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The Effect of Mycorrhizal Inoculation and Different Methods of Applying NPK Chemical Fertilizer on Certain Growth Characteristics of *Zea mays* L. in Gypsum Soil

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Citation: Hussein, A. A. K., Altai, S. H. M & Humad, S. K. The Effect of Mycorrhizal Inoculation and Different Methods of Applying NPK Chemical Fertilizer on Certain Growth Characteristics of *Zea mays* L. in Gypsum Soil. American Journal Of Biodiversity 2026, 3(10), 19-31

Received: 03rd Jul 2026

Revised: 18th Aug 2026

Accepted: 05th Sep 2026

Published: 16th Oct 2026



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Abstract: With the aim of increasing the efficiency of chemical fertilizer use and reducing nutrient losses in plants, mycorrhizal fungi were used as a safe, readily available, environmentally friendly, and sustainable method. The experiment was conducted in the fields of the College of Agriculture – University of Tikrit, following a completely randomized block design (RCBD), to study the effect of different methods of applying chemical fertilizers and inoculating with mycorrhizal fungi on the growth and yield of yellow corn, as well as certain growth and quality traits. The experiment included two factors: the first was the application of chemical fertilizers using three methods, in addition to a control treatment without fertilizer application, namely: the control treatment (Control) without chemical fertilizer application; application with irrigation water; application in rows parallel to the planting rows at a distance of 5 cm from the seeds; and broadcast application on the soil surface. The second factor consisted of two treatments: inoculation with mycorrhizal fungi and no inoculation. The results showed that the methods of applying chemical fertilizer and inoculation with mycorrhizal fungi had a significant effect on a number of growth characteristics and the nutritional status of yellow corn. The broadcast application method outperformed the others in terms of mycorrhizal infection rate, dry weight, 500-kernel weight, protein content, nitrogen content, phosphorus content, and leaf area, recording values of 80.93%, 12.13 g, 31.10 g, 8.06%, 1.80%, 0.25%, and 718.50 cm², respectively, while the addition of fertilizer to the irrigation water outperformed the other treatments in potassium content, reaching 1.53%. Inoculation with Mycorrhiza fungi also improved a number of traits, with the highest average leaf area reaching 733.08 cm², dry weight 11.28 g, weight of 500 seeds 29.91 g, protein content 8.05%, phosphorus content was 0.23%, and potassium content was 1.53%, while nitrogen content was 1.61%. Interactions were observed between the methods of adding the The phosphorus content was 0.23%, the potassium content was 1.53%, while the nitrogen content was 1.61%. The interactions between fertilizer application methods and mycorrhizae yielded different responses depending on the trait, most notably the superior performance of the mycorrhizae treatment combined with row application for certain traits.

Keywords: mycorrhizal fungi, chemical fertilizer application methods, *Zea mays* L.

Introduction

Yellow corn (*Zea mays* L.) is one of the most important cereal crops widely cultivated around the world, ranking third after wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) in terms of strategic and nutritional importance. Its importance stems from its versatility, as it contributes to human nutrition, its grains and byproducts are used to feed various animals, and it is also used in oil production and numerous food and other industrial sectors, making it a crop of great economic and nutritional importance. Chemical fertilization provides the most important nutrients, particularly nitrogen, phosphorus, and potassium (NPK). One of the most important factors affecting the growth and yield of yellow corn, as nitrogen plays a fundamental role in the formation of proteins, nucleic acids, and chlorophyll, while phosphorus contributes to root system development, energy transfer, and metabolic processes within the plant; potassium, meanwhile, plays a crucial role in regulating physiological processes, activating numerous enzymes, and improving the efficiency of water and nutrient use. However, the efficiency of applied fertilizers does not depend solely on their quantity but is also influenced by the method of application and the extent to which nutrients reach the root zone and are made available to the plant [1]. Studying the efficiency of chemical fertilizer application methods is particularly important in gypsum soils, which are widespread in large parts of arid and semiarid regions, as they are characterized by high gypsum content and associated physical and chemical properties that may affect the movement of water and nutrients and the growth of the root system [2]. Therefore, selecting the appropriate fertilizer application method can help improve plant nutrient uptake and reduce nutrient loss, which in turn affects plant growth and yield [3]. One of the recent trends in improving plant nutrition efficiency is the use of beneficial organisms in the soil, the most important of which are mycorrhizal fungi, particularly those that form root symbiosis, such as arbuscular mycorrhizal fungi. A symbiotic relationship develops between these fungi and the plant roots, and the fungal hyphae extend beyond the root zone, thereby increasing the root system's ability to explore a larger volume of soil and access nutrients and water. The importance of this symbiosis is clearly evident in the improvement of phosphorus uptake; it may also indirectly contribute to improving the plant's nutritional status and the uptake of certain other elements, in addition to its role in promoting root growth and enhancing the plant's ability to tolerate certain environmental stress conditions [4]. The efficiency of mineral fertilization and mycorrhizae is largely determined by soil type and the method of nutrient delivery to the root zone; therefore, combining mycorrhizal inoculation with NPK chemical fertilizer application may provide an integrated approach to improving nutrient use efficiency and promoting yellow corn growth. Hence the importance of studying the effect of these factors on certain growth traits and the nutritional status of the plant, particularly when growing yellow corn in gypsum soils, with the aim of developing a more efficient method of fertilizer management and harnessing the biological potential of mycorrhizal fungi [5].

