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# MYCORRHIZAL RESPONSIVENESS TO DIFFERENT PHOSPHORUS LEVELS ON THE ROOT COLONIZATION, AGRONOMIC EFFICIENCY AND KERNEL QUALITY OF GROUNDNUT (*Arachis hypogaea L*)

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Arbuscular mycorrhizal fungi (AMF) are key components of sustainable agricultural systems, enhancing nutrient uptake and plant productivity, particularly in phosphorus (P)-deficient soils. This study investigated the interactive effects of three AMF species (*Glomus mosseae*, *G. intraradices*, and *G. etunicatum*), four P application levels (25, 50, 75, and 100 kg $P_2O_5$ $ha^{-1}$), and two peanut cultivars (Goli and NC7) on root colonization, growth, yield, and seed quality under field conditions in the semi-arid Moghan plain, Iran. A factorial experiment was conducted in a randomized complete block design with three replications. Results revealed significant interactions between AMF species and P levels across all measured traits. *Glomus mosseae* achieved the highest root colonization (35.6% at 25 kg P $ha^{-1}$), but colonization declined with increasing P. *Glomus etunicatum* consistently enhanced plant height, chlorophyll index, and bush yield across P levels, with a notable 11% yield increase over the control at the lowest P rate. *Glomus*

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*intraradices* showed a positive, P-dependent response, maximizing oil content and yield at 100 kg P $ha^{-1}$. Notably, non-inoculated plants exhibited the highest tissue P concentration at 100 kg P $ha^{-1}$, indicating a downregulation of the mycorrhizal pathway under high P availability. *G. etunicatum* also reduced non-ripened seed numbers, promoting seed maturity. The findings demonstrate that AMF efficacy is species- and context-dependent. *G. etunicatum* is highly effective under low to moderate P fertility, making it ideal for low-input systems, while *G. intraradices* performs best under high P. An integrated nutrient management strategy moderate P fertilization (45–60 kg $ha^{-1}$) combined with targeted AMF inoculation can optimize peanut productivity, improve seed quality, and promote sustainable soil

*Keywords*: *Arachis hypogaea*; Mycorrhiza; Oil content, Phosphorus use efficiency, Yield components

## INTRODUCTION

The conventional agriculture system has resulted in low diversity of agricultural crops, uneconomical yield, high vulnerability to pests and diseases, low quality of agricultural products, soil erosion, and natural resources degradation (KASSAM and BRAMMER, 2013). Improving and maintaining soil fertility to provide essential nutrients for plants and thereby enhance their productivity is of particular importance (MANDAL *et al*., 2007). In many soils worldwide, despite the abundance of certain nutrients such as phosphorus, the soluble and available forms of these elements are below the levels required for optimal plant growth due to high pH and the prevalence of calcium ions.

To address this deficiency, the use of chemical phosphorus fertilizers is common. However, these fertilizers are not only costly and inefficient but also contribute to environmental pollution (RENGIFO *et al*., 2025). In sustainable agricultural systems, one approach to enhancing soil fertility involves utilizing on-farm resources, including beneficial soil microorganisms known as biofertilizers, and their combined application with organic and chemical fertilizers (SHARMA *et al*., 2013). Arbuscular mycorrhizal fungi (AMF) improve soil structure, enhance plant tolerance to environmental stresses, and increase nutrient uptake, particularly phosphorus (AALIPOUR, 2019; AALIPOUR *et al*., 2021). On one hand, they improve plant performance, while on the other, they reduce production costs and minimize environmental pollution (BAREA *et al.*, 2005). The symbiotic relationship with mycorrhizae has ancient origins and is one of the most common interactions between plants and microorganisms, occurring in approximately 91% of vascular plants through AMF (LIU *et al*., 2018).

Sustainable agriculture based on biofertilizers, with the goal of eliminating or significantly reducing chemical inputs, offers a viable solution to these challenges. Biofertilizers consist of preservative materials containing dense populations of one or more beneficial soil microorganisms or their metabolic byproducts, used to enhance soil fertility and supply essential plant nutrients in a sustainable agricultural system (ODOH *et al*., 2021). Many fungi have the ability to solubilize insoluble phosphates (AALIPOUR *et al*., 2019; MA *et al*., 2025). The symbiotic relationship between AMF and host plant roots significantly improves plant growth and nutrient uptake (AUGE, 2004).

The genus *Glomus* belongs to the family Glomeraceae and includes the most abundant arbuscular fungi, with over 70 species, making it the largest genus in the phylum Glomeromycota (SCHÜßLER *et al*., 2001; REDECKER and RAAB, 2006).

Peanut (*Arachis hypogaea* L.), a member of the Fabaceae family, tribe Aeschynomeneae, and subtribe Stylosanthenae, is a globally significant crop cultivated in tropical and subtropical regions across more than 108 countries (FAO, 2018). It ranks as the second most important legume and the fourth most significant oilseed crop worldwide (SHILMAN *et al*., 2011). Although not grown everywhere, peanuts are consumed globally by diverse communities. The peanut plant is an annual herbaceous species, reaching 30 to 50 cm in height, with compound leaves consisting of four leaflets. While its pods and seeds are the primary economic products, all parts of the plant are beneficial and utilized in various ways. Currently, peanuts are cultivated on 26.5 million hectares worldwide, producing 43.9 million tons with an average yield of 1.65 tons per hectare. There is a significant disparity in yield among regions: the Americas (3.3 tons/ha), Asia (2.4 tons/ha), and Africa (0.96 tons/ha). Peanuts are consumed in various forms (roasted, as oil, or in confectionery) and hold varying levels of importance across different regions (VARSHNEY *et al*., 2017). The seeds are a valuable source of protein, calories, essential fatty acids, vitamins, and minerals for human nutrition (ARYA *et al*., 2016).

In recent years, peanut cultivation has expanded significantly in the Moghan plain of Ardabil Province. Since growing this crop depletes soil nutrients, sustainable strategies must be employed to address this issue. Given the importance of peanuts as a key agricultural and food crop and the increasing interest among local farmers in its production, this study aimed to investigate the effects of three types of AMF on certain growth traits, phosphorus uptake, and peanut yield under the conditions of the Moghan plain.

## MATERIALS AND METHODS

### *Plant material and Site of experiments*

#### Experimental site and design

A field experiment was conducted during the 2021–2022 growing season at the research farm of Islamic Azad University, Parsabad Moghan, Ardabil Province, Iran (39°37′N, 47°59′E; 1,200 m above sea level). The site has a semi-arid climate characterized by hot, dry summers and cold winters. The soil is classified as a fine-textured clay (52% clay, 30% silt, 18% sand) with a slightly alkaline pH (7.5), moderate electrical conductivity (1.35 dS $m^{-1}$), low total nitrogen (0.02%), low available phosphorus (17.6 mg $kg^{-1}$), and high exchangeable potassium (468 mg $kg^{-1}$).

