Effect of mycorrhizal fungi, Bacillus bacteria and chemical fertilization on the growth indicators and yield of corn (*Zea mays* L.).

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Abstract:

A field experiment was conducted on corn in a field in the northern Karbala province to study the role of mycorrhizal fungi and Bacillus bacteria isolated from Iraqi soil on phosphatase enzyme activity, phosphorus availability, and the yield growth of corn (Zea mays L.). This was achieved by studying three factors: the first factor, Bacillus bacteria, at three levels: no addition (0), 10 ml of Bacillus subtitles, and 10 ml of Bacillus megaterium 2 per plant (designated B0, B1, and B2); the second factor, phosphorus fertilizer application (full nutrient recommendation and half nutrient recommendation, 50% and 100% of the nutrient recommendation, designated P1 and P2); and the third factor, mycorrhizal fungi, at three levels: no addition, Glomus mosseae, and Gigaspora (0, 5, and 10 g, designated M0, M1, and M2, respectively). This resulted in 18 treatments, each replicated three times, for a total of 54 experimental units, following a walk-through complete block design (RCBD). The results indicated that:The addition of mycorrhizae to treatment M2 resulted in the highest growth parameters for corn, specifically plant height, chlorophyll index, thousand-grain weight, vegetative growth dry weight, and total yield, with values of 168.05 cm, 55.23 spade, 357.89 g, 65.52 g plant^{-1}, and 4.52 ton.ha^{-1}, respectively.The second type of Bacillus bacteria in treatment B1 achieved the highest significant increase in all growth indicators, including plant height, chlorophyll index, thousand-grain weight, vegetative growth dry weight, and total yield, with values of 171.44 cm, 59.63 cm, 362.0 g, 73.35 g, and 4.05 ton.ha^{-1}, respectively. The P2 level (full phosphorus fertilizer recommendation) achieved the highest growth indicators and yield for corn, with values very close to those of treatment P1 (half phosphorus fertilizer recommendation). Bi- interaction of P2 (full fertilizer recommendation) with both M2 and B2 resulted in the highest growth indicators for corn. Bi- interaction of treatment M2B2 also resulted in the highest growth indicators and the highest yield for corn.The triple interaction of treatment M2B2P2 resulted in the highest growth indicators and yield for corn, with values for most traits comparable to those of the triple interaction of treatment M1B2P2.

Introduction

Root mycorrhizal fungi are among the most important microorganisms that

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form a symbiotic relationship with plant roots. They increase the surface area for nutrient absorption from the soil through a network of hyphae that extend beyond the root zone. This enhances nutrient uptake, particularly phosphorus and nitrogen, and contributes to improved vegetative growth and increased plant resistance to environmental stresses [9]. A study by [3] indicated that mycorrhizae also contribute to enhancing enzymatic activity in the soil and improving nutrient cycling, making them a vital tool for improving fertilizer use efficiency and reducing losses.Bacillus bacteria, such as Bacillus subtilis and Bacillus megaterium, play a key role in enhancing soil fertility by solubilizing unavailable phosphorus and stimulating plant growth through the production of plant growth regulators and various enzymes. This increases nutrient availability and improves nutrient uptake [4].This study confirmed that inoculating plants with Bacillus bacteria enhances the availability of macro- and micronutrients and improves crop productivity while reducing reliance on chemical fertilizers.Phosphorus is an essential element for plants, playing a vital role in energy storage, photosynthesis, and nucleic acid synthesis. However, its availability in the soil is often limited due to its fixation in non-absorbable forms, which reduces the efficiency of phosphorus fertilizers [8]. [10] study by demonstrated that managing phosphorus in conjunction with microorganisms such as mycorrhizae and Bacillus bacteria improves its availability to plants and increases fertilizer use efficiency, contributing to improved agricultural sustainability. Reducing production costs.Corn (Zea mays L.) is a field crop with high nutrient consumption, particularly phosphorus. It responds well to fertilization enhancement using bio-inoculators such as mycorrhizae and Bacillus bacteria, which contributes to increased plant growth and corn yield [12]. A study by [5] confirmed that combining these bio-inoculators with balanced phosphorus fertilization management enhances nutrient use efficiency and allows for reduced chemical fertilizer rates without impacting crop productivity. This makes studying this interaction a scientific necessity for determining effective and sustainable fertilizer recommendations for corn.The interaction between biotic and chemical soil agents is considered one of the most important methods for enhancing plant nutrient use efficiency and sustainably improving productivity. In the case of corn, recent studies have shown that combining mycorrhizae with phosphorus increases phosphatase activity in the rhizosphere (root zone), promoting the decomposition of organic phosphorus and improving its uptake by the plant [10].Studies have also shown that adding Bacillus bacteria to this equation stimulates the production of additional enzymes, including phosphotase, and leads to a synergistic effect that increases phosphorus availability to plants more than using any single agent.Based on the above, and due to the limited research on this topic, this study aimed to study the role of mycorrhizal fungi and Bacillus bacteria isolated from Iraqi soil on phosphatase enzyme activity, phosphorus availability, and the yield growth of corn (Zea mays L.).

