plants without mycorrhizal inoculation, the increase in leaf number tended to rise with increasing fertilizer dosage, reaching relatively high values at dosages of 60–100% of the recommended rate.

In mycorrhiza-inoculated plants, the greatest increase in leaf number was observed at the 60% fertilizer dosage—a result relatively comparable to that of the 80% dosage—before declining at the 100% dosage. Inoculated plants also tended to exhibit a greater increase in leaf number compared to non-inoculated plants across nearly all fertilizer dosages, including the treatment with no inorganic fertilizer. Descriptively, the 60–80% dosage range in inoculated plants resulted in a higher increase in leaf number than the 100% dosage in non-inoculated plants.

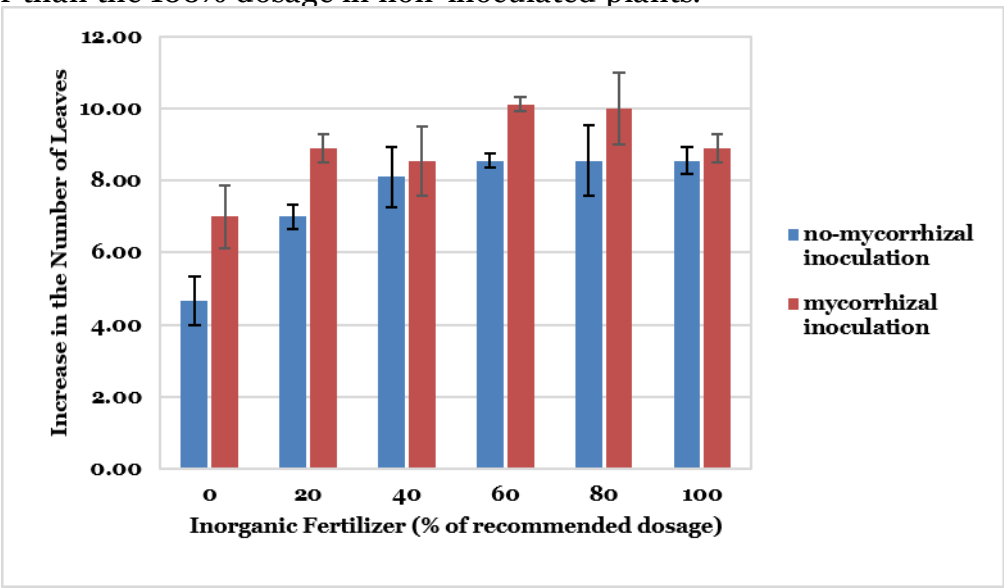

Figure 3. Increase in the number of leaves of Liberica coffee plants without and with mycorrhizal inoculation at various inorganic fertilizer dosages on Ultisol soil

Total Leaf Area Increase

The increase in total leaf area of Liberica coffee showed different response patterns between non-inoculated plants and those inoculated with mycorrhizae (Figure 4). In non-inoculated plants, the increase in total leaf area tended to rise with increasing fertilizer dosage, reaching its highest value at 100% of the recommended dosage.

In mycorrhiza-inoculated plants, the greatest increase in total leaf area was observed at a fertilizer dosage of 60% of the recommended rate, subsequently declining at dosages of 80% and 100%. The value at the 60% dosage was higher than that of non-inoculated plants at the same dosage or at the 100% dosage. Descriptively, the response of inoculated plants to increasing fertilizer dosages was non-linear, peaking at the 60% dosage.

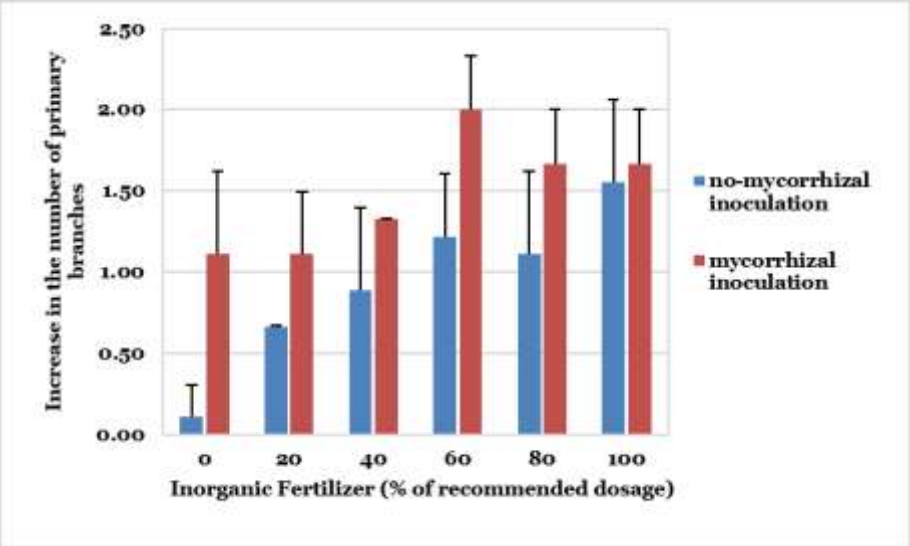

Figure 4. Increase in the number of primary branches of Liberica coffee plants without and with mycorrhizal inoculation at various inorganic fertilizer dosages on Ultisol soil

