Research Paper

Robustness of Soil Phosphorus Availability, Nutrient Dynamics, and Shallot Vegetative Growth Through Arbuscular Mycorrhizal Fungi (AMF) Inoculation

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Abstract

Phosphorus (P) is an essential plant nutrient and one of the most limiting in natural habitats as well as in agricultural production worldwide. Here, we present the experiment between shallot crops, AMF inoculated and without inoculation, to examine the impacts of the AMF symbiosis on soil phosphorus availability, nutrient dynamics, growth, and biomass. We used a Randomized Complete Block Design (RCBD) with 5 (Five) replicates. The findings show that AMF enhances Phosphorus availability, total Potassium, and C-organic matter, while not affecting total Nitrogen in the soil. The application of mycorrhiza significantly enhanced soil phosphorus availability, increasing from 30.56 ppm in non-inoculated soils to 40.81 ppm with mycorrhizal treatment, equivalent to an improvement of approximately 33%. Furthermore, AMF inoculation has affected the growth and biomass of shallots in the vegetative stage. The results revealed a significant growth-promoting effect of mycorrhizal fungi, with plant height increasing by ~23.7% (from 38.60 to 47.70 cm) and biomass nearly doubling, showing an increase of ~75.2% (from 18.15 to 31.78 g). Therefore, the utilization of AMF in Shallot cultivation is important for nutrient dynamics and vegetative growth.

Keywords *Phosphorus Availability, Nutrient Dynamics, Arbuscular Mycorrhizal, Shallot Growth*

INTRODUCTION

Shallot is a spice and economically valuable crop that is widely cultivated and consumed, particularly in Asia and Southeast Asia, including countries such as China, Vietnam, Indonesia, and Thailand. This bulb is characterized by its distinct reddish color and pungent flavor (Ratseewo et al., 2025). This plant has a distinctive flavour, making it a common ingredient in various dishes, soups, sandwiches, and salads (El-Sherbeny et al., 2022). However, shallot production in Indonesia has decreased due to several problems, including imbalanced nutrient availability and inappropriate soil fertility management practices (Aneseyee & Wolde, 2021; Arunachalam et al., 2024), as well as climate change causing abiotic stress conditions, particularly drought stress (Silva et al., 2023).

Phosphorus (P) is an essential macronutrient required for diverse cellular processes in plants, including bioenergetics, signal transduction, enzyme regulation, and the structural integrity of nucleic acids and phospholipids (Islam et al., 2025). Despite its critical role, P is often a limiting factor for crop productivity because of its inherently low solubility and mobility in soils (Peçanha et al., 2021). Consequently, large amounts of P fertilizers are routinely applied to sustain crop yields; however, plants typically utilize only 10–30% of the applied P during the cropping season, while the remainder is immobilized in the soil matrix or lost through leaching and runoff,

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contributing to eutrophication of aquatic ecosystems (Li et al., 2026; Sharma et al., 2021).

Arbuscular mycorrhizal fungi represent one of the most widespread and ecologically significant plant symbionts, colonizing the roots of approximately 80% of terrestrial plant species (Bowles et al., 2016; Shukla et al., 2025). Through the formation of extraradical hyphae, AMF extend beyond the rhizosphere, accessing pools of P otherwise unavailable to roots alone and delivering them to the host plant in exchange for photosynthetically derived carbon (Tran et al., 2022). Beyond physical exploration, AMF also enhance rhizosphere chemistry by secreting phosphatases and organic compounds that mobilize organic and mineral-bound P forms, thereby increasing the bioavailability of P in situ (Rubin & Görres, 2022). Recent studies demonstrate that AMF inoculation can significantly increase plant P uptake, biomass accumulation, and yield across diverse agroecosystems (Bitterlich et al., 2024; Qi et al., 2022).

However, the efficacy of AMF is strongly context-dependent, influenced by soil P status, chemical forms of P, plant species, and interactions with the native soil microbiome (Zhang et al., 2024). Under high-P fertilization regimes, plants often downregulate mycorrhizal pathways of P acquisition, resulting in reduced AMF colonization and benefits (Fan et al., 2024). Conversely, in low- to moderate-P soils, AMF colonization enhances P acquisition efficiency and plant growth, and promotes microbial community diversity (Bao et al., 2022). Incorporating AMF into shallot production systems thus offers a promising strategy to improve nutrient acquisition, reduce reliance on chemical fertilizers, and advance sustainable agricultural practices, with the conceptual framework highlighting the pathway from AMF root colonization and enhanced phosphorus uptake to improved nutrient dynamics, plant metabolism, and ultimately increased shallot growth (Figure 1).