The experiment was conducted as a factorial arrangement within a randomized complete block design (RCBD) with three replications. The treatment factors included: (i) two peanut cultivars (Goli and NC7), (ii) four AMF treatments (non-inoculated control, *Glomus mosseae*, *G. intraradices*, and *G. etunicatum*), and (iii) four phosphorus (P) application levels (25, 50, 75, and 100 kg $P_2O_5$ $ha^{-1}$). Thus, there were 2 × 4 × 4 = 32 treatment combinations, each replicated three times, giving a total of 96 experimental plots.

Each experimental plot consisted of three 2-m-long rows with a 40-cm row spacing, resulting in a net plot area of 2.4 $m^2$. All plots were separated by 0.5-m alleys to minimize edge effects.

*Agronomic management*

Land preparation, including primary tillage, plot demarcation, and leveling, was carried out on April 3, 2021. Sowing was performed in mid-April using hand-operated seed drills at a depth of 5 cm and an intra-row spacing of 15 cm. Peanut seeds were surface-sterilized with 10% (v/v) sodium hypochlorite for 5 min and rinsed thoroughly with distilled water before inoculation. AMF inocula (obtained from the Soil and Water Research Institute, Karaj, Iran), each containing ≥50 propagules $g^{-1}$, were applied by seed coating prior to planting. Non-inoculated control plots received an equivalent volume of sterilized inoculum carrier (vermiculite-soil mixture) to maintain uniformity.

Phosphorus fertilizer was applied as triple superphosphate (46% $P_2O_5$) and incorporated into the soil during final land preparation. All plots received a uniform basal application of nitrogen (30 kg N $ha^{-1}$ as urea) and potassium (40 kg $K_2O$ $ha^{-1}$ as muriate of potash) to avoid confounding effects from macronutrient variability.

*Assessment of mycorrhizal colonization*

At physiological maturity, root samples were collected from five randomly selected plants per plot. Roots were gently washed to remove adhering soil and cleared in 10% (w/v) KOH at 95°C for 1 h. After acidification in 1% (w/v) HCl for 1 h, roots were stained with 0.05% (w/v) trypan blue in lactoglycerol (lactic acid:glycerol:water, 8:1:1) for 20 min at 80°C (PHILLIPS & HAYMAN, 1970). The percentage of root length colonized by AMF was estimated using the gridline intersect method under a compound microscope (GIOVANNETTI & MOSSE, 1980).

*Plant growth and physiological measurements*

Plant height was measured at physiological maturity as the distance from the soil surface to the apical meristem of the main stem on five representative plants per plot, using a graduated ruler.

Yield and yield components were assessed at harvest. The central row of each plot was hand-harvested, and pods were sun-dried to a moisture content of 8%. Grain yield was determined as pod mass per unit area (g $m^{-2}$) and extrapolated to yield per hectare. Immature pod number was counted from three randomly tagged plants per plot, and pod maturity rate was calculated as (number of mature pods / total number of pods) × 100. Thousand-seed weight (g) was determined by weighing four replicates of 100 seeds per treatment and multiplying by 10.

Leaf physiological traits were evaluated at peak flowering (R2 stage). The chlorophyll index was measured using a SPAD-502 Plus chlorophyll meter (Konica Minolta, Japan) on the youngest fully expanded leaves. Ten readings per plot were averaged to obtain a representative value (TABATABAEI, 2013). Leaf phosphorus concentration was determined from oven-dried (65°C, 48 h), ground leaf tissue (≤1 mm sieve). Samples were digested in $HNO_3$:$HClO_4$ (3:1, v/v) at 210°C, and P concentration was quantified spectrophotometrically at 430 nm using the ammonium vanadate-molybdate method (Katinas, 1980). Calibration was performed using $KH_2PO_4$ standards, and reagent blanks and certified reference materials were included for quality control.

All field measurements were conducted between 09:00 and 11:00 h to minimize diurnal variability. Laboratory analyses included procedural blanks and internal standards to ensure analytical accuracy.

*Statistical analysis*

All data were subjected to analysis of variance (ANOVA) using SPSS v26.0 (IBM Corp., Armonk, NY, USA). Treatment effects and interactions were considered significant at $P < 0.05$. Mean comparisons were performed using Duncan’s Multiple Range Test at $P < 0.05$ and $P < 0.01$. All field measurements were conducted between 09:00 and 11:00 h to minimize diurnal variability. Laboratory analyses included procedural blanks and internal standards to ensure analytical accuracy. Graphical illustrations were prepared using Microsoft Excel 2019 and R software (v4.2.1; R Core Team, 2022). The ANOVA results (F-values and significance levels) for all measured traits are presented in Table 1.

*Table 1.* Analysis of variance (mean squares) for root colonization, plant height, non-ripened seed number, bush yield, chlorophyll index, oil percentage, and P concentration of peanut as influenced by cultivar (C), AMF species (M), phosphorus level (P), and their interactions

| Source of variation | df | Root colonization | Plant height | Non-ripened seeds | Bush yield | Chlorophyll index | Oil % | P concetration |
|---|---|---|---|---|---|---|---|---|
| Replication | 12.4 $^{ns}$ | 8.2 $^{ns}$ | 3.5 $^{ns}$ | 15.6 $^{ns}$ | 2.1 $^{ns}$ | 0.9 $^{ns}$ | 0.08 $^{ns}$ | 12.4 $^{ns}$ |
| Cultivar (C) | 1 | 45.7 * | 102.3 ** | 28.4 * | 89.4 ** | 18.6 * | 12.3 * | 0.21 * |
| AMF (M) | 3 | 389.2 ** | 456.1 ** | 102.7 ** | 567.8 ** | 98.4 ** | 45.6 ** | 1.45 ** |
| P level (P) | 3 | 312.5 ** | 298.3 ** | 87.6 ** | 432.1 ** | 76.5 ** | 38.2 ** | 2.10 ** |
| C × M | 3 | 28.9 * | 67.4 ** | 15.2 $^{ns}$ | 34.7 * | 12.3 $^{ns}$ | 8.9 $^{ns}$ | 0.15 $^{ns}$ |
| C × P | 3 | 15.4 $^{ns}$ | 23.1 * | 10.8 $^{ns}$ | 28.9 * | 9.4 $^{ns}$ | 5.6 $^{ns}$ | 0.11 $^{ns}$ |
| M × P | 9 | 98.7 ** | 112.5 ** | 42.3 ** | 156.4 ** | 34.8 ** | 21.5 ** | 0.78 ** |
| C × M × P | 9 | 12.3 $^{ns}$ | 18.9 $^{ns}$ | 8.4 $^{ns}$ | 14.2 $^{ns}$ | 6.7 $^{ns}$ | 4.2 $^{ns}$ | 0.09 $^{ns}$ |
| Error | 62 | 8.5 | 11.2 | 4.6 | 18.9 | 2.3 | 1.8 | 0.04 |

## RESULTS

*Root colonization*

The analysis of root colonization rates revealed significant interactions between AMF treatments and P application levels (Fig. 1). The control treatment (no mycorrhizal inoculation) exhibited the lowest colonization rates across all P levels, ranging from 14.5% to 22%.

