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Evaluation of Sustained and Regulated Deficit Irrigation Effects on the Performance of a Field-Grown Olive Cultivar 'Zard' (*Olea europaea* L.) under Semi-Arid Conditions

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ABSTRACT

Deficit irrigation as a water-saving strategy for olive trees in semi-arid regions of Iran has received limited research attention. This study addressed the current gap in such research by evaluating the effects of deficit irrigation on the 'Zard' olive cultivar over two years. Six irrigation regimes were compared, i.e., control (C) (100% of crop evapotranspiration (ETc) throughout the growing season), Sustained Deficit Irrigation 1 (SDI1) (75% ETc throughout the growing season), Sustained Deficit Irrigation 2 (SDI2) (50% ETc throughout the growing season), Regulated Deficit Irrigation 1 (RDI1) (75% ETc from 4 to 9 weeks after full bloom), Regulated Deficit Irrigation 2 (RDI2) (50% ETc from 4 to 9 weeks after full bloom), and Regulated Deficit Irrigation 3 (RDI3) (50% ETc for 2 weeks before harvest). Sustained deficit irrigation (SDI1 and SDI2) and RDI2 negatively affected flower count and perfect flower formation (except RDI3) in the second year. Fruit set was not significantly affected by RDI1 and RDI3 compared to the control, but SDI2 significantly reduced both fruit weight and pulp-to-pit ratio. Fruit yield and oil content were negatively affected by SDI1, SDI2, and RDI2 compared to the control. However, RDI1 and RDI3 showed no significant difference compared to the control in these aspects. Regulated deficit irrigation (RDI1 and RDI3) with a minor reduction in water supply is recommended for semi-arid regions, excluding Mediterranean climates, to achieve high fruit yield and oil content while conserving water.

Introduction

The Olive tree (*Olea europaea* L.) is a type of evergreen tree that can withstand long periods of drought (Bacelar et al., 2006; Fernandez, 2014). Olive tree is considered as an important fruit in arid regions (Molina-Moral et al., 2022). Olive tree is typically grown for oil production in water scarcity regiones (Tognetti et al., 2006; Fernandez, 2014). The production of olives in Iran is economically significant due to its favorable growing conditions in some areas and the demand for olive oil and table olives. The cultivated area of olive orchards in Iran is about 60,000 ha with a production about 130,000 t (Ministry of Agriculture Newsletter, 2021). The olive global cultivated area and production are higher than 10 million ha with 23 million t, respectively (FAO, 2021). The growth and yield of fruit depend heavily on water availability. Irrigation is essential in areas where water is scarce, especially for valuable crops such as fruits. The main challenge for olive orchards in Iran is the limited water supply due to long terms of drought and water scarcity. To optimize water use, it is crucial to employ effective methods such as cultivating tolerant varieties (Arzani and Arji, 2000; Calvo-Polanco et al., 2019), determining the best time for irrigation (Gholami et al., 2016; Molina-Moral et al., 2022), using mulch (Gholami et al., 2013a; Gholami and Zahedi, 2020), and applying anti-transpiration growth regulators (Gholami et al., 2013b; Ouledali et al., 2019) to reduce water consumption.

Utilizing a deficit irrigation strategy can be a beneficial approach in horticultural fruit production by enhancing water use efficiency. Implementing deficit irrigation during drought- less sensitive growth stages in compare to full irrigation improve water use efficiency (Iniesta et al., 2009; Dell'Amico et al., 2012; Rapoport et al., 2012; Giron et al., 2015; Ahumada-Orellana et al., 2019). Applying deficit irrigation during the appropriate stages of plant growth can lead to reduced vegetative growth, better fruit quality, and increased economic profits (Tognetti et al., 2006; Gholami and Zahedi, 2021). When water is scarce during the flowering stages, there is a decline in flowering, inflorescences, and perfect flowers (Rapoport et al., 2012; Tadayon and Hosseini, 2022). During the flowering stage, it's best to keep plants well-watered until pit hardening begins. This helps fruit set and cell processes. Avoiding water deficiency during this stage is essential to prevent reduced fruit set and smaller fruit sizes. However, during the pit hardening period which lasts about six to seven weeks, it's an excellent strategy to use deficit irrigation to conserve and optimize water usage. This approach has been recommended by experts such as Nikbakht et al. (2011), Dell'Amico et al. (2012), and Rapoport et al. (2012). In regiones where water is scarce, deficit irrigation can be a cost-effective way to maintain orchard production, even if the amount of production is lower compared to orchards with higher water consumption (Lavee and Wodner, 1991; Rapoport and Costagli, 2004; Tognetti et al., 2006; Costa et al., 2007; Iniesta et al., 2009; Moriana et al., 2012; Moriana et al., 2012; Goncalves et al., 2020; Fernandez et al., 2020). Olive trees are particularly vulnerable to drought stress during their phenological stages, but they are more tolerant during the pit hardening stage. Although drought stress can affect the oil accumulation stage. The oil's quality and quantity can be affected by the amount of water applied to olive trees during different growth stages (Tognetti et al., 2005; Grattan et al., 2006; Zeleke et al., 2012; Grijalva-Contreras et al., 2013; Rosecrance et al., 2015; Siakou et al., 2021).

Previous research (Patumi et al., 1999; Gomes-Rico et al., 2007; Nikbakht et al., 2011; Rosecrance et al., 2015) suggested that applying mild water deficit have a positive impact on the yield, oil content, and quality of olive trees. Conversely, implementing severe water deficit can significantly decrease growth and lead to a reduction in yield and product quality (Costa et al., 2007; Moriana et al., 2012; Chartzoulakis and Bertaki, 2015; Gucci et al., 2019; García et al., 2020). A comparison among two regulated deficit irrigation strategies and sustained deficit irrigation was done by Arbizu-milagro et al. (2023) exhibit that moderate regulated deficit irrigation was more benefit in olive fruit yield and oil production. Olive fruit yield was affected by sustained and deficit irrigation negatively but olive oil accumulation was not affected (Iniesta et al., 2009). The Zard olive cultivar is suitable for cultivation in Iran (FAO, 2008). However, there have been limited studies on the effects of deficit irrigation on Iranian olive varieties. Therefore, this project aimed to investigate and compare the impact of regulated and sustained deficit irrigation strategies on flower and fruit reproduction characteristics of the Zard olive cultivar in the west of Iran.

