

Combined Use of Mycorrhizae and Phosphorus Fertilizer on Physio Morphological Characteristics in Quinoa (*Chenopodium quinoa* Willd.) and Maize (*Zea mays* L.) Under Intercropping System

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AREEO: Agricultural Research Education and Extension Organization

Research Article

Keywords: Intercropping System, Physiological Characteristics, Mycorrhiza, Location

Posted Date: January 11th, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-3344497/v1>

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Abstract

The utilization of bio-fertilizers is a relatively new sustainable practice for improving growth and physiological characteristics in plants. Two location field experiments were performed to evaluate the effects of three levels of phosphorus fertilizer: control, 50 kg ha⁻¹, and 100 kg ha⁻¹, and Arbuscular mycorrhiza fungi at two levels: M1 (no mycorrhiza) and M2 (mycorrhizal inoculation) on plant height, yield, Total Dry Weight, Leaf Area Index, Crop Growth Rate and Net Assimilation Rate, chlorophyll a, b, and total chlorophyll of quinoa and maize in intercropping system. Different cropping patterns were included quinoa and maize sole culture and replacement intercrop ratios of 50:50, 75:25, and 25:75 (Maize/Quinoa). The results showed that growth indices, chlorophyll a, chlorophyll b, total chlorophyll, and biological yield of maize and quinoa were significantly affected by studied treatments. The highest amounts of chlorophyll a (2.205/4.74 mg g⁻¹ FW in maize/quinoa) and chlorophyll b (0.75/2.88 mg g⁻¹ FW in maize/quinoa) were achieved in a 50:50 cropping ratio, use of AMF and 50 kg ha⁻¹ phosphorus fertilizer. Generally; AMF application in a cropping ratio of 50:50 may be proposed to farmers as an eco-friendly approach to achieving desirable physiological characteristics such as plant height, Plant dry matter, Yield, and chlorophyll, in quinoa under the use of 50 kg ha⁻¹ phosphorus fertilizer. The highest growth indices, chlorophyll a, chlorophyll b, total chlorophyll and biological yield of maize were obtained by the 75:25 ratio. For the quinoa and the highest chlorophyll b and total chlorophyll were obtained by the 50:50 ratio.

Introduction

Today, the multi-cropping system is viral in developing countries and among smallholder farmers due to the use of more land, food, reduction of pests and diseases (Huang *et al.*, 2019). Considering the ever-increasing trend of the world's population, the forecast a 7.9 billion world population in 2050, and limited agricultural resources, increasing the yield of food products per unit area is inevitable (Anonymous, 2019). The 2030 Agenda for Sustainable Development of the United Nations highlighted the need for devising sustainable product systems to deliver healthy diets to the growing population. This means that prioritizing agricultural products guarantees improved efficiency in the use of natural resources and contributes to meeting the requirements of a healthy diet. In this regard, alternative crops, such as quinoa, have received significant attention (Food and Agriculture Organization, 2019).

Quinoa (*Chenopodium quinoa* Willd.) belongs to the Chenopodiaceae family, native to the Andean region in South America and mainly grown in Peru, Bolivia, Ecuador, Argentina, Colombia, and Chile (Bazile *et al.*, 2016). Numerous studies have been conducted on intercropping systems based on field experiments in several countries of the continents Africa, Asia, Europe, and Latin America (Knörzer *et al.* 2009; Lithourgidis *et al.* 2011; Pelzer *et al.* 2012; Li *et al.* 2016; Martin-Guay *et al.* 2018). Quinoa (*Chenopodium quinoa* Willd.) is a pseudocereal whose production and consumption have increased worldwide in the last decades. It was defined as "one of the grains of the 21st century" because of its resistance to extreme environmental conditions and its nutritional and functional properties. Quinoa seeds are rich in protein, lipids, fiber, vitamins, and minerals, and its excellent balance of essential amino acids, quinoa contains phytochemicals including saponins, phytosterols, phytoecdysteroids, phenolic compounds, polysaccharides, bioactive proteins and peptides.

Maize (*Zea Mays* L.), belonging to the poaceae family, is the largest food crop in the world (Liu *et al.*, 2023). Maize, with over one billion tons produced annually, is the most important produced plant in the world, (Anonymous, 2019). Using an intercropping agricultural system is one of the most effective ways to increase production depending on ecological conditions. Intercropping can be defined as growing more than one plant in the same area in a year (Portes *et al.*, 2000). Some studies showed that mixed cropping has a higher yield and income than solo culture (Gou *et al.*, 2017). In studies conducted by Turk, J (2020) on the forage yield and growth parameters of maize /quinoa intercropping system, it was shown the amount of maize dry matter increased in almost all cropping ratios, quinoa performed well only in the 50% quinoa/ maize ratio. Intercropping systems are preferred in areas with limited land, manpower, mechanization, etc., due to better use of available resources than mono-cropping systems (Takil *et al.* 2020). Quinoa is a plant is suitable for different ecological conditions, and can be grown in different soil and climatic conditions (Martinez *et al.* 2009). The use of bio-fertilizers caused a significant reduction in N. P. K fertilizers (Hazra *et al.*, 2021). The recent investigations demonstrating the beneficial effects of these compounds on metabolic, cardiovascular, and gastrointestinal health have made quinoa gain recognition as a functional food. (Hernández-Ledesma, 2019). Quinoa resistant to arid and salinity conditions can survive with very low precipitation amounts, especially after the seedling period to until the end of the vegetation period. The high nutritional value of quinoa seeds has revealed that quinoa may be an alternative agricultural product that can be used for human nutrition (Takao *et al.*, 2005). In addition to the nutritional content of the seeds as well as some other characteristics of the plants (plant height (approximately 150 cm), waxy leaves (resistant to arid conditions and pests, etc.) (Geren and Kavut., 2015; Koca *et al.*, 2018), the plant, which has a taproot structure, stands out for its resistance to dry and salty soil conditions (Koca *et al.*, 2017). In the farm study, the grain yield of maize intercropped with watermelon was reduced by more than one-third compared to maize in wheat/maize double cropping, mainly due to lower ear density and lower 100-grain weight. Under; real farm conditions, the yield of intercropped maize increased with increasing ear density and 100-grain weight, while yield of sole maize increased with increasing grain number per ear and 100-grain weight. In the field experiments, the maize cultivars commonly used in double cropping gave similar yields when grown in the intercropping system, and their yields were closely related to ear density and 100-grain weight. Our results demonstrated that ear density, rather a cultivar, was a key factor affecting the productivity of intercropped maize (Huang Cheng-dong, *et al.*, 2019). Phosphorus is one of the essential elements for plant growth and development, with a vital role in crop production, and phosphorus deficiency has become an important factor limiting present-day agricultural productivity (Efthymiou *et al.*, 2018).

Dang *et al.*, (2023) in mung bean showed, that applying phosphorus fertilizer affected yield and chlorophyll. Intercropping of soybean/maize along with AMF inoculation significantly promoted maize and soybean growth compared to the monoculture system. Also, Tang *et al.*, (2023) showed, that availability of phosphorus fertilizer was positively correlated with plant biomass (Tang *et al.*, 2023). Li and Cai, 2021, found that by use of Arbuscular mycorrhizal fungi (AMF), maize biomass, chlorophyll content, plant height and leaf area, significantly improved. Phosphorus in the soil is affected by the soil microorganisms such as arbuscular mycorrhizal fungi promote root growth and converts inorganic phosphorus into organic (Richardson, 2001). This study was conducted to evaluate the application of mycorrhiza and phosphorus fertilizer on morphological and physiological characteristics in quinoa and maize in an intercropping system at two locations with different climatic conditions.

Materials and Methods

This study was conducted as a factorial experiment in a Randomized Complete Block Design (RCBD) with three replications in two locations of Shahrood and Mayamey, Semnan province, Iran. In 2021. Geographical, climatic characteristics, and soil physical and chemical properties are shown in Tables 1 and 2.

Table 1
Geographical and climatic characteristics of experiment locations

Region	Elevation	Longitude	latitude	Maximum temperature (°C)	Minimum temperature (°C)	Climate
Bastam	1420	35.36	58.54	41.68	20.80	Temperate
Mayamey	1025	36.4108	55.6503	45.66	19.72	Warm Temperate

Table 2
Soil physical and chemical properties of experiment locations

Locations	C (%)	N (%)	K (ppm)	P (ppm)	EC (dS.m ⁻¹)	pH	Texture
Bastam	0.4	0.04	149	19	0.41	8.30	Loam-silt
Mayamey	0.189	0.08	339	33.16	3.25	7.75	Silt- loam

The maize seeds cultivar 704 and quinoa variety Titicaca were used in this study were prepared from the seed breeding institute in Karaj, Iran. The cropping ratio included 100% maize, 100% quinoa, and proportional mixtures (25%, 50%, and 75%) of both plants that resulted in five distinct cultivation systems: 100% maize, 100% quinoa, 25% maize-75% quinoa, 50% maize-50% quinoa, and 75% maize-25% quinoa. Each replicate comprised a plot 4 m wide and 6 m long. Row spacing and plant spacing were 50 and 10 cm, respectively. The distance between maize and quinoa rows was 30 cm. Both quinoa and maize were sown on 24 May 2022, in both locations. Regular irrigation was carried out every six days to ensure proper moisture levels for the plants. In the proportional mixture systems, the arrangement of rows in the plots was adjusted accordingly. In the standard practices of 100% maize and 100% quinoa, both crops were grown in four rows. For the "50% quinoa-50% maize" system, two rows of quinoa and two rows of maize were cultivated. Similarly, the "75% maize-25% quinoa" and "25% maize-75% quinoa" practices involved one row of quinoa with three rows of maize and three rows of quinoa with one row of maize, respectively, within the four-row arrangement. Phosphorus fertilizer as triple superphosphate ($\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}$) was used at three levels: no use (P0), 50 kg ha⁻¹ (P1), and 100 kg ha⁻¹ (P2), which was placed at a depth of 5 cm in the soil at the planting time. Mycorrhiza was used at two levels: M1 (use of mycorrhiza as seed grinding) and M2 (No mycorrhiza). Samples were taken from the middle of each plot to reduce the marginal effect. Mycorrhizal fungi inoculum was obtained from Green Biotechnology Company, Karaj, IRAN, for more adhesion seed with mycorrhizal inoculum, use Arabic gum. Pour the coated seeds into a polythene bag and shake vigorously for 30 seconds until the surface of all the seeds is uniformly coated. After that, 50 grams of inoculum per kilogram was added to the sticky seeds and after 10 minutes and ensuring that the seeds were mixed with the fungus, the seeds were dried in the shade for one hour, and then the planting operation was done quickly (El- Sawah *et al.*, 2021). After eight leaf stage, plants were randomly sampled every 15 days in each plot. The proportional mixture systems were arranged by adjusting the number of rows in plots with four rows. Samples were taken from the middle of each plot to reduce the marginal effect.

Evaluated Traits

Leaf Area Index (LAI)

Leaf area index (LAI) was also measured by a specific leaf area meter at each step (Once every 15 days).

Plant Dry Weight (PDW)

To calculate plant dry weight samples were placed in oven at 75°C for 48h.

Crop Growth Rate (CGR) and Net Assimilation Rate (NAR)

To determine the variations in the crop growth rate (CGR) indices and the net assimilation rate (NAR), the following equations were used:

$$\text{CGR} = (\text{W}_2 - \text{W}_1) / (\text{T}_2 - \text{T}_1) \quad (1)$$

$$\text{NAR} = \text{CGR} / \text{LAI} \quad (2)$$

Plant Dry Matter

To determine the percentage of plant dry matter, the following equation was used

$$\frac{\text{Dryweight}}{\text{wetweight}} * 100$$

Plant Height

The plant height is measured from the base of the plant to the highest leaf part of the plant. Measurements were made using a ruler and measurements of plant height were made when the plants were 12 WAP with the assumption at 12 Weeks after planting.

