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Original Article

Morphophysiological response of sunflower (*Helianthus annuus*) to various farmyard manure and irrigation frequency

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Abstract:
A field trial was set up to evaluate the effects of different irrigation levels (I_1: rainfed and no irrigation, I_2: 2 times supplementary irrigation at head development and seed setting stages, I_3: 3 times irrigation at stalking, heading, and seed filling stages, I_4: full irrigation) and the use of various types of farmyard manure (M_0: no manure application, M_1: cow manure, M_2: sheep manure, M_4: poultry manure) on growth, yield, and oil content of sunflower seeds. The largest heads were produced using poultry and sheep manure under full irrigation and I_3 conditions. The highest lateral canopy growth was achieved with the use of I_4+M_4. The highest percentage of oil was obtained under conditions I_4 and I_3, using M_1, M_4 and M_2, respectively. Reducing the frequency of irrigation to three times, along with the use of farmyard manure, resulted in acceptable economic performance while reducing water consumption.

Key words:
head diameter, empty achenes, oilseed yield, vegetative growth, water saving, water supply

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Apstrakt:
Morfo-fiziološki odgovor suncokreta (*Helianthus annuus*) na različito stajsko đubrivo i učestalost navodnjavanja
Eksperiment je postavljen na terenu, sa ciljem da se ispitaju efekti različitih nivoa navodnjavanja (I_1: bez navodnjavanja, samo kiša; I_2: dodatno navodnjavanje dva puta, u fazama formiranja glavice i zametanja semena; I_3: navodnjavanje tri puta, u fazama porasta stabljike, formiranja glavice i semena; I_4: potpuno navodnjavanje) i upotrebe različitih vrsta stajnjaka (M_0: bez stajnjaka, M_1: kravlji stajnjak, M_2: ovčiji stajnjak, M_4: živinski stajnjak) na rast, prinos i sadržaj ulja u semenu suncokreta. Najveće glavice dobijene su primenom živinskog i ovčijeg stajnjaka, pri potpunom navodnjavanju i uslovima u tretmanu I_3. Najveći bočni porast lisne mase postignut je kombinacijom I_4+M_4. Najveći procenat ulja dobijen je pri uslovima I_4 i I_3, korišćenjem M_1, M_4 i M_2, redom. Smanjenje učestalosti navodnjavanja na tri puta, uz primenu stajnjaka, dovelo je do ekonomski prihvatljivih rezultata, uz istovremeno smanjenje potrošnje vode.

Ključne reči:
prečnik glavice, prazne ahenije, prinos uljarica, vegetativni rast, ušteda vode, snabdevanje vodom

Introduction

The population of the world is growing rapidly, and the low amount of vegetable oil produced in most developing countries will pose a serious challenge to food security (Afzal et al., 2022). Therefore, the cultivation of oilseed crops is of great importance. Sunflower (*Helianthus annuus* L.) is one of the most important oilseed crops and is relatively adaptable to semi-arid conditions. It has been cultivated in eastern North America by indigenous people since about 4000 BC (Adeleke & Babalola, 2020). Sunflower achene typically contains about 20% protein and 50% fat. The major fatty acids are linoleic acid (65%) and oleic acid (25%). In recent decades, breeding and selection processes for this plant have intensified, and relatively drought-tolerant cultivars adapted to the semi-arid Mediterranean regions have been released. Sunflower seeds have high nutritional value and contain about 45% oil, more than 30% protein, and some important elements in the lipid structure, which creates a valuable nutritional composition (Petraru et al., 2021).

Although sunflowers can tolerate water shortage stress to some extent, the impact of global warming on the intensification of climate change in arid and semi-arid regions has caused the distribution of precipitation to change drastically and the total annual precipitation to decrease.

The most important sunflower-producing countries are Russia with 9.9×10^6 ha of cultivated area and 18.1×10^6 t of achenes production, Ukraine with 5.2×10^6 ha of cultivated area and 12.7×10^6 t of achenes production, Argentina with 2.4×10^6 ha of cultivated area and about 5 million t of achenes production, China with 1×10^6 ha of cultivated area and 3×10^6 t of achenes production, and Romania with 1.1×10^6 ha of cultivated area and about 2×10^6 t of harvested achenes (FAO, 2023). The area under sunflower cultivation in Iran is 62,000 ha, and the amount of harvested sunflower seeds is 65,000 t (FAO, 2023). The amount of sunflower seed imports in Iran has exceeded 99,000 t, worth 126,000 $, which places it in sixteenth place in the list of global sunflower seed importers. Considering this amount of import, assuming a yield of at least 2 t per ha, 50,000 ha of sunflower land are needed to compensate for the quantity of imports. Therefore, it is necessary to increase production through improving agronomic methods, modifying soil conditions, and applying climate-smart methods. The low rainfall in semi-arid regions has caused the soils in these areas to have relatively little development and evolution. The soils in these areas have low vegetation cover, poor structure, very little residue return, quick degradation of organic matter, and high pH (Naorem et al., 2023). Likewise, low soil moisture and low soil retention capacity are among the most important factors limiting production. However, it seems that the use of some climate-friendly and eco-friendly management practices, such as the use of farmyard manure, can improve soil conditions for sunflower production (Derpsch et al., 2024). Given the development of the livestock industry alongside agriculture and the production of a significant volume of farmyard manure, this cheap and accessible input can play a role in improving soil conditions and mitigating the effects of global warming (Nogués et al., 2023). Farmyard manure application may increase the soil organic matter (SOM) and improve structural properties and water permeability. The use of organic fertilizers can reduce soil compaction and increase cation exchange capacity. The use of farmyard manures adjusts the soil pH, which can accelerate the release of nutrients in the rhizosphere (Ferreira et al., 2022). Adjusting irrigation regularity in *H. annus* is critical for improving the water use efficiency and achene yield. While irrigation during critical stages of plant development can lead to higher yields, it may also increase water use efficiency due to decreased water loss through evaporation and drainage.

