



Evaluation of lentil (*Lens culinaris*) performance under different fertilizer application and irrigation regimes

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Abstract

Background and Objective: The scarcity of water resources in semi-arid regions necessitates the use of climate-smart methods like supplemental irrigation and soil amendments. This research aimed to investigate the effects of different fertilizers under both rainfed and supplemental irrigation conditions on the growth and yield of lentil in northwest Iran.

Methodology: A split-plot experiment was conducted with three replications under field conditions. The main factor was irrigation regimes, including rainfed (R) and supplemental irrigation (SI). SI was applied during the tillering, flowering, and seed setting stages. The subplots were allocated to various fertilizers: 1- no-fertilizer application (control), 2- the application of 100% of the recommended dose of three essential macronutrients (NPK₁₀₀), 3- the application of 50% of the recommended dose of NPK + 5 t ha⁻¹ of cattle farmyard manure (NPK₅₀+FYM₅), 4- the application of 50% of the suggested dose of NPK + biofertilizer (NPK₅₀+BI), 5- utilization of 10 t ha⁻¹ of FYM (FYM₁₀), and 6- the application of 20 t ha⁻¹ of FYM (FYM₂₀).

Main Results: SI significantly increased ($P < 0.05$) plant height (34.70 ± 3.03 cm), leaf greenness (48.45 ± 2.56 SPAD units), canopy width (20.58 ± 3.16 cm), biomass (0.97 ± 0.10 g), pod number (65.17 ± 5.51 pods per plant), and grain yield (7.59 ± 0.53 g) over the R conditions. The highest lateral and longitudinal canopy growth, as well as grain yield,

were obtained by the application of FYM₁₀, FYM₂₀, and NPK₁₀₀. The application of all doses of NPK fertilizer increased the leaf greenness (SPAD index). The highest grain yield was recorded with the application of FYM₂₀, NPK₁₀₀, and FYM₁₀ under SI conditions.

Conclusions: SI enhanced the efficacy of chemical fertilizers and cattle farmyard manure. Consequently, it is crucial to apply organic soil amendments and adhere to the suggested amounts of NPK, while also delivering three additional irrigations throughout the reproductive phases in the examined semi-arid agricultural zone.

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INTRODUCTION

One of the most important nutritious staple legumes in semi-arid regions is lentil (*Lens culinaris*), which is relatively well adapted to these areas (Noor *et al.*, 2024). Lentil is an annual, herbaceous, dwarf, self-pollinating plant and is the third most important food legume after chickpea and dry pea (Brummer *et al.*, 2015). Lentils have a relatively high content of protein and iron, and given their high nutritional value, they can play a significant role in ensuring food security for the growing population, especially in developing countries (Aghababaei *et al.*, 2024). This plant evolved about 8,500 years ago in the Mediterranean and Asia Minor regions, such as Syria and Türkiye (Montejano-Ramírez and Valencia-Cantero, 2024), and is also adapted to semi-arid climates such as Iran (Liber *et al.*, 2021). Canada is the largest producer of lentils, and countries such as India, the United States, Australia, Türkiye, Spain, and Italy are also major producers (FAO, 2023). The total harvested area of lentils in the world is 5.6 million ha, and lentil production in 2023 was 7.06 million t. Canada ranks first with 1.46 million ha of lentil cultivated area and 1.67 million t of grain production. In Iran, the lentil

cultivated area is about 131,000 ha, with 79,000 t of grain production (FAO, 2023).

The lentil root system can form a symbiotic relationship with Rhizobium bacteria (*Rhizobium leguminosarum*), thereby improving soil fertility. However, establishing a successful symbiotic relationship requires the presence of suitable strains and relatively favorable soil conditions (Singh and Singh, 2018). Some limiting factors, such as low annual rainfall, irregular precipitation distribution, low soil organic matter content, heavy soil textures, poor structure, high density, and soil salinity or alkalinity, can significantly restrict the formation of this symbiotic association (Ebrahimzadeh *et al.*, 2021). Many of these limitations are present in the semi-arid agro-zones of northwestern Iran. Therefore, increasing soil fertility through the use of organic soil amendments and providing the required nutrients for growth through chemical fertilizers appears necessary.

In the semi-cold regions of northwest Iran, lentils are planted in spring during March and April. Under these conditions, the reproductive period and the sensitive stages of grain yield component formation encounter high temperatures and very little rainfall

(Janmohammadi *et al.*, 2014a). Water shortage stress is a major limiting factor for grain legume production in semi-arid regions. Although some mitigating effects of drought stress on photosynthetic systems have been identified (Zhao *et al.*, 2020), comprehensive information about the impact of water shortage stress on the effectiveness of different fertilizers in lentil production systems is still lacking. Drought stress can also affect the nutritional status of plants by reducing root growth, disrupting nutrient absorption, and increasing oxidative stress (Khatun *et al.*, 2021). The application of organic amendments was found to mitigate the effects of drought stress by increasing the soil's water-holding capacity (Heydarzadeh *et al.*, 2021). Conversely, excessive nitrogen application under rainfed conditions may stimulate vegetative growth and increase soil moisture loss through transpiration, which can worsen soil water shortages during lentil reproductive growth (Quemada and Gabriel, 2016).

Climate change and severe water shortages in semi-arid regions have further emphasized the need for climate-smart irrigation techniques. Supplemental irrigation is a climate-smart technique, typically used in rain-fed agriculture, to supplement normal rainfall and increase or stabilize grain yields during periods of inadequate precipitation (Janmohammadi *et al.*, 2024a). In the supplemental irrigation method, water productivity is significantly higher compared to full irrigation (Martelli *et al.*, 2025). The present study hypothesized that the effectiveness of chemical fertilizers and farmyard manure (FYM) may vary under different moisture conditions. Some previous studies have observed the beneficial effects of FYM in semi-arid regions, but there is still limited information about replacing some chemical fertilizers with FYM and biological fertilizers and their effects on lentil performance. In such circumstances, applying climate-smart agronomic practices such as supplemental irrigation instead of full irrigation can be very effective

in saving water (Spalevic *et al.*, 2025). The present experiment aimed to study the morphological characteristics and grain yield of lentil under rainfed and supplemental irrigation conditions with the application of various chemical, organic, and biological fertilizers in the Hashtrud region of northwest Iran.