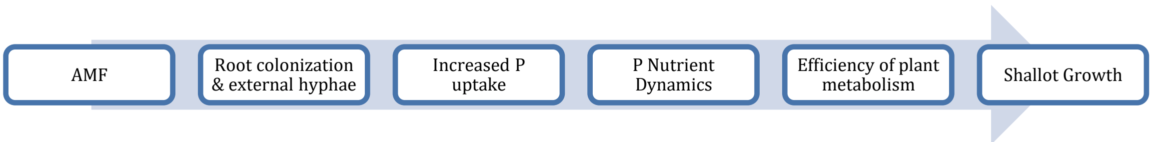

Figure 1. A Conceptual framework linking AMF mechanisms, nutrient dynamics, and plant growth

This study investigates the influence of arbuscular mycorrhizal fungi (AMF) inoculation on P availability and plant performance in shallot (*Allium cepa var. Aggregatum*) cultivation, with the broader objective of elucidating the potential contribution of AMF to improved soil P dynamics and sustainable crop production systems. Despite the well-documented role of AMF in enhancing nutrient acquisition and plant resilience, there is limited empirical evidence regarding their effectiveness in shallot-based agroecosystems, particularly under field conditions where soil fertility constraints often limit productivity. By addressing this gap, the present research seeks to provide insights into the mechanisms by which AMF may optimize nutrient use efficiency, enhance crop growth, and support the development of environmentally sound agricultural practices.

LITERATURE REVIEW

Soil physical and chemical characteristics strongly influence shallot growth and yield. Yeshiwas et al. (2024) reported that shallots perform optimally in sandy loam soils with good drainage, high organic matter content, and a pH of 6.2–7.0, conditions that promote efficient nutrient uptake and robust root development. These findings align with those of Torquato-Tavares et al. (2017), who identified four critical growth phases—pre-planting, vegetative, bulb formation, and maturation—each requiring a favorable soil environment for optimal productivity. In relation to nutrient dynamics, Islam et al. (2025) demonstrated through meta-analysis that converting natural ecosystems to cropland markedly increases soil phosphorus (P) availability, especially when fertilization is applied, elevating available and total P by 32.4% and 30.2%, respectively.

Complementary findings by Li et al. (2026) revealed that excessive P input and elevated pH enhance P desorption, underscoring the chemical complexity of P retention in soils. Beyond soil chemistry, arbuscular mycorrhizal fungi (AMF) play a central role in nutrient acquisition and plant resilience. Shukla et al. (2025) and Shi et al. (2021) demonstrated that AMF enhance P uptake and regulate nutrient cycling genes, while Pang et al. (2024) confirmed that hyphal-mediated P acquisition is highly efficient. Furthermore, Rui et al. (2022) highlighted the reciprocal nature of this interaction, where plants provide carbohydrates and lipids for fungal metabolism while benefiting from enhanced mineral nutrient absorption.

Building upon this foundation, the present study aims to elucidate the functional role of arbuscular mycorrhizal fungi (AMF) under controlled environmental conditions, taking into account soil type, texture, and the distinctive characteristics of tropical climates, in regulating soil nutrient dynamics—particularly the availability of phosphorus (P), potassium (K), and carbon (C). Furthermore, the study seeks to evaluate their consequent effects on the growth and productivity of shallots (*Allium cepa var. aggregatum*). A deeper understanding of these interactions will provide critical insights into the integration of mycorrhizal inoculation as a sustainable strategy to enhance soil fertility and crop performance within tropical agricultural systems.

RESEARCH METHOD

The experiment was performed with five replications, including both control (without mycorrhiza) and mycorrhiza-inoculated treatments, and a randomized complete block design (RCBD). Shallots were cultivated in polybags (30 cm × 30 cm) that contained 5 kg of sandy loam soil. We used Mycogrow as the AMF inoculum (produced by PT Agrofarm Nusa Raya), which contains five species of AMF (*Glomus claroideum, Glomus fasciculatum, Funneliformis mosseae, Glomus etunicatum, Aucolospora rogusa*). The polybags were routinely hydrated from transplantation until the vegetative stage. AMF was applied 1 day before transplanting with 12 g polybag−1. Additionally, we used NPK (16:16:16) fertilizer (3 g per polybag) in all treatments, as recommended by the Indonesian Ministry of Agriculture, to determine the optimal fertilizer dosage. The effects of mycorrhizal inoculation and without inoculation on the shallot cultivation were statistically analyzed with two-way ANOVA using IBM SPSS. At least 5replicates were used for each treatment of all measured parameters. The significance of the differences was calculated at a 5% level. Multiple comparisons were performed using Duncan's (HSD) post hoc test, $p < 0.05$.