Materials and Methods

Experimental site and plant materials

This research was conducted for two consecutive years from 2015 to 2016 in the Gilan-e Gharb (longitude: 45º 56´ E, latitude: 34º 8´ N, altitude: 890 m) of Kermanshah province, Iran. The study area had an average temperature of 20.47 °C, an average annual maximum temperature of 44.16 °C, and an average precipitation of 432 mm. To examine the impact of deficit irrigation in 2015, treatments were implemented from July 2014. For this experiment, self-rooted twelve-year-old Zard olive trees were used as the plant material. We carefully analyzed both the soil and water used. The soil had a sandy-clay texture and a pH level of 7.5. The water had a pH level of 7.1 and an electrical conductivity of 1.2 ds m^{-1}.

Experimental design and treatment applications

This experiment was conducted using a completely randomized block design (CRBD) with three replications. Six irrigation treatments were applied, varying in both the volume and timing of water application throughout the olive growing season. The treatments were delivered using a drip irrigation system from May 15, 2014, to October 31, 2016. The field layout consisted of 180 mature olive trees with a canopy cover exceeding 50%, planted at a spacing of 6 × 6 meters. Each experimental unit comprised 10 trees.

Irrigation Treatments

The six irrigation treatments were defined as follows:

Control (C): Full crop water requirement (ETc) applied throughout the growing season.

Sustained Deficit Irrigation 1 (SDI1): 75% of ETc applied throughout the season.

Regulated Deficit Irrigation 1 (RDI1): 75% of ETc applied during the period between 4 and 9 weeks after flowering.

Sustained Deficit Irrigation 2 (SDI2): 50% of ETc applied throughout the season.

Regulated Deficit Irrigation 2 (RDI2): 50% of ETc applied between 4 and 9 weeks after flowering.

Regulated Deficit Irrigation 3 (RDI3): 50% of ETc applied during the final two weeks before harvest.

Irrigation scheduling was performed every 3 d based on the calculated crop evapotranspiration (ETc). The irrigation volume for each treatment was adjusted accordingly and monitored using volumetric water meters installed at each plot. All other cultural practices, such as pruning, fertilization, and pest management, were applied uniformly across all treatments.

Estimation of Crop Water Requirement

The crop water requirement (ETc) was calculated based on the FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998) using the following equation:

$$ETc = Kc \times Kr \times ETo$$

Where:

ETc is the crop evapotranspiration (mm d^{-1}),

Kc is the crop coefficient, obtained from FAO guidelines,

Kr is the ground cover coefficient, considered as 1.0 due to the mature canopy coverage (>50%) (Fereres et al., 1982),

ETo is the reference evapotranspiration (mm d^{-1}).

Calculation of Reference Evapotranspiration (ETo)

The reference evapotranspiration (ETo) was calculated using CropWat software, a decision-support tool developed by the Food and Agriculture Organization (FAO). CropWat implements the FAO Penman-Monteith equation, which is considered the standard method for estimating ETo. The equation is as follows:

$$\text{ETo} = \frac{0.408\Delta(\text{Rn} - \text{G}) + \gamma(\frac{900}{\text{T} + 273})\text{u2}(\text{es} - \text{ea})}{\Delta + \gamma(1 + 0.34\text{u2})}$$

Where:

ETo = Reference evapotranspiration (mm d^{-1})

Rn = Net radiation at the crop surface (MJ m^{-2} d^{-1})

G = Soil heat flux density (MJ m^{-2} d^{-1})

T = Mean daily air temperature at 2 m height (°C)

u_2 = Wind speed at 2 m height (m s^{-1})

es = Saturation vapor pressure (kPa)

ea = Actual vapor pressure (kPa)

(es - ea) = Vapor pressure deficit (kPa)

Δ = Slope of the saturation vapor pressure curve (kPa $°C^{-1}$)

γ = Psychrometric constant (kPa $°C^{-1}$)

Daily meteorological data, including maximum and minimum temperatures, relative humidity, sunshine hours, and wind speed, were obtained from the Gilan-e Gharb synoptic weather station. This data was entered into CropWat, which calculated daily ETo values for the period between May 15 (end of the rainy season) and early November (start of the following rainy season) (Table 1).

Table 1. Monthly irrigation water applied (m^3 ha^{-1}).

Month	2015	2016
(May)	1300.92	1208.69
(Jun)	1445.49	1369.31
(Jul)	1569.48	1787.28
(Aug)	1639.38	1508.76
(Sep)	1271.96	1275.71
(Oct)	893.26	861.69
Total	8120.49	8011.45

Measured traits

The study measured various reproductive traits, including the number of flowers per inflorescence, perfect flower and final fruit set, and fruit traits such as fruit weight, pit weight, pulp/pit ratio, fruit yield per tree, and percentage of dry matter. Additionally, the study also measured oil content, including the oil percentage in fresh and dry matter, oil yield, and oil fatty acid composition.

During the peak blooming period, when about 75% of the flowers had opened according to Sanz-Cortez et al. (2002), we randomly selected 100 clusters of each replication (10 trees) and counted the total number of flowers in each cluster. We then determined the number of complete flowers. To evaluate the final fruit set, four branches were chosen in each direction of the tree and the total number of fruits counted 40 d after pollination based on the I.O.O.C (2002) method. To determine the total number of flowers/inflorescences, we collected 100 flower clusters from around each tree, at a height of 1.5 m above the ground.

Fruit characteristics

We measured the weight of 40 randomly selected fruits in harvesting time from each experimental unit (10 trees) using digital scales. To determine the weight of the pulp and pit, we separated the pulp from the pit with a knife and then weighed them. We dried the pulp and pits in the oven at 72 °C for 48 h until their weight became stable (I.O.O.C., 2002) to calculate the dry weight and percentage of dry matter. We also measured the pulp-to-pit ratio based on 40 fruits.

Oil extraction and determination

To determine the fruit yield of each tree, we harvested fruit from each one. We randomly selected twenty fruits from a half kilogram of fruit and dried them in an oven at 72 °C for 24 to 48 h. Once dried, we crushed the dried fruits using a mill and extracted the oil using the Soxhlet method with diethyl ether solvent (I.O.O.C. 2002). To extract oil from the fruits at harvest time, we used a laboratory mechanical oil extraction model (Oliomio GOLD France). The extracted oil was used for qualitative analysis.