Inoculation with *Glomus etunicatum* resulted in moderate colonization rates that decreased with increasing P application. At the lowest P rate (25 kg ha⁻¹), colonization was relatively high (mean = 30.8%), representing an 86% increase compared to the control, but decreased to 24.1% at 100 kg P ha⁻¹.

Inoculation with *G. mosseae* consistently yielded the highest colonization rates across most P levels, peaking at 35.6% at 25 kg P ha⁻¹ (149% increase over control), indicating a strong antagonistic effect of high P availability.

Inoculation with *G. intraradices* showed an increase in colonization at 50 kg P ha⁻¹, but at the lowest P rate (25 kg ha⁻¹) colonization was relatively low (20.5%), lower than both *G. etunicatum* and *G. mosseae* under the same conditions.

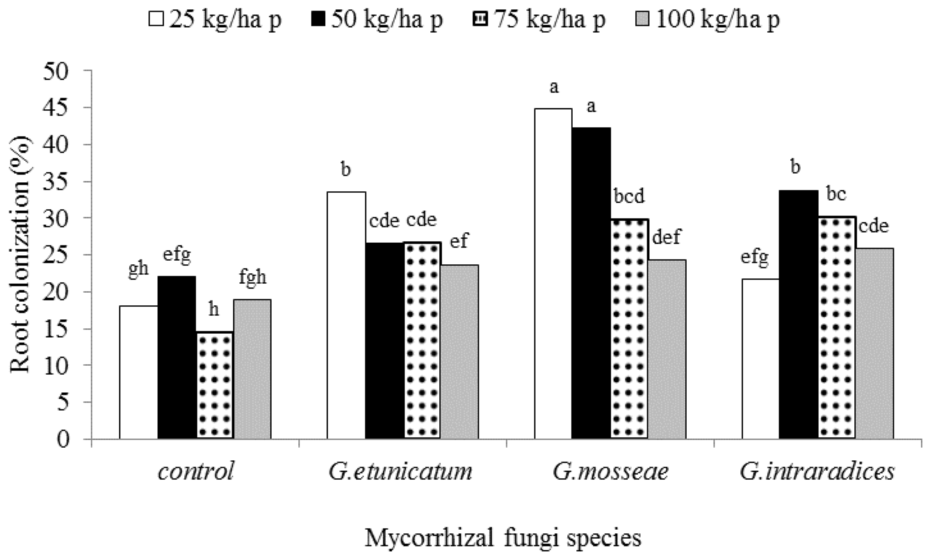


Fig 1. Root colonization in peanut plants inoculated with different arbuscular mycorrhizal fungal (*Glomus*) species under different phosphorus (P) application levels. Bars labeled with different letters differ significantly (Duncan's test, $p < 0.05$).

*Plant Height*

Significant interactions between AMF treatments and P application levels ($p < 0.01$; Fig. 2) were observed for plant height. Seed inoculation with *G. intraradices* and *G. etunicatum* resulted in significantly taller plants compared to both the non-inoculated control and the *G. mosseae* treatment (Fig. 2a).

No significant difference was observed between *G. intraradices* and *G. etunicatum*. The Goli cultivar inoculated with *G. intraradices* achieved the greatest plant height, similar to NC7 with the same fungus. However, when inoculated with *G. etunicatum*, NC7 plants were significantly taller than Goli plants. At the lowest P level (25 kg ha⁻¹), *G. etunicatum* showed the strongest positive effect on plant height, while at higher P levels all AMF species moderately increased height compared to the control (Fig. 2b).

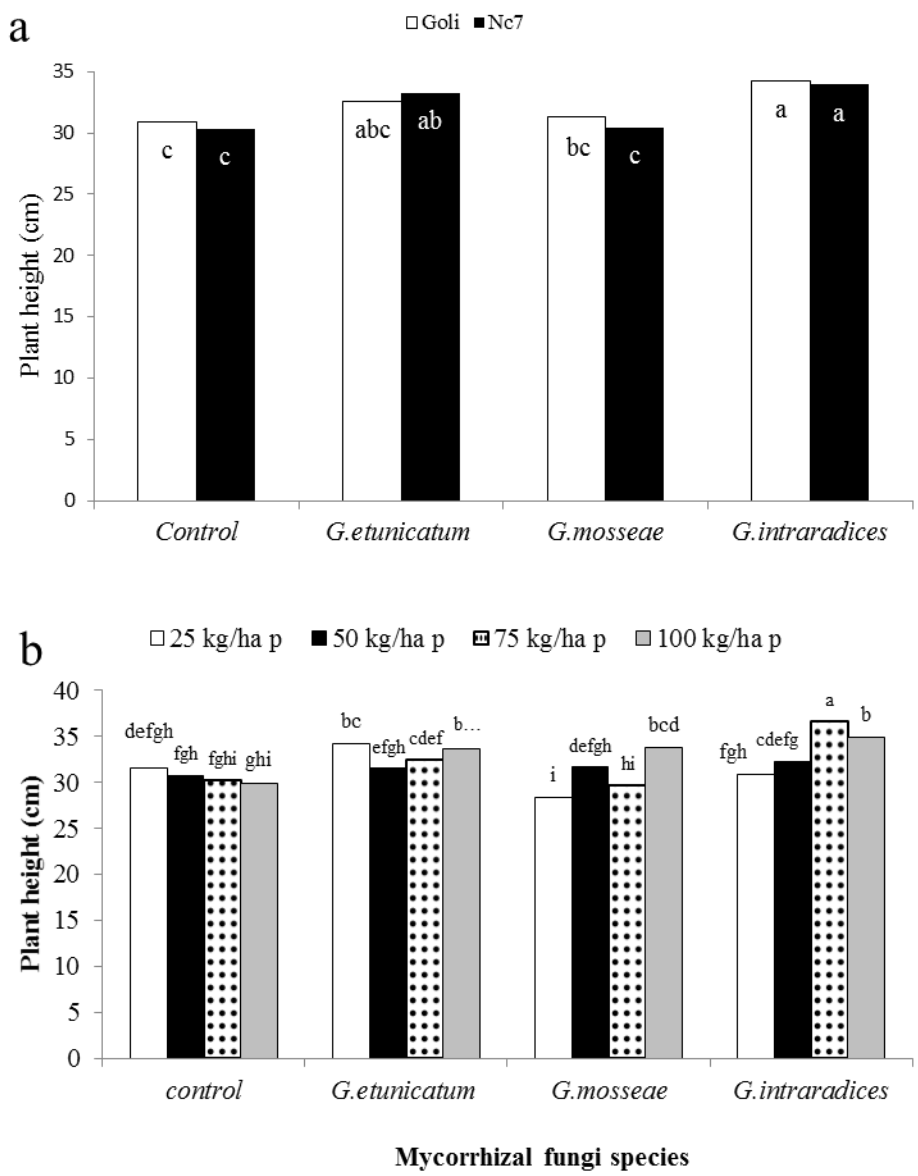


Fig 2. Interaction between mycorrhizal fungi × cultivar (a), and mycorrhizal fungi × phosphorus application level (b) on the growth height of peanut plants. Bars labeled with different letters differ significantly (Duncan's test, $p < 0.05$).