Materials and Methods

Experiment Location

The field experiment was conducted in an agricultural field in the northern part of Karbala province to cultivate corn (Zea mays L.) during the spring season, starting on March 15, 2024, in silty loam soil.

Soil Sample Collection

Soil samples were randomly collected from different locations in the field before planting, at a depth of 0-30 cm. The samples were thoroughly mixed to form a single representative sample. The sample was then air-dried, ground, and sieved through a 2 mm sieve for chemical and physical analysis, as detailed in Table 1.

Table 1: Chemical and Physical Properties of the Soil Before Planting

traits	**unit**	**values**
Ece	ds m^{-1}	4.55
pH	-	7.70
Cation Exchange Capacity	Centimol per kg^{-1} soil	8.44
Carbonate	$mmol.L^{-1}$	Nill
Bicarbonate		6.9
Chloride		7.33
Sulfate		9.76
Calcium		13.55
Magnesium		15.2
Sodium		65
Sodium Adsorption Ratio (SAR)	mmol of charge per $liter^{-1}$	11.64
Moisture Content	%	28.11
Physical Density	$Mg.m^{-1}$	1.34
Organic Matter	$g.kg^{-1}$	10.77
Organic Carbon	$g.kg^{-1}$	0.77
Available Nitrogen	mg.kg $soil^{-1}$	25.75
Available Phosphorus		5,88
Available Potassium		166
Sand	$g.kg^{-1}$	455.3
Clay		120.7

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sitl		424
texture	-	Silt Loam
Bacillus Cultures	**10^5 x CFU g $^{-1}$ dry soil**	10^5×44
Mycorrhizal Infection Rate	%	4,5

Experimental Design and Experiment Factors

The field experiment was conducted as a factorial experiment using a randomized complete block design (RCBD) with three factors: Bacillus inoculum at three levels (0, 10, and 10 ml) per plant, designated (B2, B1, and B0). The bacterial inoculum was prepared at the Al-Amin Center for Advanced Biological Research and Analysis, affiliated with the Holy Shrine of Imam Ali in Najaf. Phosphate fertilizer was applied at two levels (50 and 100 tons ha^{-1}), designated (P1 and P0). Mycorrhizal inoculum (Glomus mosseae) was obtained from the Ministry of Science and Technology/Department of Agricultural Research. The inoculum consisted of spores, infected roots, and dry soil. It was tested to count the number of pure spores using the wet sifting method, as proposed by Gerdmann and Pason (1963). It contained 42 spores per plant. One gram of soil. The inoculant, mixed with peat moss at a 1:1 ratio, was added at three levels (0, 10, and 50 grams) per plant in the field. Half of the mycorrhizal inoculant was spread at a depth of 5 cm as a seedbed, and the other half was mixed into the soil at a depth of 5 cm .The treatments were randomly distributed among the experimental units used for each of the three replicates, resulting in a total of (54) experimental units.