Oil quality determination

The Fatty acid profile was determined based on European Official Methods of Analysis (EEC 1991). One hundred milligrams of oil were dissolved in 10 mL n-hexane with 100 μL of 2 N methanolic potassium hydroxide solution. The sample was shaken gently for 30 s and centrifuged for 15 min. For chromatographic analysis, the supernatant was separated and utilized. Other indicators such as peroxide number, acidity, spectrophotometric index (*k270, k232*), and oil iodine number were determined according to EU rules (EEC, 1991).

Statistical analysis

Statistical analysis and analysis of variance were performed using SAS software (version 9/1 of North Carolina) and a comparison of the means was done using Duncan's multi-domain test.

Results

Effect of deficit irrigation on flower reproductive traits

The collected data of flower characteristics and fruit set are presented in Table 2 during 2015 and 2016. Deficit irrigation treatments had a significant impact ($P < 0.05$) on the number of flowers per inflorescence. However, the number of flowers per inflorescence was not affected by the RDI3 treatment (50% Reduced Deficit Irrigation two weeks before harvest) in 2015 or 2016 when compared to the control treatment. Compared to other treatments, the SDI2 (50% water deficit) and SDI1 (25% water deficit) treatments more effectively decreased the number of flowers per inflorescence, a result closely related to the degree of water stress. The number of perfect flowers declined due to heightened water stress in both 2015 and 2016, as shown in Table 2. The control trees exhibited better-quality flowers in both years. All treatments, except for RDI3, had a significant ($P < 0.05$) decrease in the number of perfect flowers. In 2015, alternate bearing caused a decline in the number of perfect flowers when compared to 2016.

While fruit set varied significantly ($P < 0.05$) among treatments in 2016, this was not the case in 2015 (Table 2). Notably, the SDI2, RDI1, and SDI1 treatments led to a significant decrease in fruit set ($P < 0.05$) in comparison to the remaining treatments.

Table 2. Number of flowers in an inflorescence, perfect flowers number, and fruit set in 'Zard' olive trees under six different irrigation treatments.

Treatments	Flower/Inflorescence		Perfect Flower No.		Fruit set %	
	2015	2016	2015	2016	2015	2016
C	32.00^{a}	34.00^{a}	5.00^{a}	23.33^{a}	0.50^{a}	2.83^{a}
SDI1	27.33^{b}	19.33^{c}	2.43^{c}	17.33^{b}	0.50^{a}	2.33^{b}
SDI2	24.00^{d}	14.00^{d}	2.00^{d}	10.67^{d}	0.43^{a}	1.00^{d}
RDI1	29.67^{a}	24.67^{b}	3.33^{b}	17.67^{b}	0.42^{a}	2.93^{a}
RDI2	26.67^{c}	24.00^{b}	2.33^{cd}	15.00^{c}	0.51^{a}	1.67^{c}
RDI3	31.33^{a}	33.33^{a}	4.67^{ab}	23.67^{a}	0.39^{a}	2.73^{a}

Different letters in each column indicate significant differences at ($P \leq 0.05$) by Duncan's test. C (100% ETc) control irrigation treatment during the growing season, SDI1 (75% ETc) irrigation during the whole growing season, SDI2 (50% ETc) irrigation throughout the growing season, RDI1 (75% ETc) irrigation 4 to 9 weeks after full bloom, RDI2 (50% ETc) irrigation 4 to 9 weeks after full bloom and RDI3 (50% ETc) irrigation 2 weeks before harvest.

Fruit weight, pit weight, pulp weight, and pulp/pit ratio

Fruit weight was significantly ($P < 0.05$) affected by different irrigation treatments in 2015 and 2016 (Fig. 1). In 2015, fruit weight was significantly reduced only under sustained deficit irrigation treatments (SDI1 and SDI2) compared to the control and regulated deficit irrigation treatments (RDI1, RDI2 and RDI3). In 2016, fruit weight was significantly reduced under sustained deficit irrigation treatments (SDI1 and SDI2) and regulated deficit irrigation treatment (RDI2) compared to the control and others regulated deficit irrigation treatments (RDI1 and RDI3) (Fig. 1).

Different sustained and regulated deficit irrigation treatments did not significantly affect pit weight compared to the control treatment in 2015 and 2016. However, they did have significant effects on pulp weight at a statistical probability level ($P < 0.05$). In 2015, sustained deficit irrigation (SDI2 and SDI1) treatments resulted in a more pronounced reduction in pulp weight compared to the control and regulated deficit irrigation (RDI1, RDI2 and RDI3) treatments. Subsequently, in 2016, a significant reduction in pulp weight was evident in SDI2, SDI1, and RDI2. In 2015, the sustained deficit irrigation treatments (SDI1 and SDI2) resulted in a significant ($P < 0.05$) reduction of the pulp/pit ratio compared to other treatments. In addition, the pulp/pit ratio declined in RDI treatments relative to fully irrigated trees and RDI3 (two weeks before harvest) in 2016 (Table 3).

