



# Study of water deficiency levels on ecophysiological characteristics of sunflower cultivars in Isfahan, Iran

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## Abstract

This study was aimed to investigate the effect of drought stress on some ecophysiological characteristics of sunflower cultivars. This study was conducted in the form of split plots in a randomized complete block design with three replications in the Braun area of Isfahan province for the year 2020. Drought stress at three irrigation levels after evaporation of 90, 120, and 150 mm from Class A evaporation pan as non-stress, mild, and severe stress, respectively, in the main plots and five cultivars of sunflower Chiara, Oscar, Fantasia, Hisun 33, and Shams was placed in the subplots. Drought stress affected achene yield, harvest index, and drought tolerance of sunflower cultivars. The highest biophysical water productivity (WPb) was obtained from 90 and then 120-mm irrigation and among sunflower cultivars from Fantasia and Hisun 33 cultivars. The highest economic water productivity (WPe) was obtained with 90-mm irrigation and Fantasia and Hisun 33 cultivars. The highest HI belonged to 90 and then 120-mm irrigation. The highest HI was related to Fantasia, Oscar, and Hisun 33 cultivars, and the lowest HI was related to Shams and Chiara cultivars. The highest and the lowest grain yield were obtained in 90 (control) and 150 mm of evaporation, respectively. The highest grain yield was obtained in Fantasia, Shams, and Oscar cultivars, and the lowest yield was observed in Hisun 33 and Chiara cultivars. In general, drought stress affected yield, HI, crop water productivity (WPC), and drought tolerance of sunflower cultivars.

**Keywords** Sunflower · Drought tolerance · Achene yield · Biophysical water productivity

## Introduction

Iran is located in one of the driest regions of the world with an average annual rainfall of 250 mm, which is about one-third of the global average rainfall (Wu and Chau 2011; Varvani et al. 2019). Drought is commonly known as the most common non-living stress experienced by crops. In areas where annual rainfall is reduced and its distribution is not clear, drought is the most important environmental

stress that severely reduces crop production (Richards 1996; Marengo et al. 2017). Drought stress occurs when the moisture in the roots is reduced to such an extent that the plant is not able to absorb enough water, or in other words, transpiration is more than water absorption (Wasaya et al. 2021). In 2014, the acreage of sunflower (*Helianthus annuus* L) in its 70 developing countries was about 26 million hectares, resulting in 23–33 million tons of seeds, equivalent to 2.12–4.7 million tons of oil. Sunflower is one of the crops that are relatively tolerant of various environmental conditions, especially drought stress, and if it is equipped with a developed root system through breeding methods, it will have high efficiency in extracting water from deep soil. Also, due to the ability of sunflower to withstand short periods of drought stress, this plant can provide significant yields in semiarid environments where water availability is limited (Fulda et al. 2011). Drought stress is a limiting factor for sunflower, and in various reports, the effects of dehydration stress and deficit irrigation on many of its phenological and morphological traits have been mentioned (Erdem et al. 2006; Poormohammad Kiani et al. 2007). Drought

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stress reduces leaf growth, leaf area index (LAI), HI, relative leaf moisture, leaf water potential, and optimal quantum yield in sunflower, but the rate of reduction in these characteristics is less intolerant genotypes than in sensitive genotypes (Miyashita et al. 2004; Hossain et al. 2010; Amiri et al. 2017; Amiri et al. 2018). One of the most important farm managements to achieve optimal plant growth conditions and proper yield is to provide sufficient water so that the plant does not suffer from drought stress in the critical stages of growth (Shafiq et al. 2021). Ahmadpour et al. (2016) stated that access to soil moisture is the most important factor in determining crop yields in semiarid regions. So that water scarcity during the sensitive periods has severe negative effects on the final yield (Ahmadpour et al. 2016). The number of heads per unit area, achene number per head, and the 1000-achene weight (GW) are the most important components of grain yield in sunflower, and the percentage of oil as a component of oil yield is of special importance. Yegappan et al. (1982) stated that drought stress causes premature leaf aging, reduction in leaf number, head diameter, leaf area, GW, and consequently achene yield in sunflowers. Studies by Zaffroni and Schneiter (1989) showed that the achene number per head is the most important component of sunflower yield and should be considered to increase yield. Amiri et al. (2018) found that water deficit decreased achene yield by reducing the number of achene per head, reducing photosynthesis, and increasing the percentage of achene porosity. D'Andria et al. (1995) in separate experiments concluded that reducing irrigation intervals and increasing irrigation frequency can be useful and effective in producing maximum achene yield. The yield of sunflower oil per unit area is the result of achene yield per unit area and the percentage of achene oil (Fernández et al. 2018; Soares et al. 2020). Marinkovic (1992) reported a significant positive correlation between the number of achenes per head and head diameter, GW, and oil percentage. The HI is the ratio of WPe (grain) to WPb (Fernández et al. 2020; Reddy et al. 2020). Majid and Schneider (1987) declared that the oil yield of cultivars was affected by achene yield more than the percentage of achene oil. Also, a higher oil percentage in the studied cultivars was associated with higher achene weight and lower shell percentage. Sidhara and Prasad (2002) found a very good and linear relationship between HI and achene yield. They found that seed production under drought conditions was similar for similar genotypes with the same growing season. LAI is one of the most important growth indices in the sunflower that shows maximum sensitivity to water deficit. The main sign of drought stress in the vegetative phase of sunflowers is a decrease in the number and size of leaves (Soares et al. 2016; Khodabineh et al. 2021). During this period, even very slight drought stress can reduce the leaf growth rate and number, and in later stages, the LAI, which in addition to reducing photosynthesis, by reducing the

