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ORIGINAL PAPER

Synergistic Effects of Mycorrhizal Fungi and Zeolite on Wheat Yield and Soil Chemical Properties

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Abstract

Wheat is one of the most important cereals in the world, rich in protein, carbohydrates, vitamins, and minerals. Excessive use of chemical fertilizers has led to environmental pollution, especially of water and soil. To improve the quality of agricultural products and prevent this pollution, the use of bio-fertilizers and mineral soil amendments, especially mycorrhizal fungi and zeolite, is recommended. Therefore, this research was carried out with the aim evaluation of the synergistic effects of mycorrhizal fungi and zeolite on wheat yield and soil chemical properties. This study was conducted in 2022 and 2023 in the soil of the Faculty of Agriculture of Azad University, located in Kamalvand district, Khorramabad city, as a factorial design in a randomized complete block design with 3 replications. The factors studied included mycorrhizal fungi at four levels (control, *Glomus mosseae*, *Glomus intraradices*, and *Glomus mosseae* + *Glomus intraradices*) and the application of zeolite fertilizer at four levels (0, 6, 9, and 12ton ha^{-1}). The results showed that the highest grain yield (4296.49 kg ha^{-1}), number of grains per spike (12.62), and biological yield (14243.96 kg ha^{-1}) were observed in the inoculation treatment with both mycorrhizal fungi simultaneously with 12ton ha^{-1} of zeolite in the second year, which showed increases of 43% and 48%, respectively, compared to the control in the first year. This treatment also led to the highest soil phosphorus levels (27.07 mg kg^{-1}), soil potassium (639.16 mg kg^{-1}), and an increase in harvest index and soil respiration. The highest concentrations of zinc and copper were obtained in the control treatment. The simultaneous application of *Glomus mosseae* + *Glomus intraradices* fungi with 12ton ha^{-1} of zeolite is an effective solution for improving wheat yield and the biological and chemical enrichment of the soil (especially in major elements) in the studied area.

Keywords Harvest index · Number of grains per spike · Nitrogen · Soil respiration and organic carbon

1 Introduction

Increasing pressures related to health and environmental sustainability have created the need to review dietary guidelines and rely more on plant-based foods to be beneficial food sources. Cereals are known as one of the main sources of essential amino acids in the human diet due to their high production and wide availability (Marinangeli et al. 2024). According to statistics published by FAO in (FAO 2024), China was the largest wheat producer in the world with an average production of 140.1 million tons, followed by the European Union and India with an average production of 122.12 and 113.29 million tons, respectively. During the same period, Iran was recognized as the thirteenth largest producer of this strategic crop in the world with an average production of 16 million tons (FAO 2024).

The increasing world population has made food security a major issue. Conventional agricultural techniques contribute to mass food production, but they threaten environmental sustainability due to overuse of resources and pollution. Sustainable agriculture promotes environmentally, economically, and socially sustainable practices and includes advanced technologies such as precision agriculture and genetically modified crops. It also emphasizes

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agroecological practices such as crop rotation and organic farming to increase soil fertility and biodiversity. Sustainable agriculture emphasizes the use of local resources and traditional knowledge to maintain ecological balance and ensure food production (Saikanth et al. 2023). Researchers and farmers are always looking for new ways to increase crop production while reducing the negative environmental impacts of traditional agricultural methods. One possible approach is to use zeolite, a natural, high-quality mineral, in improving plant growth (Singh et al. 2024). Zeolites, minerals with special properties, have been known for more than 250 years. The development of hydrothermal synthesis methods and their industrial applications have made these materials one of the most important materials of the 20th century. The porous and crystalline structure of zeolites and their physicochemical properties have contributed to the expansion of practical applications in various processes, especially in agriculture (Kordala & Wyszkowski 2024). Researchers studying the effect of manure and zeolite application on wheat plant yield reported that grain yield and biological yield of wheat increased with increasing percentage of zeolite and manure (Khaliq et al. 2024). In another study, researchers reported that using 10 ton ha^{-1} of zeolite increased wheat harvest index by 15% compared to not using zeolite (Hassan et al. 2024).

In recent decades, the use of chemical fertilizers has become common to increase agricultural production, but these fertilizers are known to be harmful to human, animal and environmental health due to air and water pollution, mineral depletion from soil and global warming. The residues of these fertilizers can lead to metabolic and endocrine disorders and serious diseases such as cancer and cardiovascular failure (Wade et al. 2025). The production and use of biological fertilizers is of great importance in soil biotechnology and plant nutrition management. The consumption of these fertilizers is much less than chemical fertilizers and helps to reduce environmental damage. Biological fertilizers not only meet the needs of plants, but also do not harm the environment and improve the quality of agricultural products and the health of consumers (Farid et al. 2023), Basalingappa et al. (2018), Biofertilizers are introduced as an excellent alternative to chemical fertilizers and state that these fertilizers stabilize the production and ecological preservation of nutrients in the environment by fixing nitrogen, dissolving phosphorus and stimulating plant. Also, due to the formation of hyphae, biofertilizers are a factor in root development in the soil and by facilitating the absorption of nutrients and the transfer of water into the plant, they have higher relative water content (RWC) and water use efficiency (WUE) compared to soils without biofertilizers. Biofertilizers consist of bacteria as well as beneficial fungi, each of which is produced for a specific purpose, such as fixing nitrogen and releasing phosphate, potassium and iron ions from their insoluble compounds. These bacteria have more than one role and in addition to helping absorb a specific element, they also absorb other elements, reduce plant diseases, and improve soil structure, thereby stimulating plant growth and increasing yield (Ghanbari et al. 2016). Researchers studying the effect of combined application of biological and chemical fertilizers on the quantitative and qualitative characteristics of wheat grain reported that biological and organic fertilizers have a significantly positive effect on the growth, yield, and biochemical composition of wheat grain (Lamlom et al. 2023). The effect of biological nitrogen and phosphorus bacterial fertilizers on wheat yield showed that grain yield and biological yield were significantly higher in plants inoculated with bacterial fertilizers, especially phosphate-solubilizing bacteria in liquid form (MeCarty et al., 2017). In recent years, the use of natural minerals has been recommended to improve fertility, modify the physical and chemical structure of the soil, which also leads to an increase in the water holding capacity of the soil. Zeolite is one of these materials. Zeolites, as soil and fertilizer amendments, unlike other amendments, do not break down during their presence and improve the conditions for retaining elements and moisture. Therefore, adding zeolite to biofertilizers significantly reduces the costs of fertilizer and water consumption in agricultural lands. Despite approaches based on bio-fertilizers, there is still a need for integrated management solutions. Specifically, in cold regions with medium-textured soils, such as Lorestan province, where action exchange capacity and water retention capacity in the soil need optimization through durable amendments (like zeolite), the precise mechanisms of improving soil properties through synergistic microbial activity have not been explored. The current research, using the strategic wheat cultivar Chamran 2, seeks to fill this knowledge gap to determine whether this dual combination (biological + mineral) can achieve a true synergistic effect beyond simple cumulative effects, leading to long-term stability in yield and improved soil structure. Consequently, despite approaches based on biofertilizers, there is still a need for integrated management solutions.

