Assessing the impact of deficit irrigation strategies on agronomic and productive parameters of Menara olive cultivar: implications for operational water management

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The olive tree is an iconic tree in the Mediterranean region, traditionally cultivated under rainfed conditions; however, olive cultivars are also found outside the Mediterranean region and are widely used for oil and olive production. However, with the increasing aridity and global changes, olive agroecosystems are facing sustainability challenges. This study aims to evaluate the effect of two deficit irrigation strategies on the agronomic and productive parameters of the Menara, olive cultivar as a tool for operational irrigation water management. For this purpose, an experiment was conducted on an olive orchard for two consecutive years (2021 and 2022), comparing four regulated deficit irrigation (RDI) treatments and two sustained deficit irrigation (SDI) treatments, with fully irrigated trees. The results showed that moderate and controlled water stress under RDI did not significantly affect the yield of the Menara olive cultivar. In addition, by reducing plant water requirement by 20% during sensitive periods and by 40% during normal periods, under RDI, it is possible to save between 25% and 30% of irrigation water and to increase water productivity by 5%–20% with a slight decrease in fruit yield ranging between 10% and 15%. However, the trees subjected to the sustained deficit irrigation strategy exhibited a reduced capacity for shoot growth compared to those under RDI and fully irrigated conditions. Our findings showed that water deprivation during sensitive periods reduced phenological traits and slowed down shoot growth. Furthermore, the water status of the trees was reflected in fruit volume, as a decrease in water supply resulted in a corresponding reduction in fruit volume. Although the study provides important insights into water management strategies for olive cultivation, the short observation period does not allow for long-term plant adaptation evaluation and productivity beyond 2 years. Therefore, it is recommended that future studies extend the observation period to better understand plant adaptation to irrigation regimes.

1 Introduction

The olive tree (*Olea europaea* L.) is an iconic and emblematic fruit tree of the Mediterranean region, with high and valuable cultural and economic significance (Besnard et al., 2018). It belongs to the *Olea europaea* L. complex, which comprises six olive subspecies distributed across Asia, Africa, and Europe (Medail et al., 2001; Gree, 2002). Of these, only *Olea* subsp. *europaea* has been domesticated. Today, both the wild form, *O. e.* subsp. *e.* var. *sylvestris*, known as oleaster, and the cultivated form, *O. e.* subsp. *e.* var. *sativa*, coexist in the Mediterranean Basin (Besnard et al., 2018). The cultivated olive germplasm reflects a large genetic diversity represented by more than 1,200 clonally propagated cultivars grown throughout the Mediterranean region, which accounts for 90% of the globally cultivated area (FAO, 2019). While few of these cultivars are grown in intensive olive systems (Bartolini and Cerreti, 2008), some are grown in restricted areas, especially within traditional agroecosystems (Khadari et al., 2008; Ater et al., 2016). Farmers in various Mediterranean regions have chosen locally adapted varieties, explaining the ongoing process of olive diversification at local and regional scales (Khadari et al., 2008, 2019; El Bakkali et al., 2013; Besnard et al., 2018). Therefore, the observed diversity in olive cultivars is a critical component in preserving and maintaining the productivity of olive-based agroecosystems under various environmental conditions. However, in the face of global changes, it is crucial to understand how olive cultivars will respond to environmental changes, especially drought (Khadari et al., 2019; Kassout et al., 2022). The ability of olive trees to adapt to changing environmental conditions will impact their long-term viability, making this an important area of research.

Olive, an evergreen and sclerophyllous tree species, is well adapted to the Mediterranean climate (Kassout et al., 2021). However, the seasonal variation between hot, dry summers and mild, rainy winters induces stressful conditions for its growth and development (Dichio et al., 2006; Torres-Ruiz et al., 2015). Furthermore, climate change scenarios predict extreme warming and drying trends in the Mediterranean region compared to other climatic ecoregions (Cramer et al., 2018), which are likely to challenge the sustainability of olive-based agroecosystems. The increasing demands for water, for both irrigation and domestic use, may significantly affect the agricultural sector, negatively affecting the growth and productivity of olives (Rallo et al., 2016). Despite the morphological, anatomical, and physiological adaptive traits of the olive tree (Fernandez, 2014; Kassout et al., 2021), the increasing aridity in Mediterranean agroecosystems may potentially interrupt progress toward an efficient olive production sector (Wheeler and Von Braun, 2013; Fraga et al., 2020). Given the key role of the olive sector in the Mediterranean and global food security, sustainable water management practices are urgently required to maintain olive productivity in this era of global changes (Gucci et al., 2019).