Although some researchers have investigated the effect of applying livestock manures to sunflower fields in semi-arid climates (Maia Filho et al., 2013; Vilvert et al., 2023; Mokgolo et al., 2024), there is still no comprehensive information on how these fertilizers affect different moisture regimes and the differences between livestock manures. This is important because the diet of small livestock (like sheep and goats), large livestock (like cattle), and poultry (like chickens and turkeys) differs significantly due to their digestive systems, nutritional needs, and production goals. Furthermore, it seems that the differences in the feeding habits of small, large livestock, and poultry, as well as their different digestive systems, result in the production of different qualities of manure.

Under conditions where rainfall distribution is symmetrical and normal during the season, sunflowers can produce economically without irrigation and in a rainfed manner. However, considering the changes in rainfall patterns caused by global warming, the use of supplementary irrigation techniques seems necessary. Supplementary irrigation is a method of water management that, under rainfed conditions, reduces the amount of rainfall by providing multiple irrigations during key growth stages, reducing severe yield loss and improving water efficiency compared to full irrigation methods. García-López et al. (2016) reported that the use of supplementary irrigation in semi-arid regions significantly increased sunflower yield and also increased nitrogen fertilizer use efficiency. Due to the decrease in rainfall at the end of the season and coinciding with the reproductive stages of sunflower in semi-arid Mediterranean regions, supplementary irrigation before anthesis up to flowering significantly increased yield compared to rainfed conditions (Giannini et al., 2022). This experiment aimed to evaluate the effect of different supplementary irrigation regimes and the application of different farmyard manures on sunflower performance in northwest Iran.

Materials and Methods

Site description

This field experiment was conducted during the 2023-2024 agricultural year in a private research farm in the Kharajoo region, northwest Iran, East Azerbaijan. The site was located at longitude 46° 55’ E and latitude 37° 33’ N, at 1716 m a.s.l. The total annual precipitation in the region was 392 mm, and the mean annual minimum (Tmin) and maximum temperatures (Tmax) were 5 °C and 26 °C, respectively, making it a cold semi-arid climate, often designated BSk in the Köppen climate classification. Monthly precipitation and air temperature conditions are shown in **Fig. 1**. The soil texture was silty loam, and soil analysis is shown in **Tab. 1**.

Experimental treatments

A field trial was designed to estimate the effect of applying different livestock manures under different irrigation regimes. The arrangement and allocation of treatments to plots was based on a three-replicated split plot with based on RCBD. The main plots with dimensions of 19×4 m were allocated to 4 irrigation regimes. Irrigation levels were: 1 - rainfed (no irrigation) and rainfall-dependent growth, 2 - two supplementary irrigations during advanced reproductive stages including the stage of pod development and seed setting (200 mm), 3 - three supplementary irrigations during the vegetative (stem elongation) and advanced reproductive stages (270 mm), 4 - full irrigation (530 mm). Subplots with an area of 4×4 were allocated to different types of livestock manure. Subfactors at four levels included 1 - no manure application, 2 - the use of 10 t ha^{-1} of cow manure collected from a beef calf farm before planting, 3 - the use of 10 t ha^{-1} of

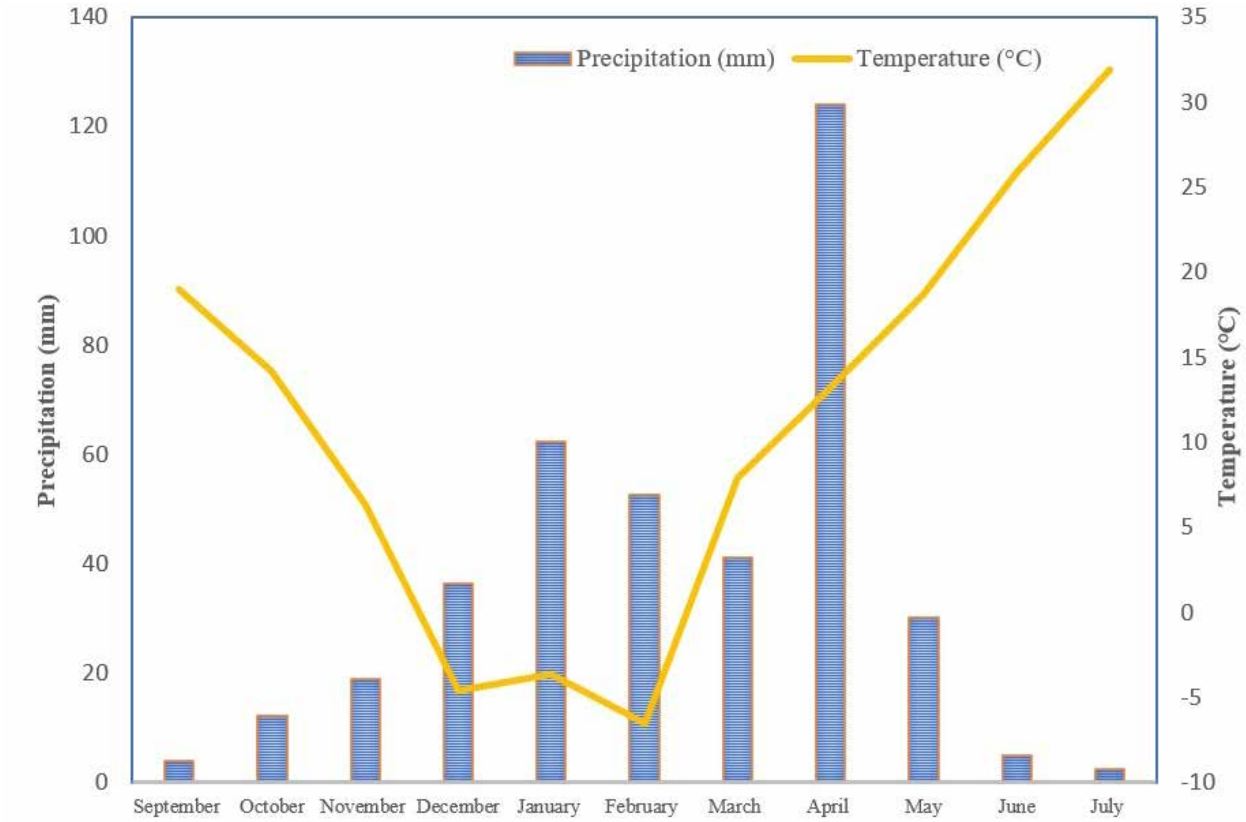

Fig. 1. Precipitation and air temperature trends in the studied area during the experimental year