transpiration level of the plant, also reduces water excretion from the leaf surface (Taiz et al. 2017; Shafiq et al. 2021). Sadras et al. (1993) concluded that with increasing irrigation frequency and sufficient water supply for sunflower, LAI improves relative to deficit irrigation and no irrigation conditions. In this regard, deficit irrigation by saving water consumption can be considered as a useful solution in the situation of water deficit and with the aim of maximum use of the volume of water consumption. However, according to Göksoy et al. (2004), the effects of deficit irrigation on crop yield and plant quality should be carefully considered before starting crop activities. Plants selected for deficit irrigation should be resistant to water stress. Sunflower, as one of the four important crops that provide oil and protein, has a wide range of climatic adaptations and is better able to tolerate drought stress than other annual crops (Marengo et al. 2017). The ability of sunflowers to withstand short periods of water deficit stress with acceptable yield reduction is a valuable feature in arid regions (Shafiq et al. 2021).

Ehdaie and Waines (1993) stated that one of the most important factors in irrigation planning is  $WP_C$  or the amount of dry matter produced per unit of water consumed. Determinants of  $WP_C$  include WPe (achene yield), WPB, and water consumption. Relatively, in agronomic conditions, increasing water deficit increases  $WP_C$ . In other words, in conditions close to water deficit stress, the plant produces more crops than the amount of water consumed compared to water conditions. Karam et al. (2007) estimated the  $WP_C$  under supplemental irrigation of sunflower at  $0.74 \text{ kg} \cdot \text{m}^{-3}$  and showed that with deficit irrigation at the beginning of flowering, this amount decreases and increases in later stages. So that deficit irrigation at the beginning of seed formation reached the highest value. In most crops, the yield of more water for the seed is not related to the improvement of biomass, but mainly related to the improvement of the HI. In the study of new and old cultivars of most crops, HI was responsible for increasing yield (Richards et al. 2002). Richards et al. (2002) believe that the higher the amount of water used after pollination, the higher the HI. Direct selection for yield is usually the easiest way to improve yield and increase  $WP_C$  in crops and under stress conditions of water deficits. Hereof, two indexes of the geometric mean productivity (GMP) and the stress tolerance index (STI) were presented by Fernandez et al. (2020). Genotypes with higher STI values have both drought tolerance and higher yield potential.

Due to the importance of irrigation water in summer crops, water deficit at this time, and the need for water for other crops, the application of deficit irrigation by stopping irrigation in stages of reproductive growth that is less sensitive to water deficit is of particular importance. Considering that a large part of cultivated lands in Iran has semiarid climatic conditions and also most of the area under sunflower cultivation is dedicated to rainfed crops, it is necessary to

know cultivars with high yield and minimum water consumption. It turns out that the present study has been conducted to achieve this goal for the first time. This study aimed to investigate the effect of drought stress on some ecophysiological characteristics of sunflower cultivars such as head diameter, GW, oil content, WPb, height, and stem diameter.

## Materials and methods

### Experiment site and measurement

The experiment was performed in a split-plot based on a randomized complete block design in three replications in the Braun area of Isfahan province for the years 2020–2021 (two seasons). Drought stress at three irrigation levels after evaporation of 90, 120, and 150 mm from Class A evaporation pan as non-stress, mild, and severe stress, respectively, in the main plots and five cultivars of sunflower Chiara, Oscar, Fantasia, Hisun 33, and Shams was placed in the subplots. Planting was done with a density of 10 plants.m<sup>-2</sup> on July 11 as the second planting. Between replications, a distance of 3 m was considered in order not to affect the moisture of the adjacent treatments. Seeds were planted in the middle of 50-cm ridges with a distance of 20 cm from each other (density of 100,000 plants per hectare) and on July 10 every year as the second planting. This plant density is suitable for most early cultivars in the second crop. Irrigation of each of the main plots was carried out uniformly when the evaporation rate reached the limit considered in the experiment from the Class A evaporation pan installed at the project site. Different moisture regimes were applied after planting and in the four-leaf stage. The amount of water used in each irrigation was measured and recorded by field meters installed at the water inlet to the main plots. A soil test was performed to determine the amount of chemical fertilizer, and after mixing the required amount of fertilizer