Agricultural Operations

The experimental plot was prepared by plowing the land twice perpendicularly using a moldboard plow, then smoothing it with a disc harrow, leveling the land, and opening the main and secondary irrigation ditches. The field was divided into three sections, leaving a distance of (2 m) between each section. Each section was divided into 18 experimental units measuring 3 x 2 m^2. Each experimental unit contained 3 rows, each 2 m long, with a distance of 70 cm between rows and a distance of 2 m between replicates, forming an irrigation channel.The corn crop was planted manually on March 15, 2024, by placing 5 seeds in each hole in the upper third of the furrow, with a spacing of 20 cm between holes. Thinning to one plant per hole was carried out three weeks after planting. Irrigation was performed using surface irrigation at regular intervals. Manual hoeing was performed to remove weeds and harmful plants as needed until the end of the experiment on August 15, 2024.Fertilization was carried out by adding 320 kg ha^{-1} of urea (46% N) as a nitrogen source in three applications: one week after the first irrigation, one

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month after the first application, and two months after the second application. DAP fertilizer was added at a rate of 200 kg ha^{-1} as a phosphorus source in a single application one week after the first irrigation. Potassium sulfate was also added at a rate of 120 kg ha^{-1} in a single application. The granular insecticide diazinon (10% active ingredient) was used to control the corn stem borer (Sesamia critica) by applying it to the growing tip of the stem twice: the first application at the 4-5 leaf stage and the second 15 days later

Study traits:

Corn Stem Height (cm): The height of the corn stem was measured at maturity in five randomly selected experimental units using a measuring tape from the soil surface to the growing tip. The average height (cm) was then calculated.

Dry weight of vegetative growth (g $plant^{-1}$)

The plants were completely uprooted from the experimental units at the end of the growing season and washed with running water to remove soil. They were then dried and transferred to an oven at 70°C until their weight stabilized. The dry weight of the vegetative growths was then calculated.

Leaf Chlorophyll Content:

Leaf chlorophyll content was measured using a SPAD-502 chlorophyll meter during the flowering stage. Three leaves were examined, and three readings were taken for each leaf. The average reading was then calculated [13].

Weight of 1000 grains (g): The weight of 1000 grains per experimental unit was calculated and its average was determined.

Total Corn Yield (ton ha^{-1})

The total yield was calculated by taking the yield of the remaining plants in experimental units and adding the yield of the five plants used in the previous study of plant trits. The total yield was then calculated based on the experimental unit.

Statistical Analysis

The experimental results were analyzed using GenStat software. A factorial experiment was conducted using a randomized complete block design (RCBD) with three replicates. The significant difference between the means was compared using the least significant difference (LSD) test at a probability level of 0.05 (as described by [2].

Results and Discussion.

Plant Height (cm)

The results of the statistical analysis in Table (2) indicate that the study parameters significantly affected the increase in corn plant height. The addition of mycorrhizal fungi significantly impacted this characteristic, with the highest value observed in treatment M2, reaching 168.05 cm, compared to treatments M0 and M1, which reached 160.45 and 152.08 cm, respectively. The table also shows that Bacillus Bacteria significantly affected the increase in corn plant height, with the highest value observed in treatment B2, reaching 171.14 cm, compared to treatments B1 and B0, which reached 159.46 and 150.48 cm, respectively. The addition of phosphate fertilizer at half and full fertilization rates significantly increased plant height, with the highest value observed in treatment P2 (171.10 cm) compared to treatment P1 (149.61 cm). Bi- interactions also significantly increased the height of corn plants, with the highest value observed in the M2P2 interaction (mycorrhizal/phosphorus), reaching 175.58 cm compared to the M0P1 interaction (137.90 cm). Similarly, the Bacillus bacteria/phosphorus interaction significantly increased plant height, with the highest value observed in the B2P2 interaction (185.29 cm) compared to the B0P1 interaction (142.27 cm). Finally, the Bacillus bacteria/mycorrhizal fungi significantly increased plant height. The highest value for this trait was 181.70 cm in the M2B2 Bi- interactions treatment, which was not significantly different from the M1B2 Bi- interactions treatment (171.26 cm). The lowest value was 145.37 cm in the M0M0 Bi- interactions treatment.The same table shows that triple -interaction of the study factors significantly increased the height of the corn plant. The highest value was 190.20 cm in the M2B2P2 triple interaction treatment, which was not significantly different from the M1B2P2 triple interaction treatment (185.63 cm). The lowest value for the height of the corn plant was 135.00 cm in the M0B0P1 triple interaction treatment, representing an increase of 40.88%.