The innovation of this research goes beyond examining individual effects; we have specifically focused on proving the synergistic effect between two species of mycorrhizal fungi and different levels of zeolite. Furthermore, this study adopts a comprehensive approach; meaning that improvements in agricultural performance (such as a 43% increase in grain yield in the second year) have been simultaneously evaluated with improvements in critical soil physicochemical parameters (such as organic carbon and bulk density). Finally, the demonstration of yield stability in the second year confirms the role of this treatment in long-term soil health stabilization. Therefore, the present study was designed and implemented with the aim of answering the following questions: First, does the combination of mycorrhiza and zeolite cause a greater increase in wheat yield and yield components compared to the separate use of these treatments? The second question is whether the use of zeolite has a significant effect on the efficiency of soil nutrient absorption under conditions of activity of biological compounds such as mycorrhiza?

2 Materials and Methods

2.1 Location and Environmental Conditions

The present study was conducted to investigate the synergistic effects of mycorrhizal fungi and zeolite on wheat yield and soil chemical properties during two cropping years (2022–2023) in the farm of the Faculty of Agriculture of Azad University, located in Kamalvand district of Khorramabad city, with a geographical location of 33º 20”N, 48º 18”E) and an altitude of 1171 m. Changes in temperature and rainfall during the period from the beginning of November to the end of June in this geographical area in both cropping years are shown in Table 1

2.2 Experimental Design and Treatments

The statistical model of this factorial experiment was based on a randomized complete block design with three replications. The factors studied included zeolite at four levels (control, 6, 9 and 12 ton ha^{-1}) and mycorrhizal biofertilizer at four levels (control, inoculation with *Glomus mosseae*, inoculation with *Glomus intraradices* and inoculation with both *Glomus intraradices* + *Glomus mosseae*). Before the start of the experiment, to determine the physical and chemical properties of the soil, samples from a depth of 0 to 30 cm were collected from different parts of the field and then sent to the soil laboratory. Data related to nutrient elements and general soil indicators (including EC, pH, and texture) are presented in Table 2 as representatives of its physical and chemical properties, to provide a comprehensive picture of the fertility status and characteristics of the wheat growth environment. The results of zeolite fertilizer analysis are given in Appendix Table 3. Cultivation was carried out in the field for both crop years without plowing, but for ease of implementation of the plan, after staking the land using a string, planting was carried out according to the experimental plan and the relevant treatments in the experimental plots. After the land preparation operation, zeolite was mixed with the surface soil of each plot according to the treatments. The zeolite used was also of the cristobalite type and had an in exchange capacity of about 200 meq 100 gr^{-1}. The required zeolite was obtained from Afrazand Company (extracted from natural zeolite mines in Semnan). The results of chemical analysis showed that the extracted rock consisted of about 70% cristobalite zeolite and the rest of clinoptilolite and quartz minerals. Basic nutritional needs were managed uniformly. To this end, before planting in each growing season, bovine manure at a constant rate of 10 ton ha^{-1} (as a basic treatment and amendment) was uniformly added to the soil. The results of the physicochemical analysis of this animal manure are presented in Table 4. Urea fertilizer was also applied as a top dressing during mid-growth. In this experiment, wheat seeds of the Chamran 2 variety were used. The Chamran variety, with its spring growth type, has a very wide adaptation to the climatic conditions of the south of the country, including the tropical and subtropical regions of Lorestan province. It is sensitive to yellow rust disease and semi-resistant to brown rust, and is tolerant of lodging and grain drop. An early-maturing, drought-resistant variety with a plant height of about 96 cm, a thousand-seed weight of 36 g, a protein content of 13%, and an average yield of 118.7ton ha^{-1} in Lorestan province. The required seeds were obtained from the Agricultural

Table 1 Metrological data including maximum, minimum and precipitation during the experimental period

Year 2022				Year 2023			
Month	Maximum Temperature(°C)	Minimum temperature (°C)	Precipitation (mm)	Month	Maximum Temperature (°C)	Minimum temperature (°C)	Precipitation (mm)
October	22	8.5	71.1	October	22.5	8.1	45.8
November	16.2	3.7	28.8	November	17.4	1.9	29.2
December	11	0.7	55.2	December	14.5	1.3	43
January	11.3	−0.3	92.7	January	13.4	1.4	99.6
February	19.5	4.1	65.8	February	15.5	2.1	67.8
March	20	5.7	123.9	March	21.9	6.2	94.6
April	27.6	8.5	21.6	April	26.1	10.5	108
May	34.8	15.1	15.1	May	36.8	16.1	0.4

Table 2 Farm soil analysis

Year	Soil texture	pH	EC (ds m^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	B (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	C (%)	N (%)	P (mg kg^{-1})	K (mg kg^{-1})
2022	Clay Loam	7. 67	1.14	1.37	0.57	1.66	9.64	3.58	1.75	0.18	23.4	218
2023	Clay Loam	7.63	1.52	1.74	0.80	1.61	9.7	3.87	1.64	0.27	23.12	245

Research Center of Khorramabad County. Each block consisted of 16 plots, and the area of each experimental plot was 2.7 m^2 (1.20 width and 6 m length), and the distance between each planting line was 20 centimeters, so that each plot consisted of 6 planting lines. A non-planting line was considered between the plots. The distance between two blocks was considered 2 m. This cultivation was repeated in the second year. To prevent mixing of treatments, the distance between the plots was one meter and the distance between the repetitions was considered two meters. The mycorrhizal biofertilizer consists of *Glomus intraradices* and *Glomus mosseae*. This fertilizer contains 15 spores per gram and 930 hyphae of mycorrhizal fungi per cubic centimeter, which was obtained from a biological fertilizer company called Organic located in Hamedan. This company has an official license to produce biological fertilizers from the Technical University of Munich, Germany, which is approved by the Soil and Water Research Institute of the Agricultural Research Organization of the country. After the inoculation process, the seeds were dried in the shade and the seeds were planted on November 10th. Weed control was carried out by manual weeding. Also, during the growing season, no significant damage was observed in terms of pest infestation or plant diseases.

2.3 Yield and Yield Components

Each year, at harvest time, when the plants were dry, 20 cm tall plants were cut from the second row of each subplot, including a 25 cm margin, and wheat yield components such as the number of spikes m^{-2}, the number of grains per spike, and the weight of 1,000 grains were measured on them. Grain yield was determined by weighing the grains of the three rows of each plot, excluding a 25 cm margin on both sides, and grain yield was calculated based on 10% moisture content. Then, the samples were transferred to the laboratory and dried in a ventilated oven at 75 °C for 48 h. After drying, their weight was measured and biological yield was calculated. Harvest index was also calculated as the percentage of grain yield divided by the biological yield.

2.4 Physical and Chemical Properties of Soil

To investigate soil properties, soil samples were prepared every year in three stages (before planting, in the middle of the growing season and after harvesting) and after being transferred to the laboratory, they were dried, crushed and passed through a 2 mm sieve. The properties of macronutrients (nitrogen, phosphorus, and potassium), micronutrients (iron, zinc, copper, manganese, and boron), soil respiration, organic carbon, bulk density and electrical conductivity were measured using the following methods.