with soil at planting, one-third of nitrogen fertilizer was given to the soil in the six- to eight-leaf stage of plants. The results of the physicochemical properties of soils in the region show that the mean pH and EC were 7.38 and 297 (µm/cm), respectively. This indicates that the soil of the area is somewhat alkaline. Also, the average rates of clay, silt, and sand were 32, 38, and 30 (%), respectively. This indicates that most of the soils in this area have medium-to-heavy textures. In the ripening stage (the stage when the heads were yellow and the brackets were brown), ten consecutive plants were selected from the four middle rows of each plot. After determining the diameter of the head, the number of full and hollow achene was counted. To determine the achene yield and HI in the ripening stage, samples were taken from the stem exit point from the second to fourth rows by removing half a meter longitudinally from the beginning and end of the rows as a marginal effect. The heads were dried in the open air, and the achene was separated. After drying the achene, the GW of treatments and achene kernel percentage along with achene yield and other traits were determined. The oil percentage of the samples from the whole achene of each plot in the laboratory was estimated by the Soxhlet extractor method using petroleum ether solvent (ACS) (Weiss, 2000). All plots were free of pests, and diseases and weeds were completely controlled by hand during two stages of vegetative growth. By determining the evapotranspiration of the reference plant (ET<sub>0</sub>) by FAO Penman–Monteith method and plant coefficients (K<sub>c</sub>) at different stages of growth, the plant water requirement (ET<sub>Crop</sub>) in the test area was determined from Eq. 1 (Allen et al. 1998).

$$ET_{Crop} = K_c \times ET_o \tag{1}$$

Irrigation was performed using a polyethylene pipe, and the amount of water used in each irrigation was controlled using a meter. All experimental treatments had uniform irrigation during vegetative growth up to the budding stage. Total rainfall and daily evaporation statistics were

**Table 1** Monthly changes in air temperature and rainfall during the growing season in the years 2019–2020

Growing season months	Average temperature (°C)		Total rainfall (mm)		Absolute temperature (°C)			
	2019	2020	2019	2020	2019		2020	
					Min	Max	Min	Max
March–April	12.3	12.4	45.5	24.6	-8	29	-7	28
April–May	16.4	16.1	19.6	21.4	-4	32	-4	33
May–June	22.2	22.5	18.8	19.2	4.5	37.6	4.8	37.4
June–July	30.5	30.6	9.3	10.1	10	41	11	40
July–August	34.4	34.6	2.3	3.5	13	43	12	42
August–September	24.7	24.1	4.5	1.1	11	42	11	41
September–October	19.4	19.7	5.6	7.1	5	39	6	40

obtained from the meteorological station located at the test site (Table 1).

To determine the final yield, at the stage of full maturity of each experimental plot, 4 m<sup>2</sup> were harvested, and WPB including the dry weight of all above-ground organs and WPe were calculated by measuring the total achene weight of each treatment. Equations 2 and 3 are used to calculate WP<sub>C</sub> and HI (Viets 1962):

$$\text{WUE} = \frac{\text{EY}}{\text{ET}_{\text{Crop}}} \quad (2)$$

$$\text{HI} = \frac{\text{EY}}{\text{BY}} \times 100 \quad (3)$$

where WP<sub>C</sub> is crop water productivity in kg.m<sup>-3</sup>, EY is economic performance in kg.ha<sup>-1</sup>, ET<sub>Crop</sub> is water requirement or volume of water consumption in m<sup>3</sup>.ha<sup>-1</sup>, HI is HI in percentage, and BY is WPB in kg.ha<sup>-1</sup>.

To evaluate the tolerance of cultivars to drought stress conditions, the STI (Eq. 4) and the GMP (Fernandez et al. 2020; Souza et al. 2019) (Eq. 5) are used. Drought tolerance indices were calculated separately for each cultivar at two levels of severe and mild stress, and the results were compared with each other.

$$\text{STI} = \frac{Y_p \cdot Y_s}{(\bar{Y}_p)^2} \quad (4)$$

$$\text{GMP} = \sqrt{y_p \cdot y_s} \quad (5)$$

where Y<sub>p</sub> is the yield of each genotype in a stress-free environment, Y<sub>s</sub> is the yield of each genotype in a stressful environment, and  $\bar{Y}_p$  is the average yield of all genotypes in a stress-free environment.

To study the trend of leaf area changes and growth indices under the influence of different treatments, 40 days after planting, sampling was started and continued at intervals of 15 days. At each sampling stage, after removing the margins, five plants were harvested from the sampling lines, and their leaf area and dry weight were measured. Leaf area was measured using Eq. 5 in which S is leaf area, and L and W are the maximum length and width of green leaves, respectively.

$$S = 0.655(L \times W) - 0.00011(L \times W)^2 \quad (6)$$

To measure the relative water content of leaves, a few days after flowering, pieces with dimensions of approximately 2 cm<sup>2</sup> were prepared from five leaves, and the fresh weight of the samples was determined. The leaf pieces were then placed in distilled water for four hours in the dark at 10° C, and the weight of turpentine was calculated. Finally, the

dry weight of the samples, which were placed in an oven at 70° C for 72 h, was determined, and the relative water content (RWC) of the leaves is calculated using Eq. 7 (Sairam and Sarivastava 2001).

$$\text{RWC} = \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \times 100 \quad (7)$$

where RWC is relative leaf water content, FW is leaf fresh weight, DW is leaf dry weight, and TW is leaf saturation weight (leaf specimen weight). Duncan's multiple range test was implemented to compare the mean of measured data at the level of 5%.