MATERIALS AND METHODS

Site Description

To evaluate the effects of supplemental irrigation (SI) and different fertilizers on lentil performance, a field trial was conducted during the 2023–2024 cropping season. Soil preparation and farmyard manure (FYM) application were completed in 2023, with lentil planting taking place in 2024. The field was situated in the semi-mountainous and elevated region of Hashtrud, East Azerbaijan, Iran (46°54'E; 37°32'N; 1,802 m altitude). The previous crop grown in the field was bread wheat under rainfed conditions. The field remained uncultivated (fallow) during the fall and winter of 2023. The soil texture was silty clay loam with an electric conductivity (EC) of 0.85 dS m⁻¹, pH of 7.79, absorbable phosphorous (P) at 6.8 ppm, potassium (K) at 283 mg kg⁻¹, total nitrogen (N) at 0.08%, iron (Fe) at 1.01 ppm, zinc (Zn) at 0.44 ppm, manganese (Mn) at 1.07 ppm, and organic carbon content 0.64%. The mean annual temperature was 12°C, with an average maximum temperature of 22.3°C, an average minimum temperature of 4.5°C, and an average annual precipitation of 337 mm.

Experimental Treatments

The experiment utilized a split-plot randomized complete block design with three replicates. The main plots were assigned to different irrigation regimes, including rainfed (R) and supplemental irrigation (SI: applied three times during tillering, flowering, and seed setting). The subplots consisted of 6 fertilizer treatments: 1) no fertilizer application (0 or control), 2) NPK₁₀₀: application of 100% of the recommended

amounts of nitrogen, phosphorus, and potassium, 3) $\text{NPK}_{50} + \text{FYM}_5$: application of 50% of the recommended amounts of NPK along with 5 t ha⁻¹ cattle farmyard manure (FYM), 4) $\text{NPK}_{50} + \text{BI}$: application of 50% of the recommended amounts of NPK along with bacterial inoculation of seeds using phosphate-solubilizing and nitrogen-fixing bacteria (*Pantoea agglomerans* and *Azotobacter vinelandii*; 10⁶ colony forming units per gram, through seed inoculation before planting), 5) FYM_{10} : utilization of 10 t ha⁻¹ FYM, and 6) FYM_{20} : application of 20 t ha⁻¹ FYM.

Tillage and Planting

The size of each experimental plot was 20 m², 5 m long, and 4 m wide. After plotting and defining the boundaries of the main and subplots, manure was applied to the area of the plots about one month before planting and mixed with the topsoil to a depth of 10 cm using a shovel. Primary tillage was performed with a moldboard plow in October, and secondary tillage was conducted by disk and tooth harrow in February. For the final tillage, the soil was furrowed with a furrower, and then seeds were sown on the ridge with a height of 15 cm. The distance between two adjacent ridges and intra-row spacing was 30 cm and 5 cm, respectively. Seeds were sown on March 8th. For bacterial seed inoculation (BI), after soaking seeds in distilled water, the bacteria were applied to the seed surface, allowed to dry, and then were planted immediately at a depth of 4 cm. For NPK applications, all amounts of phosphorus and potassium fertilizers were placed in deep banding below the planting row, 3 cm under the seed sowing depth. For the NPK_{100} treatment, 80 kg ha⁻¹ of nitrogen through urea fertilizer, 60 kg ha⁻¹ of phosphorus through triple superphosphate fertilizer, and 40 kg ha⁻¹ of potassium through potassium sulfate were applied. The farmyard manure contained 61.1% organic matter, 2.34% nitrogen, 1.94% potassium, 1.48% calcium, 0.63% sulfur, 0.41% magnesium, with a pH 7.69 and an EC 11.62 dS m⁻¹. Supplementary

water was applied using gravity through furrows (channels) that run between raised ridges where crops are planted. The irrigation height in supplementary irrigation was 80, 100, and 110 mm. Irrigation water was supplied through polyethylene pipes from a deep well equipped with a volumetric water meter. Weed control was carried out three times at ten-day intervals by hand weeding. No pests or diseases were observed during the growth period.

Evaluation of Vegetative Traits and Yield Components

During the seed setting stage, leaf greenness (SPAD index) was measured by using a portable SPAD-502Plus device (Konica Minolta, Osaka, Japan) on the upper leaves. Canopy width (CW), which represents the lateral branch spread from the left to the right of the plant, was measured at the end of the podding stage using a ruler. At the end of the growing season, when the vegetative parts of the plant dried up and the pods turned light brown, quadrats (1 m²) were randomly placed multiple times within the target area, and the plants within them were recorded. Plant height (PH) was measured in meters from the ground to the highest point on the stem. After harvesting the plants, they were dried in an electric oven at 60°C for 72 hours. Biomass and yield components such as pod number per plant (PNP), number of grains per pod (NGP), and grain yield per plant (GYP) were then measured. Harvest index (HI) was determined by calculating the ratio of economic yield to total biomass. A near-infrared whole grain analyzer (Zeltex-800, Germany) was used to measure the grain protein content.

Statistical Methods

Before conducting the analysis of variance, the normality of the data distribution was examined using Minitab software. ANOVA was performed using SAS. Mean comparison was conducted using the post hoc test (Least Significant Difference; alpha = 0.05).

Boxplots were created using SPSS, and principal component analysis was carried out using the Minitab package.

RESULTS AND DISCUSSION

Vegetative Traits

The results of the analysis of variance indicated that the main effects of irrigation and fertilizer application ($P < 0.01$) were significant for plant height. Supplemental irrigation increased plant height by 1.76 times compared to rainfed conditions. The tallest plants were obtained under supplemental irrigation conditions with the application of FYM₂₀ and FYM₁₀ (37.1 ± 2.00 and 36.9 ± 1.50 cm). Although all fertilizers significantly increased plant height compared to the control, the tallest plants were recorded under FYM₂₀ (30.5 ± 7.36 cm) and FYM₁₀ (29.8 ± 7.89 cm) conditions. The significant effect of manure application can be attributed to the improvement of poor soil physical and chemical conditions (Table 1). Among fertilizers, the least positive effect on plant height was achieved through the combined use of chemical and biological fertilizers. The increase in plant height with the application of fertilizers can be attributed to the provision of required elements for growth and improvement of soil conditions. Often, fertilizer application increases height by affecting the biosynthesis or accumulation of phytohormones, especially auxin, which promotes cell elongation (Jan *et al.*, 2022).