Table 2: Role of Mycorrhizal Fungi, Bacillus Bacteria, and Phosphorus in the Height of Corn Plants (cm)

phosphate fertilizer P	Mycorrhizae	Bacillus B				
		B0	B1	B2	P*M	average
P1	M0	135.00	137.81	140.89	137.90	149.61
	M1	141.20	153.20	156.89	150.43	
	M2	150.63	157.75	173.20	160.52	
P2	M0	155.75	163.00	180.05	166.26	171.10

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	M1	159.00	196.80	185.63	171.47	
	M2	161.31	175.25	190.20	175.58	
LSD				LSD:P*M*B=3.35	LSD:P*M	LSD:P
P*B		2.53				1.45
P1		142.27	149.58	156.99	LSD:P*B= 2.74	
P2		158.68	169.35	185.29		
M*B					M average	
M0		145.37	150.40	160.47	152.08	
M1		150.10	161.50	171.26	160.95	
M2		155.97	166.50	181.70	168.05	
LSD		LSD:M*B= 3.10			LSD:M= 1.75	
average------ B		150.48	159.46	171.14	-----------	
LSD		LSD:B=2.85			-----------	

Chlorophyll Index (spade unit)

The results of the statistical analysis in Table (3) indicate that the effects of the study factors—the addition of mycorrhizal fungi, Bacillus bacteria, and phosphorus, and their interactions—significantly increased the chlorophyll index of corn. The addition of mycorrhizal fungi at different levels of different genera significantly increased the chlorophyll index, with the highest value recorded in treatment M2 at 55.23 spade units, compared to treatments M1 and M0 at 52.67 and 46.08 spade units, respectively. Similarly, the addition of Bacillus bacteria significantly increased the chlorophyll index of corn, with the highest value recorded in treatment B2 at 59.63 spade units, compared to treatments B1 and B0 at 51.99 and 39.04 spade units, respectively. The addition of phosphate fertilizer also had a significant effect. Fertilizer recommendation had a significant effect on increasing the chlorophyll index of corn, with the highest value being 54.83 spade units in treatment P2, compared to 45.61 spade units in treatment P1. The interaction of the two study factors also led to a significant increase in the chlorophyll index of corn. The interaction between mycorrhizae and phosphorus had a significant effect on

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the chlorophyll index, with the highest value being 58.46 spade units in treatment M2P2, compared to the lowest value of 34.85 spade units in treatment M0P1. Similarly, the interaction between bacilli and phosphorus had a significant effect on increasing the chlorophyll index, with the highest value being 65.57 spade units in treatment B2P2, compared to the lowest value of 36.65 spade units in treatment B0P1. The bi-interaction between basil and mycorrhizae also had a significant effect, with the highest value (64.77 spad units) observed in the M2B2 interaction treatment, compared to the lowest value (30.95 spad units) in the M0B0 binary treatment. The same table also shows that the ternary interaction of the study factors significantly increased the chlorophyll index of corn. The highest value (67.20 spad units) was observed in the M2B2P2 ternary interaction treatment, which was not significantly different from the M1B2P2 ternary interaction treatment (65.00 spad units). The lowest chlorophyll index value (30.25 spad units) was recorded in the M0B0P1 treatment.

Table 3: The Role of Mycorrhizal Fungi, Bacillus Bacteria, and Phosphorus in the Spad unit Chlorophyll Index

phosphate fertilizer P	Mycorrhizae	Bacillus B				
		B0	B1	B2	P*M	average
P1	M0	30.25	35.55	38.75	34.85	45.61
	M1	39.70	50.20	60.00	49.96	
	M2	40.00	53.71	62.35	52.02	
P2	M0	31.65	55.81	64.52	50.66	54.83
	M1	43.73	57.43	65.00	55.38	
	M2	48.93	59.25	67.20	58.46	
LSD				LSD:P*M*B=4.33	LSD:P*M	LSD:P
P*B						1.55
P1		36.65	46.48	53.70	LSD:P*B= 1.25	

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P2	41.43	57.49	65.57	
M*B				M average
M0	30.95	45.68	61.63	46.08
M1	41.71	53.81	62.50	52.67
M2	44.46	56.48	64.77	55.23
LSD	LSD:M*B= 2.55			LSD:M= 1.69
average------ B	39.04	51.99	59.63	-----------
LSD	LSD:B=1.89			-----------