Analysis of Chlorophyll Content

The contents of both Chl a and b were analyzed according to Shin *et al.*, (2020). First, 20 mg of freeze-dried and fine-powdered samples were extracted into 5 mL of MeOH for 2 h at room temperature. The aliquot was centrifuged at 3500 rpm for 10 min, and the absorbance was measured at 652 and 665 nm using a microplate reader. Both Chl a and b were then calculated according to the formula below.

Chlorophyll a = $19.3 A_{663} - 0.86 A_{646} / V = 100W$ (3)

Chlorophyll b = $19.3 A_{646} - 3.6 A_{663} / V = 100W$ (4)

Total chlorophyll = Chl a + Chl b (5)

Measurement of Mycorrhizal Colonization

Colonization by AMF was quantified through visual analysis of stained roots. Cleaned roots were cut into 2.5 cm segments, grouped into three subsamples of ~ 20 segments each (0.25 g dry weight equivalent), and placed into a biopsy cassette for staining. Roots were cleared with hot 10% KOH and stained with trypan blue (Kormanik and McGraw, 1982). Stained roots were spread on a grid plate and observed at 20 points. Each point was assessed for arbuscular vesicles or hyphae (Giovannetti and Mosse, 1980). The average proportion of points with structures present is reported on a percent basis for each structure.

Statistical Analysis

This experiment was analyzed by combined analysis. Only the basic design of this experiment is factorial. Analysis of variance and mean comparisons of data (at a 5% probability level based on LSD test) were performed using SAS software (Ver. 9.4). MS Excel was also used to plot the diagrams.

Results and Discussion

Chlorophyll Pigments

Quinoa Chlorophyll and Carotenoid Content

As can be seen in Table 3, all treatments had a significant effect on the chlorophyll a in quinoa. Based on mean comparisons, the highest chlorophyll a (2.205 mg gr^{-1}), b (0.75 mg gr^{-1}), and total chlorophyll (2.88 mg gr^{-1}) were obtained in the cultivation treatment of 100 quinoa by use of mycorrhiza inoculated and 50 kg ha^{-1} phosphorus in the Mayamey location. The lowest chlorophyll a (1.49 mg gr^{-1}), b (0.39 mg gr^{-1}) and total chlorophyll (1.5 mg gr^{-1}) was obtained in the planting ratio of 25% quinoa + 75% maize by useless mycorrhiza and 100 kg ha^{-1} phosphorus in the Shahrood location. All mycorrhiza treatments were observed to be more effective than those without mycorrhiza inoculation (Figs. 1, 2 and 3). Mean comparisons of data showed that the highest carotenoid (3.85 mg gr^{-1}) was obtained in 100% quinoa. The lowest carotenoid (1.98 mg gr^{-1}) was obtained in the planting ratio of 25% quinoa + 75% maize by useless of mycorrhiza and phosphorus in the Shahrood location (Fig. 4).

Table 3
Results of analysis of variance (mean squared) of yield and chlorophyll in maize and quinoa.

MS (Quinoa)						MS (Maize)				
sours	DF	Chl a	Chl b	T Chl	Carotenoid	Yield	Chl a	Chl b	T Chl	Carotenoid
Location (L)	1	1.22023**	0.445967**	3.07976**	2.77361**	1083.50 ns	0.551640**	12.1250**	17.8492**	6.19180**
Error ₁	4	0.000222 ns	0.000038 ns	0.001969 ns	0.010691 ns	240727 ns	0.013725 ns	0.187504 ns	0.246302 ns	0.012328 ns
Intercropping (I)	3	1.05706**	0.337711**	1.93123**	12.9978**	114410 ns	22.0581**	45.4685**	130.678**	9.30030**
Phosphorus (P)	2	1.05706**	0.007570**	0.598824**	3.24427**	1539037**	3.0525**	0.285436**	2.63146**	2.30306**
Mycorrhizal (M)	1	0.579451**	0.002978**	0.053534**	4.53228**	1179577**	0.251259**	0.072329 ns	0.593207**	2.96987**
I* P	6	0.087819**	0.002348**	0.035566**	0.264114**	60853.5 ns	0.374477**	0.418810**	0.891663**	0.313371**
I* M	3	0.035610**	0.003558**	0.044588**	0.298845**	7003.17 ns	0.024624 ^{ns}	.157540**	0.089514 ns	0.391775**
P* M	2	0.080456**	0.002667**	0.084252**	0.380412**	705779**	0.135212**	0.072471 ns	0.195158*	0.428784**
I* P * M	6	0.095776**	0.001377**	0.029623**	0.440735**	14019.4 ns	0.027009 ^{ns}	0.325610**	0.315780**	198196**
L*I	3	0.017798**	0.007570**	0.226449**	0.108903**	29738.7 ns	.030077 ns	0.669596**	0.730319**	0.062797**
L*P	2	0.223652**	0.000434 ns	0.015057**	0.010495 ns	22562.6 ns	0.008623 ns	0.093208*	0.153884 ns	0.000613 ns
L*M	1	0.032451**	0.021670**	0.002751 ns	0.111834**	13321 ns	0.018743 ns	0.001785 ns	0.032100 ns	0.000544 ns
L*I*P	6	0.009308**	0.002982**	0.010903**	0.148179**	53248.6 ns	0.007587 ns	0.128307**	0.145988*	0.041299**
L*I*M	3	0.009794**	0.004622**	0.031065**	0.058430**	27457.1 ns	0.004479 ns	0.005027 ns	0.007017 ns	0.047805**
L*P*M	2	0.000275 ns	0.000965**	0.005289 ns	0.357942**	13072.8 *	0.018485 ns	0.176521**	0.305336**	0.038188*
L*I*P*M	6	0.006658**	0.000926**	0.016923**	0.061022**	77155.7 ns	0.012956 ns	0.074409*	0.120336*	0.044279**
Error: MS(Error)	92	0.000932	0.000174	0.002664	0.004539	50427.4	0.018970	0.028439	0.053727	0.010252
CV		1.7533	2.8678	2.3334	2.4817	10.511	2.2236	5.8149	2.5488	3.5408

Maize Chlorophyll and Carotenoid Content

As can be seen in Table 3, all treatments used had a significant effect on the chlorophyll a, b, total chlorophyll, and carotenoid in maize. Based on mean comparisons, the highest chlorophyll a (4.78 mg gr⁻¹), b (3.5 mg gr⁻¹), total chlorophyll (8.28 mg gr⁻¹), and carotenoid (3.97 mg gr⁻¹) were obtained in the cultivation treatment of 50% maize by use of mycorrhiza inoculated and 50 kg ha⁻¹ phosphorus in the Mayamey location. The lowest chlorophyll a (2.35 mg gr⁻¹), b (1.15 mg gr⁻¹), total chlorophyll (3.5 mg gr⁻¹), and carotenoid (2.15 mg g⁻¹) was obtained in the planting ratio of 100% maize by useless of mycorrhiza and phosphorus in the Shahrood location. All mycorrhiza treatments were observed to be more effective than those without mycorrhiza inoculation (Fig. 5, 6, 7, and 8).

Yield

The results of the analysis of variance Table3, showed that the simple effects of phosphorus, mycorrhizal, and the interaction effects of phosphorus with mycorrhizal on maize yield were significant at the 1% level. The mean comparison test results showed that the highest yield of maize (4739.6 kg ha⁻¹) was obtained in treatment with use of mycorrhiza and 50 kg ha⁻¹ phosphorus in the Shahrood region. The lowest yield of maize (3889.25 kg ha⁻¹) was obtained in the control treatment and non-use of mycorrhizal (Fig. 9).

Based on the results of the analysis variance Table 3, the simple effects of phosphorus, mycorrhizal, and the interaction effects of phosphorus with mycorrhizal on maize yield were significant (p < 05). The results of the highest yield of quinoa (2542.5 kg ha⁻¹) were obtained in treatment with the use

mycorrhizal and 50 kg ha⁻¹ phosphorus in the Shahrood region. The lowest yield of quinoa (1995.4 kg ha⁻¹) was obtained in the control treatment (Without the use of phosphorus) and non-use of mycorrhizal (Fig. 10).

Sandepogu and Mamatha, 2022, in their study of Mycorrhizal on two cultivars of quinoa in both field and pot experiments, showed the highest yield and significant increase in plant dry weight, fresh weight and in total plant biomass and also estimated that the difference between grains yield per plant, protein content of the grains, weight of 100 grains over the control was recorded when the experimental plants were subjected to mycorrhizal alone or in combination. Which is consistent with the results of this research.

Total Dry Weight in Quinoa (TDW)

As can be seen in Table 4, all treatments had a significant effect on the amount of maize and quinoa dry matter during the growing season. Based non mean comparisons (Fig. 11), the highest TDW in maize (395.2 gr m⁻²) was achieved in solo culture (Fig. 11a), use of phosphorus 50 kg ha⁻¹ (415.2 gr m⁻²) (Fig. 11b), and mycorrhiza inoculation (418.85 gr m⁻²) (Fig. 11c) in 75 days after planting. However, the highest TDW of quinoa (295.65 gr m⁻²) was obtained in the solo culture of quinoa in 75 days after planting (Fig. 11d).

Table 4
Results of analysis of variance (mean squares) of TDW in maize and quinoa during the growth period

TDW of Quinoa (Days after planting)						TDW of maize (Days after planting)					
sours	DF	30	45	60	75	90	30	45	60	75	90
Location (L)	1	802.777**	1764**	413.444**	1943.34*	309.173*	817.006**	1190.25**	802.777**	1899.50**	287.585 ns
Error ₁	4	83.2777 ns	211.722 ns	33.9236 ns	326.965 ns	66.8611 ns	55.3611 ns	4.5139 ns	17.0347 ns	86.2639 ns	128.293 ns
Intercropping (I)	3	27876.4**	27660.2**	35875.8**	43984.3**	52387.9**	28464.6**	61867.4**	70187.3**	50584.5**	53321.3**
Phosphorus (P)	2	1240.50**	1699.04**	3846.09**	2497.71**	4310.59**	1588.34**	2799.00**	477.520**	2322.89**	1040.67**
Mycorrhizal (M)	1	930.250**	1626.77**	3025**	5712.84**	2002.56**	495.062*	1213.36**	8070.02**	9784.50**	8258.26**
I* P	6	223.081*	152.854 ns	365.368**	881.835*	630.719**	93.6921 ns	286.692**	3662.75**	4522.17**	6041.62**
I* M	3	62.6388 ns	11.1111 ns	89.3148**	337.229 ns	128.414 ns	84.3773 ns	60.5278**	1643.04**	1681.74**	2066.25**
P* M	2	124.395 ns	23.4236 ns	37.5208 ns	445.256 ns	116.687 ns	6.27083 ns	16.9653 ns	1325.71**	1216.71**	2928.85**
I* P * M	6	83.8958 ns	187.229 ns	70.8356**	297.506 ns	73.9838 ns	132.918 ns	55.8542**	2558.42**	3594.12**	3607.61**
L*I	3	66.8703 ns	77.9629 ns	7.9074 ns	294.729 ns	125.321 ns	67.7291 ns	7.9352 ns	40.6111* ns	81.4514 ns	319.390 ns
L*P	2	144.715 ns	31.7708 ns	9.2153 ns	152.298 ns	76.7569 ns	73.7986 ns	2.4375 ns	20.6736 ns	18.5903 ns	68.1372 ns
L*M	1	84.0277 ns	277.777 ns	106.777* ns	88.6736 ns	27.5625 ns	85.5625 ns	20.2500 ns	12.2500 ns	19.5069 ns	46.1267 ns
L*I*P	6	84.3634 ns	117.594 ns	15.5116 ns	316.770 ns	91.9606 ns	68.9652 ns	7.9005 ns	14.8681 ns	102.256 ns	92.0677 ns
L*I*M	3	110.009 ns	22.8518 ns	11.4259 ns	293.506 ns	120.858 ns	106.988 ns	28.7500 ns	18.9722 ns	137.525 ns	316.339 ns
L*P*M	2	51.5486 ns	30.7569 ns	7.9236 ns	286.923 ns	80.6875 ns	38.3958 ns	2.3125 ns	36.8125 ns	58.5486 ns	215.428 ns
L*I*P*M	6	67.4189 ns	87.0254 ns	35.2940 ns	306.673 ns	92.4282 ns	87.9328 ns	15.0903 ns	19.8958 ns	64.9005 ns	95.7946 ns
Error: MS(Error)	92	77.6183	94.6715	16.6120	302.247	75.6075	87.9336	12.8545	13.9768	65.7929	123.115
CV		9.0852	8.1745	1.8267	6.6686	2.9453	5.5293	1.6555	1.1409	2.2433	2.6975