Leaf greenness (SPAD index) measurements showed that the effects of $I \times F$ on this component were not significant ($P = 0.585$). Application of NPK₁₀₀ (45.4 ± 4.90 SPAD units) and combined application of NPK₅₀+FYM₅ (46.6 ± 6.35 SPAD units) significantly increased leaf greenness compared to the control (40.6 ± 6.21 SPAD units). However, the effects of fertilizer largely depended on soil moisture status. Fertilizer effects were more evident under SI conditions. Application of NPK₁₀₀ had little effect on leaf greenness under rainfed conditions. Nitrogen, as a key component

of chlorophyll structure, can affect leaf greenness. The results showed that the use of nitrogen fertilizers under optimal moisture conditions increases chlorophyll. Drought stress conditions appear to stimulate chlorophyll degradation or inhibit its biosynthesis (Fathi, 2022). Evaluation of the effects of irrigation and fertilizer treatments on canopy width showed that the effects of $I \times F$ were significant for this trait ($P = 0.015$). Under moisture-imitted conditions (Rainfed), application of NPK₁₀₀ (17.1 ± 0.54 cm) increased canopy width by about 35% compared to the control (12.8 ± 0.65 cm). Although all fertilizer treatments increased canopy width compared to the control under rainfed conditions, the highest canopy width was obtained with the application of NPK₁₀₀ (20.1 ± 3.58 cm), FYM₁₀ (19.9 ± 4.17 cm), and FYM₂₀ (18.6 ± 3.54 cm). This trend was similar under SI conditions. The combined use of NPK₅₀+BI under SI conditions increased canopy width by only 24% (Figure 1). Canopy width is a suitable indicator for evaluating plant vegetative growth, which is influenced by nutritional status, soil conditions, moisture supply, and climate. Greater canopy growth, by providing a larger photosynthesizing surface, can also affect the supply of photoassimilates and yield. In this experiment, soil amendment with relatively high amounts of FYM or high levels of nitrogen application improved plant lateral growth (He *et al.*, 2024).

Evaluation of plant biomass showed that the main effects of irrigation and fertilizer on this component were significant ($P < 0.01$). Supplemental irrigation increased plant biomass by 41% compared to rainfed conditions. The interaction effect of irrigation and fertilizer ($I \times F$) was significant for grain yield ($P = 0.023$). The highest grain yield was recorded under SI+FYM₂₀, SI+NPK₁₀₀, and SI+FYM₁₀ conditions. The lowest grain yield was observed under R+0 and R+NPK₅₀+BI conditions. Assessment of grain yield per plant showed that under rainfed conditions, the use of NPK₁₀₀, FYM₂₀, and FYM₁₀ significantly increased this trait

Table 1 The mean comparison of growth characteristics of lentil under various fertilizer applications and different soil moisture regimes

Effect	Plant height (cm)	Leaf greenness (SPAD unit)	Plant dry matter (g)
Irrigation (I)			
R	19.68 ± 2.90 ^b	39.95 ± 2.86 ^b	0.68 ± 0.06 ^b
SI	34.70 ± 3.03 ^a	48.45 ± 2.56 ^a	0.97 ± 0.10 ^a
P-value	0.0007	0.0025	0.0052
Fertilizer (F)			
0	23.2 ± 7.16 ^c	40.6 ± 6.21 ^d	0.76 ± 0.15 ^{cd}
NPK ₁₀₀	27.0 ± 9.37 ^b	45.4 ± 4.90 ^{ab}	0.92 ± 0.19 ^a
NPK ₅₀ +FYM ₅	26.7 ± 9.65 ^b	46.6 ± 6.35 ^a	0.81 ± 0.18 ^{bc}
NPK ₅₀ +BI	25.8 ± 8.64 ^b	43.3 ± 4.22 ^c	0.75 ± 0.12 ^d
FYM ₁₀	29.8 ± 7.89 ^a	44.3 ± 3.49 ^{bc}	0.82 ± 0.14 ^b
FYM ₂₀	30.5 ± 7.36 ^a	45.0 ± 4.55 ^{abc}	0.89 ± 0.19 ^a
P-value	<0.0001	<0.0001	<0.0001
I × F			
R+0	16.9 ± 1.48	35.0 ± 1.51	0.62 ± 0.06
R+NPK ₁₀₀	18.6 ± 1.05	41.1 ± 1.35	0.75 ± 0.05
R+NPK ₅₀ +FYM ₅	18.0 ± 1.55	41.3 ± 1.41	0.66 ± 0.02
R+NPK ₅₀ +BI	18.0 ± 1.11	39.5 ± 0.95	0.65 ± 0.04
R+FYM ₁₀	22.7 ± 1.54	41.4 ± 2.06	0.70 ± 0.02
R+FYM ₂₀	23.9 ± 0.55	41.3 ± 3.25	0.72 ± 0.03
SI+0	29.6 ± 2.43	46.1 ± 1.35	0.89 ± 0.03
SI+NPK ₁₀₀	35.5 ± 1.65	49.8 ± 1.36	1.08 ± 0.04
SI+NPK ₅₀ +FYM ₅	35.4 ± 1.87	51.9 ± 3.82	0.97 ± 0.09
SI+NPK ₅₀ +BI	33.7 ± 0.99	47.0 ± 1.31	0.85 ± 0.03
SI+FYM ₁₀	36.9 ± 1.50	47.2 ± 0.95	0.95 ± 0.06
SI+FYM ₂₀	37.1 ± 2.00	48.7 ± 0.72	1.06 ± 0.05
P-value	0.056	0.585	0.141
CV (%)	5.47	3.51	5.81

Note: R = rainfed condition, SI = supplemental irrigation, 0 = no fertilizer application (control), NPK₁₀₀ = 100% of the suggested dose of chemical fertilizer containing nitrogen, phosphorus, and potassium, NPK₅₀+FYM₅ = 50% of the suggested dose of NPK and application of 5 t ha⁻¹ of cattle farmyard manure, NPK₅₀+BI = application of 50% of the suggested dose of NPK and bacterial inoculation of seeds with biofertilizer at the planting stage, FYM₁₀ = the use of 10 t ha⁻¹ of cattle farmyard manure, FYM₂₀ = the application of 20 t ha⁻¹ of cattle farmyard manure, CV = coefficient of variation. Means within the same column followed by different superscript letters (a, b, c) are significantly different at P < 0.05. Values are presented as mean ± standard deviation.

compared to the control. The combined use of NPK_{50} +BI had only a slight effect on grain yield compared to the control. Under SI conditions, the use of FYM_{20} , FYM_{10} , and NPK_{100} resulted in the highest grain yield. These fertilizers increased grain yield by 17–20% compared to the control (Figure 2). Supplemental irrigation alone increased grain yield by 79% compared to rainfed conditions. Additionally, the application of supplementary irrigation enhanced the positive effects of chemical and organic fertilizers on grain yield

significantly. Among the fertilizers tested, FYM_{20} , NPK_{100} , and FYM_{10} showed the highest grain yield. Our findings suggest that the application of manure or high levels of NPK can serve as a basis for improving grain yield by promoting vegetative growth. Increased vegetative growth and biomass in lentil crops can potentially lead to higher grain yield, as larger plants have more resources for photosynthesis and, ultimately, for developing more pods and seeds (Lake and Sadras, 2021).