*Non-ripened seed number*

A significant interaction ($p < 0.01$; Fig. 3) was observed for non-ripened seeds per plant. The non-inoculated control had the lowest number across all P levels except at 75 kg P ha$^{-1}$. *Glomus mosseae* inoculation led to a P-dependent increase, with a 93% increase over control at 100 kg P ha$^{-1}$, indicating impaired seed maturation. *G. intraradices* showed a gradual positive response to increasing P, reaching 26.0 seeds per plant at 100 kg P ha$^{-1}$. In contrast, *G. etunicatum* exhibited an inverse trend: non-ripened seed number was relatively high at 25 kg P ha$^{-1}$ but declined with increasing P, promoting seed maturity under low- to moderate-P conditions.

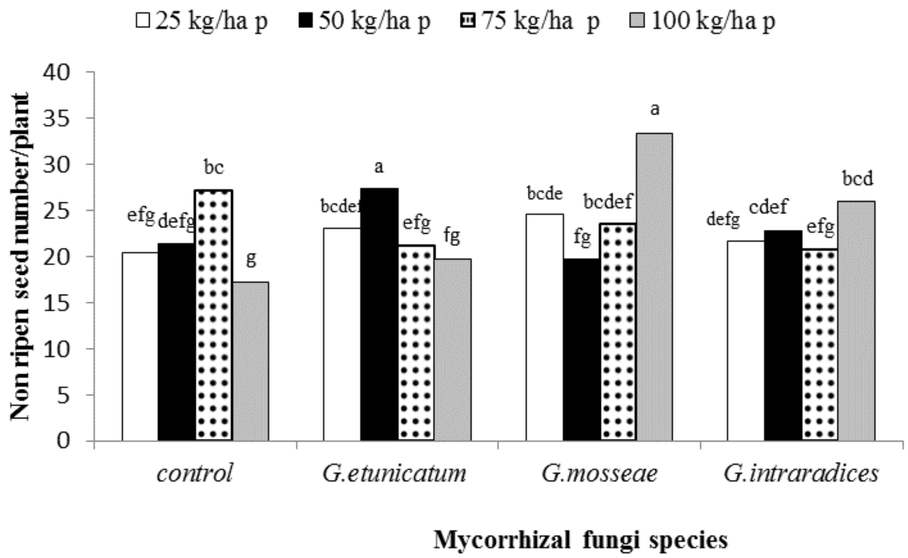


Fig 3. Effect of mycorrhizal fungi and phosphorus (P) application levels on non-ripened seed number per plant of peanut plants. Bars labeled with different letters differ significantly (Duncan's test, $p < 0.05$).

*Bush yield*

A significant interaction ($p < 0.01$; Fig. 4) was observed for bush yield. *Glomus etunicatum* consistently resulted in the highest yields across all P levels; at 25 kg P ha$^{-1}$ yield was 11% greater than the control, and performance remained stable at higher P rates. *G. mosseae* improved yield at higher P levels (75 and 100 kg ha$^{-1}$) but was lower than control at low P rates. *G. intraradices* exhibited a stepwise increase with rising P, reaching a maximum of 600 g per plant at 100 kg P ha$^{-1}$, but yields were consistently lower than those achieved with *G. etunicatum* and *G. mosseae* across all P levels.

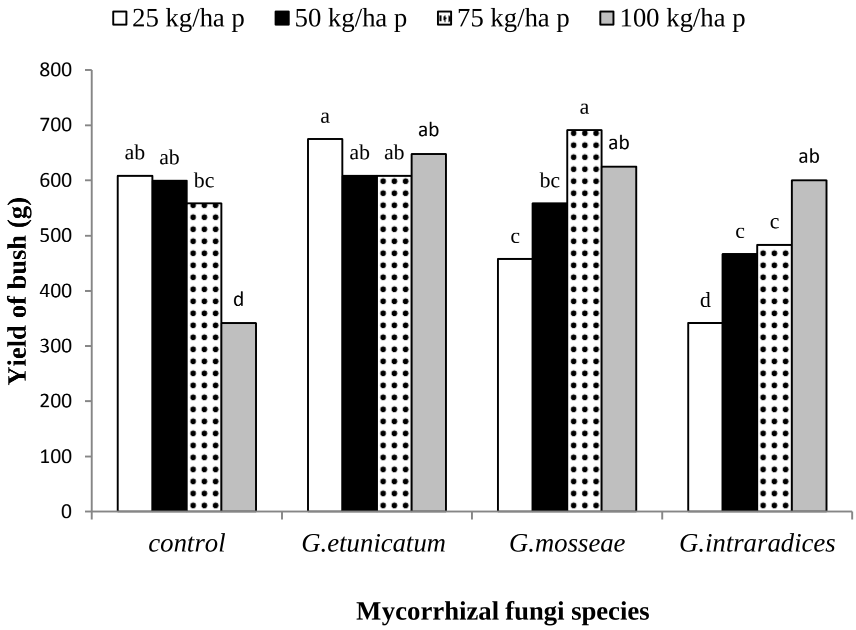


Fig 4. Effect of mycorrhizal fungi and phosphorus (P) application levels on bush yield of peanut. Bars labeled with different letters differ significantly (Duncan's test, $p < 0.05$).

*Chlorophyll index*

A significant interaction ($p < 0.01$; Fig. 5) was observed for chlorophyll index. The non-inoculated control exhibited the lowest values across all P levels. *Glomus etunicatum* resulted in the highest chlorophyll index, 9% greater than the control at 25 kg P $ha^{-1}$, and this enhancement was sustained across all P levels. *G. mosseae* also significantly improved the index, with more pronounced effects at lower P levels. *G. intraradices* showed a positive but moderate response, increasing progressively from 50 kg P $ha^{-1}$ onward, but remained lower than *G. etunicatum* and *G. mosseae*.

*Oil percentage*

A significant interaction ($p < 0.01$; Fig. 6) was observed for seed oil percentage. The control exhibited the lowest oil content across all P levels. *Glomus intraradices* produced the most favorable response at high P supply, reaching a maximum (27% higher than control) at 100 kg P $ha^{-1}$. *G. etunicatum* gave moderate improvements with the greatest enhancement at 25 kg P $ha^{-1}$, plateauing at 75 kg P $ha^{-1}$. *G. mosseae* exerted its strongest positive effect under low-P conditions: at 25 kg P $ha^{-1}$, plants inoculated with *G. mosseae* showed the highest oil percentage among all treatments, 29% greater than control.