At the beginning of the sampling period (30 Day after planting), TDW in maize and quinoa directly increased until 75 days after planting, and then its amount decreased until the 90th da

Leaf Area Index (LAI)

Analysis of variance showed that cropping ratio, phosphorus fertilizer, and mycorrhiza fungus had a significant effect on maize and quinoa leaf area index during the growing season (Table 5). The increasing trend LAI in maize and quinoa was slow up to 30 days after planting, but it increased linearly up to 75 days after planting, and then, decreased (Fig. 12). The highest maize LAI was obtained for sole culture (Fig. 12a), use of phosphorus 50 kg ha⁻¹ (Fig. 12b), and inoculated by mycorrhiza (Fig. 12c) on 75 days after planting. The lowest was observed for 25: 75 cropping ratios in maize. The highest quinoa LAI was obtained in the 100% quinoa, 75% quinoa – 25% maize, 50% quinoa, and 25% quinoa-75% maize cropping ratio were determined to be 7.57, 7.30, 8.52, 6.90 in the 75 Day after planting, respectively (Fig. 12d). In all of the treatments in two locations, at the beginning of the growth period, the development of leaves was slow, which continued until shortly before the emergence of inflorescences, but after that, the slope of the increase in leaf area increased and continued until reaching the maximum index of leaf area (Fig. 12). with aging leaves, yellowing and falling of the lower leaves of the bush, due to shading and re-transfer of materials from leaves to in the period of seed filling, this trend decreased and was observed a relatively severe drop in leaf surface reduction. The quinoa and maize and cropping ratio of quinoa - maize, 75 days after planting, the leaf area index reached its highest value.

Table 5
Results of analysis of variance (mean squares) of LAI in maize and quinoa during the growth period

LAI of Quinoa (Days after planting)							LAI of Maize (Days after planting)				
Sours	DF	30	45	60	75	90	30	45	60	75	90
Location (L)	1	2.23004**	2.34090**	2.57602**	2.9986**	2.60284**	2.06832**	1.33210**	2.63250**	3.05084**	3.05084**
Error	4	0.192329 ns	0.266134 ns	0.022954 ns	0.497829 ns	0.319569 ^{ns}	0.002312 ns	0.007361 ^{ns}	0.034511 ns	0.640116 ns	0.640116 ns
Intercropping (I)	3	9.36800**	30.2842**	55.5363**	55.1550**	30.0087**	11.2658**	25.8115**	79.6500**	58.2056**	58.2056**
Phosphorus (P)	2	0.483909**	0.200121**	0.316939**	0.687617 ns	0.195369 ^{ns}	0.728815**	0.830711**	1.23300**	1.24721**	1.24721**
Mycorrhizal (M)	1	0.084100 ns	0.263511*	1.41213**	2.85046**	0.143136 ^{ns}	0.126652**	0.493506**	0.299756**	0.004900 ns	0.004900 ns
I* P	6	2.14717**	1.304641**	0.151706**	0.742592*	0.560758 ⁿ	0.761619**	1.14603**	0.442538**	0.399595**	0.399595**
I* M	3	0.119468*	0.026605 ns	0.355915**	0.113449	0.208845 ⁿ	0.148655**	0.558022**	0.479778**	0.701246**	0.701246**
P* M	2	0.123539*	0.372125**	0.496979**	1.74838**	0.60886 ^{ns}	0.282427**	0.539175**	0.018175 ns	0.266502*	0.266502*
I* P * M	6	0.048138 ns	0.396153**	0.327992**	1.18729**	0.205217 ^{ns}	0.115839**	0.737558**	0.758252**	0.367267**	0.367267**
L*I	3	0.046601 ns	0.013379 ns	0.017197 ns	0.001797 ns	0.039338 ^{ns}	0.021697**	0.074928**	0.016980 ns	0.004524 ns	0.004524 ns
L*P	2	0.003438 ns	0.005868 ns	0.003639 ns	0.004654 ns	0.000469 ^{ns}	0.016308**	0.097152**	0.000633 ns	0.003734 ns	0.003734 ns
L*M	1	0.003025 ns	0.004900 ns	0.000544 ns	0.021025 ns	0.000025 ^{ns}	0.012250**	0.345156**	0.000006 ns	0.012469 ns	0.012469 ns
L*I*P	6	0.003053 ns	0.016381 ns	0.001122 ns	0.005641 ns	0.002080 ^{ns}	0.003486 ns	0.042580**	0.000974 ns	0.007383 ns	0.007383 ns
L*I*M	3	0.000260 ns	0.002068 ns	0.002579 ns	0.008041 ns	0.001330 ^{ns}	0.004414 ns	0.050250**	0.002347 ns	0.006186 ns	0.006186 ns
L*P*M	2	0.002493 ns	0.015664 ns	0.000471 ns	0.011377 ns	0.00070 ^{ns}	0.000731 ns	0.181058**	0.001675 ns	0.000796 ns	0.000796 ns
L*I*P*M	6	0.001287 ns	0.010077 ns	0.001901 ns	0.006268 ns	0.001177 ^{ns}	0.006838**	0.015680**	0.000821 ns	0.002304 ns	0.002304 ns
Error: MS(Error)	92	0.038583	0.039195	0.043309	0.259641	0.263931 ^{ns}	0.001684	0.003927	0.014106	0.071455	0.071455
CV		13.584	6.2756	3.4951	7.6472	14.0805	3.0616	2.2807	2.3997	4.5387	4.5387

Crop Growth Rate (CGR)

The CGR values calculated in this study are given in Table 6. As a result of the variance analysis, the mean square values, and significance of the differences were shown in Fig. 13. The values showed that the planting ratio had significant effects on the CGRs calculated for the maize and quinoa plants. The highest

values were obtained from the monoculture maize (14.5 gr m⁻²) in 75 days after planting, and the monoculture of quinoa (7.84 gr m⁻²) in 60 days after planting (Fig. 13. a and b).

Table 6
Results of analysis of variance (mean squares) of CGR in maize and quinoa during the growth period

CGR of Quinoa (Days after planting)							CGR of Maize (Days after planting)			
Sours	DF	30	45	60	75	90	30	45	60	75
Location (L)	1	0.891968**	0.012941 ns	0.544287**	0.086348**	0.171457*	0.907843**	0.0000001	0.168996 ns	0.067188**
Error ₁	4	0.092529 ns	0.013218 ns	0.107601 ns	0.003758 ns	0.011704 ns	0.061519 ns	0.003056 ns	0.118913 ns	0.005227 ns
Intercropping (I)	3	30.9738**	24.5665**	33.9455**	0.264656**	24.1130**	31.6272**	34.7237**	28.0234**	8.358116**
Phosphorus (P)	2	1.37834**	1.25232**	2.26817**	0.014248 ns	0.150561*	1.76474**	2.68673**	10.5628**	4.9279**
Mycorrhizal (M)	1	1.03360**	0.135995**	1.61447**	0.064872*	0.562318**	0.550106**	0.016520*	13.4445**	1.43842**
I* P	6	0.247867*	0.450566**	0.758117**	0.170051**	2.02110**	0.104098 ns	0.363196**	11.1970**	2.45046**
I* M	3	0.069598 ns	0.045765**	0.097593*	0.823346**	0.540876**	0.093750 ns	0.847151**	7.68092**	0.164796**
P* M	2	0.138217 ns	0.704599**	0.082348 ns	0.508685**	1.10834**	0.006967 ns	0.481621**	7.27081**	0.439935**
I* P * M	6	0.093217 ns	0.500689**	0.402116**	0.358110**	0.179819**	0.147697 ns	0.207868**	10.5321**	2.76778**
L*I	3	0.074301 ns	0.301862**	0.026747 ns	0.173639**	0.123601*	0.075256 ns	0.064177**	0.182765*	0.072742**
L*P	2	0.160794 ns	0.564430**	0.105192*	0.187752**	0.018095 ns	0.081999 ns	0.078290**	0.058559 ns	0.026689**
L*M	1	0.093362 ns	0.019017 ns	0.056768 ns	0.019292 ns	0.288072**	0.095043 ns	0.084196**	0.284453*	0.000686 ns
L*I*P	6	0.093736 ns	0.221162**	0.110339**	0.117374**	0.168478**	0.076625 ns	0.060140**	0.103284 ns	0.067081**
L*I*M	3	0.122232 ns	0.160731**	0.012582 ns	0.140289**	0.218367**	0.118881 ns	0.343338**	0.389379**	0.058581**
L*P*M	2	0.057276 ns	0.186818**	0.071046 ns	0.041572*	0.117582**	0.042662 ns	0.022997**	0.141931 ns	0.005642 ns
L*I*P*M	6	0.074910 ns	0.144512**	0.085444**	0.157743**	0.236874**	0.097699 ns	0.186695**	0.158343*	0.063218**
Error: MS(Error)	92	0.086242	0.005974	0.027389	0.012052	0.033262	0.097702	0.003714	0.064491	0.004540
CV		9.0852	5.3022	2.3712	4.1701	8.1626	5.5293	1.9757	3.4287	2.9340

The slow growth rate of the product at this stage is due to the lack of a canopy and the lack of light absorption (Gilani *et al*, 2021). The growth rate of the product is an indicator that shows the amount of dry matter accumulation per unit of time and on the surface of the earth. Because the daily growth rate has a direct relationship with the leaf surface and dry matter accumulation, high performance of these treatments is expected. It seems that with the reduction of intraspecies competition in mixed cultivation, more light reaches the lower leaves of quinoa, as a result, it has increased the growth rate of the product in this treatment compared to pure cultivation. Also, the growth rate of maize and quinoa is statistically under the influence of phosphorus fertilizer throughout the growing period. The maximum growth rate of corn from the treatment of phosphorus fertilizer was 50 kg ha⁻¹ using mycorrhiza on the 70th day after planting (maximum rate of growth) and its lowest value was obtained through the control treatment of phosphorus and mycorrhizal on the same day.