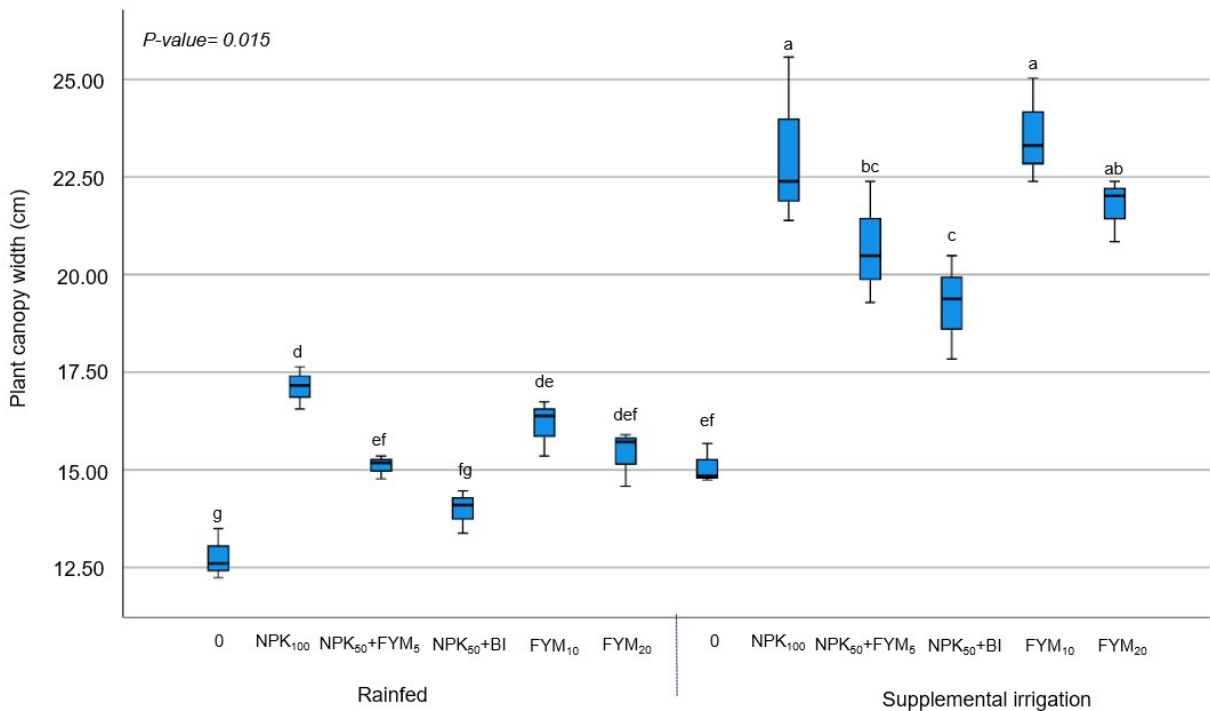


Figure 1 Evaluation of lentil canopy width under different irrigation regimes and application of different chemical, organic, and biological fertilizers in the northwestern region of Iran. 0 = no fertilizer application (control), NPK_{100} = 100% of the suggested dose of chemical fertilizer containing nitrogen, phosphorus, and potassium, $\text{NPK}_{50}+\text{FYM}_5$ = 50% of the suggested dose of NPK and application of 5 t ha⁻¹ of cattle farmyard manure, $\text{NPK}_{50}+\text{BI}$ = application of 50% of the suggested dose of NPK and bacterial inoculation of seeds with biofertilizer at the planting stage, FYM_{10} = the use of 10 t ha⁻¹ of cattle farmyard manure, FYM_{20} = the application of 20 t ha⁻¹ of cattle farmyard manure. Different letters (a, b, c, d, e, f) on the boxes indicate statistically significant differences at $P < 0.05$.