## Statistical analysis

Statistical analysis of experimental data was performed using SAS and MSTATC software, and the comparison of data averages was performed using LSD test.

## Results

### Biophysical water productivity

WPb includes the total biomass of the plant shoots. As can be seen, the effect of irrigation and cultivar treatments on WPb is significant at the level of 5%. Based on this, the highest WPb among irrigation treatments was obtained from 90-mm irrigation with 13,457.3 kg.ha<sup>-1</sup>. Also, considering the significant effect of both experimental factors on the biological performance of sunflower, the comparison of means showed that by reducing water consumption and applying deficit irrigation, especially in the 150-mm treatment, the dry weight of shoots was reduced (Table 2). So that the lowest decrease compared to 90-mm irrigation was observed in the 150-mm irrigation phase with 9778.8 kg.ha<sup>-1</sup>.

### Harvest index

Based on the results of the analysis of variance of HI, the effect of irrigation and cultivar treatments was significant at the level of 5%. But the interaction effects of irrigation and cultivar were not significant at the 5% level (Table 3a, b). The results showed that the HI at 120- and 150-mm evaporation from the evaporation pan compared to the control treatment (irrigation after 90 mm evaporation from the pan) is 95.12% and 87.80% of the control HI, respectively. The highest HI was related to Fantasia and Oscar cultivars (0.43 and 0.42, respectively), and the lowest HI was related to Chiara, Shams, and Hisun 33 cultivars (0.40, 0.39, and 0.38, respectively). Among irrigation treatments, the highest HI (41%) was obtained from 90-mm irrigation (Table 2). With

**Table 2** Analysis of variance of WPb, WPe, HI, and WPe of sunflower cultivars under the influence of irrigation treatments during two years of research

Experimental factors	LAI	HI (%)	RWC	Head diameter (cm)	GW (gr)	Achene No./Head <sup>-1</sup>	Seed yield (kg ha <sup>-1</sup> )	Oil content (%)	Oil yield (kg ha <sup>-1</sup> )	WPB (kg ha <sup>-1</sup> )	WPe (kg ha <sup>-1</sup> )	Height (cm)	Stem diameter (mm)
<i>Irrigation</i>													
90 mm	4.7a	0.41a	71.16a	17.2a	74a	9088a	4716.7a	46.6a	1341.6a	13,457.3a	4854a	186.4a	2.45a
120 mm	4.5a	0.39b	67.28b	14.4b	61.55b	8214b	3928.5b	45.8b	1301.1a	11,984.4a	3313.2b	190.2a	2.1b
150 mm	4.1b	0.37b	62.11b	10.2c	54.77c	7986c	2258.2c	42.9c	1114.3b	9778.8b	2920.4c	165b	1.85c
<i>Hybrid</i>													
Chiara	4.4b	0.4b	77.3a	12.7c	59e	7396b	2892.4b	45.2a	1185.6b	11,198.5c	3274.7c	174.2c	2.1c
Hisun 33	4.3c	0.38b	75.8a	13.4b	60.25a	8742a	2951.4b	45.7b	1222.4b	12,131.4a	3671.3b	173.6c	2.2c
Oscar	4.5a	0.42a	76.8a	13.2b	62d	7347b	3087.5a	45.37b	1207.5b	11,694.3b	3527.6b	181.2a	2.3b
Fantasia	4.4b	0.43a	76a	13.35a	65.12a	8532a	3286.1a	46.8a	1369.2a	12,268.7a	4081.5a	181.1a	2.4a
Shams	4.4b	0.39b	76.2a	12.9ab	63.57b	8813a	3145.7a	46.5a	1245.1b	11,274.2c	3435.6b	180.3b	2.3b

In each column, the averages that have common letters are not significantly different at the 5% probability level based on Duncan's multiple range test

deficit irrigation, the HI decreased. The highest decrease was observed with 150-mm irrigation with a HI of 0.38.

**Economic water productivity**

In sunflower, seed weight, which is the result of the conversion of light energy, water, and nutrients into photosynthetic materials, is considered the WPe of the plant. According to the results of analysis of variance of WPe, the effect of irrigation treatments and cultivar is significant at the level of 5% (Table 3a, b). The highest WPe among irrigation treatments was obtained from 90-mm irrigation with 4854 kg ha<sup>-1</sup> (Table 3). With deficit irrigation, WPe decreased. The lowest reduction in WPe occurred in 120-mm irrigation with 3313.2 kg ha<sup>-1</sup>. Irrigation treatment of 150 mm with a WPe of 2920.4 kg ha<sup>-1</sup> was in the next place. Among sunflower cultivars, the highest WPe was obtained from the Fantasia cultivar with 4081.5 kg ha<sup>-1</sup> (Table 2). Hisun 33, Oscar, Shams, and Chiara cultivars with a WPe of 3671.3, 3527.6, 3534.6, and 32,274.7 kg ha<sup>-1</sup> were in the next place, respectively.