Table 1. The status of soil available elements and some chemical components of livestock manures

	pH	EC	OC%	TN%	P	K	C/N	Ca	Fe	Zn	Mn
Soil	7.74	2.51	0.71	0.09	10.217	215	1.69	37.29	1.242	3.45	0.97
Cow FYM	6.61	4.62	28.37	1.87	1.53	192	14.32	193.7	142.62	128	210.3
Sheep FYM	6.52	5.37	31.92	2.69	1.31	342	24.60	268.1	664	91.7	301.5
Poultry Manure	6.43	3.67	39.41	3.42	2.74	436	31.28	318	410.2	194.6	261.4

The element concentration is mg kg^{-1}. EC: electrical conductivity (ds m^{-1}), OC: organic carbon, TN: total nitrogen, soil pH in H_2O refers to the measurement of soil acidity or alkalinity in a water solution, FYM: farm yard mannure sheep manure collected from a sheep overnight stable, 4 - application of 10 t ha^{-1} of poultry manure collected from a broiler farm. A one-meter non-planting margin was considered between the main and sub-plots to prevent moisture leakage and nutrient leaching. The nutritional value of manures and some of their natural characteristics are briefly summarised in **Tab. 1**.

Seed planting

The field was under rainfed wheat cultivation in the previous crop year. After the wheat harvest in July, the soil was plowed with 4-bottom share moldboard plows. In November, after determining the boundaries of the main and subplots, different types of manure were applied to the soil surface according to the area of the subplots and mixed with the topsoil to a depth of 15 cm using a shovel.

The single-cross hybrid Golsa was obtained from the Seed and Plant Improvement Institute, Iran. This variety has been produced by crossing the restorer RGK2 with the cytoplasmic male sterile line AGK2. The good characteristics of this variety include being single-branched, uniform maturity, full fertility, early maturity, and high yield. The growth period of this plant is 100 to 105 days, and it is classified as an early variety. It is resistant to rust, tolerant to charcoal rot, and relatively susceptible to downy mildew. This oil variety can be used as a first crop in temperate and cold regions, and as a summer crop in temperate and central regions of Iran. The weight of a thousand seeds in the Golsa variety is 50 g, and the grain yield is about 2.7 kg ha^{-1}. The height of the plant in this variety is approximately 180 cm. After secondary tillage and creating relatively soft, lump-free soil, the surface shape was transformed into a ridge-furrow archaeological pattern through a furrower. Seeds were sown manually at the top of the ridges at a depth of 4 cm on March 20. Through multiple seed sowing per hole, the chances of seeding emergence increased. However, after seedling establishment, excess seedlings were removed. A density of 9 plants per m^2 was obtained with a rectangular planting pattern with 60 cm distance between rows and 15 cm intra-row spacing. During seed planting, NPK fertilizer was applied as a band utilization 2 cm below the seeds. The recommended rates of nitrogen, phosphorous, and potassium for the studied site were 120 kg ha^{-1}, 80 kg ha^{-1}, and 40 kg ha^{-1}, respectively. N, P, and K N, P, and K were provided by the urea, triple superphosphate, and potassium sulfate fertilizers. Irrigation was carried out through polyethylene pipes equipped with volumetric meters and in the form of a surface furrow system. Due to the presence of precipitation during the vegetative stages, supplemental irrigation was performed at the stem elongation stage with a depth of 60 mm, and supplemental irrigation was performed at the reproductive stage with a depth of 100 mm. The amount of water consumed through irrigation under full irrigation conditions was 510 mm. Weed control was done through hand weeding and spraying sethoxydim herbicide at 1.5 L ha^{-1}.

Measurements of the traits

At the head emergence stage, canopy extent was obtained by measuring the distance between the tip of the leftmost leaf to the rightmost leaves in the middle of the canopy using a meter. During the achenes setting stage (BBCH-Scale: 71), photosynthetic pigments were measured using a handheld leaf chlorophyll meter (SPAD-TYS-A, China). At the end of the reproductive period, when the backs of the heads turned brown, the characteristics of the crop, such as head diameter, number of filled and empty achenes in the head, were measured or counted. Using a 1 m^2 randomly in the plots, all the heads in the area inside the quadrat were harvested, and after drying the heads at 60 °C for 36 h, the seeds were separated and weighed. The weight of one hundred seeds was obtained using a seed counter and a digital scale. The measurement of the seed oil content was done using a Soxhlet apparatus and n-hexane as the extraction solution. Relative leaf water content (RWC) was measured at the achene setting stage. The RWC was obtained through the method of Soltys-Kalina et al. (2016). Leaf disc samples were prepared from the upper leaves early in the morning using a punch (fresh weight: FW), after that they were placed in distilled water for 8 h (turgid weight: TW) and then leaf samples were dried in an electric oven at 65 °C; their dry weight (DW) was calculated. $RWC=[(FW-DW)/(TW-DW)]\times100$.

Data analysis

Before the analysis of variance, the normality of the data distribution was examined by Minitab software. ANOVA was carried out by SAS. The mean comparison was performed by the LSD test. Boxplots were drawn by SPSS, and principal component analysis plots were done by the Minitab package.