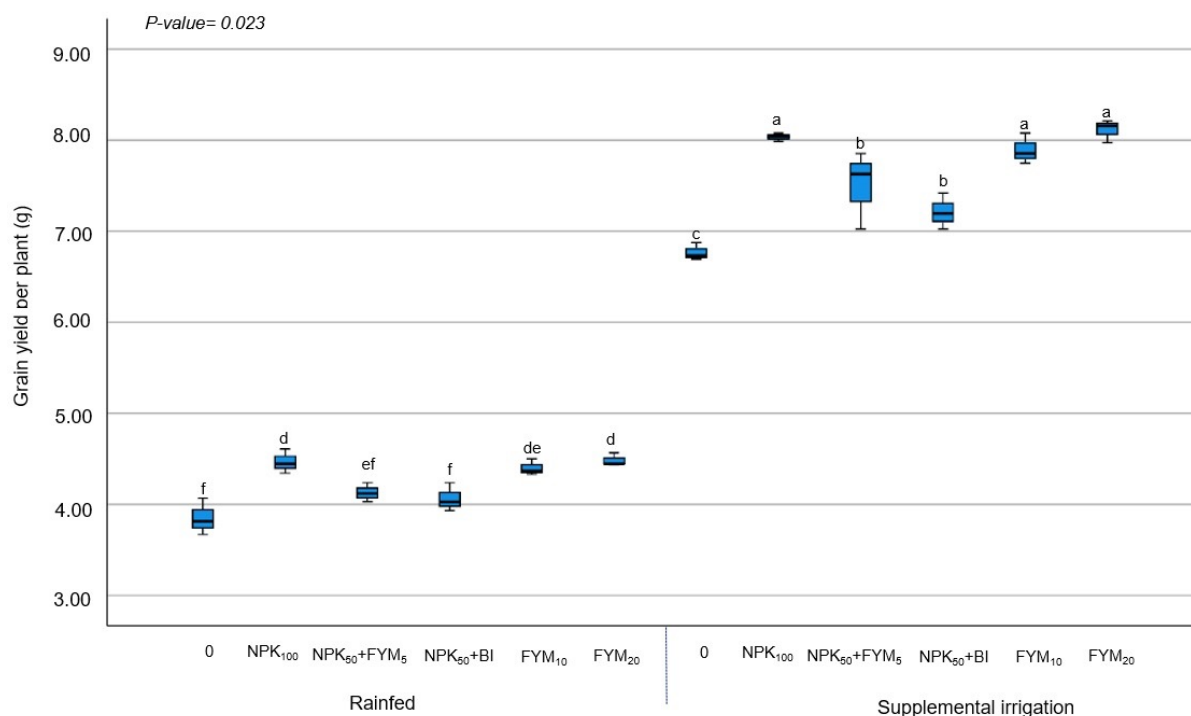


Figure 2 Evaluation of lentil grain yield under rainfed and supplemental irrigation conditions with the application of various chemical and organic fertilizers. 0 = no fertilizer application (control), NPK₁₀₀ = 100% of the suggested dose of chemical fertilizer containing nitrogen, phosphorus, and potassium, NPK₅₀+FYM₅ = 50% of the suggested dose of NPK and application of 5 t ha⁻¹ of cattle farmyard manure, NPK₅₀+BI = application of 50% of the suggested dose of NPK and bacterial inoculation of seeds with biofertilizer at the planting stage, FYM₁₀ = the use of 10 t ha⁻¹ of cattle farmyard manure, FYM₂₀ = the application of 20 t ha⁻¹ of cattle farmyard manure. Different letters (a, b, c, d, e, f) on the boxes indicate statistically significant differences at $P < 0.05$.

Grain Yield Components

The interaction effects of $I \times F$ on pod number per plant (PNP) were statistically significant ($P < 0.01$). The highest PNP was obtained in plants grown under SI conditions with the use of NPK₅₀+FYM₅, FYM₁₀, FYM₂₀, and NPK₁₀₀. The use of SI increased the PNP by 67% compared to rainfed conditions (38.72 ± 4.29 pods per plant). The mean comparison of PNP between fertilizer levels indicated that the effect of animal manure was more evident. The interaction effects of $I \times F$ on the grain number per plant (GNP) were also significant ($P < 0.05$). Under SI conditions, all fertilizers significantly increased GNP compared to the control; however, no significant difference was

observed between different chemical, organic, and biological fertilizers. Fertilizer applications increased the GNP by about 20% compared to the control under SI conditions (Table 2).

SI increased the harvest index by 5% compared to the rainfed condition (Table 2). The application of NPK₅₀+FYM₅, FYM₁₀, FYM₂₀, and NPK₁₀₀ produced the highest harvest index under SI conditions. However, under rainfed conditions, the highest harvest index was obtained with FYM₁₀ and FYM₂₀. The application of NPK under rainfed conditions did not increase the harvest index. Measurement of grain protein content showed that plants grown under rainfed conditions contained higher amounts of protein ($25.05 \pm 1.07\%$)

Table 2 The effect of various fertilizers and different soil moisture regimes on grain yield components of lentil

Effect	Pod number per plant	Grain number per plant	Harvest index (%)
Irrigation (I)			
R	38.72 ± 4.29 ^b	39.69 ± 3.25 ^b	17.29 ± 1.10 ^b
SI	65.17 ± 5.51 ^a	63.96 ± 6.29 ^a	23.29 ± 1.40 ^a
P-value	0.0026	0.0042	0.0062
Fertilizer (F)			
0	44.0 ± 13.28 ^d	45.0 ± 9.77 ^c	18.8 ± 3.06 ^c
NPK ₁₀₀	53.3 ± 14.96 ^b	53.2 ± 13.15 ^{ab}	20.4 ± 3.36 ^{ab}
NPK ₅₀ +FYM ₅	52.7 ± 18.04 ^b	53.3 ± 17.24 ^{ab}	20.4 ± 4.63 ^b
NPK ₅₀ +BI	49.8 ± 13.24 ^c	50.5 ± 14.61 ^b	19.6 ± 2.74 ^c
FYM ₁₀	56.8 ± 13.40 ^a	56.0 ± 13.90 ^a	21.3 ± 3.20 ^a
FYM ₂₀	55.1 ± 14.79 ^a	53.0 ± 13.12 ^{ab}	21.2 ± 3.20 ^a
P-value	<0.0001	<0.0001	<0.0001
I × F			
R+0	32.1 ± 1.32 ^h	36.5 ± 0.90 ^d	16.1 ± 0.57 ^e
R+NPK ₁₀₀	39.8 ± 1.36 ^{ef}	41.2 ± 0.70 ^{cd}	17.5 ± 0.75 ^{cd}
R+NPK ₅₀ +FYM ₅	36.3 ± 1.15 ^g	38.2 ± 1.11 ^d	16.3 ± 0.26 ^{de}
R+NPK ₅₀ +BI	37.8 ± 1.21 ^{gf}	37.3 ± 2.37 ^d	17.1 ± 0.09 ^{de}
R+FYM ₁₀	44.8 ± 1.36 ^d	43.7 ± 4.71 ^c	18.4 ± 0.83 ^c
R+FYM ₂₀	41.7 ± 1.39 ^e	41.3 ± 1.00 ^{cd}	18.4 ± 1.06 ^c
SI+0	55.9 ± 3.77 ^c	53.5 ± 4.51 ^b	21.6 ± 0.47 ^b
SI+NPK ₁₀₀	66.8 ± 3.12 ^a	65.1 ± 1.90 ^a	23.4 ± 0.99 ^a
SI+NPK ₅₀ +FYM ₅	69.1 ± 2.32 ^a	68.4 ± 7.80 ^a	24.4 ± 2.03 ^a
SI+NPK ₅₀ +BI	61.8 ± 2.25 ^b	63.6 ± 2.50 ^a	22.1 ± 0.67 ^b
SI+FYM ₁₀	68.9 ± 3.16 ^a	68.3 ± 2.69 ^a	24.2 ± 0.23 ^a
SI+FYM ₂₀	68.6 ± 0.89 ^a	64.8 ± 3.76 ^a	24.1 ± 0.23 ^a
P-value	0.0002	0.0254	0.0226
CV (%)	2.47	5.59	3.51

Note: R = rainfed condition, SI = supplemental irrigation, 0 = no fertilizer application (control), NPK₁₀₀ = 100% of the suggested dose of chemical fertilizer containing nitrogen, phosphorus, and potassium, NPK₅₀+FYM₅ = 50% of the suggested dose of NPK and application of 5 t ha⁻¹ of cattle farmyard manure, NPK₅₀+BI = application of 50% of the suggested dose of NPK and bacterial inoculation of seeds with biofertilizer at the planting stage, FYM₁₀ = the use of 10 t ha⁻¹ of cattle farmyard manure, FYM₂₀ = the application of 20 t ha⁻¹ of cattle farmyard manure, CV = coefficient of variation. Means within the same column followed by different superscript letters (a, b, c) are significantly different at P < 0.05. Values are presented as mean ± standard deviation.

compared to SI conditions (23.58 ± 0.75%). The highest grain protein content was recorded under rainfed+NPK₁₀₀ conditions (26.7 ± 0.39%), and the lowest protein content was recorded under SI conditions

without fertilizer (22.7 ± 0.36%). The application of NPK₁₀₀ under SI conditions caused a significant increase in grain protein content compared to the control. However, the effect of chemical fertilizers

on protein content was more evident under rainfed conditions. Under SI conditions, in addition to NPK, the use of FYM₁₀ and FYM₂₀ also caused a significant increase in grain protein content (Figure 3). The results showed that the allocation of photoassimilate resources to vegetative parts or economic organs (grain yield) strongly responds to moisture and nutritional status.