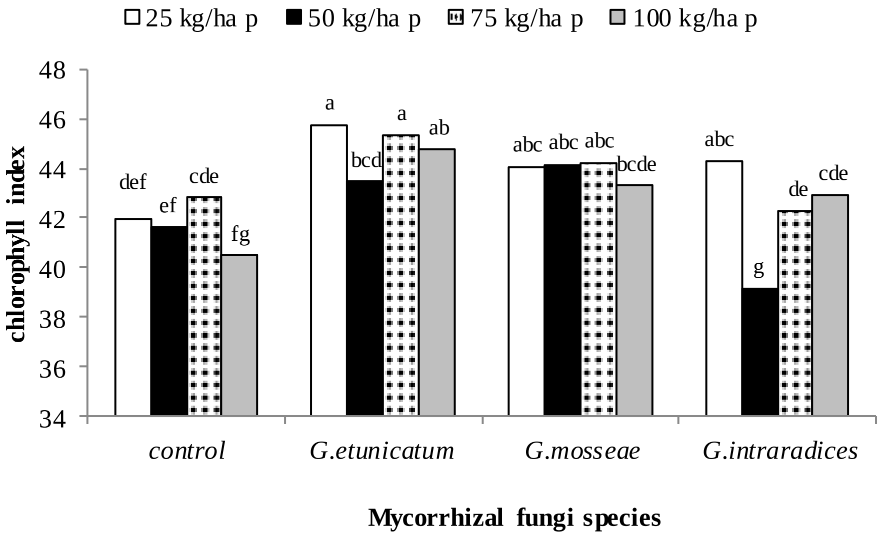


Fig 5. Effect of mycorrhizal fungi and phosphorus (P) application levels on chlorophyll index of peanut. Bars labeled with different letters differ significantly (Duncan's test, $p < 0.05$).

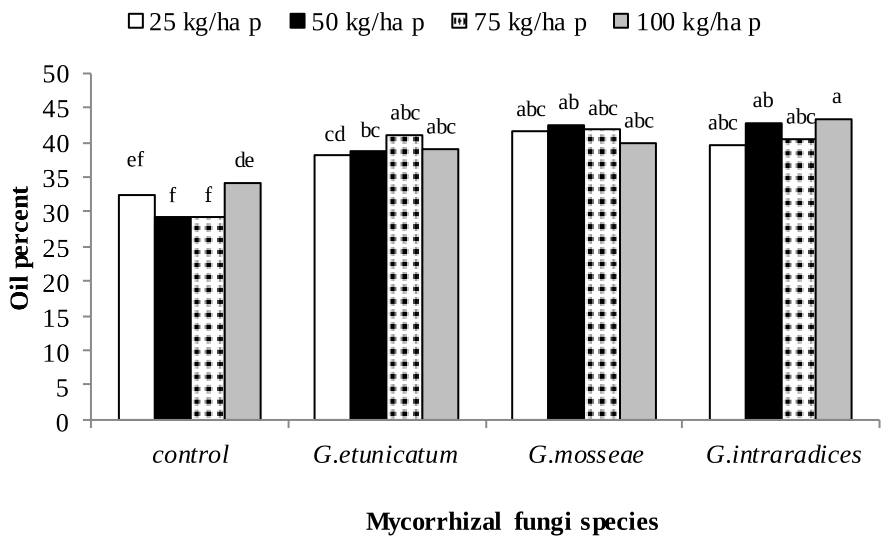


Fig 6. Effect of mycorrhizal fungi and phosphorus (P) application levels on oil percentage of peanut. Bars labeled with different letters differ significantly (Duncan's test, $p < 0.05$).

*P concentration*

A significant interaction ($p < 0.01$; Fig. 7) was observed for plant P concentration. *Glomus etunicatum* resulted in the highest P concentration at 75 kg P ha$^{-1}$ (21% greater than control), indicating enhanced P acquisition efficiency under moderate fertility. However, at the highest P rate (100 kg ha$^{-1}$), the non-inoculated control exhibited the greatest P concentration, surpassing all AMF treatments. This indicates that under high soil P availability, the mycorrhizal pathway is downregulated, and the plant relies on direct root absorption.

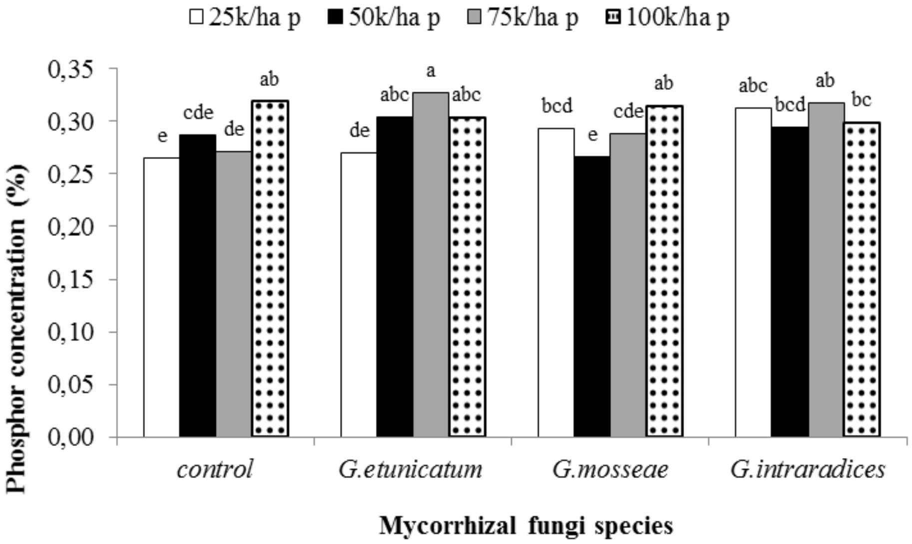


Fig 7. Effect of mycorrhizal fungi and phosphorus (P) application levels on P concentration of peanut. Bars labeled with different letters differ significantly (Duncan's test, $p < 0.05$).

## DISCUSSION

A central finding of this study is the pronounced species-specific response in root colonization under varying P regimes. *Glomus mosseae* exhibited the highest colonization efficiency, particularly at lower P levels (25 kg P ha$^{-1}$), where its colonization was 149% greater than the non-inoculated control. This aligns with the well-documented principle that AMF colonization is often favored under nutrient-limited conditions, as the plant invests in symbiosis to enhance nutrient acquisition (SMITH and READ, 2008). The decline in colonization with increasing P, observed for all AMF species, reflects a classic downregulation of the symbiosis when P is readily available via direct root uptake (BOSE and KANNAN, 2020). However, *G. mosseae* maintained relatively high colonization even at moderate P levels, suggesting a stronger host-fungal affinity or greater energetic benefit under these conditions.

In contrast, *G. etunicatum* showed a more moderate but stable colonization pattern, while *G. intraradices* exhibited delayed establishment, with peak colonization only at 50 kg P ha$^{-1}$. These differential colonization dynamics emphasize that AMF species are not functionally equivalent and that their ecological niches and symbiotic efficiencies vary significantly.