Results

The effect of different types of animal farmyard manure (M) and irrigation regimes (I) on canopy spread and plant height was significant (p<0.01). Canopy width in plants grown under fully irrigated conditions (I_4) was 51% greater than those grown under rainfed conditions (I_1). The mean comparison of stem length between moisture regimes showed that no significant difference was observed between rainfed and two times of supplementary irrigation (I_2), but I_4 and I_3 (three times of supplementary irrigation) increased this component by 52% and 40%. Among farmyard manures, the use of cow manure (M_2) resulted in the highest lateral canopy growth (20% vs. control). However, the tallest plants were obtained with poultry manure and sheep manure, which increased longitudinal growth by 27% and 15%, respectively, compared to the control (**Tab. 2**).

The I_4+M_3 condition resulted in the highest lateral canopy growth, and the smallest canopies were observed under rainfed conditions without manure application (41.33 cm). Although increasing irrigation frequency increased longitudinal growth, the effectiveness of farm yard manures became more pronounced with improved moisture compared to the control. Under I_2 conditions, the difference between fertilizers in terms of plant height was quite obvious, while under I_1 conditions, no difference was observed between fertilizers in terms of longitudinal growth. The application of (sheep and poultry) M_3 and M_4 had a greater effect on vegetative growth components compared to the control. Stem diameter was affected by soil moisture supply, and the thickest stems were produced by plants under I_4 and I_3 conditions with the application of M_4 and M_3, respectively. Regardless of the type of fertilizer, the use of all farmyard manures increased the leaf number (LN) compared to M_1, and on the other hand, increasing the frequency of irrigation also improved this trait. The highest LN was recorded in plants grown under I_3M_3, I_4M_2, I_4M_3, and I_4M_4.

The head diameter was affected by I×M at the 5% level. Under rainfed conditions, the use of farmyard manures did not have a significant effect on this trait. With increasing irrigation frequency, the effectiveness of farmyard manures on head diameter increased, and the highest diameter was obtained under I_4+M_3 conditions (19.19 cm). Under supplementary irrigation conditions, I_3, the use of poultry manure resulted in the highest head diameter.

The relative leaf water content is shown in **Fig. 2**. The interaction effects of I×M on RWC were significant (p<0.01). Under rainfed conditions, poultry manure application increased RWC. Application of cow and sheep manure under moisture-limited conditions decreased RWC compared to the M_1 condition. This could be due to the presence of nitrogen and higher water consumption of plants with the applications of M_2 and M_3. Under I_3 conditions, sheep manure application increased RWC.

The results showed that the effect of fertilizers on RWC is largely influenced by irrigation regimes.

The number of filled achenes (NFA) was also affected by manure and irrigation. As irrigation frequency increased from I_2 to I_3, the proportion of NFA increased by 32%. The most effective manures for NFA were sheep and poultry manure, which increased this trait by 18% and 15%, respectively, compared to the M_1. The plants grown under I_4M_3 produced the highest number of achenes compared to other conditions. Under I_3 circumstances, the highest NFA was obtained with the use of poultry manure.

The ratio of empty achenes (REA) was also affected by I×M. The highest REA was observed under full irrigation and no fertilizer application (4.98%). Plants grown under I_2M_1 and I_3M_1 conditions were in second and third place in terms of REA (**Fig. 3**). The lowest REA was observed in plants grown under I_1M_4 (2.95%) and I_3M_2 (3.09%).

Achen weight responded strongly to moisture regimes, and increasing irrigation frequency increased this trait. The use of farmyard manure, especially sheep manure and poultry manure, also increased achene weight compared to the control. The heaviest achenes were obtained under I_4+M_3 and I_4+M_4 conditions. Irrigation levels and manure applications also affected the oil content of achene (p<0.01). Although no significant difference was observed between the manures (M_2, M_3, M_4) in terms of achene oil content, the use of manures increased the oil content by about 2% compared to the control. Full irrigation conditions increased the oil content of achen by 5% compared to rainfed conditions. The highest oil content was obtained under I_4M_4 (41.39%) and I_4M_2 (41.69%).

The evaluation of achene yield indicated that the interaction effects of irrigation and manure were significant for this trait. The best achene yield was obtained with the application of farmyard manures (poultry, sheep, and cow) under full irrigation conditions with values of 1806 kg ha^{-1}, 1799 kg ha^{-1}, and 1762 kg ha^{-1}. Under I_3 conditions, the application of poultry and sheep manure showed a greater improvement effect than cow manure. The achene yield in the latter conditions was 1680 kg ha^{-1}, 1659 kg ha^{-1}, and 1659 kg ha^{-1}. The lowest achene yield was recorded under I_1M_1 conditions. Under rainfed circumstances (I_1), the application of sheep manure resulted in the highest achene yield (1007 kg ha^{-1}). The results showed that under supplemental irrigation conditions, the application of poultry manure significantly increased the achene yield (**Fig. 4**).

Monograph PCA showed that PC1 separated the optimal moisture conditions of I_4 and I_3 from other irrigation levels. The highest values for the evaluated agronomic traits were recorded under full irrigation conditions and three times supplemental irrigation. PC2 could distinguish the low-effective levels of fertilizer treatments from the poultry and sheep

Table 2. The effect of different livestock fertilizers in different irrigation regimes on sunflower performance in the drought-prone region of northwestern Iran