Table 3 Results of physicochemical analysis of zeolite

Sample	%CaO	Na_2O%	K_2O%	Al_2O_3%	SiO_2%	Cl%	SO_3%	Fe_2O_3%
TW0	0.84	4.50	4.32	11.46	67.33	0.98	0.20	0.54
TW2	1.06	3.84	3.82	10.81	68.75	0.45	0.42	0.59
TN1	0.72	3.18	5.02	10.62	69.29	0.58	0.30	1.33
TS2	0.86	3.99	4.21	10.87	67.93	0.47	0.34	0.72
TC3	0.73	3.73	4.65	11.00	68.32	1.44	0.56	0.53

C.E.C = 200 meq 100 g^{-1}

TWO, TE2, TS2, TC3: Clinoptilotic + Cristobalite + Quartz

TN1: Clinoptilotic + Quartz + Cristobalite

Nitrogen content was measured by titration with a fully automatic Kjeldahl equipment, phosphorus by Olsen & Sommers (1990) with half-normal sodium bicarbonate and shaking for half an hour, potassium content by one-normal ammonium acetate (NH_4OAC) solution, and microelement concentrations including iron, zinc, copper, manganese, and boron were measured in the soil sample by DTPA using an atomic absorption spectrophotometer.

Electrical conductivity was measured in a 1:1 soil-to-water extract using an electrical conductivity meter (Jackson et al. 1990). A number of intact samples were also taken in sampling cylinders to measure the soil bulk density by the method of (Black & Hartge, 1986).

Organic carbon percentage was also determined using the Walklet-Black method (Walkley & Black, 1943). To measure soil respiration, the first 50 gr of sieved soil was transferred to containers, then 20 ml of 0.5 N sodium hydroxide solution was added separately to the containers containing the soil, and the samples were kept in an incubator for 24 h at 25 °C. Finally, the amount of CO_2 released was measured by titrating the remaining sodium hydroxide with 0.25 N acid, and the amount of CO_2 was calculated in mg kg^{-1} of dry soil (Anderson, 1982).

To determine the percentage of symbiosis, wheat roots were transferred to the laboratory at the end of the growing season. The roots were cut into 1 cm pieces. Then, they were heated in a 10% KOH solution for 5–10 min on a Bunsen burner and subsequently washed with distilled water. In the next step, the roots were placed in a 2% HCl solution for 15–20 min. For staining, the roots were heated in 0.05% trypan blue for 10 min on a Bunsen burner and again washed with distilled water. The roots were stored in a solution containing lactic acid, glycerol, and water in a 1:1:1 (v: v) ratio until assessment. The colonization percentage was calculated using the gridline intersect method. For each experimental treatment, the stained roots were cut into 1 cm pieces. Then, they were placed on a 1 × 1 cm grid plate. A stereomicroscope (binocular) with 40× magnification was used to observe and count mycorrhizal-infected and uninfected roots. Infected and uninfected roots that intersected with the vertical and horizontal lines of the grid were counted separately, and the colonization percentage was obtained from the following equation (Giovannetti and Mosse 1980).

2.5 Data Analysis

After Bartlett's test and ensuring that the variance of experimental errors was homogeneous, a composite analysis of variance was performed for the measured traits. The variance analysis of the data obtained from the measurement of traits and the comparison of the mean data were performed using the least significant difference (LSD) test at a probability level of 5% using SAS over 9.1 statistical software, and the graphs were drawn using Excell software.

3 Results

3.1 Yield Components

The results of comparing the mean of the triple interaction effect of year × mycorrhizal fungi × zeolite on the number of grains per spike showed that the use of zeolite and mycorrhizal fertilizers can increase this trait, so that the highest number of grains per spike with an average of 12.62 was obtained from the treatment inoculated with *Glomus mosseae* + *Glomus intraradices* fungi and the application of 12 ton ha^{-1} of zeolite in the second year, which increased the number of grains per spike by 53% compared to the lowest number of grains per spike in the control treatment (no use of mycorrhizal fungi and zeolite fertilizer) in the first year. In this comparison, no significant difference was observed in the average between most of the experimental treatments (Fig. 1).

The results of comparing the average of the dual interaction effect of mycorrhizal fungi × zeolite on the number of spikes per plant and the weight of 1000 wheat grains showed that the application of these fertilizers increased these traits, so that the treatment inoculated with *Glomus mosseae* + *Glomus intraradices* fungi and the application of 12 ton ha^{-1} of zeolite had the highest number of spikes per plant with an average of 50.83, and the treatment inoculated with *Glomus*

Table 4 Farm fertilizer analysis

Cow manure	pH	EC (ds m^{-1})	moisture (%)	Mg (%)	Na (%)	Ca (%)	S (%)	Cu (mg kg^{-1})	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	N (%)	P_2O_5 (%)	O.M (%)	K_2O (%)
First year	7.43	2.98	34.50	0.49	1.25	1.52	0.21	18.92	141.39	197.03	511.28	1.51	0.65	77.61	1.71
Second year	7.60	2.77	34.18	0.67	1.19	1.32	0.18	18.96	152.51	201.21	519.27	1.98	0.52	78.31	1.02

mosseae + *Glomus intraradices* fungi with the application of 9 and 12 ton ha^{-1} of zeolite and *Glomus intraradices* fungus with the application of 12 ton ha^{-1} of zeolite had the highest weight of 1000 grains with averages of 43.76, 43.13, and 43.11 gr, respectively. On the other hand, the lowest number of spikes per plant with an average of 25.50 and the weight of 1,000 grains with an average of 21.26 gr were related to the control treatment (no use of mycorrhizal fungi and zeolite fertilizer) (Table 5).

3.2 Seed Yield

Based on the results of comparing the average of the triple interaction of year × mycorrhizal fungi × zeolite on wheat seed yield, the highest seed yield with averages of 4296.40, 4111.93, and 4205.12 kg ha^{-1} was obtained from the inoculation treatments of *Glomus mosseae* + *Glomus intraradices* and *Glomus intraradices* with the application of 12 ton ha^{-1} of zeolite in the second year and *Glomus mosseae* + *Glomus intraradices* with the application of 12 ton ha^{-1} of zeolite in the first year, respectively, which increased grain yield by 44% compared to the lowest amount in the control treatment (no application of mycorrhizal fungi and zeolite) in the first year (Fig. 2).

3.3 Biological Yield

A comparison of the mean data from the dual interaction of mycorrhizal fungi × zeolite fertilizer in Table 6 showed that the highest biological yield of wheat was related to the treatment of *Glomus mosseae* + *Glomus intraradices* fungi and the application of 12 ton ha^{-1} of zeolite with an average of 14243.96 kg ha^{-1}, which increased the biological yield by 25% compared to the control treatment. Also, the lowest biological yield was observed in the control treatment, which did not differ significantly from the inoculation treatments with *Glomus intraradices* and *Glomus mosseae* fungi with the application of 6 ton ha^{-1} of zeolite (Table 5).

3.4 Harvest Index

Changes in harvest index at different levels of mycorrhizal fungi showed that the highest level of this trait with an average of 29.4% was obtained from the inoculation of *Glomus mosseae* + *Glomus intraradices* fungi, which increased the harvest index by 21% compared to the control treatment. Based on the comparison of the average of zeolite fertilizer on the harvest index, the use of zeolite increased this trait, so that the treatment of 12 ton ha^{-1} of zeolite with an average of 30.9% accounted for the highest harvest index and caused a 27% increase in the harvest index compared to the lowest level in the control treatment (Table 6).