Objectives of the Study: To use symbiotic relationships (mycorrhizae) as a modern, environmentally friendly method of fertilization; to determine the best method for applying chemical fertilizers to minimize nutrient loss in gypsum-rich soil.

Materials and Methods

The experiment was conducted in the fields of the College of Agriculture at the University of Tikrit, using a completely randomized block design (RCBD), to study the effect of different methods of applying chemical fertilizers and inoculating with mycorrhizal fungi on the growth and yield of yellow corn, as well as certain growth and quality traits. After selecting the experimental site, representative soil samples were collected from the field prior to planting at a depth of 30 cm to determine certain physical and chemical properties of the soil. The samples were collected randomly from different locations in the field, then air-dried, sieved, and prepared for analysis. Laboratory analyses were conducted at the Department of Soil Science and Water Resources—College of Agriculture—University

of Tikrit, with the aim of determining the physical and chemical properties of the soil prior to the experiment.

Texture	Available phosphorus, mg/kg	Potassium, mg/kg	Available nitrogen, mg/kg	Percentage of screenings			Ds/m Ece	pH	Properties
				Clay	Silt	Sand			
Clay Pigeon	6.82	45.8	4.9	255	565	180	4.30	7.40	Value

Study Factors

First Factor: Chemical fertilization using four methods: the control treatment (Control) without the addition of chemical fertilizers; adding fertilizer to the irrigation water; applying it in rows parallel to the planting rows at a distance of 5 cm from the seeds; and broadcast application.

Second Factor: Two treatments—inoculation with Mycorrhiza fungi and no inoculation

Soil Preparation for Planting

The experimental plot was plowed twice in perpendicular directions using a disc plow, followed by leveling and smoothing of the soil to prepare a suitable seedbed and ensure a uniform soil surface. The experimental plot was then divided according to the approved field layout for the experiment, and the experimental units, treatments, and replicates were defined according to the experimental design. Each experimental unit measured $2 \times 2 \text{ m}^2$. Yellow corn was planted in rows within the experimental units, and land preparation and conditioning for planting were carried out in accordance with standard agricultural practices for this crop. The study involved the use of diammonium phosphate (DAP) as a source of phosphorus and nitrogen, potassium sulfate as a source of potassium, and urea to supplement the required amount of nitrogen. The recommended fertilizer rate was 100 kg N ha^{-1} , with the addition of 80 kg ha^{-1} of phosphorus and potassium; the fertilizers were applied according to the specific application method designated for each treatment. The experiment also included two treatments—inoculation with Mycorrhiza fungi and no inoculation—to study their individual effects and their interaction with the chemical fertilizer application methods. Crop management practices, including irrigation, weed control, and pest control, were carried out as needed, and the plants were tended until they reached maturity. Measurements were then taken and data collected for the traits under study according to the approved methods for each trait.

Characteristics Studied

Mycorrhizal Infection Rate (%): Samples were taken from plant roots and washed with water to remove adhering soil. The samples were then prepared for microscopic examination to detect mycorrhizal fungal structures within the roots, and the percentage of infection was calculated using the following equation: [6]

Mycorrhiza infection rate (%) = (number of infected root segments ÷ total number of root segments examined) × 100.

Leaf area ($\text{cm}^2 \text{ plant}^{-1}$): Leaf area was estimated using the disc method by taking a representative leaf from the plant and cutting discs of known area from it using a metal punch. The whole leaf and the cut discs were then weighed, and the leaf area was calculated using the following equation:

Leaf area (cm^2) = (weight of the whole leaf (g) × area of the discs (cm^2)) ÷ weight of the discs (g).