Although plants under drought stress conditions allocate most of their photosynthetic resources to reproductive organs for survival, the volume of photosynthetic resources is very low compared to optimal moisture conditions (Noor *et al.*, 2024). Therefore, even drought stress could not significantly increase the harvest index.

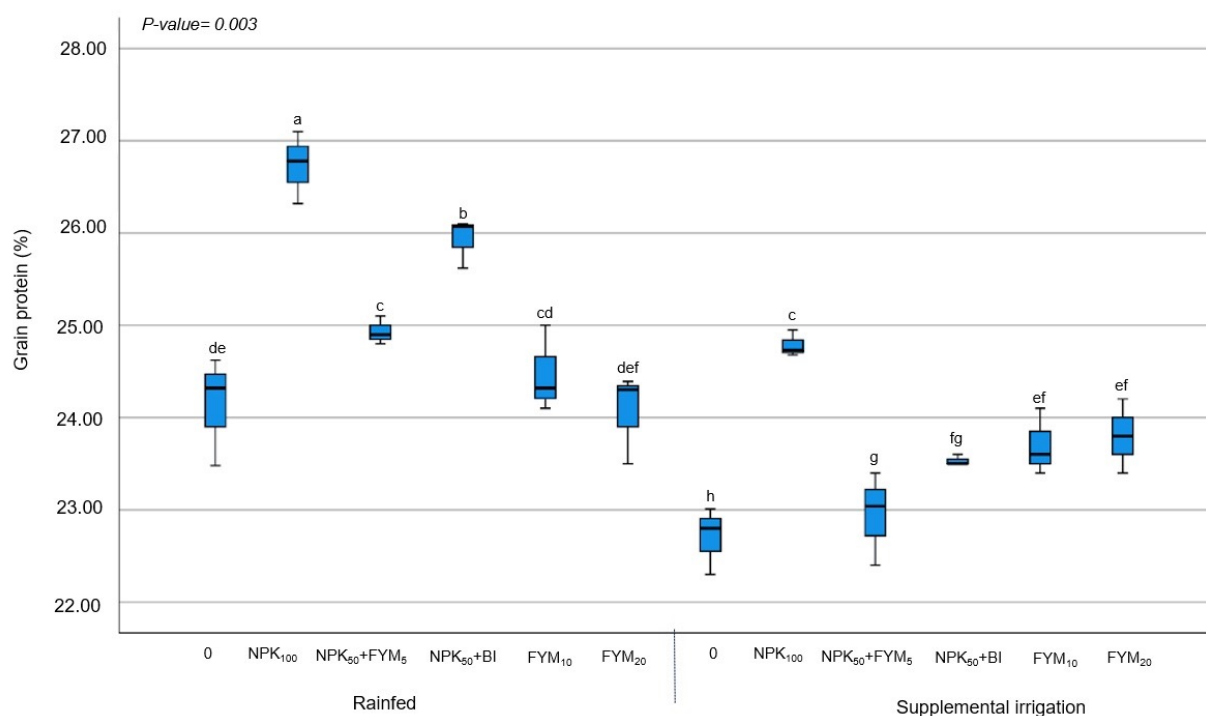


Figure 3 Evaluation of lentil seed protein percentage under rainfed and supplemental irrigation conditions with the application of various chemical and organic fertilizers. 0 = no fertilizer application (control), NPK₁₀₀ = 100% of the suggested dose of chemical fertilizer containing nitrogen, phosphorus, and potassium, NPK₅₀+FYM₅ = 50% of the suggested dose of NPK and application of 5 t ha⁻¹ of cattle farmyard manure, NPK₅₀+BI = application of 50% of the suggested dose of NPK and bacterial inoculation of seeds with biofertilizer at the planting stage, FYM₁₀ = the use of 10 t ha⁻¹ of cattle farmyard manure, FYM₂₀ = the application of 20 t ha⁻¹ of cattle farmyard manure. Different letters (a, b, c, d, e, f) on the boxes indicate statistically significant differences at $P < 0.05$.

Principal Component Analysis and Clustering

Principal component analysis (PCA) is a linear dimensionality reduction technique that has been used to simplify large volumes of data and to draw conclusions about the superiority of treatments

and their effects on traits. The first component in the PCA plot distinguished the irrigation levels. The second component also distinguished effective fertilizer treatments from less effective ones. Treatment combinations such as SI+NPK₁₀₀, SI+FYM₁₀, and

SI+FYM₂₀ showed the highest values for vegetative traits and yield components (Figure 4). Correlation analysis based on the angles between the evaluated traits showed a positive and significant correlation among leaf greenness, number of pods, number of seeds per plant, and grain yield. However, grain yield and grain protein content had an angle of 90°, indicating no significant correlation between them.

PCA showed that the effectiveness of fertilizer treatments depends largely on soil moisture status, and different fertilizer guidelines should be considered for rainfed and supplemental irrigation systems. Under rainfed conditions, high levels of FYM application appear necessary due to the importance of soil moisture storage. These findings are consistent with the results of Heydarzadeh *et al.* (2021).