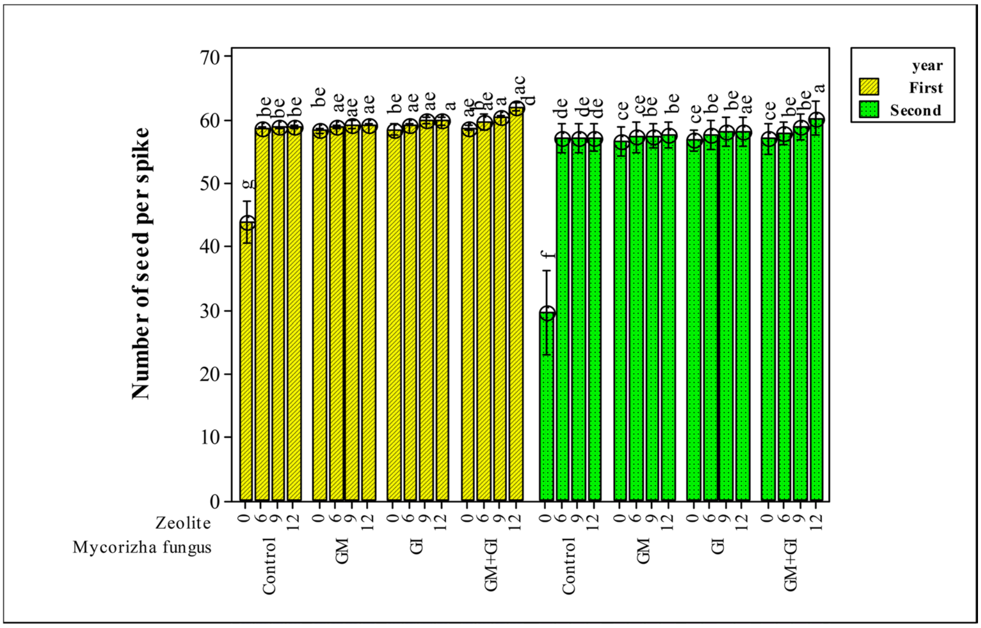

Fig. 1 The interaction effect of Year × Mycorrhiza fungus × Zeolite on number of seed per spike (GM, GI, GM + GI: *Glomus mosseae*, *Glomus intraradices*, *Glomus mosseae* + *Glomus intraradices*, respectively)

3.5 Soil Nutrients

3.5.1 Nitrogen (N)

Based on the results of comparing the average of the main effects in Table 6 on soil nitrogen, inoculation with mycorrhizal fungi increased this trait, so that simultaneous inoculation of *Glomus mosseae* + *Glomus intraradices* fungi and *Glomus intraradices* fungus had the highest amount of soil nitrogen with averages of 7.84 and 7.82 mg kg^{-1}, respectively, which was not significantly different from *Glomus mosseae* fungus and increased soil nitrogen by 7% compared to the control treatment. Changes in this trait among different levels of zeolite fertilizer also showed that the use of zeolite increased soil nitrogen, so that the highest amount of nitrogen was observed at levels of 12, 9 and 6 ton ha^{-1} of zeolite with averages of 7.92, 7.75 and 7.64 mg kg^{-1}, respectively, and increased soil nitrogen by 10, 8 and 6% compared to the control treatment.

3.5.2 Phosphorus (P)

Based on the comparison of the average of mycorrhiza fungi × zeolite on soil phosphorus, the application of mycorrhiza fungi at all levels of zeolite fertilizer increased phosphorus, such that the treatment of inoculation of *Glomus mosseae* + *Glomus intraradices* fungi and the application of 12 ton ha^{-1} of zeolite with an average of 27.07 mg kg^{-1} accounted for the highest amount of soil phosphorus. This increased phosphorus concentration by 55, 33, 31, and 22%, respectively, compared to the non-zeolite treatment in the control treatments (no mycorrhiza), *Glomus mosseae*, *intraradices*, and *Glomus mosseae* + *Glomus intraradices* (Table 5).

The results of the comparison of the mean of year × zeolite on soil phosphorus showed that in both agricultural years, the application of zeolite increased soil phosphorus, so that the highest amount of phosphorus was observed in the treatments of 12 ton ha^{-1} of zeolite with an average of 23.94 mg kg^{-1} in the second year and 23.81 mg kg^{-1} in the first year, which increased the amount of soil phosphorus by 35% in the first year and 26% in the second year, respectively, compared to the control treatment (Table 7).

3.5.3 Potassium (K)

The results of the comparison of the mean of mycorrhizal fungi × zeolite showed that the highest soil potassium content with an average of 16.639 mg kg^{-1} was observed in the treatment of inoculation with *Glomus mosseae* + *Glomus intraradices* fungi and the application of 12 ton ha^{-1} of zeolite, which increased soil potassium by 35, 43, 46 and 52%, respectively, compared to the treatment of no zeolite application at different levels of inoculation with *Glomus mosseae* + *Glomus intraradices* fungi, *Glomus intraradices*, *Glomus mosseae* and no application of mycorrhizal fungi (Table 5).

3.5.4 Iron (Fe)

The results of the comparison of the average of mycorrhiza fungi × zeolite on soil iron showed that among different levels of zeolite, inoculation with mycorrhiza fungi caused a decrease in the iron element in the soil, so that the control

Table 5 Comparison the mean interaction effects mycorrhiza fungus × zeolite on wheat quantitative and qualitative traits