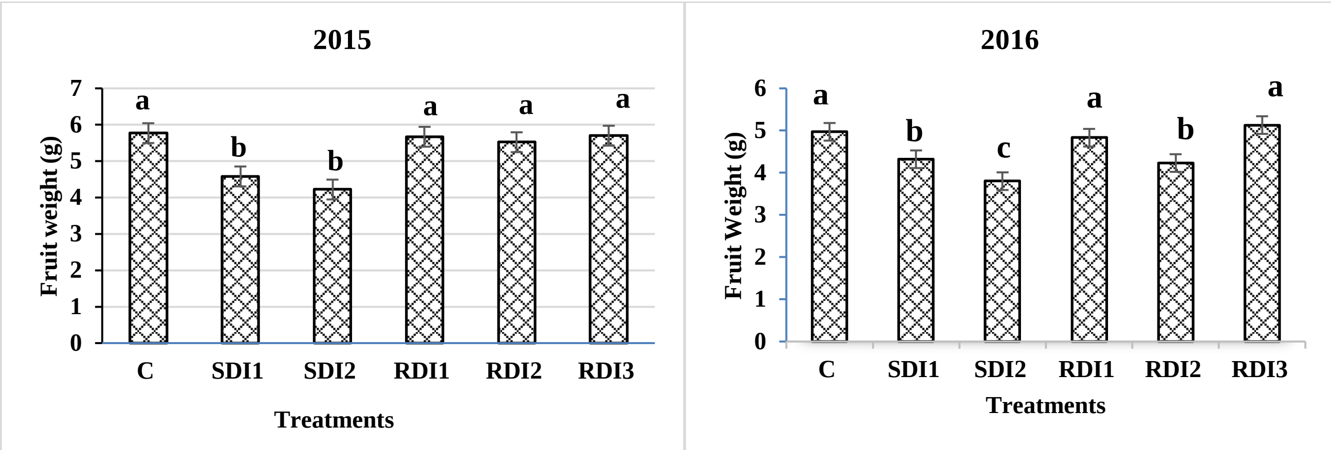

Fig. 1. Mean fruit weight of different treatments. Different letters indicate significant differences at ($P < 0.05$) by Duncan's test. (C) (100% ETc) = control irrigation treatment during the growing season, SDI1 (75% ETc) irrigation during the whole growing season, SDI2 (50% ETc) irrigation throughout the growing season, RDI1 (75% ETc) irrigation 4 to 9 weeks after full bloom, RDI2 (50% ETc) irrigation 4 to 9 weeks after full bloom and RDI3 (50% ETc) irrigation 2 weeks before harvest.

Table 3. Pit weight, pulp weight, and pulp/pit ratio in 'Zard' olive trees under six different irrigation treatments.

Treatments	Pit weight (g)		Pulp weight (g)		Pulp/Pit Ratio	
	2015	2016	2015	2016	2015	2016
C	0.87[a]	0.85[a]	4.90[a]	4.12[a]	5.63[a]	4.85[a]
SDI1	0.82[a]	0.84[a]	3.76[b]	3.48[b]	4.59[b]	4.14[c]
SDI2	0.86[a]	0.83[a]	3.36[c]	2.97[c]	3.91[c]	3.58[d]
RDI1	0.85[a]	0.87[a]	4.82[a]	3.96[a]	5.67[a]	4.55[b]
RDI2	0.82[a]	0.84[a]	4.70[a]	3.39[b]	5.73[a]	4.04[c]
RDI3	0.85[a]	0.83[a]	4.85[a]	4.30[a]	5.71[a]	5.18[a]

Different letters in each column indicate significant differences at ($P < 0.05$) by Duncan's test. C (100% ETc) control irrigation treatment during the growing season, SDI1 (75% ETc) irrigation during the whole growing season, SDI2 (50% ETc) irrigation throughout the growing season, RDI1 (75% ETc) irrigation 4 to 9 weeks after full bloom, RDI2 (50% ETc) irrigation 4 to 9 weeks after full bloom and RDI3 (50% ETc) irrigation 2 weeks before harvest.

Fruit dry matter and oil content

The two-year study revealed that fruit dry matter significantly increased ($P < 0.05$) in RDI1 and RDI3 compared to other deficit irrigation and control treatments in both 2015 and 2016 (Table 4). The oil content in fruit fresh and dry matter basis was not significantly affected by the regulated deficit irrigation treatments (RDI1 and RDI3) compared to the control treatment. However, it showed a significant decrease with sustained deficit irrigation (SDI1 and SDI2) and regulated deficit irrigation (RDI2) treatment (Table 4). The oil content in the control treatment was 14.83 and 14.55% for the years 2015 and 2016, respectively. Meanwhile, the lowest oil content in the fruit fresh matter was 9.95 and 10.98% in the sustained deficit irrigation (SDI1 and SDI2) treatment, for 2015 and 2016, respectively. The highest oil content (fresh and dry weight basis) was obtained by regulated deficit irrigation (RDI3, two weeks of water stress before harvesting) in compare to others treatments (Table 4). Additionally, a positive linear regression (R2= 0.80) between oil content and fruit dry matter was observed, as depicted in Figure 2.

Table 4. Fruit dry matter, oil content (in fresh and dry matter) in 'Zard' olive trees under six different irrigation treatments.

Treatments	Dry Matter%	Oil% on Fresh Matter	Oil% on Dry Matter

	2015	2016	2015	2016	2015	2016
C	36.17[c]	35.39[c]	14.83[ab]	14.55[a]	37.67[a]	37.00[a]
SDI1	37.43[b]	37.20[b]	12.63[c]	11.53[b]	33.47[b]	30.67[c]
SDI2	37.32[b]	37.00[b]	9.95[d]	10.98[c]	27.50[c]	24.00[d]
RDI1	39.4[a]	38.54[a]	14.33[ab]	14.27[a]	36.43[a]	34.17[b]
RDI2	37.87[b]	37.75[b]	12.76[c]	11.41[b]	30.77[c]	29.00[c]
RDI3	39.53[a]	38.77[a]	15.40[a]	15.38[a]	38.17[a]	37.50[a]

Different letters in each column indicate significant differences at ($P < 0.05$) by Duncan's test. C (100% ETc) control irrigation treatment during the growing season, SDI1 (75% ETc) irrigation during the whole growing season, SDI2 (50% ETc) irrigation throughout the growing season, RDI1 (75% ETc) irrigation 4 to 9 weeks after full bloom, RDI2 (50% ETc) irrigation 4 to 9 weeks after full bloom and RDI3 (50% ETc) irrigation 2 weeks before harvest.

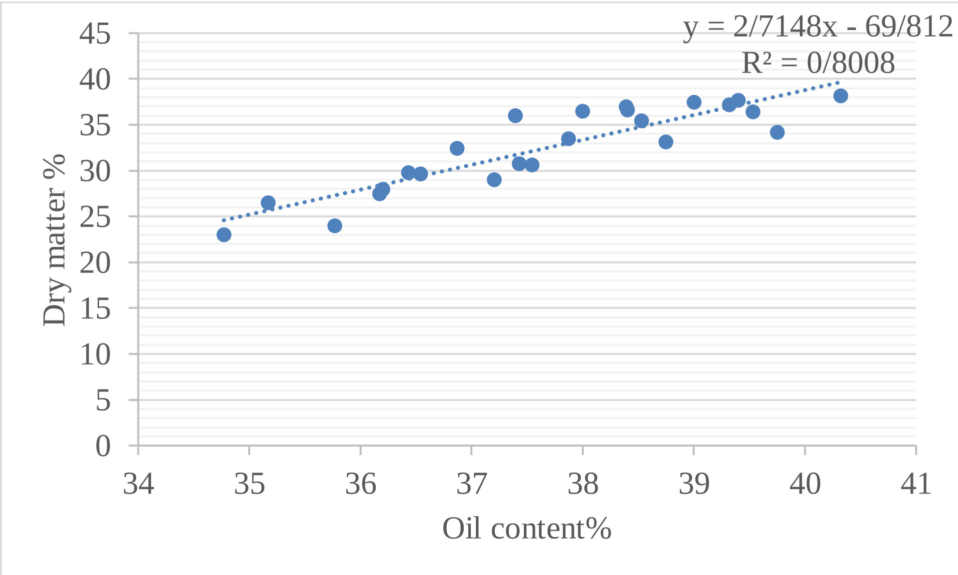

Fig. 2. Relationship between oil production and fruit dry matter in different irrigation treatments.