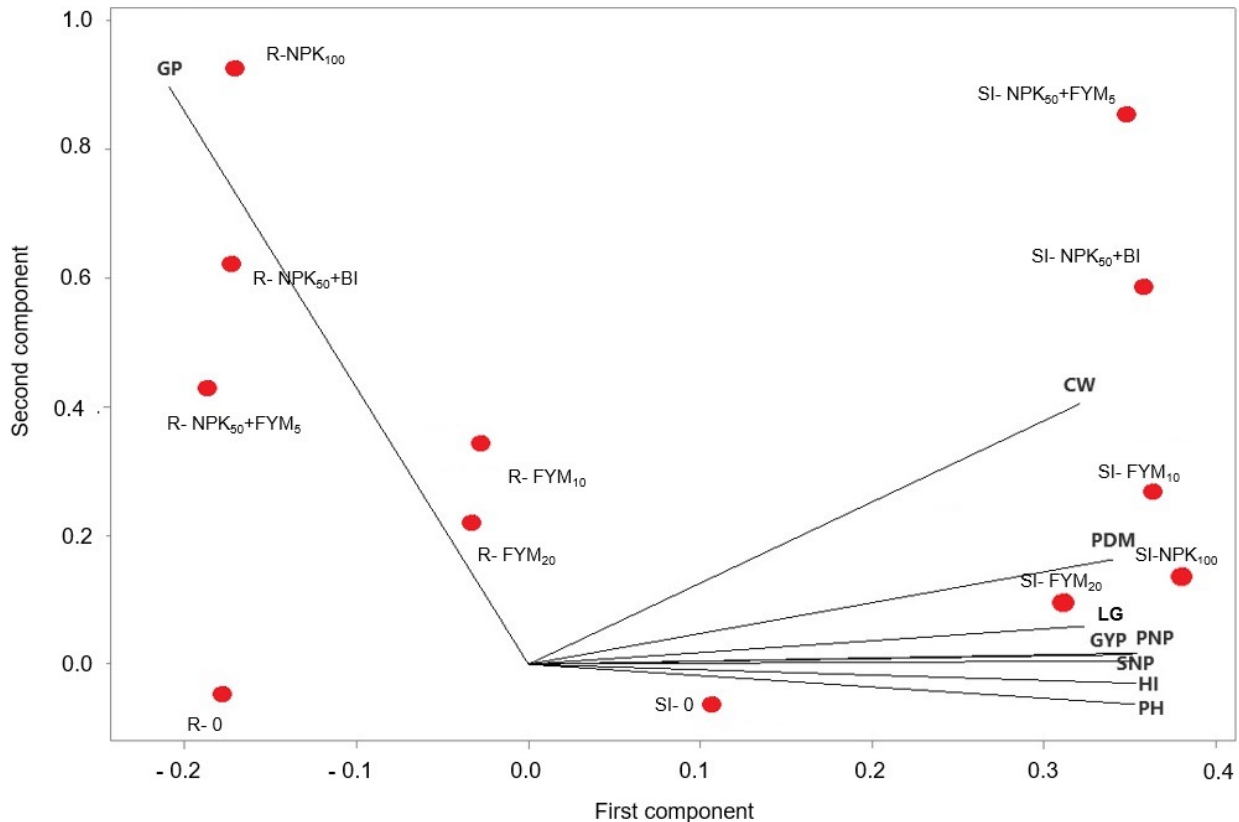


Figure 4 PCA biplot to display the spatial distribution of combined treatments and agronomic and morphological traits evaluated in lentils under different irrigation conditions and different fertilizer applications. R = rainfed condition, SI = supplemental irrigation, 0 = no fertilizer application (control), NPK₁₀₀ = 100% of the suggested dose of chemical fertilizer containing nitrogen, phosphorus, and potassium, NPK₅₀+FYM₅ = 50% of the suggested dose of NPK and application of 5 t ha⁻¹ of cattle farmyard manure, NPK₅₀+BI = application of 50% of the suggested dose of NPK and bacterial inoculation of seeds with biofertilizer at the planting stage, FYM₁₀ = the use of 10 t ha⁻¹ of cattle farmyard manure, FYM₂₀ = the application of 20 t ha⁻¹ of cattle farmyard manure, GP = grain protein content, GYP = grain yield per plant, CW = canopy width, PH = plant height, LG = leaf greenness, PDM = plant dry matter, PNP = pod number per plant, GNP = grain number per plant, HI = harvest index.

Annual precipitation at the investigated site was 337 mm, with only 57% of this occurring during the lentil growing season. However, estimated evapotranspiration during the warm season was 550 mm. These data indicate that rainfed crops may experience significant water shortages. The application of 270 mm of supplemental irrigation during the vegetative growth (stem elongation) and reproductive stages (flowering and seed setting) led to notable improvements in all vegetative traits and grain yield components compared to rainfed conditions. Supplemental irrigation increased canopy length and width compared to rainfed conditions. However, the soil in semi-arid regions is characterized by low organic matter and unavailable nutrients due to climatic constraints, low vegetation cover, excessive grazing, and lack of residue return. Therefore, it appears that any soil amendment and provision of the minimum moisture required for plant growth can have a positive impact.

Cluster analysis divided the treatment combinations into four categories (Figure 5). Cluster 1 included combined treatments with little positive effect, especially in rainfed conditions. The lowest performance was recorded under no fertilizer application in rainfed conditions. Additionally, the applications of $\text{NPK}_{50} + \text{BI}$ and FYM_{10} had little effect on growth or grain yield under rainfed conditions. Janmohammadi *et al.* (2014b) reported that the optimal efficiency of biofertilizer cannot be achieved under water scarcity conditions. The use of large amounts of nitrogen (NPK_{100}) also did not have much success in improving yield components under rainfed conditions, possibly due to increased transpiration and soil moisture loss. Cluster 2 involved the use of moderate and relatively high amounts of manure under rainfed conditions, which had a greater impact on growth and grain yield components compared to other combined treatments. Cluster 3 included the least effective combined treatments under SI conditions ($\text{SI} + 0$, $\text{SI} + \text{NPK}_{50} + \text{BI}$).

Cluster 4 comprised the most effective treatments that resulted in the highest growth and grain yield. The use of NPK_{100} , FYM_{10} , and FYM_{20} under SI conditions resulted in the highest amount of vegetative and reproductive growth. Although our findings indicated a negligible effect of biofertilizers under rainfed conditions, Heydarzadeh *et al.* (2023) reported positive effects of bacterial inoculation on yield improvement. This difference could be due to the type, strain, bacterial density, and soil and climatic conditions.

Almost all fertilizers significantly increased the evaluated traits compared to the control. Among the fertilizers tested, the combined application of $\text{NPK}_{50} + \text{BI}$ showed the least positive effects. Because biological fertilizers contain living organisms, soil conditions must be suitable for the survival of the bacteria they contain. Additionally, the bacterial strains must be adapted to the environmental conditions of semi-arid regions. High pH, low organic matter content, high soil density, limited root expansion, low water retention capacity, and unfavorable climatic conditions appear to have limited the positive effects of biological fertilizers. Similarly, Ryan *et al.* (2012) reported that bacteria and fungi in biofertilizers face serious limitations in semi-arid regions. Among the fertilizers tested, the most positive effects were observed with NPK_{100} , FYM_{10} , and FYM_{20} . Fertilizer efficiency was significantly affected by soil moisture conditions. Organic fertilizers (FYM) showed a clear advantage over NPK under rainfed conditions. This may be due to the effect of nitrogen in stimulating vegetative growth and increasing the loss of stored soil moisture (Janmohammadi *et al.*, 2024b).