The leaf areas were then summed to obtain the total leaf area of the plant.

Dry weight (g plant^{-1}): The plants selected for measurement were weighed to determine their fresh weight, then placed in perforated paper bags and dried in an electric oven at $65\text{--}70^\circ\text{C}$ for 48–72 hours until the weight stabilized, after which they were weighed again and the dry weight recorded.

Weight of 500 grains (g): 500 grains were randomly selected from the grains produced by each experimental unit, then weighed on a precision scale, and the weight was recorded in grams.

Protein content in grains (%): The protein content was estimated based on the total nitrogen content in the grains; the protein percentage was calculated by multiplying the nitrogen content by a

conversion factor of 6.25. Nitrogen Content in Grains: (%) Representative samples were taken from the ground grains and digested using the approved laboratory method; total nitrogen was determined using a Micro-Kjeldahl apparatus, and the results were expressed as a percentage of dry matter.

Phosphorus content in grains: (%) The total phosphorus content in the plant samples was determined after digestion using ammonium molybdate and measured with a spectrophotometer; the results were expressed as a percentage.

Potassium content in grains (%): The potassium content in the extract obtained from the digestion of plant samples was determined using a laboratory instrument designed for potassium analysis, and the results were expressed as a percentage of dry matter.

Statistical Analysis

The data were statistically analyzed using a completely randomized block design (R.C.B.D.) in a factorial experiment, as described above. Significant differences between the arithmetic means were then compared using Duncan's multiple range test at a significance level of 0.05, with the SAS software program.

Results

Mycorrhiza Infection Rate

The results in Table (1) showed significant differences in the mycorrhiza infection rate depending on the effects of fertilizer application methods, fungal inoculation, and their interaction. The broadcast application treatment outperformed the others, recording the highest average mycorrhizal infection rate of 80.93%, while the control treatment recorded the lowest average of 1.33%. The superiority of the broadcast method can be explained by the fact that it leads to a more uniform distribution of fertilizer in the root zone, thereby providing a suitable nutritional environment for root growth and increasing the activity of beneficial microorganisms in the soil, in addition, improved root mass growth and an increase in the soil area colonized by roots create greater opportunities for fungal colonization and the formation of a symbiotic relationship with mycorrhizae. Furthermore, the balanced availability of nutrients may stimulate the growth of fine roots, which are the parts most susceptible to mycorrhizal colonization. This finding is consistent with the observations of [7], who noted that the prevalence of mycorrhizal fungi and the establishment of symbiotic relationships are linked to root condition, nutrient availability, and the physical and chemical conditions of the soil. As for mycorrhizal inoculation, the results showed a significant effect, as the mycorrhizal inoculation treatment outperformed the other treatments and recorded the highest average mycorrhizal infection rate of 60.41%, compared to the non-inoculation treatment, which recorded the lowest average of 33.03%. This superiority is attributed to the fact that beneficial bacteria added to the soil or associated with the root zone can act as plant growth-promoting microorganisms (PGPRs), thereby increasing root mass and branching and improving nutrient uptake, They may also produce certain compounds that stimulate root growth and help create conditions conducive to mycorrhizal colonization of the roots. Furthermore, synergistic interactions can occur between beneficial bacteria and mycorrhizal fungi, as some bacteria promote fungal hyphal growth and root colonization, while mycorrhizal fungi contribute to improving the plant's uptake of nutrients and water. [8] noted the existence of important symbiotic interactions between mycorrhizal fungi and plant-growth-promoting bacteria, which can positively influence plant growth and the efficiency of mycorrhizal colonization.

The results also showed a significant interaction between the method of fertilizer application and bacterial inoculation; the treatment combining bacterial inoculation with fertilizer application in rows recorded the highest mycorrhizal infection rate of 63.85%, while the control treatment without bacterial inoculation recorded the lowest rate of 25.10%.