FINDINGS AND DISCUSSION

Soil Nutrient Dynamics

The present findings demonstrate that mycorrhizal inoculation has a significant influence on soil nutrient dynamics, particularly with respect to phosphorus (P) availability, total potassium (K) content, and organic carbon accumulation, while leaving total nitrogen (N) content unchanged. This suggests that the symbiotic interaction between plant roots and mycorrhizal fungi plays a crucial role in enhancing the mobilization and uptake of specific essential nutrients, thereby contributing to improved soil fertility and nutrient cycling processes. The results provide valuable insights into how mycorrhizal inoculation can be strategically utilized to optimize soil nutrient management and enhance plant growth.

This study highlights the pivotal role of AMF in improving nutrient-use efficiency, thereby reducing dependence on external inputs such as chemical fertilizers. Similarly, enhanced potassium availability was likely driven by AMF-induced modifications in root exudation patterns and rhizosphere chemistry, which together created a more favorable environment for the solubilization and uptake of nutrients.

The most pronounced effect of mycorrhiza was observed in the increase of P availability, from 30.56 ppm in non-inoculated soils to 40.81 ppm under mycorrhizal treatment, representing a ~33% increase. This outcome aligns with a well-established body of evidence indicating that arbuscular mycorrhizal fungi (AMF) play a key role in facilitating phosphorus mobilization in soil (Shukla et al., 2025). Previous studies have shown that AMF consistently enhance labile P pools across diverse soils, with increases ranging from 20% to 40%, depending on the soil type and plant species (Qu et al., 2021).

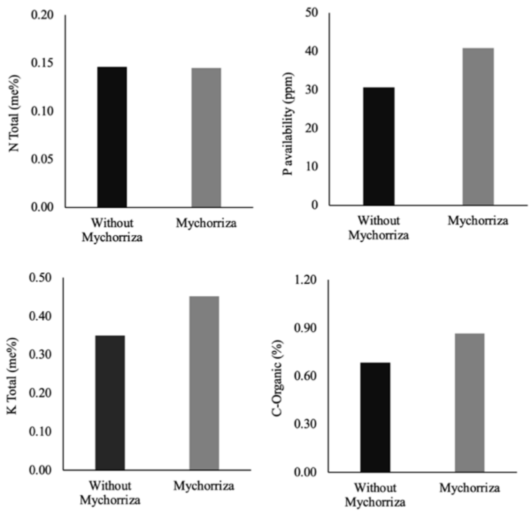

Figure 2. The soil nutrient dynamics affected by AMF inoculation

The magnitude of increase observed in the present study is therefore consistent with upper-range responses reported under nutrient-constrained conditions, highlighting the efficiency of mycorrhizal symbiosis in overcoming P limitation. Alongside phosphorus, total K increased from 0.35 me% to 0.45 me% under mycorrhizal treatment, equivalent to a 28% improvement. Previous research has highlighted that AMF contribute to K mobilization by releasing organic acids and by altering rhizosphere microbial communities that mediate mineral weathering (Etesami et al., 2021). Moreover, AMF can physically access K from interlayer positions in clay minerals through their extensive hyphal networks (Hnini et al., 2024).

Organic carbon content increased from 0.68 to 0.87 following mycorrhizal inoculation, reflecting an increase of nearly 28%. This finding corroborates recent large-scale analyses that identify mycorrhizal associations as major contributors to soil organic carbon (SOC) accumulation (Ma et al., 2025). Mechanistically, AMF contribute to SOC stabilization through the deposition of hyphal biomass, the secretion of glomalin—a glycoprotein that enhances soil aggregate stability—and stimulation of root exudation that fuels microbial activity and organic matter turnover (Li et al., 2026). This outcome is consistent with recent observations that AMF primarily influence nitrogen use efficiency and plant uptake, rather than altering total soil nitrogen pools (Bowles et al., 2016).