Effects	CC	CS	PH	SD	LN	HD	NFA	WHA	OC
Irrigations (I)									
I_1	40.38^{d}	47.75^{c}	107.00^{d}	1.25^{b}	15.24^{c}	13.21^{d}	498.50^{d}	3.89^{d}	35.73^{d}
I_2	53.49^{c}	46.83^{c}	124.25^{c}	1.28^{b}	18.73^{b}	14.73^{c}	559.87^{c}	4.16^{c}	38.73^{c}
I_3	55.59^{b}	65.92^{b}	150.08^{b}	1.43^{a}	24.75^{a}	15.85^{b}	675.97^{b}	4.39^{b}	39.86^{b}
I_4	60.16^{a}	72.25^{a}	162.75^{a}	1.40^{a}	25.41^{a}	18.09^{a}	892.92^{a}	4.96^{a}	40.60^{a}
Manure (M)									
M_1	48.55^{c}	52.75^{c}	125.75^{c}	1.32^{ab}	19.54^{b}	14.85^{b}	590.22^{c}	4.16^{c}	37.55^{b}
M_2	51.69^{b}	63.333^{a}	136.17^{b}	1.31^{b}	21.33^{a}	15.55^{a}	654.72^{b}	4.25^{b}	39.12^{a}
M_3	54.12^{a}	58.33^{b}	140.33^{ab}	1.39^{a}	21.90^{a}	15.77^{a}	699.45^{a}	4.49^{a}	38.92^{a}
M_4	55.28^{a}	58.33^{b}	141.83^{a}	1.33^{ab}	21.35^{a}	15.73^{a}	682.87^{ab}	4.50^{a}	39.32^{a}
Interactions									
I_1M_1	36.13^{h}	41.33^{i}	99.33^{h}	1.16^{f}	14.11^{i}	12.89^{h}	422.47^{h}	3.76^{i}	35.87^{g}
$I_1 M_2$	39.73^{g}	54.33^{f}	110.67^{g}	1.21^{ef}	15.67^{hi}	13.07^{h}	479.33^{gh}	3.87^{hi}	35.97^{g}
$I_1 M_3$	42.03^{fg}	46.67^{gh}	105.00^{gh}	1.36^{cd}	16.84^{hg}	13.10^{h}	535.33^{fg}	3.86^{hi}	35.97^{g}
$I_1 M_4$	43.63^{f}	48.67^{gh}	113.00^{g}	1.25^{f}	14.33^{i}	13.80^{gh}	556.87^{f}	4.07^{efg}	35.13^{g}
I_2M_1	49.30^{e}	44.33^{hi}	123.33^{f}	1.30^{def}	17.53^{fg}	14.67^{g}	561.27^{f}	4.06^{fg}	37.65^{f}
$I_2 M_2$	50.13^{de}	49.67^{g}	122.67^{f}	1.30^{def}	18.80^{ef}	15.03^{def}	591.53^{f}	4.01^{gh}	39.00^{def}
$I_2 M_3$	58.37^{bc}	45.00^{hi}	125.67^{f}	1.26^{f}	18.20^{fg}	14.83^{efg}	557.27^{f}	4.37^{d}	38.70^{fe}
I_2M_4	56.17^{c}	48.33^{gh}	125.33^{f}	1.24^{def}	20.40^{e}	14.40^{fg}	529.4^{fg}	4.20^{ef}	39.57^{cde}
I_3M_1	52.47^{d}	61.00^{e}	143.00^{de}	1.49^{abc}	23.07^{d}	14.43^{fg}	568.47^{f}	4.07^{efg}	37.63^{f}
$I_3 M_2$	57.47^{bc}	65.00^{de}	160.00^{b}	1.36^{cd}	24.47^{cd}	16.07^{cd}	675^{e}	4.23^{de}	39.83^{bcde}
I_3M_3	56.23^{c}	71.33^{b}	145.00^{cde}	1.56^{a}	26.43^{a}	15.93^{cde}	695.87^{de}	4.64^{c}	40.77^{abc}
$I_3 M_4$	56.20^{c}	66.33^{cd}	152.33^{bc}	1.32^{de}	25.03^{ac}	16.97^{bc}	764.53^{cd}	4.61^{c}	41.20^{ab}
I_4M_1	56.30^{c}	64.33^{de}	137.33^{e}	1.33^{de}	23.47^{cd}	17.42^{b}	808.67^{bc}	4.75^{bc}	39.06^{def}
$I_4 M_2$	59.41^{b}	84.33^{a}	151.33^{bcd}	1.37^{bcd}	26.40^{a}	18.02^{b}	873^{b}	4.90^{b}	41.69^{a}
$I_4 M_3$	59.83^{b}	70.33^{bc}	185.67^{a}	1.38^{bcd}	26.13^{ab}	19.19^{a}	1009.33^{a}	5.08^{a}	40.25^{abcd}
$I_4 M_4$	65.10^{a}	70.00^{bc}	176.67^{a}	1.50^{ab}	25.63^{ab}	17.73^{b}	880.67^{b}	5.11^{a}	41.39^{a}
					Significance level				
I	<0.0001	<0.0001	<0.0001	0.002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
F	<0.0001	<0.0001	<0.0001	0.1100	<0.0001	0.0100	<0.0001	<0.0001	<0.0001
I×F	0.0011	<0.0001	<0.0001	0.0149	0.0369	0.0272	0.0017	0.0046	0.0155
CV%	3.18	4.47	4.05	6.26	6.87	4.37	6.75	2.24	2.21

I_1: rainfed or no-irrigated condition, **I_2**: Two-time supplemental irrigation, **I_3**: three-time supplementary irrigation, **I_4**: full irrigation, **M_1**: control or non-use of farm yard manure, **M_2**: the application of 10 t ha^{-1} cow manure, **M_3**: the application of 10 t ha^{-1} sheep manure, **M_4**: use of 10 t ha^{-1} poultry manure. **CV**: The coefficient of variation (%), **CC**: leaf chlorophyll (SPAD unit), **CS**: canopy spread (cm), **PH**: height of stem (cm), **SD**: diameter of the stem (cm), **LN**: leaf number per plant, **HD**: head diameter (cm), **NFA**: number of the filled achene per head, **WHA**: weight of hundred achenes (g), **OC**: achene oil content (%). For each trait, the means with dissimilar letters show that they have been differently affected by treatments at $p<0.05$ when evaluated by the LSD test. Significance test (p values) is shown for determining the significance level; the values lower than 0.05 and 0.01 are significant at 5% and 1% statistical level, respectively.