Table 1. Effect of Mycorrhiza Inoculation and Methods of Chemical Fertilizer Application on the Infection Rate

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
33.03 a	83.76 a	45.63 c	1.49 d	1.25 d	Without vaccine
41.60 b	78.10 b	85.63 a	1.26 d	1.40 d	With vaccine
	80.93 a	65.63 b	1.37 c	1.33 c	Average fertilizer application methods

Leaf Area of the Plant (cm²)

The results in Table (2) showed significant differences in the leaf area of yellow corn depending on the effects of mineral fertilizer application methods, mycorrhizal inoculation, and their interaction. The treatment involving the broadcast application of mineral fertilizer outperformed the others, recording the highest average leaf area of 718.50 cm² plant⁻¹, while the control treatment recorded the lowest average of 636.50 cm² plant⁻¹. The superiority of the broadcast method can be explained by the fact that it distributes the fertilizer over a wider area of the soil, thereby increasing the availability of nutrients to the root system and improving their absorption. This improved nutrient status—particularly the availability of nitrogen—leads to increased cell division and elongation, as well as the formation of larger leaves with higher metabolic activity. Furthermore, the availability of phosphorus and potassium contributes to supporting root growth and the physiological processes associated with the formation of the aboveground biomass; thus, efficient mineral nutrition leads to an increase in leaf area [9].

The effect of inoculation with Mycorrhiza fungi was significant, as inoculated plants recorded a higher average leaf area of 733.08 cm² plant⁻¹, compared to the non-inoculated control, which recorded an average of 619.33 cm² plant⁻¹. This advantage can be attributed to the role that Mycorrhiza plays in increasing the root system's efficiency in absorbing water and nutrients—particularly phosphorus—which improves the plant's nutritional status and stimulates the growth of the aboveground parts. Furthermore, an increased supply of nutrients to the plant leads to increased leaf formation and the maintenance of their photosynthetic activity, and consequently to an increase in leaf area [10].

Furthermore, the interaction between the method of mineral fertilizer application and mycorrhizal inoculation had a significant effect on leaf area; the treatment combining mycorrhizal inoculation with row-applied fertilizer outperformed the others, recording the highest value of 778.33 cm² per plant, while the control treatment without inoculation yielded the lowest value of 521.00 cm² per plant.

Table 2. Effect of mycorrhizal inoculation and chemical fertilizer application methods on plant leaf area

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
619.33 b	744.00 b	537.66 e	674.66 d	00521. a	Without vaccine
733.08 a	693.00 c	778.33 a	709.00 c	752.00 b	With vaccine
	718.50 a	658.00 c	691.83 b	636.50 d	Average fertilizer application methods

Dry Weight of the Plant (g)

The results in Table (3) showed significant differences in the dry weight of yellow corn depending on the effects of mineral fertilizer application methods, mycorrhizal inoculation, and their interaction. The treatment involving the broadcast application of mineral fertilizer outperformed the others, recording the highest average dry weight of 12.13 g, while the control treatment recorded the lowest average of 8.95 g. The superiority of the broadcast method can be attributed to the distribution of mineral fertilizer over a larger soil area, which increases the likelihood of nutrients reaching the root system and enhances their absorption—particularly nitrogen, phosphorus, and potassium, which are essential for leaf formation, increased metabolic activity, and dry matter accumulation. Furthermore, the improvement in the plants' nutritional status is reflected in increased growth of the aboveground and root masses, and consequently, higher dry weight. [11] confirms that a balanced supply of nutrients is directly linked to increased growth and dry matter accumulation as a result of enhanced photosynthetic efficiency and organic matter formation.

As for the effect of inoculation with mycorrhizal fungi, it was significant, as inoculated plants recorded a higher average dry weight of 11.28 g compared to 9.60 g in non-inoculated plants. This increase can be explained by the symbiotic role of mycorrhizal fungi, as the fungal hyphae extending beyond the root zone increase the effective volume of the root absorption area and improve the uptake of nutrients—particularly phosphorus—as well as enhance the uptake of water and certain other minerals. Furthermore, the improvement in the plant's nutritional and water status leads to increased root and shoot growth and higher photosynthetic efficiency, which is reflected in increased dry matter accumulation. This is consistent with the findings of [7], who noted that mycorrhizal fungi contribute to improving the plant's uptake of nutrients, particularly phosphorus, and promote plant growth and dry matter production. The interaction between the method of mineral fertilizer application and mycorrhizal inoculation had a significant effect on dry weight; the treatment combining mycorrhizal inoculation with fertilizer application in rows recorded the highest value of 87.12 g, while the control treatment without inoculation recorded the lowest value of 55.70 g.