Net Assimilation Rate (NAR)

As shown in Table 7, the effect of different treatments on Nar was significant. The trend of changes in the NAR in the maize and quinoa were same. The trend of net absorption speed in all treatments in the early growth period was bullish with a slope mildness. NAR in quinoa reached the maximum (7.2 gr m⁻² day⁻¹) 45 days after planting (Fig. 14. a), and in maize, the maximum of NAR (10.2 gr m⁻² day⁻¹) reached in 75 days after planting (Fig. 14. b). In the maize, the

net assimilation rate first decreased and, then, it increased from 45 days after planting to 75days. Meanwhile, the best treatment for quinoa was 75% maize: 25% quinoa cropping ratio, which had the highest net assimilation rate during the whole growing season, probably in the intercropping system, the sunlight permeated the entire canopy cover, and the maximum rate of photosynthesis was observed in all canopy layers. The net assimilation rate represents the net amount of dry matter produced per unit area of leaf per unit time. The net assimilation rate is initially decreasing in most crops, reaching its maximum when the leaves are exposed to full sunlight. With increasing growth, the leaves are expanded, and upper leaves shade on the lower ones. The higher the shading, the more reduced the net assimilation rate. With increasing age in the leaf, photosynthesis also decreases, which in turn steepens the gradient of the net assimilation rate. However, in sugar beet, lettuce and similar plants, the trend is still increases for some time and then decreases. This is because, at the beginning of the growing season, these plants have small leaves and are closed, so they cannot utilize the full sunlight. Also, after a while, the insider leaves are not capable of photosynthesis, which reduces the net assimilation rate in these plants (Eddowes 1969).

Table 7
Results of analysis of variance (mean squares) of NAR in maize and quinoa during the growth period

NAR of Quinoa (Days after planting)							NAR of Maize (Days after planting)				
Sours	DF	30	45	60	75	90	30	45	60	75	90
Location (L)	1	21.4553**	0.009738**	0.045820 ns	0.002011 ns	0.040152**	98.5236**	1.44142**	0.355762**	0.024380**	0.000362 ns
Error ₁	4	0.216092 ns	0.008828 ns	0.031221 ns	0.012275 ns	0.001477 ns	0.053438 ns	0.001462 ns	0.003468 ns	0.000362 ns	0.000362 ns
Intercropping (I)	3	168.148**	2.35215**	7.11341**	0.472850**	4.37933**	346.027**	19.7273**	14.4872**	0.157534**	0.000362 ns
Phosphorus (P)	2	22.4283**	0.253078**	0.036567 ns	0.031009 ns	0.013399*	21.2182**	1.10876**	1.16814**	0.294338**	0.000362 ns
Mycorrhizal (M)	1	3.86516**	0.061125**	0.005562 ns	0.038692 ns	0.212540**	4.56324**	0.037091**	0.447081**	0.045322**	0.000362 ns
I* P	6	43.3339**	0.106184**	0.011707 ns	0.012728 ns	0.120015**	13.7046**	0.920775**	0.554740**	0.126288**	0.000362 ns
I* M	3	2.80266**	0.081053**	0.011578 ns	0.042465*	0.074930**	1.92742**	0.298960**	0.216159**	0.020073**	0.000362 ns
P* M	2	0.442658 ns	0.286720**	0.072991 ns	0.036039 ns	0.337501**	11.7170**	0.110403**	0.129158**	0.015624**	0.000362 ns
I* P * M	6	0.809868 ns	0.232430**	0.107558**	0.023424 ns	0.147901**	3.95897**	0.392109**	0.623953**	0.114329**	0.000362 ns
L*I	3	4.02873**	0.175917**	0.043816 ns	0.029282 ns	0.070555**	16.5374**	0.550269**	0.070661**	0.000794*	0.000362 ns
L*P	2	1.72061*	0.253059**	0.008474 ns	0.012171 ns	0.043115**	0.767394**	0.166111**	0.007104**	0.002419**	0.000362 ns
L*M	1	0.025638 ns	0.103820**	0.034872 ns	0.005561 ns	0.165418**	0.065643 ns	0.022909**	0.015221**	0.002013**	0.000362 ns
L*I*P	6	2.85753**	0.194064**	0.053163 ns	0.010599 ns	0.023913**	1.11270**	0.159040**	0.003209*	0.001421**	0.000362 ns
L*I*M	3	0.005156 ns	0.160009**	0.015099 ns	0.014867 ns	0.003543 ns	0.290836**	0.300156**	0.004760*	0.002766**	0.000362 ns
L*P*M	2	0.228822 ns	0.201307**	0.034774 ns	0.020616 ns	0.058389**	1.71883**	0.086772**	0.002761 ns	0.001895**	0.000362 ns
L*I*P*M	6	0.304226 ns	0.173188**	0.029059 ns	0.032750*	0.036640**	0.598108**	0.129102**	0.002851*	0.001856**	0.000362 ns
Error: MS(Error)	92	0.409000	0.002289	0.028563	0.012712	0.002971	0.030194	0.003038	0.001294	0.000261	0.000362 ns
CV		21.553	9.9339	13.728	26.957	8.2906	3.1984	4.2428	2.1944	4.0481	
All authors contributed to the study conception and design.											
Material preparation, data collection and analysis were performed by [Tayebe Rostami], [Hammid Abbasdokht].											
The first draft of the manuscript was written by [Tayebe Rostami]											
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Colonization Percentage in Quinoa and Maize

As shown in Table 7, treatments, such as location, mycorrhiza, phosphorus fertilizer, and cropping ratio, had a significant effect ($p < 0.01$) on the colonization percentage in quinoa and maize. The mean comparison of traits showed that the highest colonization (44.6%) was obtained in the 25% quinoa and 75% maize cropping ratio and phosphorus 50 kg ha⁻¹ concentration treatments using AMF. The lowest colonization (5%) was obtained at 100% quinoa, control (phosphorus 0 kg ha⁻¹) treatment in the Mayamey location (Fig. 15a). Also, based on the results of variance analyzed Table 7, mycorrhiza, phosphorus fertilizer, cropping ratio, and location had had a significant effect on the colonization percentage in maize ($p < 0.01$). As shown in Fig. 16b, the highest

colonization (83.0%) was obtained in the 100% maize, and phosphorus 50 kg ha⁻¹ concentration treatments by using of AMF. The lowest colonization (25.2%) was obtained at 25% maize and 75% quinoa in control (un-use of phosphorus fertilizer) treatment at Shahrood location (Fig. 15b). Quinoa belongs to a family of plants considered non-mycorrhizal (*Amaranthaceae*) (Muthukumar and Tamilselvi, 2010). AMF associations with quinoa have been observed in a few prior studies (Vestberg *et al.*, 2012), though the rates of colonization were minimal. Vestberg *et al.* (2012) observed 19% colonization, the greatest of which we know (before our observation), occurred under temperate field conditions. Notably, both vesicles and arbuscules were observed in quinoa roots, indicating that there could have been nutrient exchange occurring (Brundrett, 2009). In studies conducted by Kellog *et al.* (2021) in 10 quinoa genotypes reported 0 to 3% quinoa root colonization by AMF under greenhouse conditions. If, Benafari *et al.* (2022) reported 50% colonization. The results showed that the frequency and intensity of the AMF infection in quinoa plant roots were significantly decreased by sole culture ($p < 0.05$). The treatments intercropped with maize (75% maize-25% quinoa), and combined with AMF (AMF + p50 kg ha⁻¹), showed the highest mycorrhizal frequency. When the levels of soluble phosphorus in the soil increased, the colonization of arbuscular mycorrhizal fungi with roots decreased. These fungi have specific biochemical and physiological characteristics that can increase roots' phosphorus availability. Fungi acidify the rhizosphere by increasing the release of protons, which can increase the solubility and transfer of phosphorus, especially in alkaline soils such as the soil of the studied areas. In acid soils where phosphorus is mainly bound with iron or aluminum, the neutralization of chelating agents by mycorrhizal fungi can increase the root bioavailability of soil phosphorus (Bender *et al.*, 2015). According to Table 5, The amount of flavonoid showed a positive and significant correlation with the amount of phenol and antioxidant enzymes. However, no significant correlation was observed between phytic acid and the measured phytochemical properties, including the amount of antioxidants and related enzymes. The colonization percentage showed a positive and significant relationship with the amount of flavonoid and phytic acid ($P \leq 0.05$). Also, there was no significant correlation between saponin and antioxidant enzymes.

Discussion

In an intercropping system, the yield of each crop is usually lower than a solo culture system. (Martin-Guay *et al.* 2018). This yield reduced can be due to competitive interactions between two crops. IC significantly reduced corn and wheat/maize yield during two growing seasons in the North China Plain and the Netherlands, respectively. (Huang *et al.* 2019 and Gou *et al.* 2016). The growth and metabolic activity of plants is determined both by the plant's photosynthetic capacity and by its ability to utilize soil nutrients (Li and Cai, 2021). The addition of phosphorous and the presence of AMF can alter the metabolic environment of plants by affecting the levels of available nutrients in the ground, thereby enhancing the ability of plants to absorb and assimilate CO₂ from the atmosphere. Studies showed that AMF significantly improved antioxidant enzyme activity, net photosynthetic rate, and above-ground biomass (Ren *et al.*, 2019). AMF inoculation with reduction peroxidase activity, and increases chlorophyll content, photosynthetic rate, and above-ground biomass (Li and Cai, 2021). Mycorrhizal hyphae by increase magnesium absorption, and as a result, increased the amount of total chlorophyll and carotenoids in quinoa and maize plants (Benafari *et al.*, 2022). The increase in total chlorophyll synthesis depends on the sufficient absorption of minerals, especially nitrogen and magnesium (Begum *et al.*, 2019). The use of phosphorus has an important physiological role in the process of phytochemical biosynthesis pathway because it has a synergistic effect with nitrogen. Our results showed that the use of mycorrhizal fungi increased the amount of secondary metabolite in quinoa compared to control treatments. This increase can be due to the improvement of biochemical composition (Benafari *et al.*, 2022).

Mycorrhizal fungi are symbiotic with most crops and found on the surface of roots, in the cortex and around the epidermis of root cells. The hyphae of mycorrhizal fungi are thinner than root hairs, so they can extend into soil micropores and transport some mainly minerals such as nitrates and phosphates, and then to their host plant in exchange for carbohydrates (Van *et al.*, 2015). Although mycorrhizal fungi can significantly improve the availability of phosphorus, but their ability to secrete phosphatase and activate organophosphates is relatively weak (Tisserant *et al.*, 2013). They use other methods to improve the utilization of soil phosphorus. First, they can rapidly release carbohydrates produced by photosynthesis to the rhizosphere, thereby promoting microbial reproduction, enhancing the secretion of large amounts of phosphatase and the activation of organophosphates, and thus, indirectly increasing plants' ability to absorb phosphorus (Zhang *et al.*, 2016). Second, AMF can alter the morphology of plant roots in order to promote phosphorus uptake (Cosme and Wurst, 2013). For example, Zhang *et al.* (2016) reported that mycorrhiza can expand the absorption area of plant roots by forming a hyphal network, which can then absorb phosphorus from soil pores and transmit it to new host plants.