**Drought resistance**

The results of calculating GMP and STI indices in different irrigation conditions and ranking of genotypes are given in Table 4. High values of these indices indicate more tolerance of genotypes to water deficit stress and cause the selection of cultivars with high yield potential in both stress and non-stress environments. With 90-mm irrigation conditions, grain yield for Fantasia, Hisun 33, Oscar, Shams, and Chiara cultivars were 4552.9, 4219.7, 4178.1, 4038.4, and 3676.1 kg ha<sup>-1</sup>, respectively.

**Grain yield**

Analysis of variance showed that the effect of different levels of water deficit stress on grain yield was significant at the level of 1% probability. The interaction effect of water deficit stress with cultivar was also significant in terms of this trait (Table 3a, b). The results showed that grain yield at 120- and 150-mm evaporation from the evaporation pan compared to the control treatment (irrigation after 90-mm evaporation from the pan) was equal to 83.29% and 47.87% of the control grain yield, respectively (Table 3a, b). The results related to grain yield of different treatments show that with increasing irrigation intervals based on evaporation rate and decreasing its frequency, grain yield decreases. According to Table 3, the highest (4716.7 kg ha<sup>-1</sup>) and the lowest (22,258.2 kg ha<sup>-1</sup>) grain yield were obtained in the irrigation treatments after 90 (control) and 150 mm of evaporation, respectively. Examination of the means of interaction showed that all five

**Table 3** Analysis of variance of studied characteristics in oil sunflower cultivars

A							
S.O.V	df	MS					
		LAI	HI (%)	Head diameter	GW	Achene No.Head <sup>-1</sup>	RWC
Replication	3	0.523	0.11	0.192	27 ns	2,913,988*	331,654
Year (Y)	1	0.001	0.13	4.13	321	245,687.3	78.66
Error 1	3	0.469	0.14	0.894	0.97	1178.5	5.45
Irrigation(I)	2	1.96**	0.9**	168.369	868**	663,830**	42,327.8**
I* Y	2	0.01	0.7**	6.88	52.5	485,104	0.88
Error 2	3	0.23	0.11	3.21	1.28	224,573	18.21
Hybrid (H)	4	1.24**	1.1**	11.31	192.1**	199,159**	144.72**
H*Y	4	0.001	0.21	0.624	64.44**	574,698	33.88**
I*H	8	0.328*	0.51	0.069	157.3**	412,416	48.59*
I*H*Y	8	0.013	0.21	0.845	23.12	241,362.1	17.48
Error 3	72	0.17	0.12	3.41	11.50	303,097	13.48
C.V (%)		0.921	11.12	13.4	5.42	6.88	15.17
B							
S.O.V	df	MS					
		Seed yield	Oil content (%)	WPB (kg.ha <sup>-1</sup> )	WPE (kg.ha <sup>-1</sup> )	Height	Stem diameter (mm)
Replication	3	227,542	3.14	5,498,461.4**	273,512.4**	92.6	0.103
Year (Y)	1	2232.24	11.13	342.65	145.24	174.56	0.001
Error 1	3	16,419.2	4.94	541,765.12	52,177.6	79.45	0.07
Irrigation(I)	2	29,031,833**	108.26**	3,236,405.36**	814,982.3**	2976.8**	1.73**
I* Y	2	2878.457	5.24	342.65	2413.7	45.12	0.001
Error 2	3	213,487	7.65	2,501,657.24	63,362.3	156.37	0.007
Hybrid (H)	4	1,518,716**	7.43	1,164,605.6**	225,147**	732.4**	1.19**
H*Y	4	37,895.45	2.11	1857.08	1476.5	6.85	0.13
I*H	8	386,225**	32.4**	1,854,624.4 <sup>ns</sup>	141,460**	380.67	0.34
I*H*Y	8	8874.13	7.87	1857.08	1478.2	32.66	0.001
Error 3	72	18,576.12	10.23	2,132,241.16	74,125.2	111.86	0.13
C.V (%)		-29.8**	8.14	8.89	6.94	6.4	15.24

\*, \*\*are significantly different at  $\alpha=0.05$  and  $\alpha=0.01$ , respectively, and ns is non-significant

cultivars under irrigation of 150 mm produced the lowest grain yield with an average of 2258 kg.ha<sup>-1</sup> (Table 4).

