Employing various species of mycorrhiza and different levels of phosphorus to enhance phosphorus efficiency and corn growth in arid and semi-arid environment

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Abstract :

A field experiment was conducted during the spring season of 2025 at the Extension Station in Abi Gharaq / Al-Muhanawiya. The study aimed to evaluate the effect of the interaction between different genera of mycorrhizal fungi and phosphorus levels on nutrient availability, methodology . *Zea mays L* maiowth, and yield ofgr The treatments included Mycorrhizal Inoculants: Two types were used,denoted as M1 (Gigaspora spp.) and M2 (Glomus mosseae).Fungal Inoculum (A): Applied at three levels (0, 10, and 50 g).Phosphorus (P): Applied at three levels (0, 100, and 200 kg/ha).The experiment followed a Randomized Complete Block Design (RCBD) with a tri-factorial arrangement and three replicates.

Key Results The results demonstrated significant differences between treatments in their ability to enhance soil nutrient availability and stimulate maize growth.

The M2 *(Glomus mosseae*) treatment significantly outperformed the M1 (*Gigaspora spp*.) and the control treatment across all studied traits.

The triple interaction of mycorrhiza, fungal inoculum, and phosphorus yielded the best results.

Specifically, the combination M2A2P2 achieved a significant increase in infection intensity, bacterial populations, available nitrogen, available phosphorus, available potassium, and plant height compared to the control treatment.

Keywords: Arbuscular Mycorrhizal Fungi (AMF), phosphorus, Mineral Fertilization, Zea mays L

Introduction:

Mycorrhizae are living organisms capable of forming symbiotic relationships with the majority of plants [39]. Arbuscular Mycorrhizal Fungi (AMF) are widely distributed in the soil and can establish symbiotic associations with the roots of more than 80% of terrestrial vascular plants [52]. Mycorrhizal fungi are considered rhizosphere-dwelling organisms that also reside within plant tissues, where they stimulate growth and increase

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considered one of the major strategic cereal crops in the world due to its high nutritional value and its significant role in the food industry. This importance stems from its high content of oil and starch, as well as minerals, elements, and vitamins, particularly Vitamin C. These vitamins are essential in the feed industry, providing the basic amino acids necessary for animal growth [2][34]. Therefore, interest has been directed toward maize (Zea mays L.) cultivation through the use of bio-fertilizers, which represent one of the most critical sustainable alternatives. Due to the scarcity of studies regarding the effectiveness of local Mycorrhizal inoculants, and to increase environmental awareness while identifying diverse nutritional sources, the current study aimed to:

1. Evaluate the interaction between different species of Mycorrhizal fungi and various phosphorus levels on the availability of nutrients within the rhizosphere zone.
2. Study the impact of different Mycorrhizal species and phosphorus levels on the soil microbial community.

Assess the influence of exudates from various Mycorrhizal genera and phosphorus levels on the growth and yield of maize.

Materials and Methods

1-Study Site

A field experiment was conducted at one of the agricultural research stations affiliated with the Agricultural Extension Department in the Al-

yield through various mechanisms. In this relationship, a mutual exchange occurs between the fungus and the plant involving compounds and nutrients utilized for the growth and reproduction of both partners [53, 15]. Furthermore, AMF function to enhance the uptake of mineral nutrients, particularly phosphorus and nitrogen [20].

This symbiotic relationship facilitates nutrient acquisition for plants and also plays an important role in the global carbon cycle [59].

Mycorrhiza can also improve the rhizosphere environment and may contribute to reducing soil contamination [13].

Phosphorus is an essential nutrient for the growth of plants and microorganisms and is considered one of the major limiting factors in crop production. In many agricultural soils, plant-available phosphorus remains low because much of it is fixed in the soil, bound to organic molecules or mineral surfaces, and precipitated as insoluble phosphates [56]. Phosphorus deficiency is considered a common phenomenon in agricultural soils, despite the high applications of phosphate fertilizers [16].

Phosphorus deficiency leads to poor root growth and reduced absorption of other elements, thereby decreasing the overall nutrient use efficiency of the plant [61].

Phosphorus deficiency impairs root growth and reduces the uptake efficiency of other nutrients, thereby lowering overall nutrient use efficiency [60]. Maize (Zea mays L.) is

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with a layer of soil on March 24, 2025, and irrigated immediately. Upon completion of the vegetative growth phase, several traits were evaluated.

Mycorrhizal Inoculation and

4-Measurements

Mycorrhizal inoculant (G. mosseae and Gigaspora sp.) was added to the soil at levels of 0, 10, and 50 g, prepared according to the method described by [40]. The inoculant consisted of infected plant roots and surrounding rhizospheric soil containing fungal spores. It was applied to the designated treatments in a 5 cm wide and 5 cm deep furrow directly beneath the seeds during sowing.