One possible mechanism relates to the ability of AMF hyphae to increase water and nutrient uptake by plants as a result of the symbiotic relationship between plants and AMF (Smith *et al.*, 2010). In particular, mycorrhiza can absorb and transport large amounts of nutrients, such as phosphorus, thus improving plant resistance to stressful environments (Doubkova *et al.*, 2013). In parallel with many previous studies, 100% corn showed the highest values of green and dry grass (Koca *et al.*, 2010; Koca and Ereku, 2016). It was determined in the studies of Baghdadi *et al.* (2016) the crop combination rate significantly affected the total dry matter yield of corn-soybean feed. Among the corn and soybean monocropping and corn-soybean intercropping, it was reported that the total dry matter yield of maize (1477 kg ha⁻¹) was the highest value. Similarly, Stoltz *et al.* (2013) in their studies, sole corn had a higher dry matter yield than intercropped corn. Other studies have shown in their studies have shown that corn in the intercropping systems increased dry matter yield significantly (Kizilsimsek *et al.*, 2020; Javanmard *et al.*, 2009; Geren *et al.*, 2008; Azim *et al.*, 2000). Temel and Tan, 2020, reported that quinoa may be recommended to improve the quality of feed quality. It may even be argued that yield losses can be tolerated with good farming practice conditions. Erdogan *et al.*, 2020, determined that maize has serious adverse effects on quinoa during plant grow and quinoa also had some negative effects on maize. None of the mixture treatments (25%, 50%, or 75% quinoa) containing quinoa plants showed as high green and dry grass yield values as 100% maize (Erdogan *et al.*, 2020). The optimal temperature during the growth and development period of the plant leads to early, fast and uniform germination of seeds, and as a result, it causes favorable greening and rapid initial growth in plants, and this in turn causes more solar radiation and more leaf growth and development. Moreover finally, the increase in the growth rate and the accumulation of photosynthetic materials increases (Chimenti, and Hall, 2002). High temperature improved the photosynthesis rate of quinoa plant. Quinoa has high flexibility to high temperatures (Hinojosa *et al.*, 2019). In my study, the use of AMF and Phosphorus, which is in agreement with Benafari *et al.* (2022), who reported that quinoa plants treated with AMF improved physiological characteristics. In study of Mathur *et al.* (2019) and Mathur and Jajoo (2020) It was found that inoculation with AMF helps plants to maintain the integrity and stability of PSI and PSII under abiotic stress. AMF hyphae are likely to increase Mg uptake, which can increase total chlorophyll content in mycorrhizal quinoa plants (Benafari *et al.* 2022).

Some study showed that the improvement of chlorophyll synthesis is linked to adequate uptake of mineral elements, particularly Mg and N (Begum *et al.* 2019;). In addition, Phosphorus has a synergistic effect with nitrogen, and as a result, increases the yield and growth of the plant (Hashem *et al.* 2018).

Conclusions

Our study showed the different effects of mycorrhizal fungus inoculation and phosphorus on mor traits of quinoa and maize plants in intercropping system. Morphological and physiological traits affected with an intercrop ratio, AMF inoculation, and phosphorus fertilizer. Phosphorus fertilizer optimized the symbiotic relationship between plants and arbuscular mycorrhizal fungi and improved the inoculation rate of AMF. This is closely related to the function of improving plant growth performance (both physiology and phenotype). AMF can significantly increase rhizosphere microbial and phosphatase activity, thus, enabling plants to activate and absorb larger amounts of phosphorus. Our study showed AMF plays different roles in optimizing plant strategies for phosphorus uptake and the efficient utilization of phosphorus in intercropping system. Based on the results of our research, the increase of some phytochemical compounds was related to the activity of antioxidant enzymes. Considering the decline in available agricultural land, especially in arid and semi-arid areas such as our study areas, a cropping ratio with AMF inoculation and phosphorus fertilizer (50 kg ha⁻¹) is a more sustainable solution for improving crop productivity in intercropping system than monocropping. Based on the results obtained in our study, in different climate conditions, intercropping maize with quinoa under the inoculation of AMF as biofertilizer is recommended as a feasible and eco-friendly alternative strategy to improve the Morphological and physiological characteristics compared with the sole culture. It is suggested to investigate different species of arbuscular fungi in mixed cultures of maize/quinoa and other phosphorus concentrations. Also, the other performance components and physiological characteristics should be investigated in the future.

Declarations

Acknowledgments

He thanks and appreciates the efforts of the professors and staff of the Faculty of Agriculture of Shahrood University of Technology who helped in accomplishing this task.

Declarations

There is no conflict of interest between the authors of the article.

All authors contributed to the study conception and design.

Material preparation, data collection and analysis were performed by [Tayebe Rostami], [Hamid Abbasdokht].

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Figures

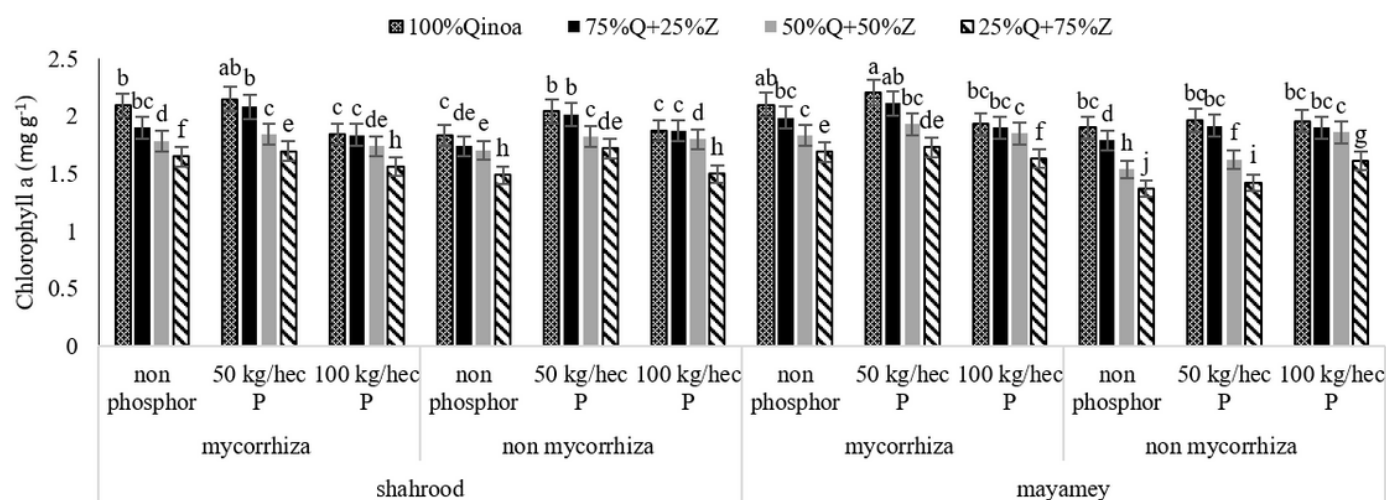


Figure 1

The interaction effect of cropping ratio, phosphorus and mycorrhiza on chlorophyll a in quinoa

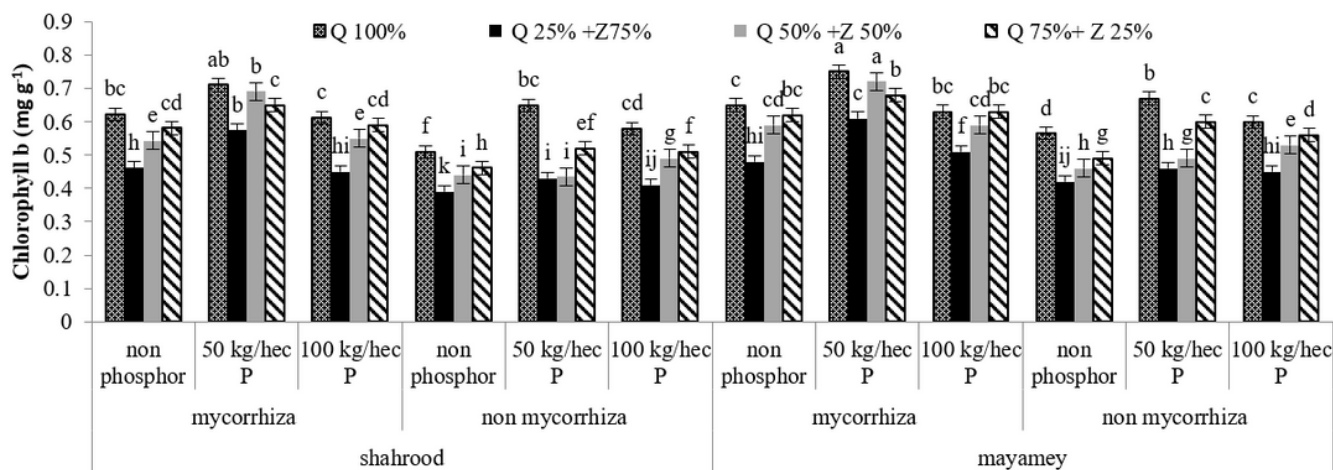


Figure 2

The interaction effect of cropping ratio, phosphorus and mycorrhiza on chlorophyll b in quinoa.

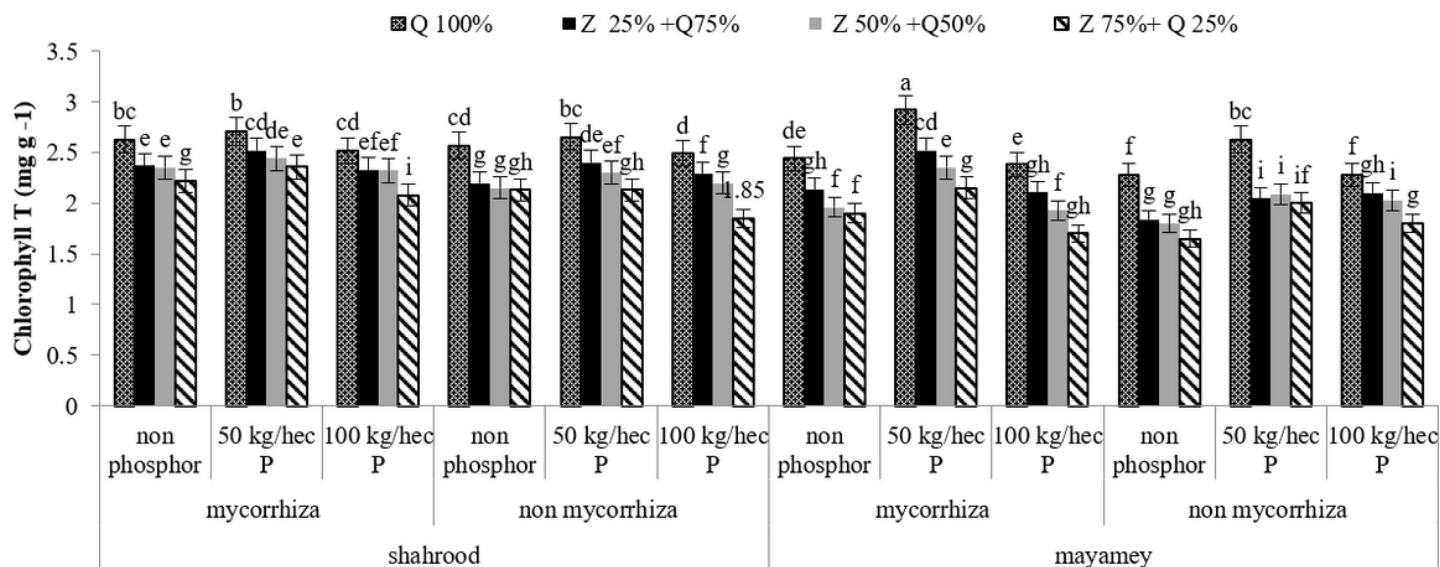


Figure 3

The interaction effect of cropping ratio, phosphorus and mycorrhiza on total chlorophyll T in quinoa