Fruit yield per tree (kg)

Under control conditions, the fruit yield per tree was 8.07 kg in 2015 and 24.17 kg in 2016. However, when subjected to sustained deficit irrigation (SDI1 and SDI2), the fruit yield decreased significantly in both years. The yield was also reduced significantly in the severe stress treatment (RDI2) under regulated deficit irrigation conditions. However, RDI1 and RDI3 did not show any decrease in fruit yield compared to the control in 2015 and 2016 (Fig. 3).

The fatty acid compositions of olive oil under different irrigation treatments are given in Table 5. Myristic acid (C14:0) slightly increased by deficit irrigation intensity (Table 5). The application of 50% deficit irrigation caused a further increase in myristic acid (Table 5). Palmitic acid (C16:0) slightly decreased with more stress treatments, but the Palmitoleic (C16:1) amount increased with water stress treatments. Stearic (C18:0) and Linoleic acid (C18:2) showed significantly higher values under water stress treatments. Oleic (C18:1) significantly decreased under sustained deficit irrigation in comparison to full irrigation and RDI treatments. There were no significant differences in Linolenic (C18:3), Arachidonic (C20:0), and Eicosenoic (C20:1) among different treatments (Table 5). Peroxide values, Free fatty acids, Iodine Index, K270, and K232 are presented in Table 6. There were no significant differences in mentioned oil qualitative parameters among sustained, deficit irrigation, and control treatments.

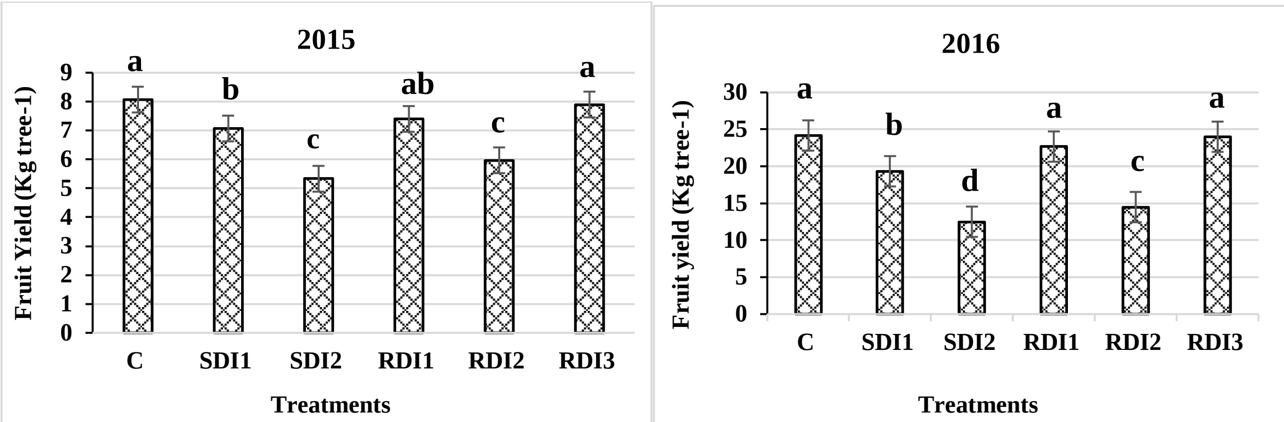

Fig. 3. Fruit yield under different irrigation treatments in 2015 and 2016. Different letters indicate significant differences at ($P < 0.05$) by Duncan's test. (C) (100% ETc) = control irrigation treatment during the growing season, SDI1 (75% ETc) irrigation during the whole growing season, RDI1 (75% ETc) irrigation 4 to 9 weeks after full bloom, SDI2 (50% ETc) irrigation throughout the growing season, RDI2 (50% ETc) irrigation 4 to 9 weeks after full bloom and RDI3 (50% ETc) irrigation 2 weeks before harvest.

Table 5. Fatty acid composition of olive oils (%) under different irrigation treatments in 'Zard' olive trees under six different irrigation treatments.

Fatty acid	**Irrigation treatments**					
	C	**SDI1**	**SDI2**	**RDI1**	**RDI2**	**RDI3**
Myristic acid (14:0)	0.03^{c}	0.04^{b}	0.05^{a}	0.04^{b}	0.05^{a}	0.03^{c}
Palmitic acid (16:0)	16.46^{a}	14.86^{b}	14.63^{c}	15.86^{a}	15.33^{b}	16.04^{a}
Palmitoleic acid (16:1)	2.40^{b}	3.45^{a}	3.42^{a}	3.01^{ab}	3.31^{ab}	2.24^{b}
Stearic acid (18:0)	4.22^{b}	4.94^{a}	5.08^{a}	4.19^{b}	4.81^{ab}	4.37^{b}
Oleic acid (18:1)	68.18^{a}	64.15^{c}	65.39^{c}	69.23^{a}	66.70^{b}	70.12^{a}
Linoleic acid (18:2)	5.44^{c}	9.15^{a}	9.04^{a}	5.21^{c}	7.09^{b}	5.60^{c}
Linolenic acid (18:3)	0.55^{a}	0.61^{a}	0.67^{a}	0.53^{a}	0.52^{a}	0.51^{a}
Arachidonic acid (20:0)	0.49^{a}	0.46^{a}	0.48^{a}	0.42^{a}	0.52^{a}	0.39^{a}
Eicosenoic acid (20:1)	0.39^{a}	0.41^{a}	0.35^{a}	0.34^{a}	0.41^{a}	0.35^{a}

Different letters in each row indicate significant differences at ($P \leq 0.05$) by Duncan's test.
C (100% ETc) control irrigation treatment during the growing season, SDI1 (75% ETc) irrigation during the whole growing season, RDI1 (75% ETc) irrigation 4 to 9 weeks after full bloom, SDI2 (50% ETc) irrigation throughout the growing season, RDI2 (50% ETc) irrigation 4 to 9 weeks after full bloom and RDI3 (50% ETc) irrigation 2 weeks before harvest.