The following properties were measured:

Soil pH: Measured in a saturated soil paste extract following the method

-described by [44].

-Available Nitrogen (N): Available nitrogen in the soil (N) was determined by extraction with a 2M potassium chloride (KCl) solution, using magnesium oxide (MgO), followed by distillation through a Micro-Kjeldahl apparatus, according to the method described by [44].

-Available Phosphorus (P): Extracted using the [43] method with 0.5M NaHCO3. Color development was achieved using ammonium molybdate and ascorbic acid, and measured via a Spectrophotometer at a wavelength of 882 nm per [44].

-Available Potassium (K): Estimated through extraction with 1N ammonium acetate using a (Flame Photometer, as detailed by [23].

Mahanawiyah region, Babylon Governorate – Abi Gharaq, during the spring season of 2024–2025. Sowing was carried out on March 24, 2025, utilizing 54 experimental units dedicated to the cultivation of the maize crop (Zea mays L.), Al-Furat cultivar.

2-Soil Preparation

The field soil was prepared by clearing it of plant debris and weeds. Subsequently, it was harrowed using a spike-tooth harrow and plowed twice perpendicularly with a moldboard plow to ensure a well-pulverized and aerated soil structure. The soil was then smoothed using disc harrows, leveled, and divided into equal experimental units.

3-Soil Analysis

Random soil samples were collecte d from various locations across the field at a depth of 0–30 cm. The samples were thoroughly mixed to ensure homogeneity, air-dried for two days, crushed using a polyethylene hammer, and passed through a 2 mm sieve. A composite sample was then taken to estimate several chemical, physical, and biological properties of the soil prior to planting, as detailed in Table (1).

The soil used had a clay-loam texture. The experiment consisted of 54 experimental units where mycorrhiza, phosphorus, and fungal inoculants were added according to the experimental treatments before sowing. Seeds were soaked for an hour and a half in a liquid medium. Subsequently, maize seeds (Al-Furat cultivar) were sown at a rate of 4–5 seeds per hole, covered

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Staining with Acid Fuchsin (prepared per [36]: 63ml glycerin, 875ml lactic acid, 63ml distilled water, and 0.1g dye) at 70°C for 30 minutes.
The root segments were then arranged on glass slides (10 pieces per slide), examined under a microscope, and the infection percentage was calculated.
Mycorrhizal Infection Calculation
The percentage of mycorrhizal colonization was calculated using the following formula

Mycorrhizal Colonization Percentage (%)

$$\frac{\text{Number of infected roots}}{\text{Total number of roots}} \times 100$$

Upon obtaining the experimental data, it was statistically analyzed using GenStat software for analysis of variance (ANOVA) between treatments. Mean comparisons were performed using the Least Significant Difference (L.S.D) test at a 5% probability level [17].

Bacterial Count: Determined using the dilution and plate counting method -according to [22].
-Plant Height: Measured in centimeters for eight plants, from the soil surface to the highest node of the male inflorescence [18].
-Mycorrhizal Colonization Percentage
The colonization rate was calculated using the method described by [47], based on the principle that root cortical cell walls do not retain the stain while fungal cell walls do.
The procedure involved:
Cutting roots into small pieces (1 cm), with 10 pieces per plant.
Placing them in 20 ml vials with 10% KOH solution in a water bath at 70°C for 15 minutes.
Washing with distilled water using a 60µm sieve.
Treating roots with 1% H2O2 at room temperature for 10 minutes, followed by washing.
Treating with 1% HCl for 3 minutes.

Table (1): Some Chemical and Physical Properties of the Experimental Soil Before the Study

Property	Unit	Value
Soil Reaction (pH)	-	7.78
Electrical Conductivity (EC)	$dS.m^{-1}$	4.68
Cation Exchange Capacity (CEC)	$cmol_{c}.kg^{-1}$	28.50
Organic Matter (O.M)	$g.kg^{-1}$	1.55
Nitrogen (N)	$mg.kg^{-1}$	22.30
Phosphorus (P)	$mg.kg^{-1}$	10.88
Potassium (K)	$mg.kg^{-1}$	78.96
Soluble Ions:	$mmol.L^{-1}$	

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Property	Unit	Value
- Sodium (Na^+)	$mmol.L^{-1}$	3.16
- Calcium (Ca^{2+})	$mmol.L^{-1}$	9.48
- Magnesium (Mg^{2+})	$mmol.L^{-1}$	7.60
- Chloride (Cl^-)	$mmol.L^{-1}$	8.75
- Carbonate (CO_3^{2-})	$mmol.L^{-1}$	Nil
- Bicarbonate (HCO_3^-)	$mmol.L^{-1}$	6.50
- Sulfate (SO_4^{2-})	$mmol.L^{-1}$	10.27
Soil Separates:	$g.kg^{-1}$	
- Sand	$g.kg^{-1}$	332
- Silt	$g.kg^{-1}$	463
- Clay	$g.kg^{-1}$	200
Soil Texture	Silty Clay Loam	
Bacterial Count	$cells.g^{-1}$ soil	2.80×10^6
Fungal Count	$CFU.g^{-1}$	1.58×10^3

Results and Discussion

Infection Percentage (%)

environmental adaptation to arid conditions. These findings are consistent with [4] and [55].