The functional outcomes of colonization were not always proportional to its extent, reinforcing the concept that mycorrhizal responsiveness is best assessed through integrated physiological and agronomic metrics rather than colonization alone. *G. intraradices* and *G. etunicatum* significantly enhanced plant height compared to the control and *G. mosseae*, with *G. intraradices* showing a positive response to increasing P, particularly in the Goli cultivar. This cultivar-specific response indicates a genetic component to symbiotic compatibility, suggesting that optimal AMF-cultivar pairings can be leveraged to maximize growth.

The chlorophyll index, an indicator of photosynthetic capacity, was most strongly enhanced by *G. etunicatum*, especially under low-P conditions. This suggests that this species may play a critical role in maintaining plant physiological function when nutrient stress is present. The ability of *G. etunicatum* to sustain high chlorophyll content across P levels points to a robust symbiosis that supports carbon assimilation even under suboptimal fertility.

Plants establishing mycorrhizal symbioses typically exhibit enhanced growth and yield, primarily due to improved water and nutrient uptake from the soil (AALIPOUR *et al*., 2021). Mycorrhizal inoculation induces significant modifications in plant root morphology, notably increasing lateral root formation (BERTA *et al*., 2002), thereby expanding the root surface area available for resource absorption. By penetrating soil micropores inaccessible to fine root hairs, AMF augment the plant's absorptive surface area, leading to increased uptake of both macro- and micronutrients, particularly phosphorus, and consequently promoting overall plant growth (ARPANA and BAGYARAJ, 2007). The enhanced plant height observed in mycorrhizal-inoculated treatments is primarily attributed to improved nutrient acquisition, especially phosphorus, which subsequently stimulates key growth parameters including plant height, branching, and leaf production (BAUM *et al*., 2015). Consistent with these findings, previous studies have documented significant increases in plant height following mycorrhizal inoculation in sorghum (WIDADA *et al*., 2007), chickpea (MORADI *et al*., 2009), and wheat (ENAYATI *et* al., 2020), underscoring the generalizability of these beneficial effects across diverse crop species.

The present study demonstrates a complex and dynamic interaction between AMF and P fertilization in groundnut, where the suppression of root colonization at high P levels is counterbalanced by significant improvements in agronomic efficiency and kernel quality when AMF are integrated into the nutrient management strategy. This observation aligns with a well-documented phenomenon: the inverse relationship between soil P availability and AMF root colonization.

The P concentration data revealed a critical insight: while *G. etunicatum* significantly enhanced P uptake at moderate P rates (75 kg ha$^{-1}$), the non-inoculated control exhibited the highest tissue P concentration at 100 kg ha$^{-1}$. This counterintuitive result underscores a fundamental principle — that under conditions of high soil P availability, the mycorrhizal pathway becomes redundant or even energetically unfavorable. The plant likely downregulates fungal symbiosis to conserve carbon, relying instead on direct root absorption (QIN *et al*., 2015). This phenomenon, while limiting P uptake via AMF, does not negate the broader benefits of inoculation, such as improved soil structure, enhanced micronutrient acquisition, and stress tolerance (WAHANE *et al*., 2024).

However, the reduction in colonization does not equate to a reduction in the functional benefits of the symbiosis. The concept of "mycorrhizal responsiveness" transcends simple colonization metrics and is better understood through integrated outcomes such as yield, nutrient use efficiency, and quality. WAHANE *et al*. (2022; 2024) provided compelling field evidence that the highest pod yields (3,586 kg $ha^{-1}$) were achieved with 60 kg P $ha^{-1}$ in combination with dual inoculation of AMF and phosphate-solubilizing bacteria (PSB). Crucially, this yield was statistically comparable to the treatment receiving only 45 kg P $ha^{-1}$ with the same biofertilizers. This finding is pivotal, as it demonstrates a 25% reduction in chemical P requirement without compromising productivity, thereby significantly improving P agronomic efficiency and supporting the development of more sustainable and cost-effective cropping systems.

The mechanism behind this synergy lies in the complementary roles of the microbial inoculants. PSB solubilize fixed inorganic P in the soil, making it available, while AMF hyphae, which can extend several centimeters beyond the root depletion zone, efficiently absorb and transport this liberated P back to the host plant (GIANINAZZI *et al.,* 2010). This division of labor not only enhances P uptake but also improves the acquisition of other essential nutrients. Wahane et al. (2024) documented a significant increase in DTPA-extractable micronutrients (Fe, Mn, Zn, Cu) in the soil and their subsequent uptake in plant tissues under combined P and biofertilizer treatments, highlighting the role of AMF in improving overall nutrient homeostasis.

Furthermore, the benefits of AMF extend beyond the immediate growing season. Long-term studies, such as those by HIGO *et al*. (2018), have shown that AMF community structure and spore density are influenced by crop rotation and cover cropping. Their structural equation modeling confirmed that AMF variables are directly or indirectly related to crop yield, underscoring the role of AMF as a vital component of long-term soil biological infrastructure. Excessive P fertilization, as noted by QIN *et al*. (2015), can lead to a decline in AMF diversity and community stability, potentially undermining the resilience of the agroecosystem. This highlights the importance of a balanced approach that avoids over-reliance on chemical inputs.

The findings of ORTAS and BYKOVA (2018) on wheat, while not directly on groundnut, provide a valuable comparative perspective. They demonstrated that mycorrhizal inoculation significantly improved P efficiency in wheat, particularly under low to moderate P conditions, reinforcing the universal principle that AMF are most beneficial when they provide a service that the plant cannot easily achieve on its own. This principle is directly applicable to groundnut cultivation.

The most significant agronomic implications of this study are evident in the bush yield and seed oil percentage results. *Glomus etunicatum* consistently produced the highest yields across all P levels, with a notable 11% increase over the control even at 25 kg P $ha^{-1}$. This demonstrates its potential as a high-performing inoculant for low-input systems, where it can compensate for reduced chemical fertilizer use. The stability of its performance across P gradients suggests a high degree of functional resilience, making it a prime candidate for sustainable peanut production in variable environments.

*Glomus intraradices*, while less effective at low P, showed a strong positive response to higher P, achieving peak yield and the highest oil content at 100 kg P $ha^{-1}$. This indicates that its symbiotic benefits are realized primarily under conditions of adequate fertility, where the plant can afford the carbon cost of supporting the fungus. Conversely, *G. mosseae* underperformed at low P, suggesting a possible lag in establishment or a higher initial carbon investment, but improved at higher P rates.

The reduction in non-ripened seed number under *G. etunicatum* inoculation further highlights its role in promoting reproductive success and seed maturation, particularly under moderate fertility. In contrast, *G. mosseae* led to a 93% increase in non-ripened seeds at the highest P rate, indicating a potential disruption in pod development under high fertility, possibly due to imbalanced nutrient allocation or hormonal interference.