Table 6. Quality parameters of olive oil under different irrigation treatments in 'Zard' olive trees under six different irrigation treatments.

Quality parameters	**Irrigation treatments**					
	C	**SDI1**	**SDI2**	**RDI1**	**RDI2**	**RDI3**
Peroxide value (meq O_2 kg^{-1})	8.90^{a}	9.59^{a}	10.17^{a}	8.52^{a}	8.87^{a}	8.03
Free fatty acids (% oleic acid)	0.77^{a}	0.88^{a}	0.73^{a}	0.78^{a}	0.83^{a}	0.90^{a}
Iodine Index	74.49^{a}	78.68^{a}	79.56^{a}	75.57^{a}	77.03^{a}	76.29^{a}
K270	0.09^{a}	0.12^{a}	0.13^{a}	0.08^{a}	0.10^{a}	0.08^{a}
K232	1.25^{a}	1.31^{a}	1.39^{a}	1.22^{a}	1.28^{a}	1.23^{a}

Different letters in each row indicate significant differences at ($P \leq 0.05$) by Duncan's test. C (100% ETc) control irrigation treatment during the growing season, SDI1 (75% ETc) irrigation during the whole growing season, SDI2 (50% ETc) irrigation throughout the growing season, RDI1 (75% ETc) irrigation 4 to 9 weeks after full bloom, RDI2 (50% ETc) irrigation 4 to 9 weeks after full bloom and RDI3 (50% ETc) irrigation 2 weeks before harvest.

Discussion

Water deficit has a negative impact on the yield and yield components of olive trees (Fernandes-Silva et al., 2010; Beya-Marshall et al., 2018). Olive trees experience a decrease in flower formation in inflorescence, perfect flower, and fruit set due to water deficit, according to Trentacoste et al. (2019). Compared to the control, regulated and sustained deficit irrigation significantly reduced both flowers per inflorescence and complete flowers (Table 2). Specifically, in 2015, SDI2 (50% deficit) and SDI1 (25% deficit) decreased flowers per inflorescence by 25 and 14.6%, respectively, while in 2016, the reductions were 58.8% and 43.1%. RDI2 (50% deficit) and RDI1 (25% deficit) reduced flowers per inflorescence by 16.7 and 7.3% in 2015, and 29.4 and 27.4% in 2016. Conversely, RDI3 (deficit irrigation two weeks before harvest) showed no significant impact on flower count per inflorescence in either year. Sustained deficit irrigation (SDI2 and SDI1) in 2015 resulted in 60 and 51.4% reductions in perfect flowers, and 54.3 and 25.7% in 2016 respectively. Regulated Deficit Irrigation (RDI2 and RDI1) in 2015 reduced perfect flowers by 53.4 and 33.4%, and by 35.7 and 24.3% in 2016 respectively. The reduction in both floral traits correlated with the severity of water stress, with SDI2 and SDI1 showing the most pronounced effects (Table 2).

The results clearly shows that the severity and duration of water stress significantly impact the reduction in flowering. Sustained deficit irrigation (SDI), being a continuous stress, likely exerts a more prolonged and intense impact on the physiological processes mentioned above compared to regulated deficit irrigation (RDI), where water is withheld during specific, less sensitive periods. The fact that RDI applied two weeks before harvest had no significant impact suggests that the critical period for flower development is earlier in the reproductive cycle. The study's findings align with the cited research (Moriana et al., 2012; Hueso et al., 2021; Rapoport et al., 2012; Nikbakht et al., 2011), reinforcing the well-established sensitivity of flowering stages to water availability in various plant species, including olive trees. In essence, the reduction in flowering observed under deficit irrigation is a complex response involving hormonal signaling, carbon allocation, nutrient dynamics, and developmental regulation, all of which are negatively impacted by the lack of sufficient water. The degree of impact is directly related to the intensity and duration of the water stress.

Fruit set is a sensitive stage to water stress (Fernandes-Silva et al., 2018). During the study, it was discovered that sustained deficit irrigation had a greater impact on reducing fruit set compared to deficit RDI and full irrigation. In particular, sustained deficit irrigation (SDI2 with 50% deficit irrigation and SDI1 with 25% deficit irrigation) decreased fruit set by 64.7% and 17.7% respectively in 2016. On the other hand, regulated deficit irrigation (RDI2 with 50% deficit irrigation 4-9 weeks after full bloom) reduced fruit set by 41% in 2016, while RDI1 (25% deficit irrigation 4-9 weeks after full bloom) increased fruit set by 3.5% in 2016. In 2016, applying deficit irrigation (RDI3, 50% deficit irrigation two weeks before harvest) did not have a significant impact on the fruit set compared to the control group which received full irrigation (Table 2). Caruso et al. (2013) found that trees experiencing severe water stress produced fewer fruits than trees were received the mild water deficit, while fully-irrigated trees produced the most fruits. The text clearly indicates that SDI had a more significant negative impact on fruit set compared to RDI. This is likely because SDI imposes a continuous stress throughout the critical period following flowering, affecting all the physiological processes mentioned above more severely and for a longer duration. The fact that RDI applied 4-9 weeks after full bloom reduced fruit set at a 50% deficit but slightly increased it at a 25% deficit in 2016 suggests a nuanced response to the timing and severity of the stress. Mild, regulated stress during specific periods might trigger certain adaptive responses without severely compromising the crucial physiological processes for fruit set. However, more severe RDI, as seen with the 50% deficit, can still lead to significant reductions, aligning with the findings of Trentacoste et al. (2019). The observation that RDI applied two weeks before harvest had no significant impact on fruit set indicates that the critical physiological events determining fruit set largely occur earlier in the post-flowering period. By this late stage, the fruits have already been established and are likely more resilient to short-term water deficits. Sustained stress has a more pronounced negative effect because it impacts these sensitive physiological processes continuously during the critical fruit set period. The timing and severity of the stress in RDI regimes can lead to variable outcomes, highlighting the complexity of plant responses to water deficit.