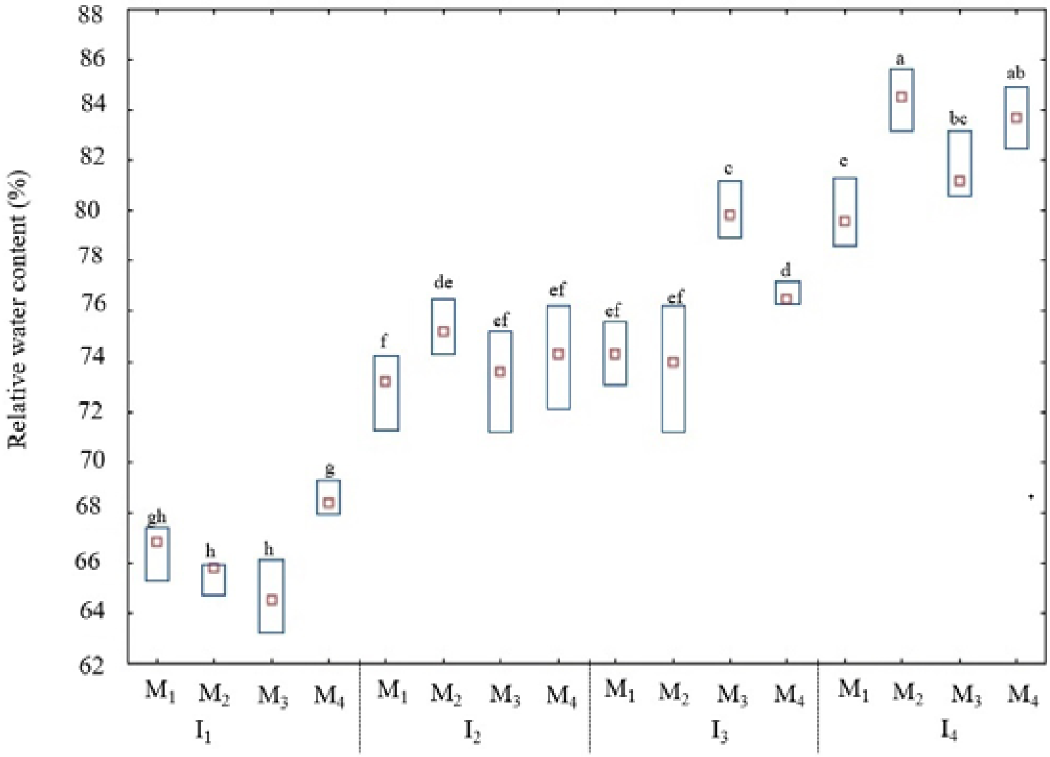

Fig. 2. The mean comparison of the relative water content (RWC) in sunflower leaves under different manure application conditions and soil moisture regimes in northwest Iran. **I_1**: rainfed, **I_2**: two-time supplemental irrigation, **I_3**: three-time supplemental irrigation, **I_4**: full irrigation. **M_1**: control or no manure application, **M_2**: application of cow manure, **M_3**: sheep manure, **M_4**: poultry manure

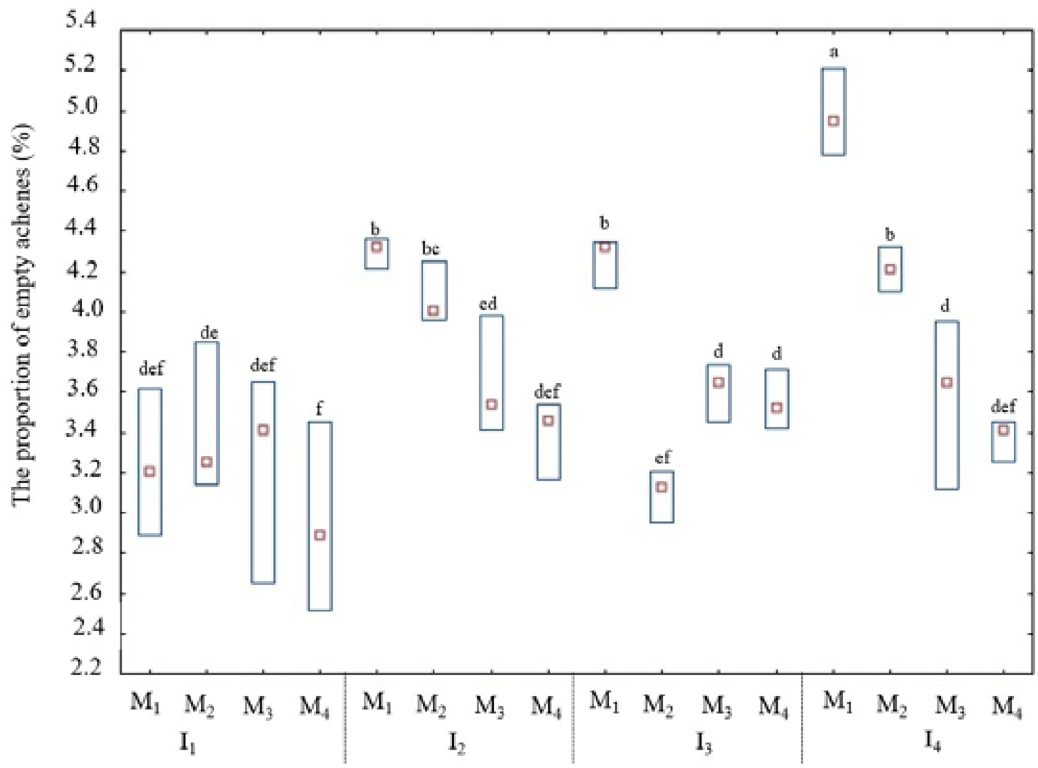

Fig. 3. The proportion of empty achenes in sunflowers was affected by irrigation regimes and farmyard manures. **I_1**: rainfed, **I_2**: two-time supplemental irrigation, **I_3**: three-time supplemental irrigation, **I_4**: full irrigation. **M_1**: control or no manure application, **M_2**: application of cow manure, **M_3**: sheep manure, **M_4**: poultry manure