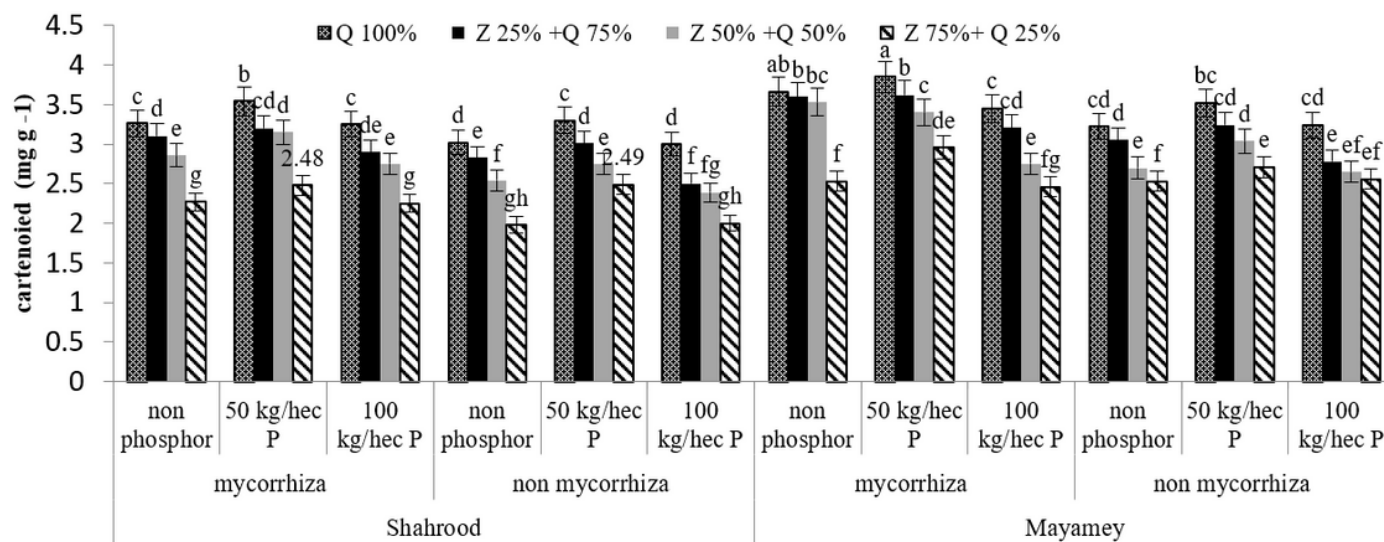


Figure 4

The interaction effect of cropping ratio, phosphorus and mycorrhiza on carotenoid in quinoa.

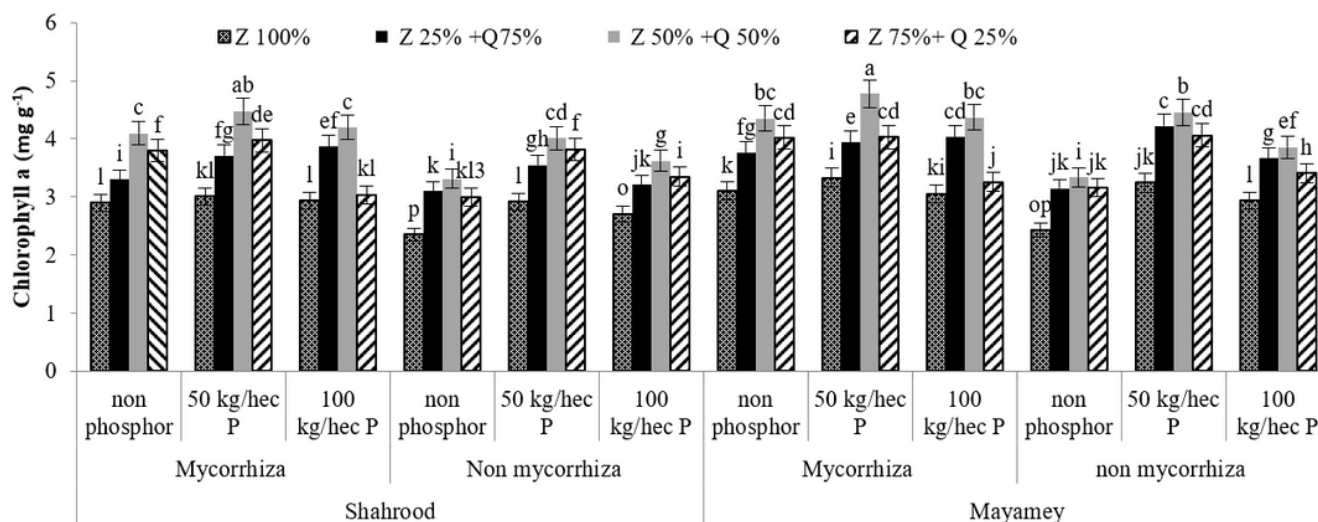


Figure 5

The interaction effect of cropping ratio, phosphorus, and mycorrhiza on chlorophyll a in maize

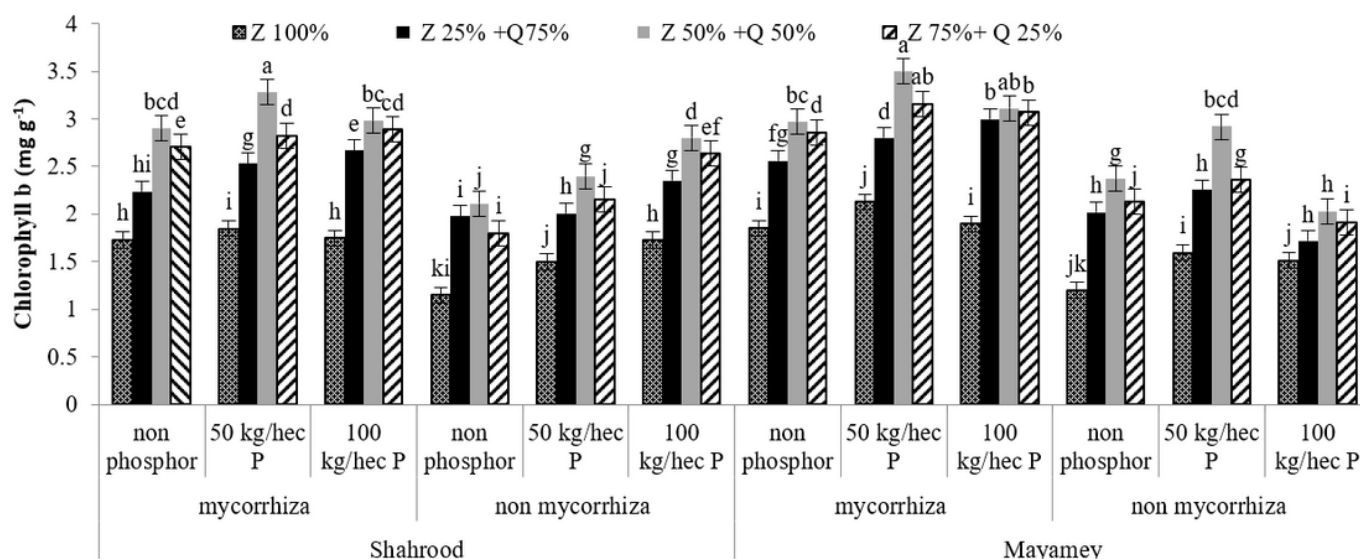


Figure 6

The interaction effect of cropping ratio, phosphorus and mycorrhiza on chlorophyll b in maize

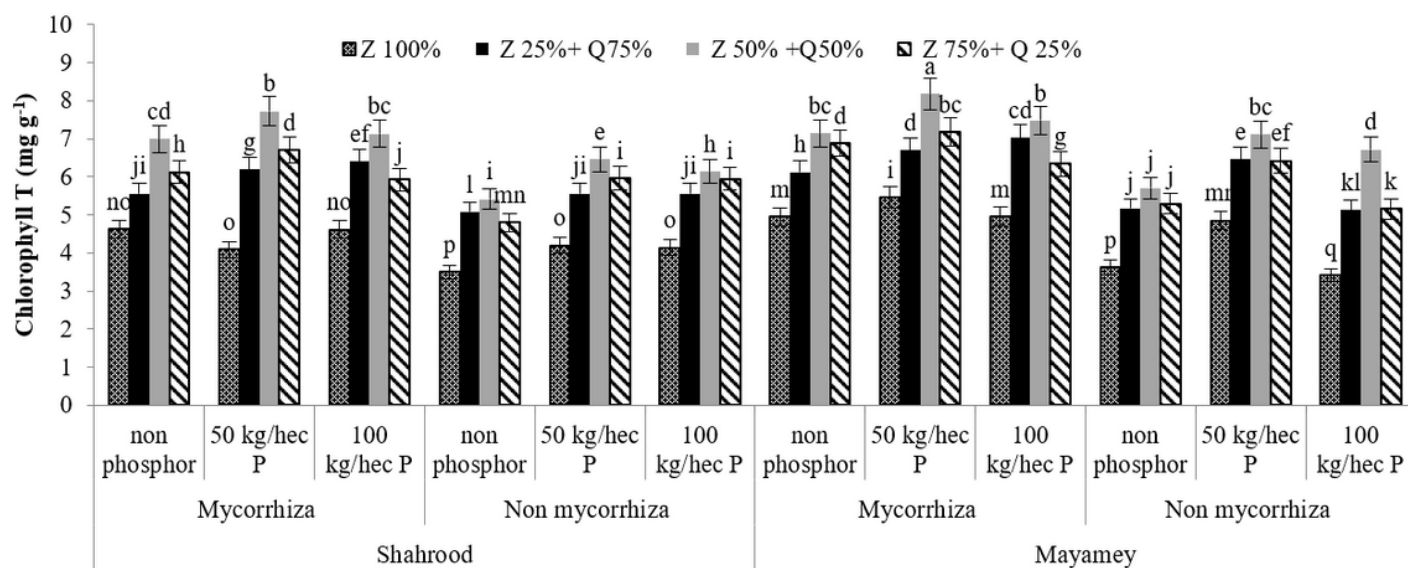


Figure 7

The interaction effect of cropping ratio, phosphorus and mycorrhiza on total chlorophyll T in maize.

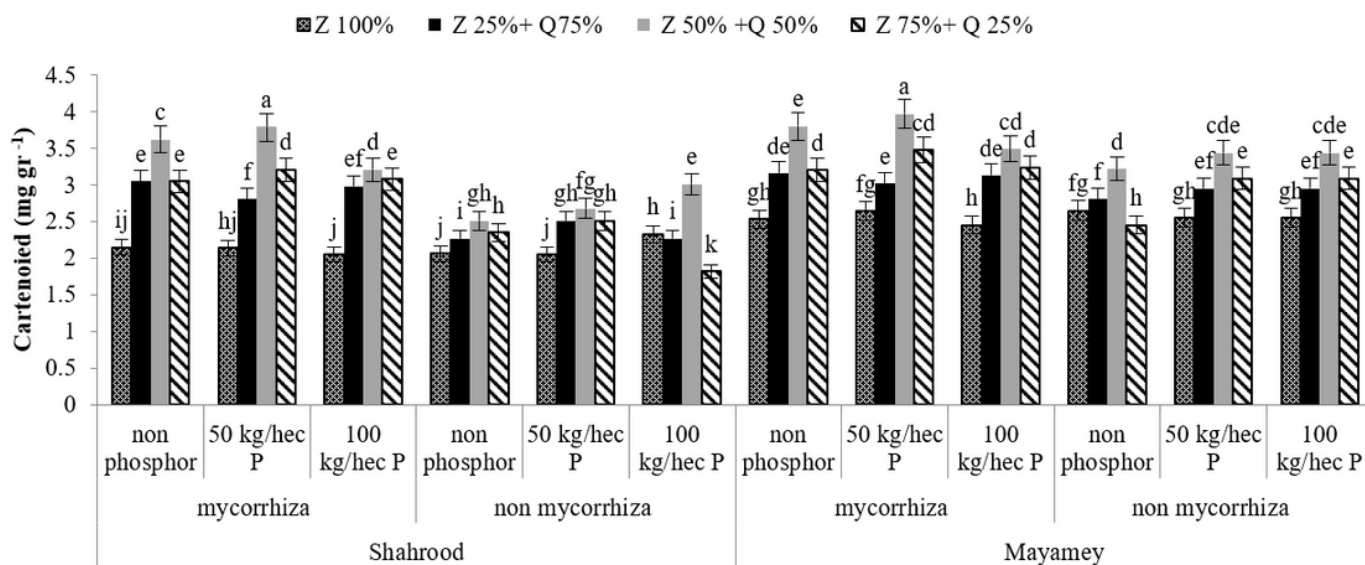


Figure 8

The interaction effect of cropping ratio, phosphorus and mycorrhiza on carotenoid in maize.