Table 3. Effect of inoculation with Mycorrhiza fungi and methods of chemical fertilizer application on plant dry weight

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
9.60 b	12.19 b	8.80 e	9.88 d	7.55 f	Without vaccine
11.28 a	12.07 b	12.87 a	9.83 d	10.35 c	With vaccine
	12.13 a	10.83 b	9.85 c	8.95 d	Average fertilizer application methods

Weight of 500 kernels (g)

The results in Table (4) showed significant differences in the weight of 500 kernels of yellow corn depending on the effects of mineral fertilizer application methods, mycorrhizal inoculation, and their interaction. The treatment involving the broadcast application of mineral fertilizer outperformed the others, recording the highest average weight of 500 kernels at 31.10 g, while the control treatment recorded the lowest average at 26.66 g. The superiority of the broadcast method can be attributed to a more comprehensive distribution of fertilizer within the root zone, which improves the availability and uptake of nutrients—particularly nitrogen, phosphorus, and potassium—during the growth and grain-filling stages. This improved mineral nutrition is reflected in increased photosynthetic efficiency and carbohydrate synthesis, and a larger portion of photosynthetic products is then transferred to the grains during the filling stage, contributing to increased grain weight. [10] A study by [12] showed that the addition of mineral fertilizers containing nitrogen and phosphorus improved maize growth and yield.

As for the effect of inoculation with mycorrhizal fungi, it was significant, as the inoculated plants recorded the highest average weight of 500 seeds at 29.91 g, while the non-inoculated treatment yielded the lowest average at 27.74 g. This increase can be explained by the vital role of mycorrhizal fungi in expanding the absorptive capacity of the root system through a network of fungal hyphae, particularly in increasing the efficiency of phosphorus uptake, which is an important element in grain formation and the transport of photosynthetic products to the grains. Furthermore, improving the plant's nutritional status may lead to increased photosynthetic efficiency and a prolonged grain-filling period, thereby increasing grain weight. [13] confirmed that inoculating maize with mycorrhizal fungi enhanced phosphorus uptake and increased the dry weight of the aboveground biomass, illustrating the role of mycorrhizae in improving the nutritional status and growth of maize plants.

As for the interaction between the method of applying mineral fertilizer and mycorrhizal inoculation, the effect was significant: the treatment combining mycorrhizal inoculation with fertilizer application in rows outperformed the others, recording the highest value of 59.32 g, while the control treatment (without inoculation) yielded the lowest value of 24.53 g.

Table 4. Effect of Mycorrhiza Inoculation and Methods of Chemical Fertilizer Application on Seed Weight

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
27.74 b	31.68 a	26.32 de	28.45 bcd	24.53 e	Without vaccine
29.91 a	30.51 ab	32.59 a	27.74 cd	28.79 bc	With vaccine
	31.10 a	29.45 b	28.09 bc	26.66 c	Average fertilizer application methods

Protein Content in Yellow Corn Kernels

The results in Table (5) showed significant differences in the protein content of yellow corn kernels depending on the effects of mineral fertilizer application methods, inoculation with Mycorrhiza fungi, and their interaction. The treatment involving the broadcast application of mineral fertilizer outperformed the others, recording the highest average protein content of 8.06%, while the control treatment recorded the lowest average of 6.34%. The superiority of the broadcast application treatment can be explained by the more uniform distribution of fertilizer in the soil, which contributes to improved nutrient availability and uptake, particularly nitrogen—a key component in the synthesis of amino acids and proteins. Furthermore, improved nitrogen nutrition during the growth and grain-filling stages increases nitrogen transfer to the grain which is reflected in a higher protein content [14].

As for the effect of inoculation with mycorrhizal fungi, it was significant, as inoculated plants recorded the highest average protein content of 8.05%, compared to 7.42% in the non-inoculated treatment, This can be attributed to the ability of symbiotic mycorrhizal fungi to increase the efficiency of roots in exploring the soil and absorbing nutrients—particularly phosphorus and nitrogen—which improves the plant's nutritional status and enhances the efficiency of nitrogen compound formation and transport to the grains [15].

As for the interaction between the application of mineral fertilizer and mycorrhizal inoculation, it was significant: the treatment combining mycorrhizal inoculation with fertilizer application in rows outperformed the others, recording the highest value of 77.8%, while the control treatment (without inoculation) recorded the lowest value of 55.6%.