Increase in the Number of Primary Branches

The increase in the number of primary branches of Liberica coffee is presented in Figure 5. In plants without mycorrhizal inoculation, the number of primary branches tended to increase with the fertilizer dosage, reaching the highest value at the 100% recommended dosage.

In mycorrhiza-inoculated plants, the greatest increase in the number of primary branches was observed at a fertilizer dosage of 60% of the recommended rate, after which it tended to decline at dosages of 80% and 100%. The value at the 60% dosage was higher than that of non-inoculated plants at the same dosage or at the 100% dosage. Inoculated plants receiving no inorganic fertilizer also exhibited a greater increase in the number of primary branches compared to non-inoculated plants at the 0% dosage.

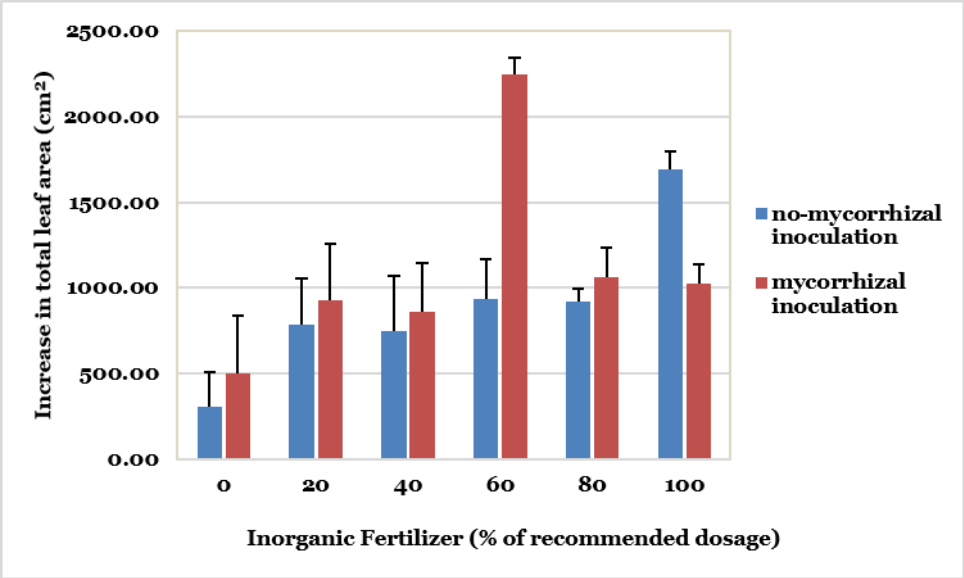

Figure 5. Increase in total leaf area of Liberica coffee plants without and with mycorrhizal inoculation at various inorganic fertilizer dosages on Ultisol soil

Root Colonization

The root colonization percentage of Liberica coffee showed a clear difference between non-inoculated plants and those inoculated with mycorrhizae across various inorganic fertilizer dosages (Figure 6). Non-inoculated plants exhibited root colonization of approximately 5–7% at all fertilizer dosages, whereas inoculated plants showed higher colonization, ranging from approximately 71% to 78%.

In inoculated plants, the highest level of colonization (based on descriptive data) was observed at fertilizer dosages of 40–80% of the recommended rate, whereas a slight decrease occurred at the 100% dosage. Changes in colonization resulting from increased fertilizer dosages were relatively minor compared to the differences observed between the two inoculation statuses.