1000 Grain Weight (g)

It is observed from the statistical analysis results in Table (4) that the effect of different genera of mycorrhizal fungi, compared to the control group, significantly increased the 1000 grain weight (g) of corn. The highest value for this trait was observed in treatment M2, which reached 357.89 g, compared to treatment M1, which reached 362.33 g, and treatment M, which reached 343.15 g. The control group (treatment M0), which did not add mycorrhizae, recorded the lowest value for 1000 grain weight (g) at 296.57 g.Furthermore, the addition of different types of Bacillus bacteria led to an increase in the 1000 grain weight (g), with the highest value being... In treatment B2, the weight of 1000 grains (g) reached 362.01 g, while in treatment B1 it reached 338.21 g. The control treatment B0 gave the lowest value for the 1000 grains (g) trait, at 297.40 g. The table also shows that the interaction of the study factors significantly increased the 1000 grain weight (g). The interaction of mycorrhizae and phosphorus significantly increased the 1000 grain weight (g), with the highest value in the M2P2 interaction treatment, which reached 372.20 grains (g), compared to 242.21 g in the M0P1 treatment. Similarly, the interaction of bacilli and phosphorus significantly increased the 1000 grain weight (g), with the highest value in the B2P2 treatment, which reached 393.53 g, compared to 242.21 g in the B0P1 treatment. The table shows that the interaction between Bacillus bacteria and mycorrhizae significantly increased the 1000-grain weight (g) of the corn crop. The highest value was observed in the M2B2 interaction treatment (392.87 g), compared to the lowest value in the M0B0 interaction treatment (270.20 g). The table also indicates that the 3-factor interaction significantly increased the 1000-grain weight (g) of the corn crop. The highest value was observed in the M2B2P2 interaction treatment (410.00

g), while the M1B2P2 interaction treatment (390.20 g) gave the lowest value (225.20 g) for the 1000-grain weight of the corn crop (g) in the M0B0P1 treatment. 82.06%

Table 4. Role of Mycorrhizal Fungi, Bacillus Bacteria, and Phosphorus in 1000 grains (g).

phosphate fertilizer P	Mycorrhizae	Bacillus B				
		B0	B1	B2	P*M	average
P1	M0	225.20	245.73	255.70	242.21	303.90
	M1	270.62	347.18	360.00	325.93	
	M2	300.00	355.00	375.75	343.58	
P2	M0	315.20	357.20	380.41	350.93	361.17
	M1	330.25	360.71	390.20	360.38	
	M2	343.17	363.45	410.00	372.20	
LSD				LSD:P*M*B=4.33	LSD:P*M	LSD:P
P*B		2.10				1.55
P1		265.27	315.97	330.48	LSD:P*B= 2.36	
P2		329.54	360.45	393.53		
M*B					M average	
M0		270.20	301.46	318.05	296.57	
M1		300.43	353.94	375.10	343.15	
M2		321.58	359.22	392.87	357.89	
LSD		LSD:M*B= 3.39			LSD:M= 1.45	
average------ B		297.40	338.21	362.01	-----------	
LSD		LSD:B=1.88			-----------	

Dry Weight of vegetative growth (g/plant)

The results of the statistical analysis in Table 5 indicate that the combined effects of the treatments mycorrhizal fungi, Bacillus bacteria, phosphorus, and their interaction significantly increased the dry weight of the green parts (g/plant) of corn. The addition of mycorrhizal fungi, in their various genera, significantly increased this trait, with the highest value (65.52 g/plant) observed in treatment M2, compared to treatments M1 and M0 (62.54 g/plant and 49.88 g/plant, respectively). Similarly, the addition of Bacillus bacteria significantly increased the dry weight of the green parts of corn, with the highest value (73.35 g/plant) observed in treatment M2, compared to treatments M1 and M0 (60.17 g/plant and 44.34 g/plant, respectively).The application of phosphate fertilizer at half the recommended amount significantly increased the dry weight of the vegetative growth. The highest value was observed in treatment P2, reaching 66.22 g per plant, compared to 52.37 g per plant in treatment P1 (half the recommended amount). The table

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also shows that Bi- interactions significantly increased the dry weight of the vegetative growth. The bi-interaction between mycorrhizal fungi and phosphorus significantly affected this trait, with the highest value observed in treatment M2P2 (70.53 g per plant), compared to the lowest value in treatment M0P1 (39.38 g per plant). Similarly, the bi-interaction between Bacillus bacteria and phosphorus significantly increased the dry weight of the vegetative growth, with the highest value observed in treatment B2P2 (80.27 g per plant). The highest value for this trait was observed in treatment B0P1, which was 38.77 g plant. Bi-interaction of mycorrhizal and bacilli also significantly increased the dry weight of the vegetative growth, with the highest value recorded in Bi-interaction treatment M2B2 (79.35 g plant), compared to the lowest value in treatment M0B0 (34.84 g plant). The same table also shows that the triple interaction of the study factors significantly increased the dry weight of the vegetative growth, with the highest value recorded in the triple interaction treatment M2B2P2 (82.90 g plant), compared to the lowest value in treatment M0B0P1 (30.33 g plant).