Under rainfed conditions, leaf senescence occurs earlier due to greater moisture limitations. Leaf proteins are broken down into amino acid components, which can then be translocated to the growing seeds through the remobilization process and used for the biosynthesis of new proteins in the seed. The effect of FYM_{10} and FYM_{20} on growth and yield components

was greater than that of other fertilizers under rainfed conditions. It appears that the application of FYM and increasing soil organic matter can improve soil permeability and improve soil moisture content by reducing runoff. Our previous findings were consistent with the results of the present experiment, confirming that FYM application in the semi-arid climates of northwestern Iran improved plant growth under water shortage stress (Janmohammadi *et al.*, 2022; 2024c). Under SI conditions, the use of NPK₁₀₀, NPK₅₀+FYM₅, FYM₁₀, and FYM₂₀ was found to be the most effective for enhancing growth and components of grain yield.

The findings indicated that supplying 270 mm of water through SI not only promoted vegetative and reproductive growth but also enhanced the distribution of photo-assimilates to economically important reproductive organs, leading to a significant increase in the harvest index. The highest harvest index recorded in this experiment was achieved with the application of NPK₁₀₀, FYM₁₀, and FYM₂₀. Implementing suitable chemical fertilizers, organic soil amendments, and SI during crucial developmental periods in semi-arid regions can boost economic outcomes by influencing source-sink dynamics.

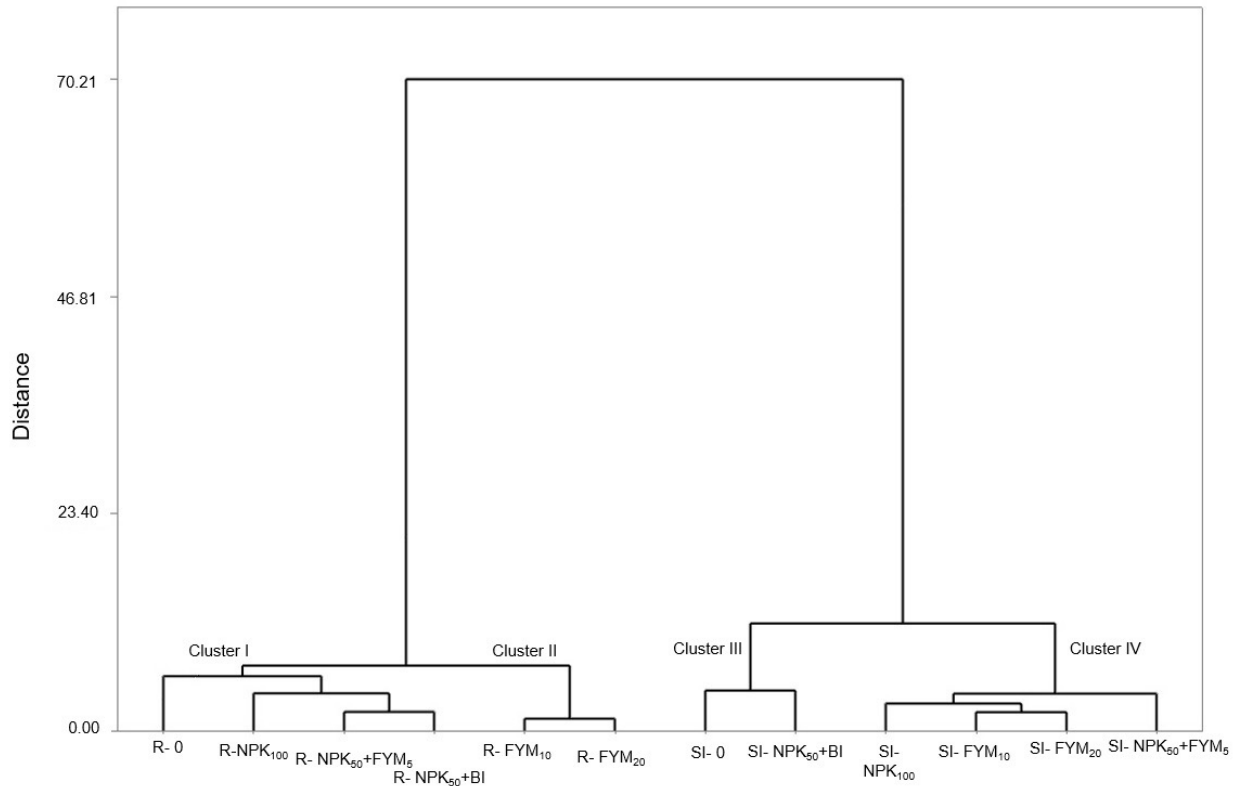


Figure 5 Cluster analysis for grouping combined treatments according to similarity in their effects on agronomic and morphological characteristics evaluated in lentils. R = rainfed condition, SI = supplemental irrigation, 0 = no fertilizer application (control), NPK₁₀₀ = 100% of the suggested dose of chemical fertilizer containing nitrogen, phosphorus, and potassium, NPK₅₀+FYM₅ = 50% of the suggested dose of NPK and application of 5 t ha⁻¹ of cattle farmyard manure, NPK₅₀+BI = application of 50% of the suggested dose of NPK and bacterial inoculation of seeds with biofertilizer at the planting stage, FYM₁₀ = the use of 10 t ha⁻¹ of cattle farmyard manure, FYM₂₀ = the application of 20 t ha⁻¹ of cattle farmyard manure.

CONCLUSIONS

The results showed that lentil production under rainfed conditions in the studied area is not economically beneficial, even with fertilizer applications. Low annual rainfall and very low soil moisture during the plant's reproductive growth period presented serious challenges to lentil production. However, applying supplemental irrigation three times during tillering, flowering, and seed setting improved lentil grain yield by about 70% compared to rainfed conditions. The application of chemical or organic fertilizers under rainfed conditions did not significantly affect the evaluated traits. However, under supplemental irrigation conditions, the application of FYM and the suggested dose of chemical fertilizers significantly increased growth and grain yield. Using FYM₂₀, NPK₁₀₀,

and FYM₁₀ resulted in an acceptable grain yield. The results indicate that successful lentil production in the semi-arid agroclimatic zone of the northwest requires supplemental irrigation, organic soil amendment, or the recommended dose of NPK.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this research.

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