The findings of this study align with the growing body of evidence that optimal crop productivity is achieved not through the substitution of chemical inputs with biological ones, but through their strategic integration. The synergy between AMF and PSB, as demonstrated by WAHANE *et al.* (2024, 2025), exemplifies this principle, where microbial consortia can reduce P fertilizer requirements by 25% without compromising yield. This integrated nutrient management approach represents a robust, sustainable, and economically viable pathway for groundnut cultivation across diverse soil types and agroecological zones.

## CONCLUSIONS

This study demonstrates that the efficacy of AMF in peanut production is highly dependent on the fungal species and P fertilization level. The significant interactions observed across root colonization, plant growth, yield, and seed quality traits underscore the complexity of the mycorrhizal symbiosis and the need for a precision agriculture approach in its application.

*Glomus etunicatum* emerged as the most versatile and resilient inoculant, consistently enhancing plant height, chlorophyll content, and bush yield across a wide range of P inputs, with particularly strong performance under low- to moderate-P conditions. This species is well-suited for low-input or sustainable farming systems where chemical fertilizer use is minimized. In contrast, *G. intraradices* showed a strong positive response at high P levels, maximizing oil content and yield, indicating its suitability for high-fertility environments. *Glomus mosseae*, while a superior root colonizer, exhibited a context-dependent response, with benefits largely restricted to lower P levels and potential trade-offs in yield and seed maturation under high P fertility.

The findings highlight that AMF inoculation can significantly improve peanut productivity and seed quality, but its success depends on strategic alignment with soil fertility management. The paradoxical reduction in P uptake by mycorrhizal plants at high P rates emphasizes that the benefits of AMF extend beyond direct nutrient acquisition and include enhanced photosynthetic capacity, improved soil structure, and better reproductive performance.

Therefore, the optimal strategy for sustainable peanut cultivation is not the replacement of chemical fertilizers with biofertilizers, but their strategic integration. A moderate P application rate (45–60 kg P $ha^{-1}$), combined with targeted inoculation — *G. etunicatum* for resource-limited systems or *G. intraradices* for intensive systems — can maximize yield, improve oil quality, enhance nutrient use efficiency, and support long-term soil health. This integrated approach offers a viable pathway for climate-resilient and environmentally sustainable peanut production in semi-arid regions like the Moghan plain.

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REFERENCES

AALIPOUR, H., A. NIKBAKHT, N. ETEMADI (2019): Relationship between chlorosis, photosynthesis and the nutrient content of plane trees in the presence of chemical and organic fertilizers. Advances in Horticultural Science, *33*(2): 171–178.

AALIPOUR, H., A. NIKBAKHT, N. ETEMADI, J.E. MACDONALD (2021): Co-inoculation of Arizona cypress with mycorrhizae and rhizobacteria affects biomass, nutrient status, water-use efficiency, and glomalin-related soil protein concentration. Urban Forestry & Urban Greening, *60*: 127050.

ARPANA, J., D.J. BAGYARAJ (2007): Response of Kalmegh to an arbuscular mycorrhizal fungus and a plant growth promoting rhizomicroorganism at two levels of phosphorus fertilizer. American-Eurasian Journal of Agricultural Science, *2*: 33–38.

ARYA, S.S., A.R. SALVE, S. CHAUHAN (2016): Peanuts as functional food: A review. Journal of Food Science and Technology, *53*(1): 31–41.

AUGE, R.M. (2004): Arbuscular mycorrhizae and soil/plant water relations. Canadian Journal of Soil Science, *84*: 373–381.

BAUM, C., W. EL-TOHAMY, N. GRUDA (2015): Increasing the productivity and product quality of vegetable crops using arbuscular mycorrhizal fungi: A review. Scientia Horticulturae, *187*: 131–141.

BERTA, G., A. FUSCONI, J.E. HOOKER (2002): Arbuscular mycorrhizal modifications to plant root systems: Scale, mechanisms and consequences. In: S. Gianinazzi, H. Schuepp, J.M. Barea, K. Haselwandter (Eds.), Mycorrhiza technology in agriculture: From genes to bioproducts (pp. 71–85). Birkhäuser Verlag.

BOSE, K.S.C., P.K. KANNAN (2020): Mycorrhizal responsiveness to different phosphorus levels on yield attributes and mycorrhizal colonization of groundnut genotypes. Journal of Oilseeds Research, *37*(1): 170.

ENAYATI, A., M. BARMAKI, R. SEYED SHARIFI, A. GHOLIZADEH (2020): Effect of Azotobacter chroococcum and Glomus intraradices on yield, yield components, and germination of derived seeds under supplementary irrigation in some wheat (Triticum aestivum L.) varieties. Journal of Agroecology, *11*(4): 1309–1326 (In Persian).

FAO (2018): FAO Statistical Yearbook 2018. Food and Agriculture Organization of the United Nations, Rome.

GIANINAZZI, S., A. GOLLOTTE, M.N. BINET, D. VAN TUINEN, D. REDECKER, D. WIPF (2010): Agroecology: The key role of arbuscular mycorrhizas in ecosystem services. Mycorrhiza, *20*(8): 519–530.

GIOVANNETTI, M., B. MOSSE (1980): An evaluation of techniques for measuring vesicular arbuscular mycorrhizal infection in roots. New Phytologist, *84*(3): 489–500.

HIGO, M., Y. TAKAHASHI, K. GUNJI, K. ISOBE (2018): How are arbuscular mycorrhizal associations related to maize growth performance during short-term cover crop rotation? Journal of the Science of Food and Agriculture, *98*(4): 1388–1396.

KASSAM, A., H. BRAMMER (2013): Combining sustainable agricultural production with economic and environmental benefits. Geographical Journal, *179*(1): 11–18.

KATINAS, V. (1980): Spectrophotometric determination of phosphorus at 430 nm using ammonium vanadate-molybdate. Laboratory Methods in Plant Analysis, *12*: 45–48.

LIU, H., F. SONG, S. LIU, X. LI, F. LIU, X. ZHU (2018): Arbuscular mycorrhiza improves nitrogen use efficiency in soybean grown under partial root-zone drying irrigation. Archives of Agronomy and Soil Science, *65*(2): 269–279.

MA, Y., S. CHEN, S. LIU, L. GUO, C. ZHANG, X. YE, D. TIAN (2025): Phosphate solubilizing fungi enhance insoluble phosphate dissolution via organic acid production: Mechanisms and applications. Frontiers in Microbiology, *16*: 1600231.

MANDAL, A., A.K. PATRA, D. SINGH, A. SWARUP, R.E. MASTO (2007): Effect of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. Bioresource Technology, *98*(18): 3585–3592.

MORADI, S., H. BESHARATI, V. FEIZI ASL, H. NADIAN, E. KARIMI, A. GOLCHIN (2009): Effect of different levels of humidity, mycorrhiza, and Rhizobium on germination, flowering time, and morphological traits in chickpea. In: Proceedings of the 11th Iranian Soil Science Congress (pp. 243–244). Gorgan, Iran (In Persian).