Table 5. Effect of Mycorrhizal Inoculation and Methods of Chemical Fertilizer Application on Protein Content

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
7.42 b	8.39 b	7.02 d	7.72 c	6.55 e	Without vaccine
8.05 a	7.74 c	8.77 a	7.56 c	8.13 b	With vaccine

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
	8.06 a	7.89 a	7.01 b	7.34 c	Average fertilizer application methods

Nitrogen Content in Yellow Corn Kernels

The results in Table (6) showed significant differences in nitrogen content depending on the effects of mineral fertilizer application methods, inoculation with Mycorrhizae fungi, and their interaction. The broadcast application treatment outperformed the others, recording the highest average nitrogen content of 1.80%, while the control treatment recorded the lowest average of 1.52%. The superiority of the broadcast method can be explained by the more uniform distribution of fertilizer in the soil, which provides a larger root zone for nutrient uptake, particularly nitrogen. Improved nitrogen availability and uptake lead to increased formation of nitrogenous compounds and the incorporation of nitrogen into the synthesis of amino acids and proteins, with a portion of it subsequently transferred to the grains during the filling stage [16].

As for the effect of inoculation with mycorrhizal fungi, it was significant; however, the results showed a different trend from some of the previous traits, as the non-inoculated treatment recorded the highest average nitrogen content at 1.73%, while the plants inoculated with mycorrhizal fungi recorded the lowest average at 1.61%. The lower nitrogen content in inoculated plants can be explained by the fact that mycorrhizae do not necessarily lead to an increase in the element's concentration in tissues under all conditions; improved growth and increased dry matter resulting from inoculation may lead to a dilution effect, that is, a decrease in the relative nitrogen concentration due to increased plant growth and dry matter accumulation at a rate exceeding the rate of increase in accumulated nitrogen in the tissue [17].

As for the interaction between the method of mineral fertilizer application and mycorrhizal inoculation, it was significant: the treatment without inoculation but with fertilizer applied in rows recorded the highest value for the trait at 45.2%, while the treatment with broadcast fertilizer application combined with mycorrhizal inoculation recorded the lowest value at 1.15%.

Table 6. Effect of mycorrhizal inoculation and chemical fertilizer application methods on the nitrogen content

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
1.73 a	2.45 a	1.41 cd	1.77 bc	1.29 d	Without vaccine
1.61 a	1.15 d	2.06 ab	1.49 cd	1.75 bc	With vaccine
	1.80 a	1.73 a	1.63 a	1.52 a	Average fertilizer application methods

Phosphorus Content in Yellow Corn Kernels

The results in Table (7) showed significant differences in the phosphorus content of yellow corn kernels depending on the effects of mineral fertilizer application methods, mycorrhizal inoculation, and their interaction. The treatment involving the broadcast application of mineral fertilizer outperformed the others, recording the highest average phosphorus content of 0.25%, while the control treatment recorded the lowest average of 0.17%. The superiority of the broadcast method can be explained by the increased distribution of fertilizer in the soil zone and its availability to a larger area of the root system, which improves phosphorus availability to the plant and increases its uptake and transfer to the kernels [9].

As for the effect of inoculation with mycorrhizal fungi, it was significant, as inoculated plants recorded the highest average phosphorus content of 0.23%, compared to 0.20% in the non-inoculated treatment. This advantage can be attributed primarily to the ability of mycorrhizal fungi to form a network of fungal hyphae outside the roots, which increases the volume of explored soil and enhances phosphorus uptake efficiency—especially since phosphorus is a poorly mobile element in soil. Mycorrhizae also help transport phosphorus from areas of the soil from the root surface to the plant. The improved phosphorus status then contributes to enhanced metabolic processes, root growth, and grain formation. This finding is consistent with [13], who noted that arbuscular mycorrhizal fungi contribute to enhancing phosphorus uptake in maize and improving the plant's nutritional status.

As for the interaction between the method of applying mineral fertilizer and inoculation with Mycorrhiza, it was significant: the treatment involving Mycorrhiza inoculation combined with fertilizer application in rows outperformed the others, recording the highest value of 0.26%, while the control treatment (without inoculation) recorded the lowest value of 0.16%.

Table 7. Effect of Mycorrhizal Inoculation and Methods of Chemical Fertilizer Application on the Phosphorus Content

Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
0.23 b	0.24 b	0.20 c	0.20 c	0.16 d	Without vaccine
0.20 a	0.25 ab	0.26 a	0.23 b	0.18 c	With vaccine
	0.25 a	0.23 a	0.22 b	0.17 c	Average fertilizer application methods

Potassium Content in Yellow Corn Kernels

The results in Table (8) showed significant differences in the potassium content of yellow corn kernels depending on the effects of mineral fertilizer application methods, inoculation with Mycorrhiza fungi, and their interaction. The treatment involving fertilizer application with irrigation water outperformed the others, recording the highest average potassium content of 1.53%, while the control treatment recorded the lowest average of 1.34%. The superiority of the fertilizer application with irrigation water can be explained by the more uniform distribution of nutrients in the root zone, which improves fertilizer solubility and facilitates potassium uptake by the root system [18].