Sustained deficit irrigation (SDI1 and SDI2) significantly reduced fruit weight, pulp weight, and pulp/pit ratio over two years compared to other treatments. In 2015, SDI2 (50% deficit) and SDI1 (25% deficit) decreased fruit weight by 26.9 and 20.6%, respectively, and in 2016 by 23.5 and 13.1%. Regulated deficit irrigation (RDI1 and RDI2 applied 4-9 weeks after full bloom) also reduced fruit weight, with more pronounced effects in 2016. Pit weight remained unaffected by deficit irrigation. The impact on pulp weight and pulp/pit ratio mirrored the trends observed in fruit weight. The severity of the impact on fruit characteristics followed the order: SDI2 > SDI1 > RDI2 > RDI1 > RDI3 > Control. These findings align with Siakou et al. (2021) and Goncalves et al. (2020), who also reported a greater negative impact of sustained deficit irrigation on fruit and pulp weight compared to regulated deficit irrigation and full irrigation. Furthermore, the observation that full irrigation enhances the pulp/pit ratio, as seen by Conde-Innamorato et al. (2022) for Arbequina and Frantoio cultivars, supports our results. The reduced fruit size under water shortage, impacting weight, pulp weight, and pulp/pit ratio in the order of stress severity, is consistent with findings from Rapoport and Costagli (2004), Nikbakht et al. (2011), and Dell'Amico et al. (2012). The consistent and prolonged water stress imposed by SDI throughout the entire growing season has a cumulative negative effect on the physiological processes critical for fruit development. The plant experiences chronic limitations in water uptake, photosynthesis, and nutrient transport, leading to a more substantial reduction in fruit size, pulp weight, and consequently, the pulp/pit ratio. RDI, by strategically applying water stress during specific periods (in this case, 4-9 weeks after full bloom), appears to have a less severe impact. This suggests that while fruit development is sensitive during this phase, the plant might have some capacity to recover or that the stress is not as prolonged as in SDI. The timing of the stress is crucial; applying stress during periods of rapid cell division and expansion would likely have a more significant impact on final fruit size. The findings of this study are consistent with the cited literature, reinforcing the understanding that water availability is a critical factor influencing fruit development and composition in various fruit crops, including olives. The order of impact (SDI2 > SDI1 > RDI2 > RDI1 > RDI3 > Control) directly reflects the severity and duration of the water deficit. The reduction in fruit weight, pulp weight, and pulp/pit ratio under deficit irrigation is a consequence of reduced physiological responses, and ultimately, a limitation in the resources available for fruit growth and development. Sustained stress exacerbates these physiological limitations, leading to more pronounced effects on fruit characteristics compared to strategically applied, regulated deficit irrigation.

Sustained deficit irrigation (SDI2 and SDI1) resulted in the lowest fruit dry weight, followed by regulated deficit irrigation (RDI2, RDI1, RDI3), with the control (C) exhibiting the highest (Table 4). Notably, both sustained and regulated deficit irrigation increased fruit dry matter compared to the control in both 2015 (SDI: 9.29-8.93%; RDI: 4.7-5.9%) and 2016 (SDI: 9.55-8.9%; RDI: 6.67-4.55%). These findings align with Goncalves et al. (2020), who also observed increased fruit dry matter under both SDI and RDI compared to full irrigation. However, Vaio et al. (2013) reported a contrasting result in the Leccino cultivar, where deficit irrigation (25 and 50% of water transpiration) decreased fruit dry matter relative to full irrigation. Similarly, Monasterio et al. (2021) noted a decrease in fruit moisture content due to deficit irrigation, which inherently implies an increase in dry matter. This study corroborates the general trend of increased fruit dry matter under SDI and RDI, with the extent of the increase being influenced by the level of water deficit. The discrepancy with Vaio et al. (2013) highlights potential cultivar-specific responses to deficit irrigation regarding fruit dry matter accumulation.

Sustained deficit irrigation (SDI) at 50% (SDI2) significantly reduced olive oil in fresh weight by 32.91% and 24.54% in 2015 and 2016, respectively, while a 25% deficit (SDI1) resulted in lower reductions (14.83 and 20.76%). Similarly, regulated deficit irrigation (RDI) at 50% (RDI2, 4-9 weeks post-bloom) decreased oil content by 13.96 and 21.58%, and at 25% (RDI1) by a smaller 3.37 and 1.94%. Our findings indicate that a 25% RDI during 4-9 weeks post-bloom in our semiarid conditions minimally impacted oil content (2-4% reduction), contrasting with Fernandez et al. (2013) who reported a substantial 26% oil yield decline in Arbequina olives with a 72% water reduction in Spain. Gomez-del-Campo (2013), also on Arbequina, observed a smaller 15% oil production decrease with a 27% water reduction. Notably, our study found a 15-20% oil content reduction (dry weight basis) with a 25% water reduction in our non-Mediterranean area. Conversely, RDI at 50% applied two weeks pre-harvest increased oil content in both years, likely due to fruit moisture loss concentrating the oil, a finding consistent with Monasterio et al. (2021) who reported a 0.16% oil content increase for every 1% moisture decrease. We also found a strong correlation (R^2= 0.80) between oil content and fruit dry matter, aligning with Gomez-del-Campo's (2013) R^2= 0.88 correlation.

The period of 4-9 weeks after full bloom is a crucial phase for fruit development and the initiation of significant oil accumulation in olives. Water stress during this period can disrupt the physiological processes necessary for oil synthesis, similar to the mechanisms described for SDI, but potentially to a lesser extent if the stress is applied for a limited duration. Unlike sustained stress, RDI applied during a specific window might allow the plant to recover somewhat once irrigation is resumed, potentially mitigating the long-term impact on oil production compared to continuous stress. This could explain the generally lower reductions observed with RDI compared to SDI.