## Discussion

The effect of water deficit stress on the WPb has been reported (Flénet et al. 1997; Taiz et al. 2017). The results of this study showed that mild (120 mm) and severe (150 mm) drought stress reduced the WPb of sunflower 89.05% and 72.66%, respectively. Flénet et al. (1997) found that mild and severe drought stress reduced the WPb of sunflower by 43% and 69%, respectively. In this regard, Fantasia and Hisun 33 cultivars (with a yield of 12.268 and 12.131 tons.ha<sup>-1</sup>, respectively) had the highest yield. Oscar, Shams, and Chiara

cultivars (11,694.3, 11,274.2, and 11,198.5, respectively) were not significantly different from each other (Table 2). Fantasia and Sun 33 cultivars seem to have higher dry matter accumulation than other cultivars. It can be concluded that Fantasia and Hisun 33 cultivars have more potential in material transfer from organs to seeds, which increases achene yield. In the present study, the biomass produced in the control treatment was higher than the other treatments. Discontinuation of irrigation at the budding stage caused a significant reduction in WPb. The WPb was lower in 150-mm treatment than other treatments. Decreased WPb is due to reduced dry matter accumulation, and since the plant still accumulates dry matter at a fairly high rate at the budding stage, cessation of irrigation at this stage causes extensive damage to the accumulated dry matter and ultimately WPb.

**Table 4** Comparison of mean grain traits under the influence of water deficit stress interaction and cultivar as well as drought indices of sunflower cultivars in different stages of irrigation and mean water-deficit stress conditions

Stress level	Hybrid	Height (cm)	LAI	HI (cm)	Seed yield (kg.ha <sup>-1</sup> )	Oil yield (kg.ha <sup>-1</sup> )	Oil content	GMP	STI
Irrigation after 90-mm evaporation	Chiara	176.3d	4.17c	0.21b	2892.4b	2101.4b	48.6a	3678.1	0.65
	Hisun 33	175.2d	4.28c	0.19b	2951.4b	2188.6b	48.54a	4219.7	0.76
	Oscar	188.5c	5.21a	0.24a	3087.5a	2145.7b	47.1b	4178.1	0.74
	Fantasia	191.6a	4.85b	0.25a	3286.1a	2214.4a	48.2a	4552.9	0.88
	Shams	190.24b	4.71b	0.22b	3145.7a	2194.5b	48.8a	4038.4	0.69
Irrigation after 120-mm evaporation	Chiara	172.7c	4.61b	0.19b	2287.2c	2055.3b	48.1b	3780.5	0.64
	Hisun 33	174.4c	4.22c	0.18b	2456a	2091.1a	48.14a	3994.2	0.74
	Oscar	188.1b	4.85a	0.2a	2203.8c	2084.4a	46.8a	3933.3	0.72
	Fantasia	189.6a	4.53b	0.22a	2557.5a	2115.7a	47.4b	4188.7	0.82
	Shams	189.25a	4.64b	0.18b	2321.5b	2044.6b	47.65a	3815.4	0.68
Irrigation after 150-mm evaporation	Chiara	171.3d	3.88c	0.17a	2160.5b	1300.3d	46.8c	3315.1	0.58
	Hisun 33	173.2c	4.18b	0.17a	2322a	1402.8b	47.83a	3475.7	0.71
	Oscar	171.2d	4.19b	0.16b	2116.1c	1385.5b	45.5b	3405.4	0.65
	Fantasia	175.2b	4.18b	0.17a	2351.2a	1546.4a	46.4a	3514.5	0.75
	Shams	178.78a	4.35a	0.16b	2217.4b	1346.9c	45.44b	3347.2	0.61

Reduction in cumulative dry matter or WPb by cessation of irrigation has also been reported in many experiments including Ghaffari et al. (2016) and Ghaffari et al. (2019). In the studies of Cox and Jollieff (1986), Mafouasson et al. (2018), Taiz et al. (2017), Aydin et al. (2019), and Soares et al. (2020), the intensity of sunflower dry matter production in the deficit irrigation treatment was significantly lower than the optimal irrigation conditions. Reduction in dry matter accumulation in deficit irrigation conditions of sunflower was reported also by Karam et al. (2007). By applying deficit irrigation at the beginning, middle of flowering, and early seed formation, they found that the final accumulation of dry matter in deficit irrigation of early flowering was less than other treatments of deficit irrigation and supplemental irrigation (De Carvalho et al. 2020).

The effect of water deficit stress on the HI has been reported (Soriano et al. 2004; Soares et al. 2016; and Birck et al. 2017). In the present study, with increasing water restriction, HI in treatments decreased. But this decrease was not statistically significant. The lack of significance of HI in different irrigation treatments can indicate that WPb and achene yield in different treatments have changed equally. Abul Hashem et al. (1998) studied the effect of drought stress on different stages of sunflower growth and concluded that the HI was not significantly affected in different stress treatments. The interaction of cultivar at stress levels was not significant (Tables 2, 3, 4). This indicates that with the occurrence of drought stress from the reproductive stage, the allocation (R3) of photosynthetic materials of the plant in the reproductive part (seeds) was less compared to the control (Wasaya et al. 2021). The reason for the decrease in HI is a greater reduction in achene yield than WPb in

water stress conditions, especially at the time of flowering (Ahmadpour et al. 2017).