As for the effect of inoculation with mycorrhizal fungi, it was significant, as inoculated plants recorded a higher average potassium content of 1.53% compared to the non-inoculated treatment, which yielded an average of 1.42%. This can be explained by the ability of mycorrhizae to increase the

effective area for soil exploration through fungal hyphae, thereby improving the efficiency of nutrient uptake from the root zone. Although the most obvious effect of mycorrhizae is often the improvement of phosphorus uptake, improved root growth and plant nutritional status can also be reflected in increased uptake of certain other elements, including potassium [19].

As for the interaction between the method of applying mineral fertilizer and inoculation with Mycorrhiza, it was significant: the treatment involving Mycorrhiza inoculation combined with fertilizer application in rows outperformed the others, recording the highest value of 70.1%, while the control treatment (without inoculation) recorded the lowest value of 1.24%.

Table 8. Effect of Mycorrhizal Inoculation and Methods of Chemical Fertilizer Application on Potassium Content

Potassium Content					
Average Inoculant Application Rates	Methods for Applying NPK Chemical Fertilizer				Bacterial Inoculant
	Applied by broadcasting	Applied in rows parallel to the planting rows	With Irrigation Water	Comparison Treatment	
1.42 b	1.54 a	1.33 d	1.57 b	1.24 d	Without vaccine
1.53 a	1.48 a	1.70 a	1.49 bc	1.45 c	With vaccine
	1.51 a	1.51 a	1.53 a	1.34 b	Average fertilizer application methods

Discussion

The current results demonstrated the importance of integrating mineral fertilizer application with mycorrhizal inoculation in improving the productive and nutritional characteristics of yellow corn; the data showed clear, statistically significant differences in growth traits and yield resulting from the efficient delivery of nutrients to the root zone. Furthermore, the role of mycorrhizae – whether used alone or in combination with mineral fertilization – contributed to enhancing the efficiency of nutrient uptake, particularly phosphorus, which had a positive impact on grain quality and yield components.

Based on these findings, it is recommended that mycorrhizal inoculation be adopted as an essential and integral part of yellow corn nutrition programs, taking into account the selection of an appropriate application method. Furthermore, there is a need for future studies to determine the optimal timing and rates of fertilization, with the aim of reducing reliance on chemical fertilizers while maintaining high yields and the required quality.

Conclusion

The study demonstrated that the method of NPK fertilizer application and mycorrhizal inoculation significantly influenced the growth, yield components, and nutritional status of yellow corn grown in gypsum soil. Broadcast fertilizer application generally produced the best results for mycorrhizal infection, leaf area, plant dry weight, 500-kernel weight, protein content, nitrogen content, and phosphorus content, while fertilizer application through irrigation water resulted in the highest potassium content. Mycorrhizal inoculation improved most growth and quality traits, particularly leaf area, dry weight, grain weight, protein, phosphorus, and potassium, although its effect on nitrogen concentration differed from the other traits. The interaction between fertilizer placement and mycorrhizal inoculation further showed that an appropriate combination of mineral and biological fertilization can enhance nutrient-use efficiency and crop performance. Therefore, integrating mycorrhizal inoculation with an effective NPK application method can be considered a promising

strategy for improving maize production in gypsum soils while supporting more efficient and sustainable fertilizer management.