Table 5 The role of mycorrhizal fungi, bacteria (Bacillus) and phosphorus in the dry weight of vegetative growth (g plant $^{-1}$).

phosphate fertilizer P	Mycorrhizae	Bacillus B				
		B0	B1	B2	P*M	average
P1	M0	30.33	37.62	50.20	39.38	52.37
	M1	40.25	58.25	73.25	57.25	
	M2	45.73	60.00	75.80	60.51	
P2	M0	39.35	64.43	77.40	60.39	66.22
	M1	52.70	69.75	80.52	67.65	
	M2	57.96	71.00	82.90	70.53	
LSD				LSD:P*M*B=6.25	LSD:P*M	LSD:P
P*B		3.21				1.75
P1		38.77	51.95	66.41	LSD:P*B= 3.00	
P2		50.00	68.39	80.27		

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M*B				M average
M0	34.84	51.02	63.80	49.88
M1	46.74	64.00	76.88	62.54
M2	51.71	65.50	79.35	65.52
LSD	LSD:M*B= 4.33			LSD:M= 1.83
B ------average	44.34	60.17	73.35	-----------
LSD	LSD:B=2.59			-----------

Total yield (tons/ha)

The results of the statistical analysis in Table 6 show that all the study indicators, including the addition of mycorrhizae, bacilli, phosphorus, and their interactions, significantly increased the total yield of corn. The addition of different levels of mycorrhizal fungi of various genera significantly increased the total yield of corn, with the highest value being 4.52 tons/ha in treatment M2, compared to 4.22 and 3.54 tons/ha in treatments M1 and M0. The addition of different types of Bacillus bacteria also had a significant effect on increasing the total yield of corn, with the highest value being in treatment B2, which reached 4.93 tons/ha, compared to treatments B1 and B0, which reached 4.05 and 3.30 tons/ha, respectively. The treatment of adding half and full phosphate fertilizer recommendations also had a significant effect on increasing the total yield of corn, with the highest value being in treatment P2, which reached 4.47 tons/ha, compared to treatment P1, which reached 3.71 tons/ha. As can be seen from the table, the interaction of the two factors in the study significantly increased the total yield of corn. Specifically, the interaction between mycorrhizae and phosphorus supplementation significantly increased the total yield of corn, with the highest value observed in the M2P2 treatment (4.85 ton.ha) compared to the M0P1 treatment (3.00 ton.ha). Similarly, the interaction between bacilli and phosphorus significantly increased the total yield of corn, with the highest value observed in the M2P2 treatment (5.54 ton.ha) compared to the lowest value in the M0P1 treatment (3.13 ton.ha). The interaction between Bacillus bacteria and mycorrhizal fungi significantly increased the total yield of corn, with the highest value observed in the M2B2 treatment (5.57 ton.ha) compared to the lowest value in the M0B0 treatment (2.77 ton.ha). The same table also shows that triple - interaction of the studied factors significantly increased the total yield of corn, with the highest value observed in the M2B2P2 treatment (6.25 ton.ha) compared to the lowest value in the control treatment (M0B0P1) (2.55 ton.ha).