Furthermore, the addition of fungal inoculum levels led to a significant increase in the infection percentage. Treatment A2 yielded the highest value at 88.9%, compared to treatments A0 and A1, which recorded 69.2% and 41.4%, respectively. This suggests that the inoculum quantity in A2 contains a high spore count that germinates into hyphae, increasing infection opportunities. These results align with the findings of [48] .

The table also shows that adding phosphorus levels significantly

The results presented in Table 2 indicate that all study factors had a significant effect on increasing the infection percentage (%). Inoculation with the mycorrhizal fungus G. mosseae led to a significant increase in the infection rate; the highest value was recorded at treatment M2, reaching 67.4%, compared to M1, which recorded 65.6%. This increase is attributed to the positive role of G. mosseae, characterized by an extensive network of hyphae and mycelium containing glomalin and carbon. This network encourages root elongation to interface with the hyphae, thereby increasing the infection rate, in addition to its

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addition enhances mycorrhizal activity and the high affinity between phosphorus and mycorrhizal roots. Symbiotic root fungi utilize their extensive fungal network to increase the contact area between the soil and plant roots, activating insoluble phosphorus and enhancing the plant's ability to absorb various nutrients [46]. The same table shows that the triple interaction of the study factors significantly increased the available nitrogen content in the soil. The highest value for the triple interaction (M2A2P2) was 96.7%, compared to the lowest value for treatment M1A0P0, which was 26.7%. The increase in infection percentage in the triple interaction is attributed to an increase in root exudates in the rhizosphere. These exudates play a vital and positive role in enhancing symbiotic relationships between roots and mycorrhizal fungi, as they contain compounds that stimulate spore germination and germ tube development, thus initiating infection [25]

Finally, it was observed that the genus Glomus mosseae outperformed Gigaspora sp. in infection percentage across all treatments. This may be attributed to the prevalence of Glomus mosseae in the Iraqi environment and its suitability to soil pH and high temperatures This result is in agreement with previous findings [10, 32].

affected the increase in available infection percentage (%) content in the soil. The highest value was observed in treatment P2 (75.61%) compared to P0 and P1 (68.9% and 55.0%, respectively). This may be attributed to the increased availability of nutrients in the soil, which stimulates wider root growth and enhances mycorrhizal infection. Increased nutrient availability promotes the decomposition of organic matter, improving plant biomass production through the root-fungal growth environment in the soil, ultimately leading to higher root infection rates. These results agree with [8].

The dual interaction between mycorrhiza and fungal inoculum also led to a significant increase in infection intensity. The highest value was recorded at treatment M2A2 (91.1%), while the lowest was at M1A0 (39.4%). This is likely due to the positive role of mycorrhiza, specifically G. mosseae, in increasing the spore count in the soil, which transforms into abundant hyphae that raise the infection rate. These results are consistent with [48] .

Similarly, the dual interaction between fungal inoculum levels and phosphorus levels significantly impacted the infection percentage. The highest value was recorded at A2P2 (95.0%), while A0P0 recorded the lowest (30.0%). This may be explained by the fact that phosphorus

Table (2): Effect of Different Mycorrhizal Genera, Fungal Inoculum, Phosphorus Levels on Infection Percentage (%)

Mycorrhiza M × Fungal Inoculum A	P Phosphorus			Transaction	
	200	100	0	Fungal Inoculum A	Mycorrhiza M
39.4	50.0	41.7	26.7	0	Gigspora
70.6	80.0	70.0	61.7	10	
86.7	93.3	85.0	81.7	50	
43.3	50.0	46.7	33.3	0	G.mossea
67.8	83.3	80.0	40.0	10	
91.1	96.7	90.0	86.7	50	
8.08	14.00			LSD .(0.05)	
Mycorrhiza Effect	75.6	68.9	55.0	Effect Phosphorus P	
	5.72			LSD. (0.05)	
	P Phosphorus			Mycorrhiza M	
	200	100	0		
65.6	74.4	65.6	56.7	Gigspora	
67.4	76.7	72.2	53.3	G.mossea	
4.67	8.08			LSD.(0.05)	
Effect Fungal Inoculum A	Phosphorus P			Fungal Inoculum A	
	200	100	0		
41.4	50.0	44.2	30.0	0	
69.2	81.7	75.0	50.8	10	
88.9	95.0	87.5	84.2	50	
5.72	9.90			LSD .(0.05)	

dry soil {1-text{g}^{\times 10^6 \Bacterial Counts (CFU)

effects of the studied factors on soil bacterial counts. The mycorrhizal The results presented in the table indicate significant differences in the

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findings of [27] who noted that phosphorus, besides being an essential energy source for growth, promotes an increase in viable bacterial cell counts per gram of soil.