Treatments		Number of spike plant	100 seeds weight	Biological Yield	P	K	Fe	Zn	Cu	Organic carbon	EC
Mycorrhiza fungus	Zeolite (ton ha^{-1})	-	(gr)	(kg ha^{-1})	(mg kg^{-1})					(%)	ds m^{-1}))
Control	0	25.50 ± 3.76 g	21.26 ± 1.89f	10691.32 ± 838d	12.17 ± 0.31k	306.82 ± 16 h	5.84 ± 0.56a	5.88 ± 0.02a	1.55 ± 0.04a	0.83 ± 0.02j	0.65 ± 0.01i
	6	32.33 ± 1.12f	38.31 ± 1.01e	11589.25 ± 876 cd	17.03 ± 0.47j	328.18 ± 14gh	5.64 ± 0.53a	5.66 ± 0.02a	1.13 ± 0.02b	0.98 ± 0.01i	0.69 ± 0.01 h
	9	36. 50 ± 1.00e	38.50 ± 0.79e	11,656. 30 ± 825 cd	17.33 ± 0.36hi	331.15 ± 15gh	5.48 ± 0.49ab	5.48 ± 0.03ab	1.11 ± 0.04bc	1.02 ± 0.01gi	0.70 ± 0.01gh
	12	39.66 ± 1.02e	39.32 ± 0.68de	11662.67 ± 703 cd	18.17 ± 0.31 fg	345.45 ± 21gh	5.08 ± 0.49bc	5.05 ± 0.01bc	1.10 ± 0.02bc	1.03 ± 0.02fh	0.73 ± fg
Glomus *mosseae*	0	42.82 ± 1.14d	39.39 ± 0.79de	11665.07 ± 561 cd	18.17 ± 0.43 h	347.25 ± 18 fg	5.01 ± 0.52 cd	5.04 ± 0.01 cd	1.07 ± 0.03bc	1.05 ± 0.03fh	0.74 ± 0.02ef
	6	44.49 ± 1.15bd	41.52 ± 1.01ad	10777.54 ± 712d	22.33 ± 0.45f	427.28 ± 12de	4.71 ± 0.48 cd	4.74 ± 0.01 cd	0.96 ± 0.01de	1.10 ± 0.01de	0.75 ± 0.01ef
	9	46.33 ± 1.00bd	42.23 ± 0.67ac	11547.62 ± 479 cd	23.27 ± 0.52de	522.13 ± 20c	4.02 ± 0.59e	4.09 ± 0.02f	0.93 ± 0.02def	1.13 ± 0.05 cd	0.77 ± 0.02e
	12	46.66 ± 1.06bc	42.27 ± 0.99ab	11639.14 ± 786 cd	23.33 ± 0.36bc	525.44 ± 19c	3.85 ± 0.47ef	3.86 ± 0.03 g	0.93 ± 0.01def	1.16 ± 0.02bc	0.81 ± 0.01d
Glomus intraradices	0	43.83 ± 1.14 cd	40.01 ± 1.06ce	11551.54 ± 682 cd	18.83 ± 0.46 h	364.38 ± 23f	4.94 ± 0.59 cd	4.91 ± 0.01 cd	1.07 ± 0.05c	1.07 ± 0.01eg	0.74 ± 0.01ef
	6	45.14 ± 1.11bc	42.17 ± 0.84ac	11005.91 ± 427d	22.46 ± 0.21df	446.32 ± 14d	4.64 ± 0.42 cd	4.65 ± 0.03d	0.94 ± 0.01def	1.11 ± 0.01de	0.76 ± 0.01ef
	9	46.48 ± 1.14ac	42.83 ± 0.76ac	11653.90 ± 481 cd	24.15 ± 0.50bd	532.18 ± 17c	3.95 ± 0.34f	3.59 ± 0.02 g	0.92 ± 0.02ef	1.19 ± 0.01b	0.85 ± 0.01c
	12	47.50 ± 1.20ab	43.11 ± 1.03a	12284.52 ± 428bc	24.97 ± 0.32b	596.53 ± 15b	2.76 ± 0.58 h	2.78 ± 0.03i	0.88 ± 0.01 g	1.33 ± 0.03a	0.90 ± 0.01b
Glomus *mosseae* + intraradices Glomus	0	44.51 ± 1.13bd	40.49 ± 1.19be	11271.80 ± 828 cd	21.13 ± 0.52 g	412.5 ± 21e	4.80 ± 0.52 cd	4.81 ± 0.01 cd	0.99 ± 0.02d	1.09 ± 0.02eg	0.75 ± 0.02ef
	6	45.31 ± 1.20bd	42.21 ± 0.68ac	11423.10 ± 538 cd	22.97 ± 0.37de	517.56 ± 18c	4.6 ± 0.54e	4.23 ± 0.02f	0.93 ± 0.02def	1.13 ± 0.01 cd	0.76 ± 0.01e
	9	46.65 ± 1.24bc	43.13 ± 0.96a	12807.67 ± 170b	24.67 ± 0.24b	545.36 ± 12c	3.08 ± 0.22 g	3.17 ± 0.02 h	0.91 ± 0.01ef	1.15 ± 0.02 cd	0.86 ± 0.01c
	12	50.83 ± 1.08a	43.76 ± 0.80a	14243.96 ± 520a	27.07 ± 0.25a	639.16 ± 18a	2.57 ± 0.40 h	2.55 ± 0.02i	0.81 ± 0.01 g	1.34 ± 0.02a	1.03 ± 0.02a

Similar letters in each column are not significantly different based on LSD test ($p \leq 0.05$)

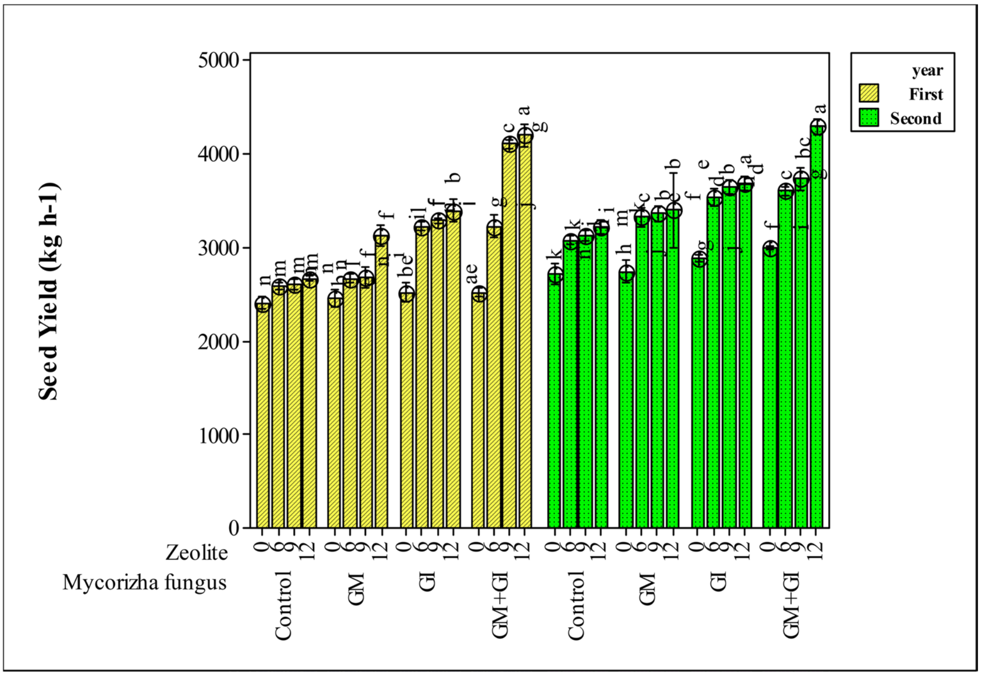

Fig. 2 The interaction effect of Year × Mycorrhiza fungus × Zeolite on seed yield (GM, GI, GM + GI: *Glomus mosseae*, *Glomus intraradices*, *Glomus mosseae* + *Glomus intraradices*, respectively)

Table 6 Comparison the mean effects mycorrhiza fungus and zeolite on wheat quantitative and qualitative traits

Treatments	Harvest Index	*N*	Mn	B	Bulk density Case	Soil respiration	Root colonization
Mycorrhiza fungus	(%)	(mg kg^{-1})			gr cm^{-3}))	(mgco$_2$$^{-1}$ kg soil^{-1} day)	(%)
Control	23.4 ± 0.77d	7.38 ± 0.16b	9.73 ± 0.22a	2.87 ± 0.02a	1.30 ± 0.02c	1.15 ± 0.02b	26.22 ± 1.65d
Glomus *mosseae*	27.6 ± 0.62c	7.75 ± 0.11ab	9.47 ± 0.25b	1.98 ± 0.05b	1.42 ± 0.02bc	1.22 ± 0.02a	28.98 ± 1.01c
Glomus intraradices	28.8 ± 0.69b	7.82 ± 0.11a	8.42 ± 0.23c	1.86 ± 0.05c	1.46 ± 0.02ab	1.25 ± 0.03a	30.06 ± 0.99b
Glomus *mosseae* + Glomus intraradices	29.4 ± 0.85a	7.84 ± 0.10a	8.17 ± 0.20d	1.79 ± 0.04d	1.49 ± 0.02a	1.26 ± 0.02a	32.62 ± 1.30a
Zeolite (ton ha^{-1})							
0	22.8 ± 0.58d	7.12 ± 0.18b	10.33 ± 0.26a	2.62 ± 0.04a	1.32 ± 0.02b	1.18 ± 0.02c	20.87 ± 1.20 c
6	27.7 ± 0.56c	7.64 ± 0.09a	8.17 ± 0.16b	1.84 ± 0.04b	1.44 ± 0.03a	1.20 ± 0.03bc	31.68 ± 1.22b
9	28.8 ± 0.62b	7.75 ± 0.05a	8.42 ± 0.19c	1.75 ± 0.03b	1.45 ± 0.02a	1.25 ± 0.02ab	31.85 ± 1.02b
12	30.9 ± 0.59a	7.92 ± 0.07a	8.67 ± 0.18c	1.62 ± 0.04c	1.45 ± 0.01a	± 1.26 ± 0.02a	33.79 ± 0.95a