The effect of water deficit stress on the WPe has been reported (Cox and Jullieff (1986); Fereres et al. (1986); D'Andria et al. (1995); Tarsitano et al. (2016); Ahmadpour et al. (2017); Soares et al. 2020; Weisany et al. 2021). The results of this study showed that mild (120 mm) and severe (150 mm) drought stress reduced the WPe of sunflower 68.25% and 60.16%, respectively. Due to the decrease in WPe with deficit irrigation, the decrease in achene yield, which is a part of it, can be justified. In the present study, sunflower response to deficit irrigation showed a decrease in grain yield by deficit irrigation. In this regard, Goksoy et al. (2004) obtained the highest achene yield from supplemental irrigation, deficit irrigation at a budding stage, and 3% deficit irrigation at the seed milking stage. They reported that grain yield decreased with decreasing amount and number of irrigations. So that the lowest grain yield was obtained from the treatment without irrigation, and water deficit at the time of flowering significantly reduced seed yield. Karam et al. (2007) reported a 20% and 15% reduction in seed yield with deficit irrigation in early and mid-sunflower flowering. They also did not observe a significant reduction in the result of deficit irrigation in the grain yield stage.

The effect of water deficit stress on drought resistance has been reported (Soriano et al. 2004; Birck et al. 2017; Taiz et al. 2017; Souza et al. 2019; Soares et al. 2020; Khodabinet al. 2021; Ullah et al. 2021; Wasaya et al. 2021). The results of this study showed that Fantasia cultivars and in the next rank, Hisun 33 cultivars based on all studied indices and in all stages of irrigation, as well as the average stress conditions, are the most tolerant cultivars to water deficit. This

can be related to the high yield potential of these cultivars. In general, in semiarid regions where the distribution of rainfall is non-uniform, yield stability is accepted as a more appropriate criterion for evaluating the response of genotypes to moisture stress compared to the yield under stress and favorable conditions. In this study, it seems that GMP and STI indices have good performance in determining potential drought cultivars. According to Fernandez (2020), the GMP index is stronger than the MP index, so it is less sensitive to threshold values if there is a large difference between performance under optimal conditions and performance under stress conditions. Accordingly, genotypes with high yields in both stress and non-stress environments can be recommended as drought-tolerant genotypes (Marengo et al. 2017; Shafiq et al. 2021). Karimi Kakhki et al. (2010) announced that among the various drought resistance indices including TOL, SSI, MP, GMP, and STI, the GMP and STI indices are more efficient in determining drought tolerance cultivars.

The effect of water deficit stress on the grain yield has been reported (Goksoy et al. 2004; Shafiq et al. 2021). Most researchers have considered the increase in water restriction during the plant reproductive period to be effective in reducing grain yield (Tarsitano et al. 2016; Taiz et al. 2017). Di Andrea et al. (1995) during a two-year study concluded that regulating the irrigation time of sunflower based on the most sensitive stages of life to deficit irrigation can be useful and effective in improving the grain yield of this plant. By doing this, the water required by the plant can be saved. Flénet et al. (1996) declared that the application of drought stress and increasing irrigation intervals in sunflower cultivation causes a severe decline in grain yield. Considering the significant interaction of irrigation and cultivar on grain yield at the level of 5% probability (Table 2) and their comparison (Table 4), Fantasia and Shams cultivars with irrigation levels of 90 and 120 mm have the highest values. This indicates the high potential of these cultivars in favorable moisture conditions and timely irrigation. It seems that balanced water consumption during different stages of development, including flowering and seeding, leads to improved sunflower seed yield (Shafiq et al. 2021). This is because, during these stages, two important components of grain yield (number of seeds per head and weight of 100 seeds) are formed. It seems that the lack of sufficient moisture during the budding to grading stage had the greatest effect on the grain yield of sunflower cultivars. In the present study, with increasing levels of deficit irrigation stress from 90 mm onward, grain yield decreased significantly, which could be due to a decrease in head diameter and consequently a decrease in the number of seeds as well as 100-achene weight and LAI (Table 2). The difference between sunflower cultivars in terms of the intensity of the reaction to irrigation restrictions can be attributed to the stability of these cultivars. Among the cultivars, the highest grain yield was obtained in Fantasia, Shams, and Oscar cultivars (3286.1,