M \times A: The interaction treatment M2A2 recorded the highest average of 3.84 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, while the control treatment M1A0 recorded the lowest rate of 1.28 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil The reason is attributed to fungal secretions, such as acids, sugars, and proteins, which lead to a reduction in soil pH. This, in turn, increases microbial activity, which is consistent with the findings of [14].

M \times P: The interaction between mycorrhiza and phosphorus showed that treatment M2P2 was superior, yielding 3.75 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, compared to M1P0, which recorded 1.80 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil.

A \times P: The interaction between fungal inoculum and phosphorus showed that treatment A2P2 excelled with an average of 4.76 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, while the control A0P0 gave the lowest average of 1.06 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil.

Triple Interaction: The triple interaction between mycorrhiza, fungal inoculum, and phosphorus significantly impacted bacterial counts. The M2A2P2 treatment recorded the highest average of 5.00 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, compared to the control treatment G. mosseae significantly outperformed the Gigaspora treatment, yielding the highest average of 2.83 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, compared to the latter's minimum average of 2.37 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil. This increase may be attributed to enhanced microbial activity in the rhizosphere driven by mycorrhizal secretions, which play a vital role in improving soil structure and plant growth; this, in turn, is reflected in the increased number of viable bacterial cells per gram of soil. Furthermore, the nature of these organisms contributes significantly to the bulk of the biomass associated with various crops [3].

Regarding the fungal inoculum levels, treatment A2 yielded the highest average of 3.76 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, whereas treatments A0 and A1 recorded the lowest averages of 2.44 and 1.60 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, respectively. The results also show that the addition of phosphorus levels significantly influenced bacterial counts. Treatment P2 achieved the highest rate of 3.31 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil, compared to P0 and P1, which gave lower averages of 1.96 and 2.53 \times 10^6 \text{ CFU } \text{g}^{-1} dry soil. This may be due to the role of phosphorus in developing a root system that provides the necessary surface area and secretions for bacterial adsorption. This aligns with the

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CFU } \text{g}^{-1} dry soil.

M0A0P0, which yielded the lowest average of 1.00 \times 10^6 \text{

(3) Effect of Different Mycorrhizal Genera, Fungal Inoculum, Phosphorus Levels onBacterial Counts (CFU)

Mycorrhiza M × Fungal Inoculum A	Phosphorus P			المعاملات	
	200	100	0	Fungal Inoculum A	Mycorrhi M za
1.28	1.66	1.20	1.00	0	Gigspora
2.13	2.40	2.13	1.86	10	
3.68	4.53	4.00	2.53	50	
1.91	2.53	2.06	1.13	0	G.mossea
2.75	3.73	2.33	2.20	10	
3.84	5.00	3.46	3.06	50	
0.485			0.840	LSD .(0.05)	
Mycorrhiza Effect M	3.31	2.53	1.96	Effect Phosphorus P	
			0.343	LSD. (0.05)	
	Phosphorus P			Mycorrhiza M	
	200	100	0		
2.37	2.86	2.44	1.80	Gigspora	
2.83	3.75	2.62	2.13	G.mossea	
0.280			0.485	LSD.(0.05)	
Effect Fungal Inoculum A	Phosphorus P			Fungal Inoculum A	
	200	100	0		
1.60	2.10	1.63	1.06	0	
2.44	3.06	2.23	2.03	10	
3.76	4.76	3.73	2.80	50	
0.343			0.594	LSD .(0.05)	

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Available Soil Nitrogen

The results presented in the The statistical analysis results in Table 3 indicated that all study factors had a significant effect on increasing the soil's available nitrogen content. Mycorrhizal inoculation led to a significant increase in available soil nitrogen, with the highest value recorded in the M2 treatment ($42.17\text{ mg N kg}^{-1}\text{ soil}$) compared to the M1 treatment ($40.04\text{ mg N kg}^{-1}\text{ soil}$).

Similarly, the application of fungal inoculum levels resulted in a significant increase in available soil nitrogen; the A2 treatment yielded the highest value at $47.66\text{ mg N kg}^{-1}\text{ soil}$, compared to the A0 and A1 treatments, which recorded 42.20 and $33.45\text{ mg N kg}^{-1}\text{ soil}$, respectively. It is also noted from the table that the addition of phosphorus levels significantly influenced the increase in available nitrogen; the highest value was observed in the P2 treatment ($43.41\text{ mg N kg}^{-1}\text{ soil}$) compared to P0 and P1, which recorded 38.83 and $41.06\text{ mg N kg}^{-1}\text{ soil}$, respectively.