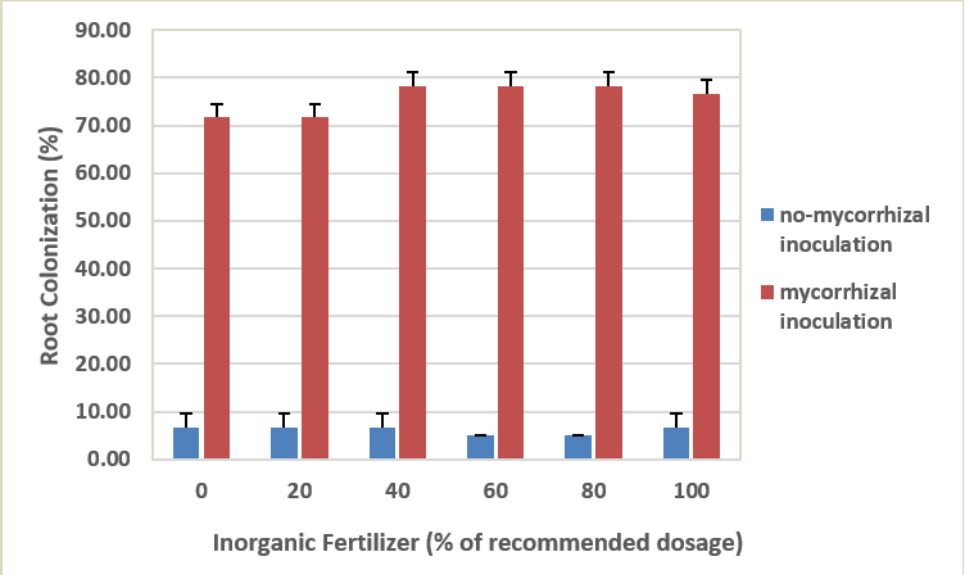

Figure 6. Root colonization of Liberica coffee plants without and with mycorrhizal inoculation at various inorganic fertilizer dosages on Ultisol soil

DISCUSSION

Vegetative Growth Response to Mycorrhizal Inoculation and Inorganic Fertilizer Dosage

In general, non-inoculated plants tended to achieve maximum vegetative growth at a 100% inorganic fertilizer dosage, whereas inoculated plants showed the best response at a dosage of 60–80%. This pattern was observed in increases in plant height, stem diameter, number of leaves, total leaf area, and number of primary branches. These differing response patterns indicate a likely relationship between mycorrhizal inoculation status and fertilizer dosage.

The superior growth response observed in inoculated plants is thought to be linked to the development of extraradical hyphae, which expand the soil volume accessible to the root system. This expansion of the absorptive surface area can enhance the acquisition of nutrients with low mobility—particularly phosphorus—while also supporting nitrogen (N) and potassium (K) uptake. In coffee plants, mycorrhizal inoculation combined with phosphate fertilization has been reported to increase shoot growth, leaf area, biomass, phosphorus content, and nutrient uptake (28–30). Inoculation with *Rhizophagus clarus* in several Arabica coffee genotypes also increased plant height and stem diameter and showed a correlation with root colonization and the accumulation of N, P, and K (31).

An increase in the number and surface area of leaves in inoculated plants can enhance the canopy's capacity to capture light and support biomass accumulation. Silveira et al. (32) demonstrated that the response of coffee seedlings to arbuscular mycorrhizal fungi is influenced by the type of isolate and the growth medium. Chialva et al. (33) also reported that mycorrhizal symbiosis stimulates the growth of Arabica coffee under low-phosphate conditions through the coordination of root and canopy responses. These findings support the hypothesis that sustained colonization in Liberica coffee contributes to vegetative organ development at lower fertilizer dosages.

Fertilizer Dosage and Mycorrhizal Effectiveness

The response of inoculated plants did not increase linearly with rising fertilizer dosages. Most parameters peaked at the 60% dosage, whereas stem diameter reached its maximum at the 80% dosage and subsequently tended to decline at the full dosage. Moreira et al. (34) reported that the benefits of arbuscular mycorrhizal fungi for coffee growth and leaf area depend on the phosphorus dosage and may diminish at higher phosphorus levels. Araújo et al. (2020) also demonstrated that coffee growth responses are determined by the combination of mycorrhizal inoculation and the form of phosphate fertilizer. Thus, increased nutrient availability does not necessarily enhance the relative benefits of the mycorrhizal symbiosis.

This trend aligns with the study by Kartika et al. (20) on Liberica coffee grown on peatland, which observed good growth using a combination of mycorrhiza and 50–75% of the standard inorganic fertilizer dosage. Further research also indicates that mycorrhiza application can support Liberica coffee production at lower fertilizer dosages (Kartika et al., 21). Since both studies were conducted on peatland, the results serve to support the observed biological trend rather than acting as a direct comparison with Ultisol conditions.

Root Colonization and Persistence of Mycorrhizal Associations

Root colonization levels of 71–78% in previously inoculated plants indicate that the mycorrhizal association was maintained after the plants had developed in the field. Conversely, the approximately 5–7% colonization observed in non-inoculated plants is attributed to indigenous arbuscular mycorrhizal fungi naturally present at the study site. Natural colonization in non-inoculated Liberica coffee plants has also been

reported by Kartika et al. (20), while Sariasih and Aditiawati (30) observed high root colonization in field-grown Arabica coffee and linked it to enhanced growth and nutrient uptake.