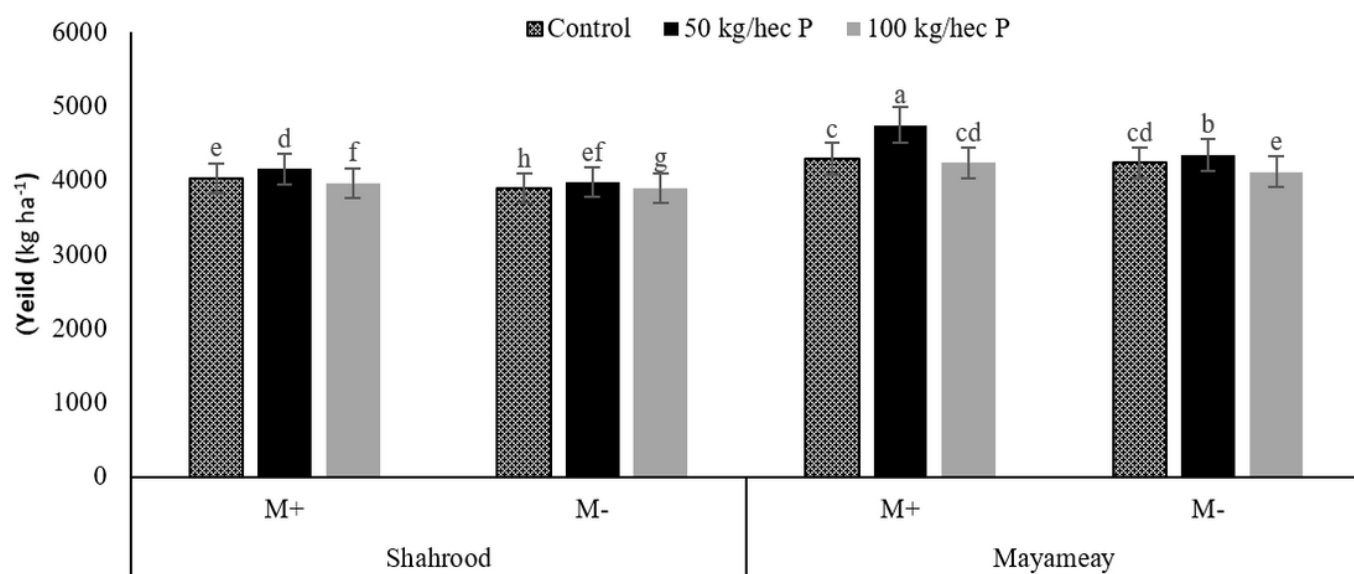


Figure 9

The interaction effect of location, phosphorus and mycorrhizal on yield in maize.

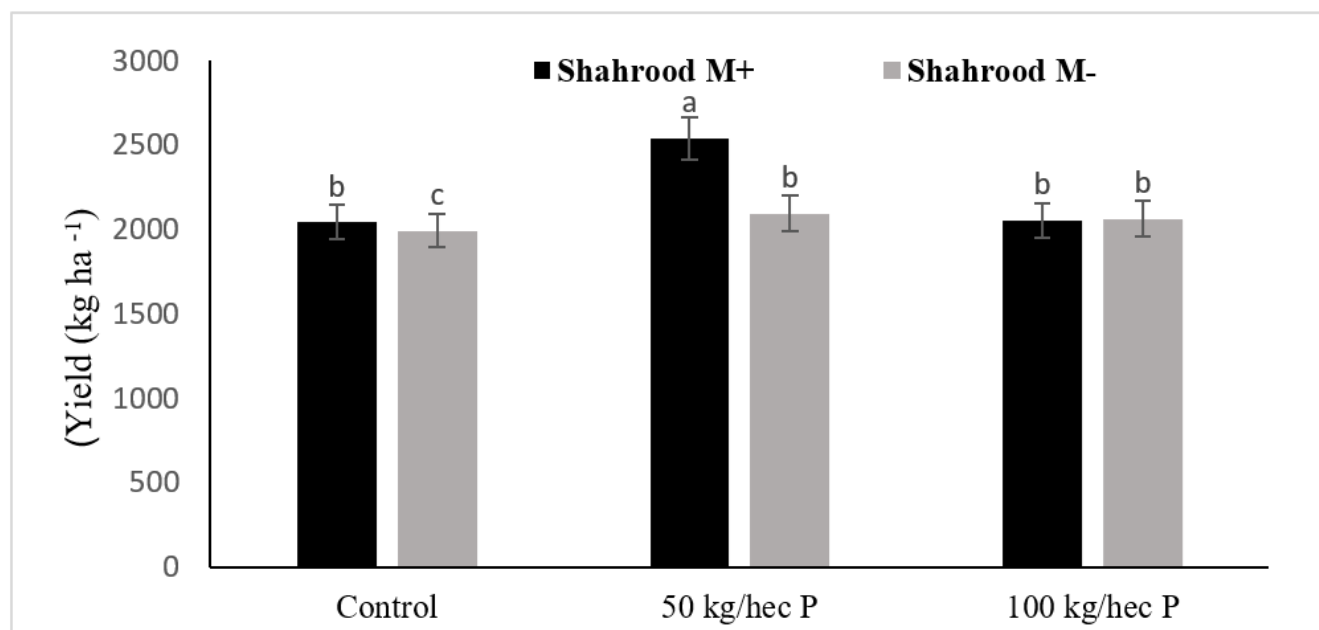


Figure 10

The interaction effect of location, phosphorus and mycorrhizal on yield in quinoa.

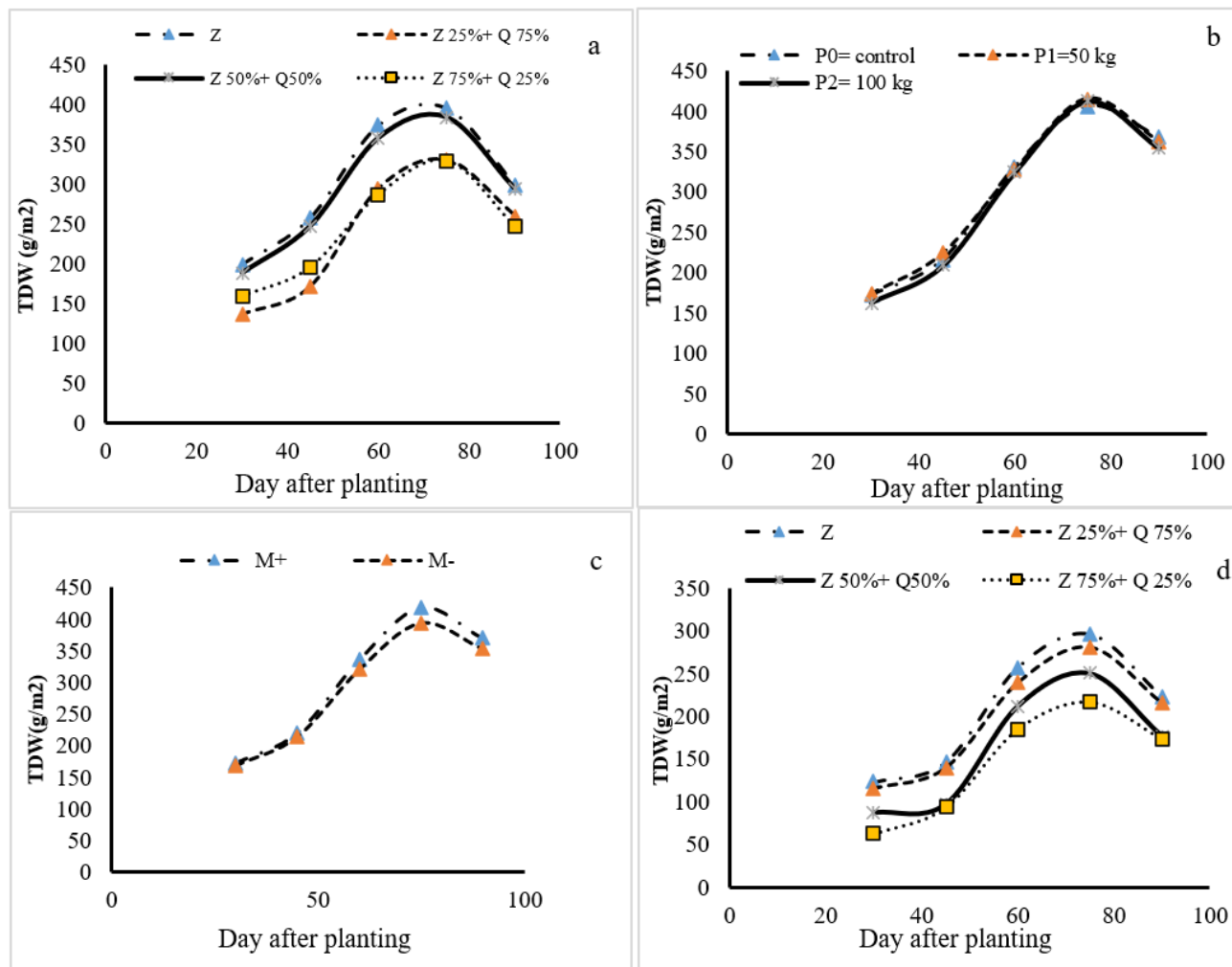


Figure 11

Effect of cropping ratio (a), phosphorus(b), mycorrhizal (c), on TDW in maize and cropping ratio in quinoa (d).