Table 5: The Role of Mycorrhizal Fungi, Bacillus Bacteria, and Phosphorus in Total Yield (ton.ha $^{-1}$)

phosphate fertiliz P er	Mycorrhizae	Bacillus B				
		B0	B1	B2	P*M	average
P1	M0	2.55	3.15	3.30	3.00	3.71
	M1	3.31	3.80	4.75	3.95	
	M2	3.55	4.15	4.89	4.19	
P2	M0	3.00	4.25	5.00	4.08	4.47
	M1	3.65	4.45	5.39	4.50	
	M2	3.77	4.55	6.25	4.85	
LSD				LSD:P*M*B=1.22	LSD:P*M	LSD:P
P*B					0.43	0.35
P1		3.13	3.70	4.31	LSD:P*B= 0.31	
P2		3.47	4.41	5.54		
M*B					M average	
M0		2.77	3.70	4.15	3.54	
M1		3.48	4.12	5.07	4.22	
M2		3.66	4.35	5.57	4.52	
LSD		LSD:M*B= 1.10			LSD:M= 0.25	
B ------average		3.30	4.05	4.93	-----------	
LSD		LSD:B=0.88			-----------	

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The results in Tables 4, 5, 6, 7, and 8 show that the addition of different genera of mycorrhizae and Bacillus bacteria significantly affected plant height, chlorophyll index, vegetative dry weight, and corn yield. Adding different genera and levels of mycorrhizae promotes root growth with a larger surface area, increasing the plant's ability to absorb nutrients, particularly phosphorus, which is a crucial factor to study. Furthermore, recent studies have shown that mycorrhizal fungi form a filamentous network extending beyond the root zone, increasing the root's absorbent surface area and improving the plant's ability to adapt to unfavorable environmental conditions [5] Mycorrhizae also play a role in improving soil environment and increasing the efficiency and activity of microorganisms in the root zone, making them a cornerstone of sustainable agriculture and reducing reliance on chemical fertilizers.

These results are consistent with those of [14] who indicated that plants treated with mycorrhizae showed a significant increase in plant height, leaf area, and vegetative growth dry weight compared to untreated plants. This is attributed to improved nutrient uptake and activation of physiological processes within the plant. Mycorrhizae enhance root growth, which positively impacts nutrient and water absorption efficiency, leading to increased plant height, chlorophyll index, and vegetative growth dry weight, ultimately resulting in higher overall yield.

This illustrates the vital role of mycorrhizae in improving nutrient utilization efficiency and increasing the final yield of corn [11]. The increased growth indicators for corn, as shown in the tables above, may also be attributed to the ability of mycorrhizal fungi to absorb nutrients through the networking of fungal hyphae in the root hair zone, resulting in the aforementioned growth indicators. Mycorrhizae also secrete growth regulators such as auxins and amino acids, increasing the plant's ability to absorb nitrogen, which positively impacts plant growth and leads to an increase in all growth indicators for corn [1].

Furthermore, the addition of Bacillus bacteria, a bacterium known for its growth-promoting properties (PGPR), contributes to improved nutrient utilization by the plant from the soil. This is reflected in increased plant height, chlorophyll index, and vegetative dry weight, ultimately leading to higher corn yield. This may also be attributed to the fact that Bacillus bacteria produce plant hormones such as IAA and gibberellins, stimulate nutrient uptake, and enhance plant resistance to biotic and abiotic stresses. This leads to cell elongation and is reflected in the growth indicators of corn as shown in the tables above [14].

Furthermore, the application of phosphate fertilizer at half and full recommended amounts increased plant height, chlorophyll index, and thousand-grain weight. This, in turn, increased the dry weight of the vegetative growth and the yield, especially with full recommended phosphate fertilizer. Phosphorus plays a crucial role in plant growth and development, participating in vital processes such as energy transfer via molecules like ATP. It also enhances root activity and promotes photosynthesis, thus improving the nutritional efficiency of many crops, particularly corn [6]. As can be seen from the tables above, the interaction of phosphorus with mycorrhizae and bacilli significantly increased all growth indicators for corn. Recent research indicates that both mycorrhizae and bacilli promote root development and increase surface area, thereby enhancing the plants' ability to absorb phosphorus from the soil, which in turn improves growth and yield.

Compared to the absence of these organisms, the interaction between them significantly increased all growth indicators in the tables above. These studies indicate that this interaction leads to increased phosphorus availability in the soil, improved phosphorus uptake, and enhanced root and vegetative growth growth, which positively impacts the increase in vegetative dry weight and yield.

Furthermore, the addition of these organisms with Bacillus leads to longer and more extensive root growth, increasing the roots' ability to absorb water and nutrients, including phosphorus. This, in turn, increases cell elongation, plant height, thousand-grain weight, and yield [7].