Extensive colonization potentially expands the absorptive surface area via extraradical hyphae, enabling the plant to acquire water and nutrients from zones beyond the immediate reach of the roots. These benefits are generally more pronounced under conditions of low phosphate availability (33–34). However, observations based on root staining merely confirm the presence of mycorrhizal structures; they cannot definitively establish that the entire colonization originated from the *Glomus* sp-1a and *Glomus* sp-3c strains applied during the seedling stage. Confirming the specific persistence of these isolates requires molecular identification.

Implications for Fertilizer Use Efficiency

Descriptive analysis shows that Liberica coffee plants inoculated with mycorrhizae and supplied with inorganic fertilizer at 60–80% of the recommended dosage exhibited vegetative growth comparable to or greater than that of non-inoculated plants receiving the full 100% dosage. This response was evident in metrics such as plant height, stem diameter, leaf count, total leaf area, and the number of primary branches. The 60% dosage yielded the most consistent responses across most variables, while the greatest increase in stem diameter among mycorrhizal plants was observed at the 80% dosage. This pattern indicates that sustained mycorrhizal colonization of the roots enables the plants to maintain growth despite lower fertilizer input levels.

This increased fertilization efficiency is thought to be linked to the ability of arbuscular mycorrhizal fungal extraradical hyphae to expand the soil volume explored by the root system. This expansion of the absorption zone enables the plant to acquire water and nutrients—particularly phosphorus, which has low mobility—from soil areas inaccessible to the roots alone. In field-grown Arabica coffee, endomycorrhizal inoculation has been reported to increase plant height, dry weight, and the uptake of N, P, and K compared to control plants. Other studies also indicate that mycorrhizal symbiosis coordinates root and shoot responses and stimulates coffee growth under conditions of low phosphate availability (30, 33).

In Ultisols, this role is crucial because a portion of the phosphorus applied via fertilizer can be adsorbed or fixed, rendering it unavailable to plants for immediate uptake. With an active hyphal network, mycorrhizal plants are thought to utilize soil nutrients and fertilizers more effectively. Araújo et al. (28) demonstrated that a combination of mycorrhizal inoculation and specific phosphate fertilizers increased leaf area, shoot and root biomass, and leaf phosphorus content in coffee plants. These results indicate that the plant response is determined not only by the quantity of fertilizer but also by the interplay between mycorrhizal colonization, fertilizer form, and nutrient release patterns.

The lack of increased growth when fertilizer dosage was raised to 80–100% indicates that the relationship between fertilizer and the benefits of mycorrhizae is not always linear. Under conditions of high phosphorus availability, plant reliance on the mycorrhizal uptake pathway may diminish. Moreira et al. (34) reported that the growth response of coffee to mycorrhizae depends on the phosphorus dosage, while Araújo et al. (28) found that the use of readily available phosphorus sources can reduce the percentage of root colonization. Therefore, increasing fertilizer application beyond the plant's sufficiency level does not necessarily yield proportional additional growth and may reduce the relative benefits of the mycorrhizal symbiosis.

From an agronomic perspective, the results of this study indicate a potential 20–40% reduction in inorganic fertilizer use for Liberica coffee plants inoculated with mycorrhizae during the nursery stage. These findings align with the study by Kartika et al. (21), which identified a combination of mycorrhizae and 50% of the standard inorganic fertilizer dosage as the optimal treatment for the production of intra- and inter-specifically grafted Liberica coffee on peatlands. Although soil conditions and plant ages differed between the studies, the results reinforce the potential of mycorrhizae as a nutrient management component for reducing reliance on inorganic fertilizers. Reducing fertilizer dosage has the potential to lower input costs and minimize the risk of nutrient loss due to non-uptake by the plants.

CONCLUSIONS

Mycorrhizal colonization established during the nursery phase persists in Liberica coffee roots during growth in Ultisol soils and is associated with superior morphological responses at lower inorganic fertilizer rates. Non-inoculated plants generally achieved maximum growth at a 100% inorganic fertilizer rate, whereas inoculated plants exhibited optimal vegetative growth at rates of 60–80%, with the most consistent response observed at the 60% rate. These results indicate that the persistence of mycorrhizal colonization has the potential to enhance inorganic fertilizer use efficiency, allowing for a 20–40% reduction in dosage without compromising the morphological characteristics of Liberica coffee grown in Ultisols.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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