Growth and Biomass Analysis

The current results clearly demonstrate that inoculation with mycorrhizal fungi significantly enhances both plant height and biomass, with plant height increasing by ~23.7% (from 38.60 to 47.70 cm) and biomass by ~75.2% (from 18.15 g to 31.78 g). These findings align with and contribute to the growing body of literature highlighting the beneficial effects of arbuscular mycorrhizal fungi (AMF) on plant growth and development under various soil and environmental conditions (Huang et al., 2021).

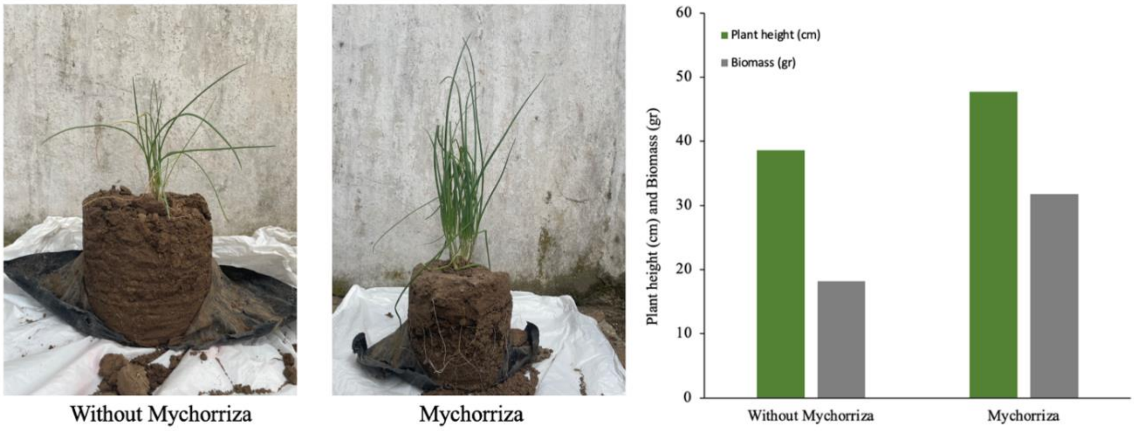

Figure 2. The Result of Growth and Biomass Analysis

Plant height is a widely recognized morphological indicator of growth performance, reflecting integrated responses to nutrient availability, water balance, and hormonal regulation. In this study, the increase of approximately 23.6% in plant height following mycorrhizal inoculation demonstrates the significant positive impact of AMF symbiosis. Recent studies have confirmed that AMF colonization promotes shoot elongation by enhancing the uptake of phosphorus (P) and other immobile nutrients, which are crucial for cell division and expansion (Huang et al., 2021). Furthermore, AMF are known to modulate phytohormone levels, particularly auxins and gibberellins, which directly stimulate stem elongation and internode expansion (Begum et al., 2020). The significant increase in biomass observed in this study (a 75.1% enhancement with mycorrhiza) highlights the profound contribution of AMF symbiosis to plants.

Enhanced biomass accumulation in AMF-associated plants is strongly linked to improved nutrient acquisition, particularly P and N. For instance, soybean plants inoculated with AMF showed biomass increases exceeding 60% compared with controls, attributed to superior P acquisition and root morphological adjustments (Alotaibi et al., 2023). Similarly, wheat biomass under saline stress conditions improved significantly with AMF inoculation due to improved ionic balance and antioxidative enzyme activity (Pooja et al., 2025).

CONCLUSIONS

This study demonstrates that mycorrhizal inoculation significantly enhances soil nutrient dynamics and plant growth. Inoculated plants showed greater phosphorus and potassium availability, accompanied by increased height and biomass compared with non-inoculated controls. These effects reflect the ability of arbuscular mycorrhizal fungi (AMF) to improve nutrient uptake efficiency and optimize carbon allocation, thereby promoting overall plant vigor. Beyond productivity gains, AMF inoculation supports soil fertility and sustainability by reducing reliance on synthetic fertilizers.

LIMITATIONS & FURTHER RESEARCH

Despite the promising results, this study has certain limitations. This study was conducted under specific soil and climatic conditions that may not fully represent the complexity and variability of heterogeneous agroecosystems. Consequently, the findings should be interpreted within the context of these environments. Addressing these uncertainties is essential for evaluating the consistency and scalability of AMF-mediated benefits across diverse agricultural environments. Future research should therefore focus on large-scale, multi-environment field trials to validate

AMF performance under variable soil types and climatic regimes.

Further investigations into the mechanisms of stress tolerance—particularly under drought, salinity, and temperature fluctuations—will be essential for optimizing inoculant formulations and ensuring their effective and widespread application in sustainable crop production.

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