Similar letters in each column are not significantly different based on LSD test ($p \leq 0.05$)

Table 7 Comparison the mean interaction effects year × zeolite on wheat P and Fe

Year	Zeolite (ton ha^{-1})	P (mg kg^{-1})	Fe
First	0	15.66 ± 0.62f	5.16 ± 3.12b
	6	21.66 ± 0.74d	4.46 ± 0.13c
	9	22.03 ± 0.84c	3.93 ± 0.25d
	12	23.81 ± 0.67a	3.54 ± 0.27e
Second	0	17.32 ± 0.69e	5.66 ± 0.17a
	6	22.27 ± 0.57c	4.37 ± 0.24c
	9	23.06 ± 0.72b	4.06 ± 0.31d
	12	23.94 ± 0.69a	3.81 ± 0.31d

Similar letters in each column are not significantly different based on LSD test ($p \leq 0.05$)

treatment (no application of mycorrhiza and zeolite) and the treatment without inoculation with mycorrhiza fungi with the application of 6 ton ha^{-1} of zeolite, respectively, with averages of 84.5 and 64.5 mg kg^{-1}, accounted for the highest soil iron, which was placed in the same statistical group with the treatment without inoculation with mycorrhiza and the application of 9 ton ha^{-1} of zeolite. In addition, the lowest soil iron content was observed in the treatment with inoculation with *Glomus mosseae* + *Glomus intraradices* and *Glomus intraradices* fungi with the application of 12 ton ha^{-1} of zeolite, with averages of 57.2 and 76.2 mg kg^{-1}, respectively (Table 5).

3.5.5 Zinc (Zn)

Based on the comparison of the mean of the dual interaction of mycorrhiza fungi × zeolite on the zinc present in the soil, the highest soil zinc content with averages of 5.88 and 5.66 mg kg^{-1} was obtained from the control treatments (no mycorrhiza and zeolite application) and the no mycorrhiza treatment with 6 ton ha^{-1} of zeolite application, respectively, which was significantly different from the 9 ton ha^{-1} zeolite application treatment at the same fungal level. On the other hand, the lowest soil zinc content was observed in the inoculation treatments with *Glomus mosseae* + *Glomus intraradices* and *Glomus intraradices* fungi with averages of 2.55 and 2.78 mg kg^{-1}, respectively (Table 5).

Based on the data obtained from the comparison of the average year × zeolite on iron in the soil, zeolite fertilizer caused a decrease in this element, such that the highest amount of iron was obtained from the control treatment in the second year with an average of 66.5 mg kg^{-1}, and compared to the 12 ton ha^{-1} zeolite treatment, it increased soil iron by 37% in the first year and 32% in the second year (Table 7).

3.5.6 Copper (Cu)

The results of comparing the average of the dual interaction effect of mycorrhizal fungi × zeolite fertilizer on the copper element present in the soil showed that at all levels of mycorrhizal fungi, the use of zeolite caused a decrease in copper, so that the highest amount of copper with an average of 1.55 mg kg^{-1} was observed in the control treatment (no use of mycorrhiza and zeolite), which increased the copper present in the soil by 47 and 43% compared to the lowest amount in the inoculation treatments with *Glomus mosseae* + *Glomus intraradices* and *Glomus intraradices* with the use of 12 ton ha^{-1} of zeolite (Table 5).

3.5.7 Manganese (Mn)

The results showed that inoculation with mycorrhizal fungi caused a decrease in soil manganese, so that the highest and lowest amounts with averages of 9.73 and 8.17 mg kg^{-1} were observed in the control and inoculation treatments with *Glomus mosseae* + *Glomus intraradices*, respectively. Comparison of the average zeolite fertilizer on soil manganese yield showed that zeolite application reduced manganese, with the highest amount obtained with an average of 10.33 mg kg^{-1} from the control treatment, and increased soil manganese by 16 and 18% compared to the lowest amount in the 12 and 9 ton ha^{-1} zeolite treatments (Table 6).

3.5.8 Boron (B)

A comparison of the average application of mycorrhizal fungi on the concentration of boron in the soil showed that the highest and lowest amounts of boron with averages of 2.87 and 1.79 mg kg^{-1} were observed in the control and *Glomus mosseae* + *Glomus intraradices* mycorrhizal inoculation treatments, respectively. On the other hand, zeolite fertilizer on boron concentration showed that the application of zeolite caused a decrease in this element in the soil, so that the highest amount with an average of 2.62 mg kg $^{-1}$ was obtained from the control treatment, which increased the boron concentration by 50% compared to its lowest amount in the 12 ton ha^{-1} zeolite treatment. In this comparison, no significant difference was observed between the average concentrations of 6 and 9 ton ha^{-1} zeolite (Table 6).

3.6 Soil Bulk Density

Changes in bulk density at different levels of inoculation with mycorrhizal fungi showed that mycorrhizal fungi increased this trait, so that the inoculation treatment with *Glomus mosseae* + *Glomus intraradices* fungi had the highest bulk density with an average of 1.49 g cm^{-3} and there was no significant difference with the *Glomus intraradices* fungus treatment and increased the bulk density by 13% compared to the control treatment. The use of zeolite fertilizer also increased the bulk density of the soil in this experiment, so that the highest amount was observed in the treatments of 12, 9 and 6 ton ha^{-1} of zeolite with an average of 1.45 g cm^{-3} and increased the bulk density of the soil by 9% compared to the control treatment (Table 6).

3.7 Soil Respiration

Based on the results of the main effects of treatments in Table 6 on soil respiration, mycorrhizal fungi had a positive effect on soil respiration, such that the highest rate of respiration was observed in the inoculation treatment with *Glomus mosseae* + *Glomus intraradices*, *Glomus intraradices* and *Glomus mosseae* fungi with average mgco$_2$$^{-1}$ kg soil^{-1} day soil of 1.26, 1.25 and 1.22, respectively, and increased soil respiration by 9, 8 and 6% compared to the control treatment. Changes in soil respiration at different levels of zeolite fertilizer showed that the 12 ton ha^{-1} treatment had the highest soil respiration with an average mgco$_2$$^{-1}$ kg soil^{-1} day of 1.26, which was not significantly different from the 9 ton ha^{-1} treatment, and increased soil respiration by 6% compared to the control treatment.

3.8 Soil Organic Carbon

The results of comparing the mean of the dual interaction effect of mycorrhizal fungi × zeolite fertilizer on soil organic carbon showed that among all levels of mycorrhizal fungi, the application of zeolite increased soil organic carbon, such that the inoculation treatments with *Glomus mosseae* + *Glomus intraradices* and *Glomus intraradices* fungi with an application of 12 ton ha^{-1} had the highest soil organic carbon with averages of 1.34 and 1.33%, respectively. The lowest soil organic carbon was observed with averages of 0.83 and 0.98% in the treatment without the application of mycorrhizal fungi and zeolite and the treatment with 6 ton ha^{-1} of zeolite, which caused a 38 and 27% decrease in soil organic carbon, respectively, compared to the treatment with the highest amount of soil organic carbon (Table 5).