Regarding dual interactions, the Mycorrhiza and fungal inoculum interaction (M×A) led to a significant increase in available soil nitrogen, with the highest value recorded in the M2A2 treatment ($47.90\text{ mg N kg}^{-1}\text{ soil}$) compared to the lowest value in the M1A0 treatment ($32.29\text{ mg N kg}^{-1}\text{ soil}$). Furthermore, the dual interaction between Mycorrhiza and phosphorus (M×P) showed a significant increase, peaking in the M2P2 treatment at $44.75\text{ mg N kg}^{-1}\text{ soil}$ compared to the lowest interaction value of $38.25\text{ mg N kg}^{-1}\text{ soil}$ in the M1P0 treatment. The dual interaction between fungal inoculum and phosphorus (A×P) also significantly affected available soil nitrogen, with the highest recorded value in the A2P2 treatment ($49.23\text{ mg N kg}^{-1}\text{ soil}$) compared to the lowest value in the A0P0 treatment ($30.76\text{ mg N kg}^{-1}\text{ soil}$).

The same table demonstrated that the triple interaction of the study factors (M×A×P) significantly increased the available soil nitrogen content. The highest value was recorded in the M2A2P2 triple interaction treatment ($49.98\text{ mg N kg}^{-1}\text{ soil}$), while the lowest value for the Mycorrhiza, fungal inoculum, and phosphorus triple interaction was observed in the M1A0P0 treatment at $30.04\text{ mg N kg}^{-1}\text{ soil}$

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4) Effect of Different Mycorrhizal Genera, Fungal Inoculum, Phosphorus Levels on Available Soil Nitrogen

Mycorrhiza M × Fungal Inoculum A	Phosphorus P			المعاملات	
	200	100	0	Fungal Inoculum A	Mycorrhiza M
32.29	34.84	31.99	30.04	0	Gigspora
40.40	42.93	39.60	38.66	10	
47.42	48.47	47.76	46.04	50	
34.60	37.25	35.09	31.48	0	G.mossea
43.99	47.02	44.19	40.77	10	
47.90	49.98	47.73	45.98	50	
0.794			1.376	LSD .(0.05)	
Mycorrhiza Effect M	43.41	41.06	38.83	Effect Phosphorus P	
			0.562	LSD. (0.05)	
	Phosphorus P			Mycorrhiza M	
	200	100	0		
40.04	42.08	39.78	38.25	Gigspora	
42.17	44.75	42.34	39.41	G.mossea	
0.459			0.794	LSD.(0.05)	
Effect Fungal Inoculum A	Phosphorus P			Fungal Inoculum A	
	200	100	0		
33.45	36.05	33.54	30.76	0	
42.20	44.97	41.90	39.72	10	
47.66	49.23	47.75	46.01	50	
0.562			0.973	LSD .(0.05)	

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Available Phosphorus in Soil

effect on available soil phosphorus, with the highest value recorded in the M_2A_2 interaction treatment, reaching 35.89 mg P kg^{-1} soil, compared to the lowest As also observed from the same table, the three-way interaction among the studied factors significantly increased the available soil phosphorus content. The highest value was recorded in the $M_2A_2P_2$ three-way interaction treatment, reaching 37.36 mg P kg^{-1} soil, compared to the lowest value observed in the $M_1A_0P_0$ three-way interaction treatment, which was 24.86 mg P kg^{-1} soil. value in the M_1A_0 treatment, which was 25.18 mg P kg^{-1} soil. Similarly, the two-way interaction between mycorrhizae and phosphorus led to a significant increase in available soil phosphorus; the highest value was recorded in the M_2P_2 interaction treatment, reaching 32.55 mg P kg^{-1} soil, compared to the lowest value in the M_1P_0 interaction treatment, which was 27.50 mg P kg^{-1} soil. Additionally, the two-way interaction between fungal inoculum and phosphorus showed a significant effect on the soil's available phosphorus content, where the highest value was observed in the A_2P_2 interaction treatment, reaching 37.31 mg P kg^{-1} soil, compared to the A_0P_0 interaction treatment, which recorded the lowest value of 25.20

The statistical analysis results in Table 5 indicated a significant effect of mycorrhizal species, fungal inoculum levels, and phosphorus levels on increasing the soil's available phosphorus content. Mycorrhizal inoculation led to a significant increase in available soil phosphorus, where the M2 fungus significantly outperformed the M1 fungus, recording the highest value of 31.10 mg P kg^{-1} soil compared to the second type, which reached 29.72 mg P kg^{-1} soil. Furthermore, the application of fungal inoculum levels had a significant effect on increasing the available soil phosphorus content; the A2 treatment yielded the highest value of 35.36 mg P kg^{-1} soil compared to the A0 and A1 treatments, which recorded 30.19 and 25.67 mg P kg^{-1} soil, respectively. It is also noted from the table that the application of phosphorus levels significantly affected the increase in available soil phosphorus content, with the highest value observed in the P2 treatment, reaching 32.05 mg P kg^{-1} soil compared to the P0 and P1 treatments, which recorded 30.63 and 28.54 mg P kg^{-1} soil, respectively..As observed from the table, the two-way interactions among the studied factors significantly affected the soil's available phosphorus content. The two-way interaction between mycorrhizae and fungal inoculum had a significant