Reducing irrigation significantly decreased fruit yield. In 2015 and 2016, 50% sustained deficit irrigation (SDI2) reduced yield by 33.95 and 48.28%, respectively, while 25% SDI (SDI1) caused reductions of 12.39 and 20.02%. Regulated deficit irrigation (RDI) during weeks 4-9 post-bloom also reduced yield: 50% RDI (RDI2) by 26.02 and 40.09%, and 25% RDI (RDI1) by 8.30 and 6.20% in 2015 and 2016, respectively. Full irrigation consistently resulted in the highest yields (Fig. 3), a finding supported by Tognetti et al. (2006), d'Andria et al. (2000), and Girona et al. (2000), and further corroborated by Corell et al. (2020) who observed lower yields with reduced irrigation in 'Manzanillo' olives. While Iniesta et al. (2009) proposed RDI aims to maintain yield with water conservation, Rosecrance et al. (2015) emphasized the strong negative impact of water deficit on fruit yield. Our study indicates that RDI1 (25% deficit) was the most effective strategy for balancing water conservation with substantial fruit yield, a result that contrasts with the yield-maintenance goal suggested by Iniesta et al. (2009).

Similar to the effects on flowering, the severity of water restriction directly correlates with the reduction in fruit yield. Sustained deficit irrigation (SDI), with its continuous water limitation, imposes a more prolonged and intense stress, leading to more significant yield reductions compared to regulated deficit irrigation (RDI), where water is withheld during specific developmental stages.

The fact that RDI applied between 4-9 weeks after full bloom significantly impacted yield highlights the sensitivity of fruit development during this period, likely encompassing crucial stages of cell division and early fruit growth. The effectiveness of RDI in conserving water while maintaining a considerable yield (as suggested by the study for the 25% deficit) points to the possibility of strategically managing water stress to optimize both water use efficiency and fruit production, although the optimal strategy might vary depending on the cultivar and environmental conditions, as indicated by the contradiction with Iniesta et al.'s (2009) findings.

In conclusion, the reduced fruit yield under deficit irrigation is a consequence of impaired physiological processes at multiple levels, including water relations, photosynthesis, nutrient uptake and transport, hormonal regulation, and carbon allocation. The extent of the yield reduction is directly linked to the severity and timing of the water deficit.

Fatty acid composition varied significantly by irrigation (Table 5). Lower irrigation slightly increased myristic (C14:0), palmitoleic (C16:1), stearic (C18:0), and linoleic (C18:2) acids. Palmitic acid (C16:0) slightly decreased with more stress, while oleic acid (C18:1) significantly decreased under sustained low irrigation versus full irrigation and RDI. Linolenic (C18:3), arachidic (C20:0), and eicosenoic (C20:1) acids showed no significant differences. Conflicting with Motilva et al. (2000) and Ahumada-Orellana et al. (2018) who found no impact, Goncalves et al. (2020) reported minor reductions in palmitoleic, linoleic, and linolenic acids under sustained deficit irrigation. Conversely, Garcia et al. (2013) observed an increase in palmitoleic acid with deficit irrigation and higher oleic but lower linoleic acid in the deficit group compared to the control. Fernandes-Silva et al. (2021) found higher palmitic acid in well-irrigated plants, but no effect of water deficit on oleic and linoleic acids. This study's findings indicate that water stress, particularly sustained low irrigation, can alter specific fatty acid levels, a result not consistently observed across different studies, highlighting the complexity of this interaction.

The specific increases or decreases in individual fatty acids reflect the differential impact of water deficit on the various biochemical pathways involved in lipid synthesis and modification within the developing olive fruit. The inconsistencies observed across different studies underscore the complexity of these physiological responses and the influence of various experimental and environmental factors.

This study found no significant differences in peroxide, free fatty acids, iodine index, K270, and K232 among irrigation treatments (Table 6). This aligns with Issaoui et al. (2012) and Dag et al. (2015) regarding the iodine index, and Dag et al. (2008) concerning peroxide values. However, Dag et al. (2008) noted increased free acidity with higher irrigation, a finding not replicated here. In contrast, Nanos et al. (2008) reported increased free acidity, K232, and K270 under deficit irrigation in Conservolia olives. Conversely, Garcia et al. (2020) and Siakou et al. (2021) observed no impact of deficit irrigation on these parameters in Arbequina oil, with Fernandes-Silva et al. (2021) even finding decreased peroxide values with increased water stress. Romero-Trigueros et al. (2019) also reported no significant effect of deficit irrigation on K232 and K270. Thus, the impact of deficit irrigation on olive oil quality parameters appears variable and potentially cultivar-specific.

The absence of significant changes in olive oil quality parameters in this study suggests that the applied sustained and deficit irrigation regimes did not induce substantial physiological shifts that negatively impacted lipid metabolism, oxidation, or hydrolysis in the olive fruits. However, the contrasting findings from other research underscore the complex interplay between water availability, cultivar-specific responses, environmental conditions, and the timing and severity of stress in determining olive oil quality. Further research is needed to fully elucidate these interactions and develop irrigation strategies that optimize both yield and oil quality across different cultivars and environments.

Conclusion

Olive trees (*Olea europaea L.*) usually exhibit notable drought tolerance, rendering them a suitable crop for semi-arid climates. Faced with increasing water scarcity in Iran, deficit irrigation strategies are being implemented to mitigate water consumption in olive cultivation. Identifying methods to reduce irrigation without compromising olive yield and oil quality is therefore critical. This study demonstrated that Regulated Deficit Irrigation applied between 4-

9 weeks after full bloom (RDI1, 25% water reduction) and late-season RDI applied two weeks before harvest (RDI3, 50% water reduction) effectively conserved water without significantly impacting fruit yield or oil quality when compared to the fully irrigated control. Over the experimental period, total water consumption in the control group was 8011 m^3 ha^{-1} in 2015 and 7288 m^3 ha^{-1} in 2016. Implementing the RDI1 treatment resulted in a water saving of approximately 400-500 m^3 ha^{-1}, while RDI3 saved 260-330 m^3 ha^{-1} depending on the year. This reduction in irrigation volume is particularly significant for water-limited semi-arid regions. Furthermore, the application of late-season drought stress (RDI3) led to a modest but notable increase (3-5%) in extracted oil content on a fruit fresh weight basis.

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Author Contributions
Samira Ahmadipour: Methodology; Running the experiment; Data curation; writing original draft. Isa Arji: Running the experiment; Methodology; data curation; Supervision; writing, review and editing. Ali Ebadi: Running the experiment; Methodology; Supervision; review and editing. Vahid Abdoosi: Running the experiment; review and editing.

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Conflict of Interest
The authors indicate no conflict of interest in this work.

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