The triple interaction of the study factors, including the addition of mycorrhizae, bacilli, and different levels of phosphorus at half and full recommendations, led to an increase in all growth indicators for the corn crop, such as plant height, chlorophyll index, thousand-grain weight, and dry weight of the green part. This was reflected in the increase in the corn yield, indicating the accuracy of the extension of these study factors and their interactions. This works to provide a suitable environment for lowering the soil pH and increasing the availability of most nutrients, including phosphorus and other elements, which contributed to increasing the surface area of the roots and reflecting on the increase in growth indicators for the corn and its yield [1].

Conclusions

Treatments M2 and B showed significant superiority in most indicators of vegetative growth and yield. Treatment P2 (full recommended phosphorus fertilizer application) achieved the highest values for the studied traits, indicating that the fertilization level used was appropriate for maximizing the utilization of soil biological activity. For some traits, it did not differ from treatment P1 (half recommended fertilizer application.bi-interaction between bacteria and fungi, and treatment (M2B2) with mineral phosphorus fertilization (P2), resulted in an increase in most traits compared to the individual treatments.

References

[1] Al-Maamouri, Haider Abbas Fadhil (2020). The effect of the interaction between biofertilizer, mineral fertilizer, agricultural sulfur, and vermicompost on nitrogen and phosphorus availability in the soil and potato growth and yield. PhD dissertation - College of Agricultural Engineering Sciences - University of Baghdad/Iraq

[2] Al-Rawi, Khashaa Mahmoud and Abdul Aziz Khalaf Allah. 2000. Book: Design and Analysis of Agricultural Experiments, College of Agriculture and Forestry - University of Mosul.

[3] Delavaux, C. S., Weigelt, P., Dawson, W., Essl, F., van Kleunen, M., König, C., ... & Bever, J. D. (2021). Mycorrhizal types influence island biogeography of plants. *Communications Biology*, *4*(1), 1128.

[4] Kumar, A., Patel, J. S., Meena, V. S., & Srivastava, R. (2021). Recent advances of PGPR based approaches for nutrient use efficiency and soil sustainability. Agronomy, 11(3), 1–25.

[5] Li, M., Perez-Limón, S., Ramírez-Flores, M. R., Barrales-Gamez, B., Meraz-Mercado, M. A., Ziegler, G., & et al. (2023). Mycorrhizal status and host genotype interact to shape plant nutrition in field grown maize. Mycorrhiza, 33, 345–358

[6] Ma. Cet al (2025) Optimizing Phosphorus Fertilization for Enhanced Yield and Stress Resilience in Crop Production. Land, 14(6), 1241.

[7] Plants (2023).Effect of Phosphorus Solubilizing Bacteria in Combination with Poultry Manure on Soil Health and Sugarbeet Productivity Under Arid Climate. Asian Journal of Research in Crop Science (2023).

[8] Richardson, A. E., Simpson, R. J., & McLaughlin, M. J. (2019).Plant mechanisms to optimize access to soil phosphorus. Crop & Pasture Science, 70(2), 1–12.

[9] Smith, S. E., & Smith, F. A. (2019). Roles of arbuscular mycorrhizas in plant nutrition and growth: new paradigms from cellular to ecosystem scales. Annual Review of Plant Biology, 70, 227–250..

[10] Spohn, M., & Kuzyakov, Y. (2019 .(Microbial nutrient mining and its role in nutrient availability in soils. Soil Biology and Biochemistry, 134, 1–10.

[11] Tian, M., Feng, C., Zhang, X., Gilliam, F. S., Giri, B., Chen, Y., & et al. (2023). Arbuscular mycorrhiza enhances maize grain yield and nitrogen uptake during the grain filling stage. Plant

Growth Regulation, 100(3), 691–701.

[12] Wahid, F., Sharif, M., Steinkellner, S., Khan, M. A., & Khan, S. A. (2021). Synergistic effects of arbuscular mycorrhizal fungi and phosphate-solubilizing bacteria on nutrient availability and soil fertility. Journal of Plant Nutrition, 44(10), 1–14.

[13] Williams, J., &, Jemison M. (2006). Potato–Grain Study Project Report. Water Quality Office. University of Maine, Cooperation Extension.

[14] Zhu, Y., Wang, X., Chen, Y., Li, Y., & Feng, G. (2022). Mycorrhizal symbiosis promotes nutrient content accumulation and affects root exudates in maize. BMC Plant Biology, 22, 64.