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5- Effect of Different Mycorrhizal Genera, Fungal Inoculum, Phosphorus Levels on Available Soil Phosphorus

Mycorrhiza M × Fungal Inoculum A	Phosphorus P			المعاملات	
	200	100	0	Fungal Inoculum A	Mycorrhiza M
25.18	25.46	25.23	24.86	0	Gigspora
29.15	31.91	30.06	25.47	10	
34.82	37.25	35.06	32.17	50	
26.16	26.75	26.19	25.54	0	G.mossea
31.23	33.55	31.34	28.81	10	
35.89	37.36	35.89	34.43	50	
0.640	1.109			LSD .(0.05)	
Mycorrhiza Effect M	32.05	30.63	28.54	Effect Phosphorus P	
	0.452			LSD. (0.05)	
	Phosphorus P			Mycorrhiza M	
	200	100	0		
29.72	31.54	30.11	27.50	Gigspora	
31.10	32.55	31.14	29.59	G.mossea	
0.369	0.640			LSD.(0.05)	
Effect Fungal Inoculum A	Phosphorus P			Fungal Inoculum A	
	200	100	0		
25.67	26.11	25.71	25.20	0	
30.19	32.73	30.70	27.14	10	
35.36	37.31	35.47	33.30	50	
0.452	0.784			LSD .(0.05)	

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Available Soil Potasium

inoculum led to a significant increase in available soil potassium. The highest value was recorded in treatment M2A2 (119.34 \text{ mg K kg}^{-1} \text{ soil}), while the lowest was in M1A0 (115.43 \text{ mg K kg}^{-1} \text{ soil}). Likewise, the dual interaction between mycorrhiza and phosphorus significantly increased soil potassium content, with the highest value in M2P2 (119.34 \text{ mg K kg}^{-1} \text{ soil}) and the lowest in M1P0 (115.43 \text{ mg K kg}^{-1} \text{ soil}).

Additionally, the dual interaction between the fungal inoculum and phosphorus had a significant effect on available potassium, with the highest value recorded in A2P2 (121.94 \text{ mg K kg}^{-1} \text{ soil}) and the lowest in A0P0 (111.53 \text{ mg K kg}^{-1} \text{ soil}). The table also demonstrates that the triple interaction of the study factors significantly increased available soil potassium. The highest value was observed in the triple interaction treatment M2A2P2 (122.21 \text{ mg K kg}^{-1} \text{ soil}), compared to the lowest value in M1A0P0 (111.11 \text{ mg K kg}^{-1} \text{ soil}).

The results presented in the table 6 indicate that all study factors had a significant effect on increasing the soil's available potassium content. Inoculation with the mycorrhizal fungus *G. mosseae* led to a significant increase in available soil potassium, with the highest value recorded in treatment M2 (117.87 \text{ mg K kg}^{-1} \text{ soil}), compared to the second type, *Gigaspora* (M1), which recorded the lowest value of 116.99 \text{ mg K kg}^{-1} \text{ soil}. Similarly, the addition of fungal inoculum levels led to a significant increase in available soil potassium. Treatment A2 yielded the highest value (119.92 \text{ mg K kg}^{-1} \text{ soil}) compared to treatments A0 and A1, which recorded 117.79 and 114.57 \text{ mg K kg}^{-1} \text{ soil}, respectively.

The table also shows that the addition of phosphorus levels significantly affected the increase in available soil potassium. The highest value was observed in treatment P2 (119.01 \text{ mg K kg}^{-1} \text{ soil}) compared to treatments P0 and P1 (117.50 and 115.77 \text{ mg K kg}^{-1} \text{ soil}, respectively).

Furthermore, the dual interaction between mycorrhiza and the fungal

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(6): Effect of Different Mycorrhizal Genera, Fungal Inoculum, Phosphorus Levels on Available Soil Potasium

Mycorrhiza M × Fungal Inoculum A	P Phosphorus			المعاملات	
	200	100	0	Fungal Inoculum A	Mycorrhiza M
113.82	116.22	114.14	111.11	0	Gigspora
117.55	118.19	117.63	116.84	10	
119.58	121.67	118.72	118.35	50	
115.32	117.39	116.64	111.95	0	G.mossea
118.03	118.41	118.15	117.52	10	
120.27	122.21	119.71	118.88	50	
0.604	1.047			LSD .(0.05)	
Mycorrhiza Effect M	119.01	117.50	115.77	Effect Phosphorus P	
	0.427			LSD. (0.05)	
	Phosphorus P			المايكورايزا M	
	200	100	0		
116.99	118.69	116.83	115.43	Gigspora	
117.87	119.34	118.17	116.12	G.mossea	
0.349	0.740			LSD.(0.05)	
Effect Fungal Inoculum A	Phosphorus P			Fungal Inoculum A	
	200	100	0		
114.57	116.80	115.39	111.53	0	
117.79	118.30	117.89	117.18	10	
119.92	121.94	119.22	118.61	50	
0.427	0.604			LSD .(0.05)	