3.9 Soil Electrical Conductivity

Changes in soil electrical conductivity in comparison with the average of the dual interaction of mycorrhizal fungi × zeolite fertilizer showed that the inoculation treatment with *Glomus mosseae* + *Glomus intraradices* fungi had the highest electrical conductivity with an average of 1.03 ds m^{-1}, and compared to the lowest electrical conductivity in the control treatment (no use of mycorrhizal fungi and zeolite), and increased electrical conductivity by 38% (Table 5).

3.10 Root Colonization

Inoculation with different mycorrhizal fungi also increased symbiosis, such that the treatment inoculated with Glomus *mosseae* + Glomus intraradices fungi had the highest colonization rate with an average of 32.62%, and increased root colonization by 19% compared to the lowest colonization rate in the control treatment. Changes in root colonization at different zeolite levels showed that the application of zeolite increased this trait, such that the concentration of 12 ton ha^{-1} had the highest colonization rate with an average of 33.79%, which increased root colonization by 39% compared to the control treatment. No significant difference was observed between zeolite concentrations of 6 and 9 ton ha^{-1} (Table 6).

4 Discussion

The combination of mycorrhiza and zeolite resulted in a greater increase in wheat yield and yield components compared to the separate use of these treatments. The results of this experiment indicate that the increase in grain yield in the mycorrhizal inoculation treatment could be due to the cooperation of these microorganisms with the plant, which were able to significantly increase grain yield through improvements in yield components. Regarding the positive effect of the simultaneous use of different mycorrhizal strains, it can be stated that there is a synergistic and intensifying feature between these soil microorganisms that causes their simultaneous participation and increase in activity in the soil and by increasing the absorption of nutrients (phosphorus and nitrogen), it improves the efficiency of photosynthesis in the plant, which consequently leads to improved growth and subsequent increase in the economic yield of grain and yield components (Lee et al. 2018). Mycorrhiza increases the absorption of nutrients and water by expanding the plant's root system, which helps to improve plant yield. This increased absorption leads to improved leaf area and consequently increased photosynthetic material. Zeolite (12ton ha^{-1}) optimizes the living environment for fungi (soil physics and access to water/nutrients), and mycorrhizal fungi in this optimized environment unleash their maximum biological potential for absorbing vital elements, which directly leads to a significant increase in grain yield (6500 kg ha^{-1}). In other words, zeolite provided the foundation for the fungi to perform their work in the best possible way, and this collaboration resulted in a leap in performance. In the reproductive phase, this process can improve grain yield. Studies show that mycorrhizae increase the plant's ability to absorb elements and soil resources. The increase in biological yield in the presence of mycorrhizae can be attributed to various reasons for the benefits of mycorrhizae, including increased nutrient absorption mainly due to the spread of mycorrhizal fungal mycelium, increased water absorption due to increased absorption surface and greater absorption capacity of hyphae compared to the root system, production of plant growth-stimulating hormones such as auxins, cytokinins, etc., reduction of environmental stresses and increased plant resistance to pathogens, creation of stable soil grains, intensification of nitrogen fixation activity, and synergistic relationship with microorganisms that solubilize non-absorbable phosphates (Mott et al. 2022). Mycorrhizal inoculation has caused sufficient sap to be transferred to the seeds at the seed filling stage, which has improved the thousand-grain weight. Regarding the increase in thousand-grain weight with the use of mycorrhiza, it seems that there is a synergistic relationship between mycorrhizal fungi and phosphate-solubilizing microorganisms, which has been able to improve the thousand-grain weight by increasing the absorption of mineral elements, especially phosphorus, and the rate of plant photosynthesis. Some researchers have stated that the use of biofertilizers has improved the yield and yield components of wheat by improving the physical properties of the soil and increasing the availability of nutrients for plant absorption (Ahmed et al. 2011). Zeolite, as a soil amendment, has improved wheat plant growth by selectively absorbing and controlling the release of nutrients. This substance increases the available water of the plant by increasing the long-term availability of water, and consequently increases grain yield. Studies have shown that the use of zeolite fertilizer has a positive effect on soil properties and can help improve production and increase grain yield in barley (Mahmoud et al. 2023). The biological yield of a crop refers to its ability to convert true photosynthesis into pure photosynthesis. A study has shown that zeolite, as a source of silica, can help increase plant biological yield by stimulating photosynthesis (Elrys et al. 2021). Also, (Khalig et al., 2024) by investigating the effect of manure and zeolite application on biological yield reported that increasing the percentage of zeolite in manure increased the biological yield of wheat. Zeolite provides suitable conditions for plant growth by strengthening the soil, preventing erosion and water absorption, and thus increasing the harvest index.

The application of zeolite had a significant positive effect on the efficiency of soil nutrient absorption under conditions of activity of biological compounds such as mycorrhiza. In general, the application of zeolite in soil can lead to an improvement in the amount of macro and micro nutrients in the soil. As a porous mineral, zeolite has the ability to absorb and retain nutrients and gradually make them available to the plant. This can lead to a reduction in the need for chemical fertilizers and an increase in the efficiency of water and nutrient use. Zeolites have positive effects on soil properties, including increasing moisture, improving hydraulic conductivity, and increasing yield in acidic soils. These materials are used as soil amendments to improve the physical and chemical properties of the soil and increase the cation exchange capacity of the soil. Zeolites are alkaline and can help maintain soil pH and reduce the need for lime. Also, zeolites help improve soil conditions in semi-arid and arid environments and have a positive effect on nutrient availability and microbial activity (De Campos Bernardi et al. 2013). The high use of chemical fertilizers poses serious environmental risks, as only a part of them is absorbed by the soil and the rest is transferred to surface and groundwater, leading to pollution. To solve these problems, slow-release fertilizers (SRFs) can be used. Zeolites, due to their high selectivity for actions, are effective in the preparation of chemical fertilizers and increase the nutrient retention capacity of the soil. By modifying the surface of zeolite-A with a national surfactant, its capacity to retain phosphate anions has been increased. Research has shown that zeolite with slightly soluble phosphate rock provides a sustained and slow release of phosphorus, helping to increase yield and nutrient uptake in crops such as spinach (Ahmed et al. 2010).

Mycorrhizae, fungi that live in symbiosis with plant roots, increase nutrient uptake and help plants adapt to poor soil conditions by forming a network of filaments around the roots. These fungi absorb essential minerals such as phosphorus, nitrogen and zinc and in return receive fixed carbon from the plants. Mycorrhizae also produce antibacterial and antifungal compounds that help protect the roots and secrete enzymes that dissolve inaccessible nutrients. Phosphorus is taken up by mycorrhizal hyphae, moving into the roots and exchanging with the root cortex cells. These fungi also absorb nitrogen from the soil and transfer it to the plants, especially in association with legumes and rhizobia. As a result, mycorrhizae help improve plant yield and reduce the need for fertilizer. Mycorrhizae help increase the activity of nitrate reductase and glutamine synthetase in plants, indicating that nitrogen and phosphorus are transported in a similar manner. These fungi can access mineral forms of N and P and help the roots by transporting amino compounds through hyphae. Research shows that Glomus bacteria can transport nutrients to plants and alter plant physiology to reduce stress during dry seasons. Enhanced nutrition and colonization of mycorrhizae can increase the resistance of plants to drought. AMF increases plant growth under stress conditions and helps improve water capacity and leaf turgor. Mycorrhizal hyphae prevent diseases and improve soil structure by increasing water and nutrient uptake. Glumalin, a sticky substance produced by fungi, helps stabilize soil structure and increase water and nutrient uptake. This process leads to improved plant growth and reduced need for chemical fertilizers. Given the increasing population and demand for phosphate, the use of mycorrhizal fungi can help reduce the need for chemical fertilizers and improve soil health. These fungi help improve plant growth and health by absorbing and transporting nutrients and can reduce agricultural costs (Wahab et al. 2023; Kaur et al., 2020; Sagar et al. 2021; Ortas et al., 2019; Hallama et al. 2019).