ODOH, C.K., C.N. EZE, C.J. OBI, F. ANYAH, K. EGBE, U.V. UNAH, U.S. ADOBU (2020): Fungal biofertilizers for sustainable agricultural productivity. In: Agriculturally important fungi for sustainable agriculture: Volume 1: Perspective for diversity and crop productivity (pp. 199–225). Springer.

ORTAS, I., A. BYKOVA (2018): The effect of mycorrhiza inoculation and phosphorus application on phosphorus efficiency of wheat plants. Communications in Soil Science and Plant Analysis, *49*(10): 1199–1207.

PHILLIPS, J.M., D.S. HAYMAN (1970): Improved procedures for clearing roots and staining parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assessment of infection. Transactions of the British Mycological Society, *55*(1): 158–161.

QIN, H., K. LU, P.J. STRONG, Q. XU, Q. WU, Z. XU, H. WANG (2015): Long-term fertilizer application effects on the soil, root arbuscular mycorrhizal fungi, and community composition in rotation agriculture. Applied Soil Ecology, *89*: 35–43.

R CORE TEAM (2022): R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

REDECKER, D., P. RAAB (2006): Phylogeny of the Glomeromycota (arbuscular mycorrhizal fungi): Recent developments and new gene markers. Mycologia, 98(6): 885–895.

RENGIFO, A.F.C., Á.A. ARRIETA, M. PALENCIA (2025): Phosphorus slow release from cassava starch-hydroxyapatite composites derived from aquaculture waste. Journal of Environmental Chemical Engineering, *13*(3): 116651.

SCHÜßLER, A., D. SCHWARZOTT, C. WALKER (2001): A new fungal phylum, the Glomeromycota: Phylogeny and evolution. Mycological Research, *105*(12): 1432–1441.

SHARMA, R.C., S. SARKAR, D. DAS, P. BANIK (2013): Impact assessment of arbuscular mycorrhiza, Azospirillum, and chemical fertilizer application on soil health and ecology. Communications in Soil Science and Plant Analysis, *44*(7): 1116–1126.

SHILMAN, F., Y. BRAND, A. BRAND, I. HEDVAT, R. HOVAV (2011): Identification and molecular characterization of homeologous Δ9-stearoyl acyl carrier protein desaturase 3 genes from the allotetraploid peanut (Arachis hypogaea). Plant Molecular Biology Reporter, *29*(1): 232–241.

SMITH, S.E., D.J. READ (2008): Mycorrhizal symbiosis, 3rd ed. Academic Press.

TABATABAEI, S.A. (2013): Use of SPAD meter for chlorophyll assessment in peanut leaves. Technical Report, Islamic Azad University.

VARSHNEY, R.K., M.K. PANDEY, N. PUPPALA (2017): The peanut genome. Springer.

WAHANE, M.R., V.G. SALVI, S.B. DODAKE, M.S. JOSHI (2025): Interactive effect of bio-organic and inorganic fertilizers on crop growth, quality, productivity, and profitability of groundnut (Arachis hypogaea L.) in an alfisol of Western Ghats of Maharashtra, India. Communications in Soil Science and Plant Analysis, *56*(1): 1–19.

WAHANE, M.R., V.G. SALVI, S.B. DODAKE, N.H. KHOBRAGADE (2022): Effect of phosphorus, vesicular arbuscular mycorrhizae (VAM), and phosphate solubilizing bacteria (PSB) on yield and nutrient content of groundnut and soil physical properties of alfisols. Agricultural Research Journal, *59*(3): 407–417.

WAHANE, M.R., V.G. SALVI, S.B. DODAKE, J.S. DHEKALE, N.H. KHOBRAGADE, N.A. MESHRAM (2024): Groundnut (Arachis hypogaea L.) production, soil biological characteristics, micronutrient content in soil and plant parts, and their uptake are all influenced by phosphorus, AMF, and PSB application. Journal of Plant Nutrition, *47*(19): 3343–3366.

WIDADA, J., D.I. DAMARJAYA, S. KABIRUN (2007): The interactive effects of arbuscular mycorrhizal fungi and rhizobacteria on the growth and nutrient uptake of sorghum in acid soil. In: E. Velazquez, C. Rodríguez-Barrueco (Eds.), First international meeting on microbial phosphate solubilization (pp. 173–177). Springer.

## MIKORIZNA REAKCIJA NA RAZLIČITE NIVOE FOSFORA NA KOLONIZACIJU KORENA, AGRONOMSKU EFIKASNOST I KVALITET ZRNA KIKIRIKIJA (*Arachis hypogaea* L)

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Izvod

Arbuskularne mikorizalne gljive (AMG) su ključne komponente održivih poljoprivrednih sistema, poboljšavajući usvajanje hranljivih materija i produktivnost biljaka, posebno u zemljištima sa deficitom fosfora (P). Ova studija je istraživala interaktivne efekte tri vrste AMG (*Glomus mosseae, G. intraradices i G. etunicatum*), četiri nivoa primene fosfora (25, 50, 75 i 100 kg $P_2O_5$ ha$^{-1}$) i dve sorte kikirikija (Goli i NC7) na kolonizaciju korena, rast, prinos i kvalitet semena u poljskim uslovima u polusušnoj ravnici Mogan, Iran. Faktorijalni eksperiment je sproveden u randomizovanom kompletnom blok dizajnu sa tri ponavljanja. Rezultati su otkrili značajne interakcije između vrsta AMG i nivoa fosfora u svim merenim osobinama. *Glomus moseae* je postigao najveću kolonizaciju korena (35,6% pri 25 kg fosfora/ha$^{-1}$), ali je kolonizacija opadala sa povećanjem P. *Glomus etunicatum* je konstantno povećavao visinu biljke, indeks hlorofila i prinos grma na svim nivoima fosfora, sa značajnim povećanjem prinosa od 11% u odnosu na kontrolu pri najnižoj količini fosfora. *Glomus intraradices* je pokazao pozitivan, fosfor zavisan odgovor, maksimizirajući sadržaj ulja i prinos pri 100 kg fosfora/ha$^{-1}$. Neinokulirane biljke su pokazale najveću koncentraciju fosfora u tkivu pri 100 kg fosfora/ha$^{-1}$, što ukazuje na smanjenje mikoriznog puta pod visokom dostupnošću fosfora. *Glomus etunicatum* je takođe smanjio broj nezrelog semena, promovišući zrelost semena. Rezultati pokazuju da efikasnost AMF-a zavisi od vrste i konteksta. *G. etunicatum* je veoma efikasan u uslovima niske do umerene plodnosti fosfora, što ga čini idealnim za sisteme sa niskim unosom fosfora, dok *G. intraradices* najbolje funkcioniše u uslovima visoke plodnosti fosfora. Integrisana strategija upravljanja hranljivim materijama, umereno đubrenje fosforom (45–60 kg ha$^{-1}$) u kombinaciji sa ciljanom inokulacijom AMF-a, može optimizovati produktivnost kikirikija, poboljšati kvalitet semena i promovisati održivo zemljište.

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