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phosphorus fertilization in soil originally characterized by low available phosphorus content [21, 9]. Specifically, the addition of mineral phosphate fertilizer increased nutrient availability, leading to the formation of a robust and efficient root system capable of absorbing and transporting nutrients to the upper parts of the plant [12].

A significant superiority was also observed due to the interaction between Mycorrhizal species and fungal inoculum levels in increasing the availability of N, P, and K in the soil. This is due to the synergy between the Mycorrhizal fungi and the inoculum levels; this symbiotic relationship enhances the plant's nutrient acquisition. Mycorrhizal fungi increase macronutrient absorption through a network of fungal filaments that extend into the soil, increasing the root surface area and improving nutrient uptake. This result is consistent with [54, 57].

Results also indicated that the interaction between phosphorus levels and Mycorrhizae significantly affected the increase of macronutrient concentrations in the soil. This is because, at optimal phosphorus levels, Mycorrhizal symbiosis can simultaneously enhance plant productivity and phosphorus use efficiency [38]. Mycorrhizal fungi possess the ability to secrete the phosphatase enzyme, which effectively contributes to dissolving phosphorus and extracting it from various soil sources, making it available to the plant [45]. Thus, The results presented in Tables 3, 4, and 5 indicate that all study indicators—including inoculation with different genera of Mycorrhizae, various levels of fungal inoculum, and different phosphorus levels—led to a significant increase in the availability of macronutrients (Nitrogen, Phosphorus, and Potassium) in the soil. This is attributed to the efficiency of Mycorrhizal fungi in absorbing macronutrients (N, P, and K), particularly phosphorus, by extending fungal filaments (hyphae) from the roots to zones beyond the reach of the root system. These hyphae are characterized by a higher phosphorus absorption efficiency compared to root hairs, in addition to increasing the surface area of Mycorrhiza-infected roots, which positively reflects the plant’s absorption capacity. These findings are consistent with [37] and [54].

Furthermore, the results showed that adding levels of fungal inoculum had a significant effect on increasing the concentrations of N, P, and K in the soil solution. This is attributed to the fact that increasing inoculum doses enhanced the biological density of beneficial organisms in the soil. Mycorrhizae also play a positive role in forming a large mass of root hairs by extending hyphae into distant soil regions, thereby increasing nutrient quantities [35], which aligns with the findings of [33].

Regarding phosphorus, the addition of different levels had a significant effect on increasing nutrient availability in the soil. This may be due to

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the soil. The highest values were recorded in the triple interaction treatment (M2A2P2), indicating an integrative effect between bio-fertilization and mineral fertilization. The highest increase in N, P, and K concentrations was recorded using the fungus G. mosseae, attributed to its efficiency in root colonization and increasing the absorption area via external hyphae [37], as well as the efficiency of the inoculum used and the plant's response to Mycorrhizal inoculation [8]. These fungi are distinguished by their ability to colonize plant roots, creating a network of fine fungal filaments that extend into the soil [54], increasing the root surface area and improving the absorption of nutrients and water by the plant [57]. Mycorrhizal fungi stimulate the absorption of nutrients—especially the less mobile phosphorus—by solubilizing insoluble phosphates in the soil [42][51].

Moreover, the results showed a significant superiority in the interaction treatments between inoculum levels and phosphorus levels in increasing macronutrient availability. This is attributed to the efficiency of phosphorus in stimulating root growth and improving nutrient efficiency, particularly when interacting with microorganisms, which agrees with [28].

Finally, the results indicate that Mycorrhizal inoculation, fungal inoculum levels, and phosphorus levels all led to a significant increase in the availability of N, P, and K in

Plant Height (cm)

development. Furthermore, mycorrhizae produce growth regulators and expand the root absorption surface, leading to increased plant height and growth rate [30]. These findings align with those of [5] . Additionally, the application of fungal inoculant levels resulted in a significant increase in plant height. Treatment A2 yielded the highest plant height of 173.47 cm, compared to treatments A0 and A1, which recorded the lowest heights of 156.13 cm and 159.62 cm, respectively. The increase in mycorrhizal infection rate may be attributed to the efficiency of the inoculant used and the plant's