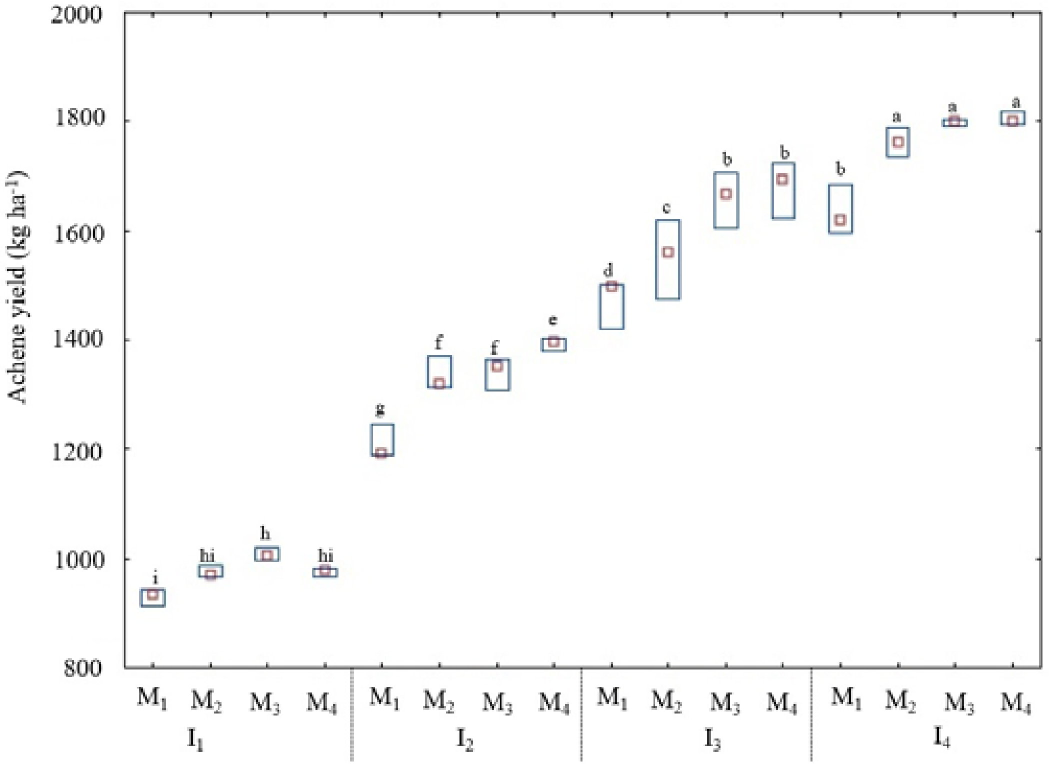

Fig. 4. Evaluation of sunflower seed yield grown under different levels of supplementary irrigation and application of various types of farmyard fertilizers in the northwestern region of Iran. **I_1**: rainfed, **I_2**: two-time supplemental irrigation, **I_3**: three-time supplemental irrigation, **I_4**: full irrigation. **M_1**: control or manure application, **M_2**: application of cow manure, **M_3**: sheep manure, **M_4**: poultry manure

manures. The best appearance of sunflower and the highest vegetative growth were obtained under M_3 and M_4 conditions (**Fig. 5**).

Discussion

Soil condition assessment showed that the soil in the study area was severely limited due to low organic matter and nutrients. In addition, meteorological data showed that the end season of the sunflower growth period is characterized by dry spells. The total annual rainfall in the region was 390 mm, while the estimated evapotranspiration rate for the region was 594 mm. These data indicate that precipitation is low compared to evapotranspiration unless soil moisture reserves are significant at the beginning of the growing season. The results indicated that vegetative traits such as stem height, canopy spread, stem diameter, and leaf number showed their lowest amounts under rainfed conditions and increased significantly with increasing irrigation frequency. Only the stem diameter did not show a significant difference between supplementary and full irrigation levels. According to the hypothesis of acidic cell growth, water accumulation in vacuoles is the main driving factor in plant growth (Jiang et al., 2021), and it seems natural that reducing irrigation frequency would severely affect growth. Chlorophyll, as the most important photosynthetic pigment, also showed a significant decrease with reducing irrigation frequency. It seems that water scarcity increases the decomposition or inhibition of the biosynthesis of this pigment. These findings are consistent with the results of Kheshtpaz et al. (2024), who reported that water deficit stress reduced leaf chlorophyll content. A relatively similar trend was observed for the number of leaves per plant. In this connection, it can be stated that water deficit stress affects both the size of photosynthetic sources and the power of the sources (Zhao et al., 2020). In addition to the effects of water deficit stress on growth, reduced photosensitizer levels and reduced chlorophyll content can also limit growth by reducing the amount of current photo-assimilates (Yusuf & Hamed, 2021). On the other hand, the application of farmyard manure improved the vegetative traits compared to the control conditions (M_1). This increase can be attributed to overcoming physical limitations of the soil by supplying a significant volume of organic matter from farmyard manure (Nouraein et al., 2019). Also, the use of farmyard manure can facilitate and expedite the supply and availability of nutrients by adjusting the soil pH and optimizing the rhizosphere condition (Liu et al.,