REFERENCES

- [1] N. Wang, Z. Ai, P. Leng, Y. Qiao, Z. Li, C. Tian, H. Cheng, G. Chen, and F. Li, "Impacts of nitrogen (N), phosphorus (P), and potassium (K) fertilizers on maize yields, nutrient use efficiency, and soil nutrient balance: Insights from a long-term diverse NPK omission experiment in the North China Plain," *Field Crops Research*, vol. 318, Art. no. 109616, 2024.
- [2] A. A. Khalaf, A. S. Ismael, and S. H. Altai, "Evaluation and biological properties maps of gypsiferous soil using geomatic techniques, Tikrit city, Salahaldin, Iraq," in *IOP Conference Series: Earth and Environmental Science*, vol. 735, no. 1, Art. no. 012067, 2021.
- [3] A. F. M. Al-Enzy, B. A. Ziydan, and M. A. J. Salih, "Improvement of gypsum soil properties by adding organic and mineral fertilizers and its productivity for oil crops," *Kirkuk University Journal for Agricultural Sciences*, vol. 16, no. 2, pp. 51–57, 2025, doi: 10.58928/ku25.16207.
- [4] S. H. Altai, H. M. AL-Hamandi, A. M. Khairo, O. N. Ali, and I. Ortas, "Effect of mycorrhizal fungi inoculation on the water consumptive use, growth, and yield of barley (*Hordeum vulgare* L.) under drought stress in gypsiferous soil," *Tikrit Journal for Agricultural Sciences*, vol. 25, no. 2, pp. 177–190, 2025.
- [5] A. F. Fall et al., "Combined effects of indigenous arbuscular mycorrhizal fungi (AMF) and NPK fertilizer on growth and yields of maize and soil nutrient availability," *Sustainability*, vol. 15, Art. no. 2243, 2023, doi: 10.3390/su15032243.
- [6] P. P. Kormanik, W. C. Bryan, and R. C. Schultz, "Procedures and equipment for staining large numbers of plant root samples for endomycorrhizal assay," *Canadian Journal of Microbiology*, vol. 26, pp. 536–538, 1980.
- [7] S. E. Smith and D. J. Read, *Mycorrhizal Symbiosis*, 3rd ed. London, U.K.: Academic Press, 2008.
- [8] V. Artursson, R. D. Finlay, and J. K. Jansson, "Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth," *Environmental Microbiology*, vol. 8, no. 1, pp. 1–10, 2006.
- [9] S. Sharifi, S. Shi, H. Obaid, X. Dong, and H. He, "Differential effects of nitrogen and phosphorus fertilization rates and fertilizer placement methods on P accumulations in maize," *Plants*, vol. 13, no. 13, Art. no. 1778, 2024.
- [10] A. Zhang, X. X. Wang, D. Zhang, Z. Dong, H. Ji, and H. Li, "Localized nutrient supply promotes maize growth and nutrient acquisition by shaping root morphology and physiology and mycorrhizal symbiosis," *Soil and Tillage Research*, vol. 225, Art. no. 105550, 2023.
- [11] H. Marschner, Ed., *Marschner's Mineral Nutrition of Higher Plants*. Academic Press, 2011.
- [12] M. Battisti, L. Zavattaro, L. Capo, and M. Blandino, "Maize response to localized mineral or organic NP starter fertilization under different soil tillage methods," *European Journal of Agronomy*, vol. 138, Art. no. 126534, 2022.
- [13] Y. Lu, Y. Yan, J. Qin, et al., "Arbuscular mycorrhizal fungi enhance phosphate uptake and alter bacterial communities in maize rhizosphere soil," *Frontiers in Plant Science*, vol. 14, 2023.
- [14] C. Akpode et al., "Impact of combinations of native arbuscular mycorrhizal fungi and mineral fertilizers on the production and nutrition of maize plants on ferruginous soil," *Agricultural Research*, vol. 14, no. 4, pp. 782–793, 2025.
- [15] S. Mondal et al., "Grain nitrogen content and productivity of rice and maize under variable doses of fertilizer nitrogen," *Heliyon*, vol. 9, no. 6, 2023.
- [16] N. Rawal, S. P. Vista, D. Khadka, and P. Paneru, "Grain yield, nitrogen accumulation, and its use efficiency of maize (*Zea mays* L.) as influenced by varying nitrogen rates," *International Journal of Agronomy*, vol. 2024, no. 1, Art. no. 4104123, 2024.
- [17] M. Li et al., "Mycorrhizal status and host genotype interact to shape plant nutrition in field grown maize (*Zea mays* ssp. *mays*)," *Mycorrhiza*, vol. 33, no. 5, pp. 345–358, 2023.
- [18] N. Patel, R. Kumar, and D. K. Vishwakarma, "Status and prospect of precision farming in India," in *Agricultural Impacts of Climate Change*, vol. 1, pp. 119–159, CRC Press, 2019.

[19] N. S. Bolan, "A critical review on the role of mycorrhizal fungi in the uptake of phosphorus by plants," Plant and Soil, vol. 134, no. 2, pp. 189–207, 1991.