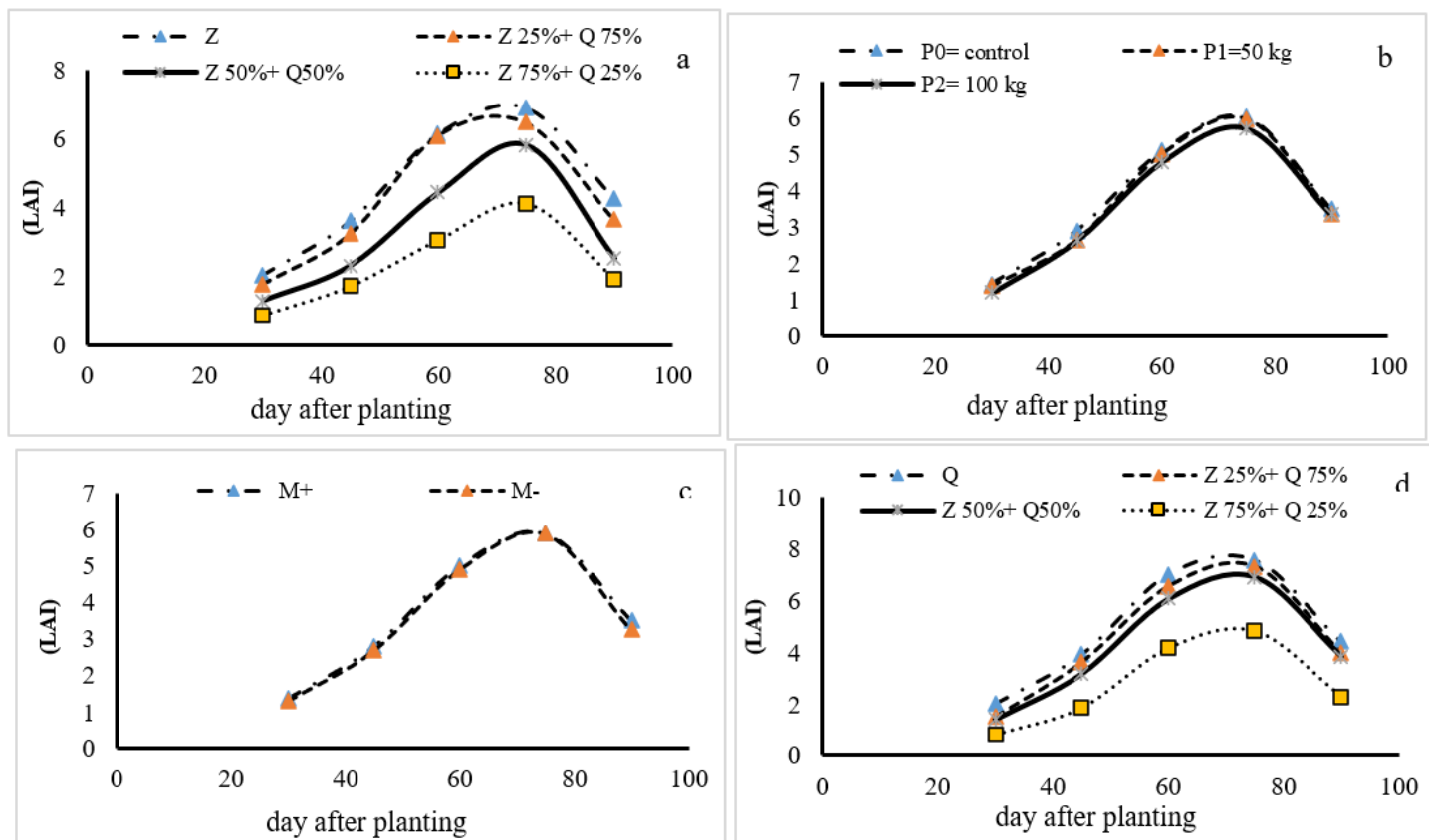


Figure 12

The values showed that the planting ratio had significant effects on the LAI calculated for the maize and quinoa plants.

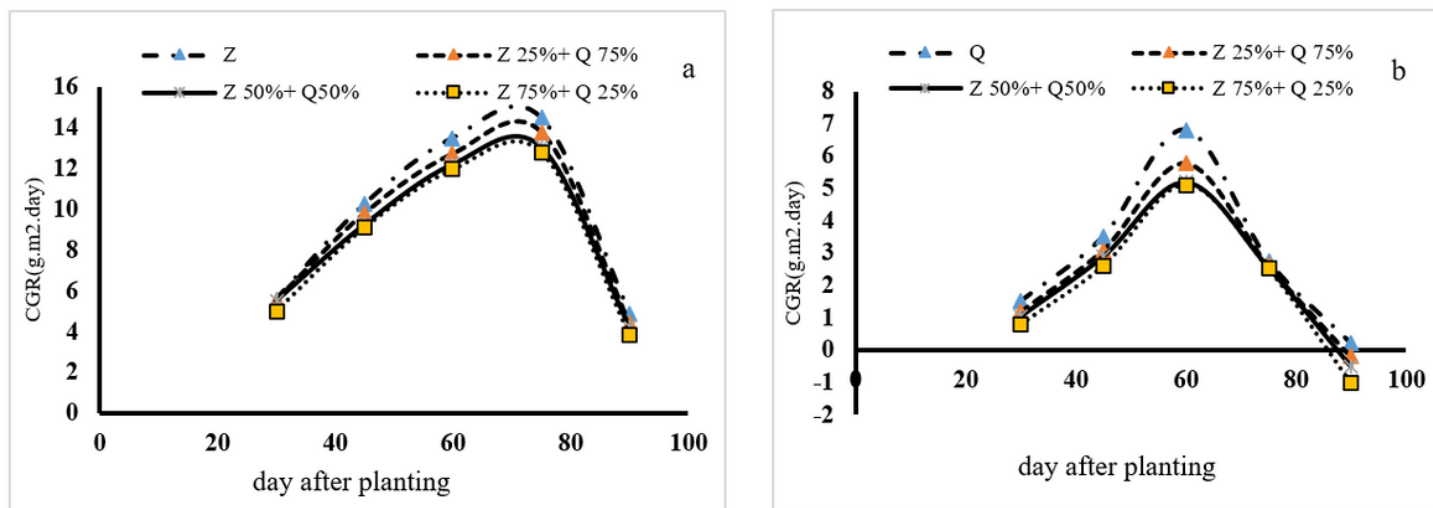


Figure 13

Effect of different intercropping ratios on the trend of changes in CGR, quinoa (a) and maize (b).

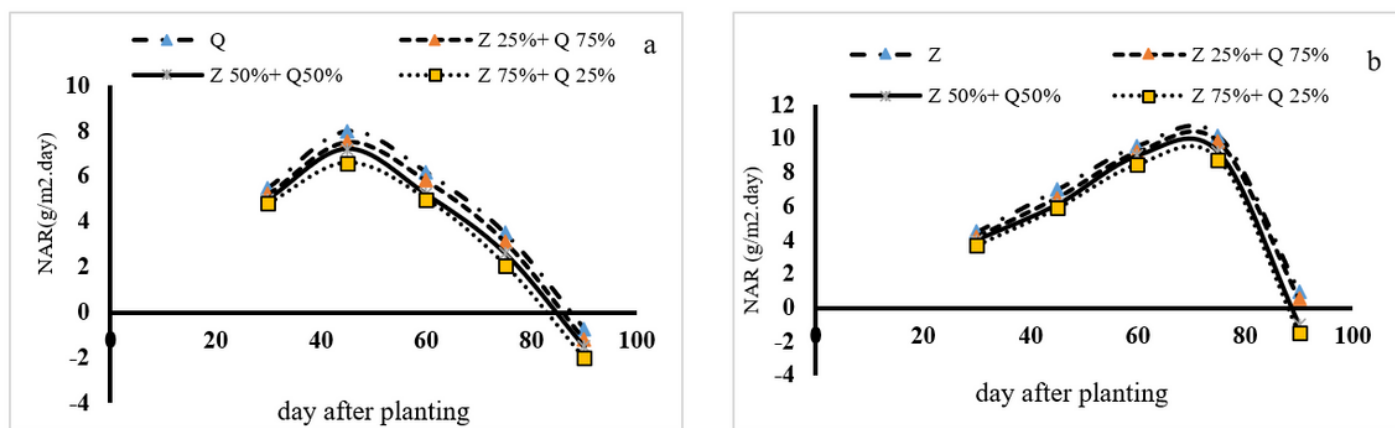


Figure 14

Effect of different intercropping ratios on the trend of changes in NAR , quinoa (a) and maize (b).

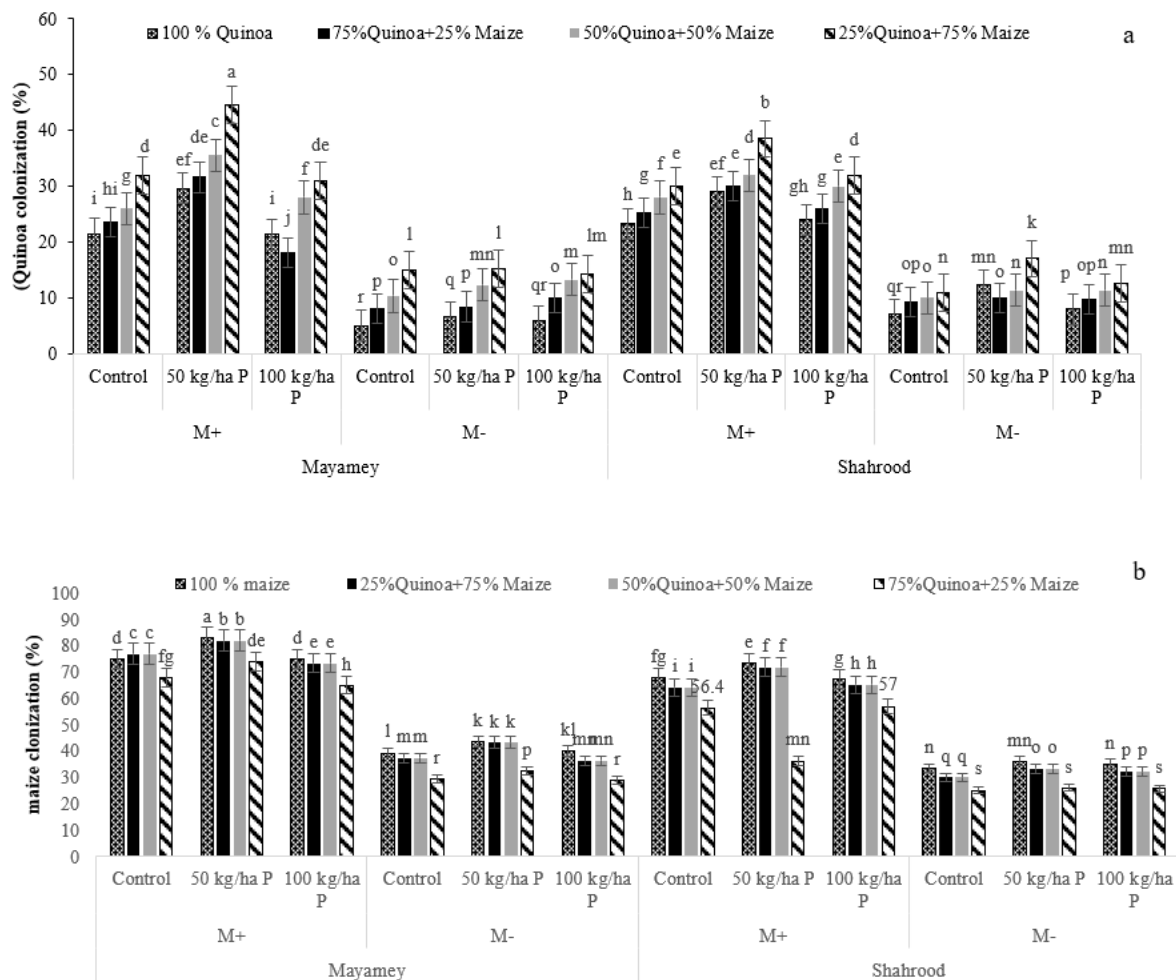


Figure 15

Effect of cropping ratio, phosphorus, mycorrhiza, and location on colonization percentage in quinoa (a) and maize (b)