The observed reduction in trace element concentrations in the soil following the application of mycorrhiza and zeolite can be attributed to the enhanced nutrient absorption facilitated by mycorrhizal mycelia. These mycelia establish connections with the internal tissues of plant roots, thereby creating an additional absorption system that augments the plant's root system. This adaptation enables the plant to exploit a greater volume of soil, including areas that are typically inaccessible to feeder roots. The impact of biofertilizers on the mobility and availability of microelements in the soil is variable and is primarily influenced by the solubility of organic matter. For instance, the mobility and availability of trace elements such as iron are limited due to the formation of stable complexes with insoluble organic compounds (Havlin et al. 1999). Furthermore, zeolite plays a significant role in influencing the concentrations of micronutrients, including iron, copper, zinc, and manganese, in the soil. Overall, zeolite enhances the soil's in exchange capacity and improves its structure, thereby facilitating the absorption of these essential nutrients. The uptake of these elements by plants subsequently alters their concentrations in the soil. A study conducted by Rahimi-Alashti et al. (2021) in Tehran investigated the levels of macro and micro-nutrients in the soil and found that among various organic amendments, only zeolite resulted in a reduction of available iron, zinc, copper, and manganese in the soil. Furthermore, research by Moein et al. (2020) has demonstrated that the application of zeolite diminishes the bioavailability of heavy metals, such as copper and zinc, in contaminated soils. Consequently, under these conditions, the enhancement of nutrient absorption by plant roots leads to a natural decrease in soil element concentrations, directing these elements towards the plants.

The application of arbuscular mycorrhizal fungi (AMF) inoculum to the soil in areas cultivated with Common Vetch and Narbonne Vetch resulted in a reduction of both lime and electrical conductivity (EC) levels, while exhibiting no significant impact on soil pH, likely due to the short duration of the cultivation cycle. The influence on soil enzyme activities, microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN) were predominantly positive. The findings of this study substantiated the notion that AMF facilitate the release of nutrients from complex substrates by enhancing soil enzyme activities. This investigation clearly illustrated that AMF can elevate soil enzyme activity, thereby contributing to improved nutrient cycling (Burac et al., 2024). A study was conducted to examine the impact of varying doses of biochar on cotton plants, both those inoculated with mycorrhizae and those that were not. The results indicated that as the biochar doses increased, there was a corresponding enhancement in several parameters, including plant height, root length, number of nodes, and the quantity of spores (Ramazanoglu et al. 2025). As the diameter of particles diminishes, there is a corresponding reduction in apparent specific gravity, which can be attributed to an increase in overall porosity. Specifically, the weight contribution of solid particles per unit volume declines, resulting in a decrease in specific gravity. Additionally, an increase in the apparent specific gravity of soil has been noted in barley plants following mycorrhizal inoculation (Samaei et al. 2015). Zeolite, due to its high action exchange capacity and porous structure, not only provides aeration conditions for aerobic microorganism activity but also absorbs nutrients and soil organic matter, especially nitrogen. In another experiment, it was stated that zeolite can help preserve organic carbon in the soil by reducing nitrogen and ammonia losses from the soil (Antonoglou et al. 2025). Mycorrhiza, by increasing plant access to phosphorus and other nutrients, increases the production of organic matter by wheat plants and thus increases soil organic carbon (Liu et al. 2022). Zeolite-modified sediments increase microbial biomass and the activity of enzymes such as urease and dehydrogenase in the soil. In particular, the addition of chitosan-modified zeolite significantly increased enzyme activity, demonstrating its strong potential to improve soil microbial processes. This indicates that zeolite can support microbial respiration by reducing the impact of inhibitors (Wang et al. 2024). The presence of mycorrhiza can significantly affect soil respiration, a critical component of the carbon cycle, by contributing to overall microbial activity in the soil. Mycorrhizal inoculation enhances the absorption of nutrients, especially nitrogen and phosphorus, which are vital for plant growth and microbial activity in the soil (Zou et al. 2024). Zeolites possess a high specific surface area and can trap cations and anions within their crystalline framework, allowing them to hold substantial quantities of salts. This characteristic enables them to release ions into the soil solution and the root zone. Consequently, incorporating zeolites into the soil has resulted in elevated electrical conductivity and increased soil acidity. According to Ma et al. (2023), the use of zeolite has been shown to enhance electrical conductivity. Additionally, mycorrhizal fungi form networks within the soil that enhance permeability and improve soil structure, ultimately leading to greater hydraulic conductivity and better water access for plants.

An important indicator of mycorrhizal fungal activity is the colonization rate of the root system by these fungi, which is affected by various factors including the morphological and structural characteristics of the root system, the quantity and quality of root exudates, the use of phosphorus chemical fertilizers, and high concentrations of heavy metals (Al-Karaki & Clark, 1998). Zeolite, by improving the physical and chemical properties of the soil, including regulating moisture and pH, increasing nutrient availability, and reducing environmental stresses, can indirectly provide a more favorable environment for the growth and proliferation of arbuscular mycorrhizal fungi. This, in turn, leads to an increased percentage of wheat root colonization by arbuscular fungi. Increased mycorrhizal colonization means improved water and nutrient absorption (especially phosphorus), increased plant resistance to stresses, and ultimately better wheat performance. Baghaei et al. (2019) stated in their research on wheat that different levels of zeolite had a significant effect on the colonization percentage in the presence of mycorrhizal fungi, such that with increasing zeolite concentration, the colonization percentage increased when inoculated with mycorrhizal fungi. A significant increase in root colonization has been observed in wheat inoculated with a species of mycorrhizal fungus (Elliott et al. 2021). In this regard, another study on wheat showed that inoculation of wheat with mycorrhizal fungi significantly increased the percentage of root symbiosis (Liu et al., 2023). Sarmiento-López et al. (2025), in their study on the effect of zeolite on the percentage of maize symbiosis, stated that zeolite, especially in combination with nitrogen, improves arbuscular mycorrhizal colonization, which is vital for nutrient exchange between plants and fungi, such that it led to a 4% increase in maize root colonization compared to the control treatment.

5 Conclusion

The simultaneous application of Glomus mosseae and Glomus intraradices mycorrhizal fungi along with zeolite significantly improved the yield and soil quality of Chamran 2 wheat. This combination, compared to the individual application of each, significantly increased nutrient uptake, soil respiration, and harvest index. The results showed that zeolite, by providing a suitable physical environment for mycorrhizal expansion, enhances the efficiency of nutrient absorption and plant growth, consequently leading to the highest grain yield in the combined treatment. Therefore, the use of mycorrhizal inoculation along with zeolite at a rate of approximately 12 ton ha^{-1} can be recommended as an effective strategy for integrated wheat nutrition management in soils similar to the studied region.

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