3145.7, and 3087.5 kg.ha<sup>-1</sup>, respectively), and the lowest yield was observed in Hisun 33 and Chiara cultivars (2951.4 and 2892.4 kg.ha<sup>-1</sup>, respectively) (Table 4). The results of this experiment showed a decrease in both components of sunflower seed yield (1000-seed weight and number of seeds per head) under deficit irrigation conditions, which ultimately led to a more severe decrease in grain yield. This result is consistent with the reports of various researchers in this field (Mafouasson et al. 2018). In this regard, Ghaffari et al. (2020) in the study of physiological characteristics of sunflower seed yield stabilizing under deficit irrigation conditions found that grain yield decreased by about 40% due to drought stress. According to them, impaired grain size due to increased sterility of pollen grains (Reddy et al. 2003; Hussain et al. 2018) and photosynthetic organ damage due to premature leaf fall (Rauf and Sadaqat 2007) are the main reasons for reduced yield under drought stress. It seems that the lack of adequate moisture supply with increasing irrigation intervals during the stage of head to seed has had the most negative effect on the grain yield of sunflower cultivars. In general, based on the results, it can be said that sunflower growth in water-restricted conditions is a function of the balance between plant moisture status and photosynthetic level, which is affected by proline content, osmotic regulation, fluorescence, chlorophyll index, and leaf temperature, depending on the genotype. The participation of these components and their manifestation in the general growth of the plant reflects the tolerance and stability of production of each line in conditions of water deficit. Prolonged periods of severe drought stress in the soil, especially in water-sensitive growth stages, lead to a significant reduction in grain yield due to reduced evapotranspiration by closing pores, reduced carbon uptake, and reduced production and biomass (Demir et al. 2006). According to grain yield data, the recommendation of 120-mm irrigation treatment as the superior level in terms of this trait for all five cultivars is economically viable. Because sunflower plants have enough water (irrigation after 90 mm) and were set in the sensitive stage of head-to-pollination and relatively sensitive stages such as emergence to head view and pollination to physiological maturity of irrigations with a distance of 120-mm evaporation. Because Fantasia and Shams cultivars in this experiment performed better than other cultivars in terms of the number of seeds per head and 1000-seed weight, these factors could have a positive effect on increasing grain yield of these cultivars. Under conditions of sufficient moisture, tall sunflower hybrids had the highest grain yield. However, dwarf and early types of this plant are better adapted for areas with short and deficit water growth seasons (Angadi and Entz 2002; Shafiq et al. 2021). The Fantasia and Shams cultivars were superior in terms of grain yield compared to other cultivars, so it seems that the top two cultivars in terms of grain yield show such a situation due to high leaf area in the reproductive stage, rapid physiological growth, and sending sufficient photosynthetic



material to peripheral organs. The increase in grain yield in Fantasia and Shams cultivars was due to the increase in head diameter and the number of seeds per head. D'Andria et al. (1995) in the study of sunflower response to deficit irrigation reported a decrease in grain yield by deficit irrigation so that the lowest grain yield was obtained in severe treatment and water deficit at the flowering time significantly reduced seed yield. Rosales-Serna et al. (2004) stated that phenological changes in the plant play an important role in yield stability to increase drought resistance and reduce its destructive effects.

## Conclusion

The biophysical properties of the seed in sunflower cultivars are affected by the type of cultivars and the moisture conditions prevailing in the field so that by applying drought stress, the biophysical dimensions of the sunflower cultivars showed a significant decrease. The results showed that with increasing drought stress intensity from 90 (control) irrigation treatment to 120- and 150-mm evaporation from Class A evaporation pan, achene yield, harvest index, and drought tolerance of sunflower cultivars decreased. The greatest effect of drought was on leaf area index, grain yield, biophysical water productivity, and oil yield. The most sensitive morphological trait sensitive to water stress is the leaf area index which decreased significantly with increasing stress. Any delay in irrigation led to reduced yields by reducing the reproductive stage, producing fewer seeds, and the impossibility of transferring assimilates to fill the grains. In general, drought stress at different stages of growth reduced photosynthesis and reduced dry matter production. Also, the growth of sunflowers in deficit irrigation conditions is a function of the balance between plant moisture status and photosynthetic level. In general, the highest biophysical water productivity, harvest index, head diameter, grain yield, oil yield, and economic water productivity were obtained from 90-mm irrigation and then 120-mm irrigation. The highest biophysical water productivity among sunflower cultivars was from Fantasia and Hisun 33 cultivars. The highest economic water productivity was obtained from Fantasia and Hisun 33 cultivars. The highest harvest index was related to Fantasia, Oscar, and Hisun 33 cultivars, and the lowest harvest index was related to Shams and Chiara cultivars. In general, deficit irrigation affected yield, harvest index, crop water productivity, and drought tolerance of sunflower cultivars. The highest biophysical water productivity was obtained from Fantasia, Hisun 33, and Oscar cultivars.

Fantasia cultivar, due to the higher number of leaves and diameter of the head, had more ability in photosynthesis and seed production per head, and since its 1000-seed weight was superior to other cultivars, it had higher grain yield. These characteristics eventually led to a significant increase

in the economic water productivity of sunflowers. Furthermore, due to the simultaneous decrease in leaf area index and grain yield, the harvest index also showed a significant decrease due to stress. Simultaneously with the decrease in harvest index, the percentage of oil also decreased significantly. Considering that the Fantasia cultivar in this experiment performed better than other cultivars in terms of harvest index, head diameter, grain yield, percentage, oil yield, biophysical water productivity, and economic water productivity, it can be recommended for Isfahan climate. Considering that sunflower is used as a marginal plant in most of the agricultural areas of Isfahan, the initial suggestion is to collect the seeds of local masses of this plant in the region and compare them with commercial cultivars.

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## Declarations

**Conflict of interest** There is no conflict of interest among authors.

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