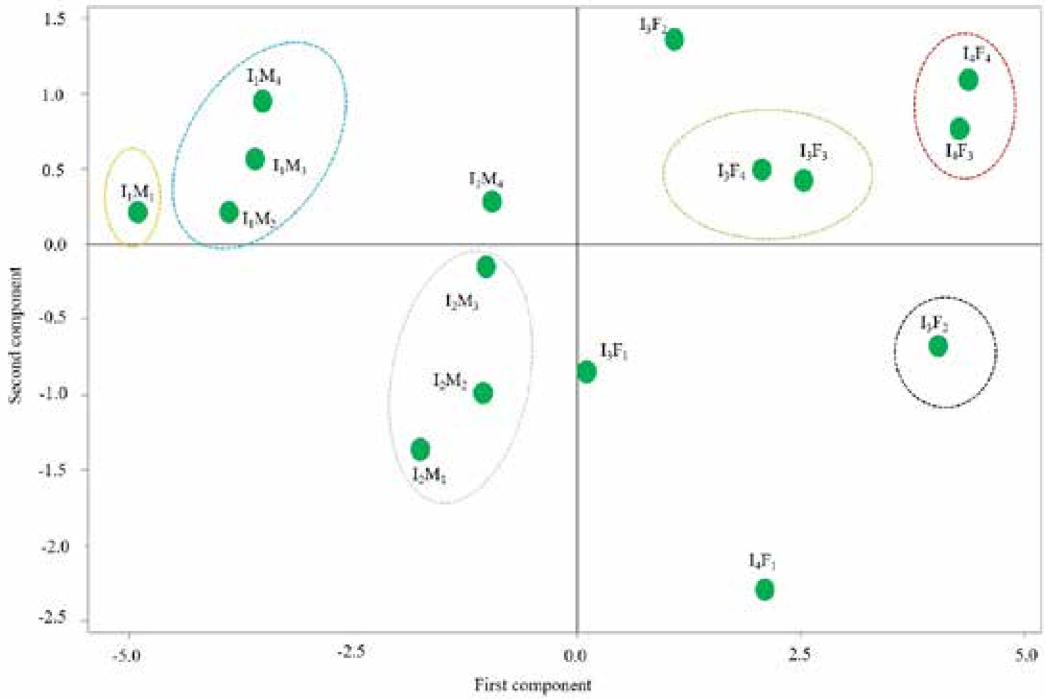

Fig. 5. Principal component analysis plot to evaluate the similarity of the effects of supplementary irrigation treatments and different farmyard fertilizers on growth traits and yield of sunflower. **I_1**: rainfed, **I_2**: two-time supplemental irrigation, **I_3**: three-time supplemental irrigation, **I_4**: full irrigation. **M_1**: control or manure application, **M_2**: application of cow manure, **M_3**: sheep manure, **M_4**: poultry manure

2024).

Among the livestock fertilizers studied, the use of poultry and sheep manure increased chlorophyll content the most. Given the key role of nitrogen in the structure of this pigment, it seems that poultry and sheep manure provided greater amounts of nitrogen to the root system (Tagar et al., 2016). In a brief comparison of the applied manures with the control conditions, it was found that all manures led to increased growth. The soil of this region, like other semi-arid regions of northwest Iran, had very low organic matter, and it appears that the application of manures, by improving the organic matter content of the soil, improved some key soil properties such as water retention capacity, the formation of micropores, and the cation exchange capacity of the soil (Zhu et al., 2025).

The results showed that the effect of water supply under different conditions of manure application was different. The application of manure increased the effect of supplementary irrigation on both vegetative growth components and achene yield components. In the present experiment, the highest yield of achene was obtained under full irrigation conditions, using either poultry or sheep manure. Considering six irrigation events carried out under full irrigation conditions, 530 mm of water was used.

However, water resources in the region are facing serious limitations, and providing water during sunflower growth - due to its simultaneous irrigation with other crops - is one of the key challenges facing local farmers (Kouchakkhani et al., 2024).

Therefore, it appears that the use of three-time supplemental irrigation (I3) in conjunction with farmyard manure can significantly reduce water consumption by producing achene relatively reasonably and economically, thereby conserving water resources for other crops. Although increasing the frequency of irrigation resulted in a higher achene number in the head, it also increased the proportion of unfilled achenes. This could be due to the limitation of photoassimilative resources to fill the empty cup of the produced achenes. The intensification of climate change has also complicated the situation regarding available water resources in the region (Janmohammadi & Sabaghnia, 2023), which increases the acceptability of using supplementary irrigation (I_3) instead of full irrigation among farmers. Eliminating three irrigations saves 260 mm of water, which can be used to produce another crop. Our previous findings also indicated significant water savings by using supplemental irrigation techniques in chickpea fields (Janmohammadi et al., 2024). The long-term application of manure can improve soil properties and enhance the rate of root development, allowing roots to spread deeper into the soil, which can further reduce the need for irrigation (Liu et al., 2013). The qualitative characteristics of the oil, such as oil content, also showed that under I_3 conditions, where this component showed an acceptable increase with the use of poultry manure, and it can be stated that the oil yield under the mentioned conditions can be economical and acceptable. The findings showed that supplementary irrigation should not only focus on the reproductive stages, but also that applying supplementary irrigation once during vegetative growth can improve vegetative growth and the sufficient production of photo-assimilates, allowing the plant to enter the reproductive stage with sufficient photo-assimilate reserves. This will compensate for the lack of photo-assimilates during the formation of achene components through the utilization of photo-assimilate reserves and the remobilization process (Saadatmand et al., 2024).

Conclusion

The annual precipitation and rainfall distribution in the studied location were insufficient for rainfed sunflower production, and the crop's economic performance was not encouraging. Therefore, supplemental irrigation for sunflower production is a climate-smart solution to prevent the negative impact of water shortage stress, especially at the end of the season. Although the application of all farmyard fertilizers improved the growth and achene yield compared to the control, some differences in the effect of fertilizers were evident. Under rainfed conditions, sheep manure application increased achene yield. With increasing soil moisture through irrigation, the effectiveness of livestock fertilizers also showed a significant increase. However, the scarcity of water resources in the region is a serious limiting factor, and the use of three supplementary irrigations, as well as the use of poultry and sheep manures, had the best effect, and the water efficiency was also significantly increased. The use of livestock manures alone is not sufficient to improve growth and increase achene yield under rainfed conditions, and supplementary irrigations must be included in sunflower field management and crop production systems.

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