The results in Table (7) indicate that the type of mycorrhizae had a significant effect on the plant height of maize. Inoculation with the mycorrhizal type M2 (*G. mosseae*) led to a significant increase in plant height, reaching 164.70 cm, compared to the second type M1 (*Gigaspora spp*.), which recorded the lowest value of 161.46 cm. This increase is attributed to the wide host range of mycorrhizal fungi and their ability to colonize plant roots, thereby improving growth by increasing the availability and absorption of nutrients—particularly phosphorus, which contributes to plant

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The highest value was recorded in treatment M2P2 (169.29 cm), while the lowest value for the interaction was in M1P0 (159.93 cm). This effect is attributed to the extensive fungal network used by mycorrhizae to increase the contact area between the soil and plant roots, activating insoluble phosphorus in the soil. This enhances the plant's ability to absorb various nutrients, thereby improving growth characteristics [46].

The binary interaction between fungal inoculant levels and phosphorus levels also had a significant effect on plant height. The highest value was recorded in treatment A2P2 (176.93 cm), while the lowest value was in A0P0 (150.85 cm). This is because mycorrhizae function as a type of phosphatic biofertilizer that plays a role in increasing nutrient absorption and positively affects root colonization through symbiotic relationships. This leads to increased nutrient accumulation and growth indicators by extending external hyphae to extract phosphorus from soil zones beyond the reach of the roots [37]. This is consistent with [19, 11].

Finally, the same table shows that the triple interaction of the studied factors significantly increased plant height. The highest value was observed in the triple interaction treatment M2A2P2, reaching 180.13 cm, compared to the lowest value in the triple interaction of mycorrhizae, fungal inoculant, and phosphorus M1A0P0, which was 149.73 cm response to mycorrhizal inoculation [8], which is consistent with the findings of [58].

The table also shows that the addition of phosphorus levels significantly increased the available plant height. The highest value was observed in treatment P2, which recorded a plant height of 165.83 cm, compared to treatments P0 and P1, which recorded the lowest heights of 159.39 cm and 164.01 cm, respectively. This is because phosphorus shows a clear response as one of the essential elements for maize growth. Phosphate fertilization enhances dry matter accumulation, which significantly reflects on plant height and subsequently leads to increased yield; this is in agreement with [41].

The binary interaction between mycorrhizae and the fungal inoculant also led to a significant increase in plant height. The highest value was recorded in treatment M2A2 (177.63 cm), while the lowest value was in treatment M1A0 (169.31 cm). This may be due to the positive role of fungal hyphae in nutrient availability, increasing soil stability by binding soil particles, and secreting growth regulators such as gibberellins, auxins, and cytokinins. These regulators assist in cell organization and elongation, positively impacting plant growth and increasing vegetative growth indicators [49]; [50]; [6]). These results are consistent with [30] and [22].

Furthermore, the binary interaction between mycorrhizae and phosphorus significantly increased plant height.

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(6): Effect of Different Mycorrhizal Genera, Fungal Inoculum, Phosphorus Levels, and Their Interaction on Plant Height (cm)

M Mycorrhiza × × Fungal Inoculum A	Phosphorus P			المعاملات	
	200	100	0	Fungal Inoculum A	Mycorrhi M za
155.04	152.43	162.97	149.73	0	Gigspora
160.01	160.93	161.20	157.90	10	
169.31	173.73	162.03	172.17	50	
157.22	161.70	158.00	151.97	0	G.mossea
159.23	166.03	159.37	152.30	10	
177.63	180.13	180.47	172.30	50	
4.212	7.295			LSD .(0.05)	
Effect M Mycorrhiza	165.83	164.01	159.39	Effect Phosphorus P	
	2.978			LSD. (0.05)	
	Phosphorus P			Mycorrhiza	
	200	100	0		
161.46	162.37	162.07	159.93	Gigspora	
164.70	169.29	165.94	158.86	G.mossea	
2.432	4.212			LSD.(0.05)	
Effect Fungal Inoculum A	Phosphorus P			Fungal Inoculum A	
	200	100	0		
156.13	157.07	160.48	150.85	0	
159.62	163.48	160.28	155.10	10	
173.47	176.93	171.25	172.23	50	
2.978	5.158			LSD .(0.05)	

Glomus over the genus Gigaspora across all studied traits. This indicates the high efficiency of this fungus in

Conclusions

1. The results demonstrated a significant superiority of the genus

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establishing effective symbiotic relationships with the plant.

2. Increasing the mycorrhizal inoculant levels to 50g led to an increase in the infection percentage and improved nutrient uptake, which was positively reflected in plant growth.

3. Inoculated treatments, particularly those involving Glomus mosseae, resulted in an increase in the concentration of macronutrients (Nitrogen, Phosphorus, and Potassium) compared to the non-inoculated treatments.

4. The triple interaction treatment (M2A2P2) yielded a significant increase in most growth indicators, including plant height, enhanced nutrient availability in the soil, infection percentage, and bacterial populations

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