Traditional low-density olive farms are the prevailing production systems in Morocco, as in many other Mediterranean regions, with a density range of 50–160 trees/ha. These farms are typically located in arid and semi-arid agricultural lands under rainfed conditions and could be seen as a strategy to cope with low water availability and poor soils (Lorite et al., 2018). However, with the introduction of new management techniques and olive varieties, high-density (350 – 700 trees/ha) and super-density (1,200 − 2,500 trees/ha) olive orchards, which are usually irrigated, have emerged recently (Fernández-Escobar et al., 2013). The sustainability of olive productivity in arid lands, including the Mediterranean region and Morocco, is challenged by the impact of climate change on olive orchards (Lorite et al., 2018). Despite olive trees being regarded as drought-tolerant, water deficit during sensitive periods such as flowering, fruit set, and oil accumulation can cause significant economic losses in olive productivity Moriana et al. (2003); Díaz-Espejo et al. (2018). Thus, optimizing irrigation in olive orchards during sensitive periods can mitigate the impacts of water deficit, hence maintaining profitable olive productivity under arid and semi-arid conditions (Fereres and Soriano, 2007; Fernandes et al., 2018). Numerous studies have explored the impact of restricted irrigation on various olive cultivars, which has generally resulted in water savings but accompanied by yield reductions (Lavee et al., 2007; Servili et al., 2007; Gómez-del Campo, 2013; Caruso et al., 2017; Gucci et al., 2019; Serman et al., 2021). However, adequate deficit irrigation strategies have been shown to maintain profitable olive productivity (Lavee et al., 2007; Gucci et al., 2019). To this end, different deficit irrigation (DI) approaches have been developed to match commercial objectives in the olive sector, including sustained deficit irrigation (SDI) and regulated deficit irrigation (RDI) (Moriana et al., 2003; Iniesta et al., 2009; Ramos and Santos, 2009). SDI involves providing a regular volume of water that is less than the crop evapotranspirative (ET_c) demand during the entire irrigation season, while RDI consists of replacing the ET_c demand at specific phenological stages that are sensitive to water stress and applying much lower irrigation levels than ET_c demand where the stress has no significant impact on yields (Moriana et al., 2003; Fereres et al., 2012). Consequently, RDI is a crucial consideration in arid regions, where water scarcity necessitates the adoption of sustainable water management practices. Previous research (Fernández-Escobar et al., 2013; Gómez-del Campo, 2013; Gucci et al., 2019) has demonstrated that applying moderate RDI to olive trees, especially from fruit drop to the onset of the oil synthesis stage, achieves a balance between water savings, yield, and oil quality. However, implementing RDI strategies during highly sensitive periods can significantly impact the growth and productivity of olive trees (Gucci et al., 2019) and subsequently influence oil quality (García et al., 2020).

The main objective of this study is to identify the most appropriate water irrigation strategy for a new and local grown

FIGURE 1
Aerial view of the research station, with the trees subjected to the experiment highlighted in green. The black square on the right represents the irrigation basin, which has a side length of 30 m.
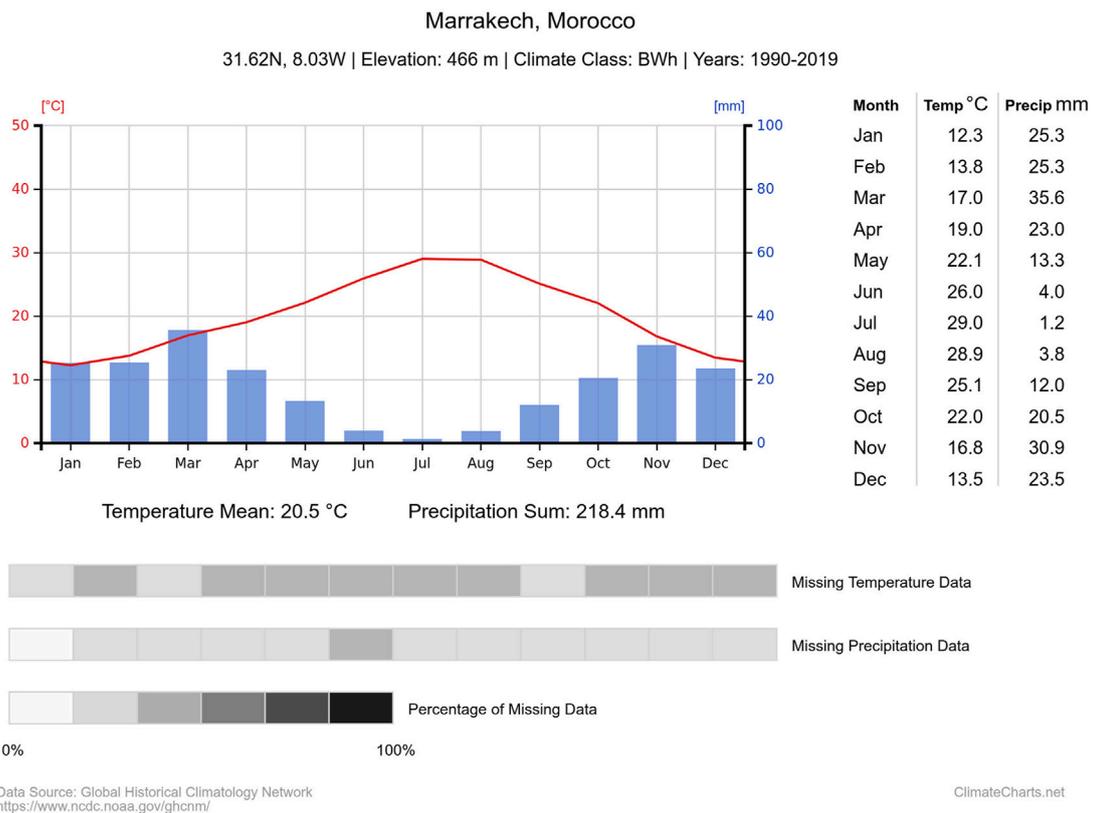
FIGURE 2
Climatograph of the study site, showing monthly climatic data from 1990 to 2019. The red line represents temperature, and the blue bars represent monthly precipitation. The data source is cited by Zepner et al. (2020).

variety of olives orchards in Morocco, called "Menara". To achieve this goal, two specific objectives were targeted: i) to evaluate the effect of sustained deficit irrigation and regulated deficit irrigation on the agronomical and productive parameters of the Menara cultivar and ii) to determine the most suitable RDI strategy depending on different phenological stages.

FIGURE 3
Daily meteorological data from the study site during the experiment. The records start on 4 January 2021 and end on 5 October 2022.
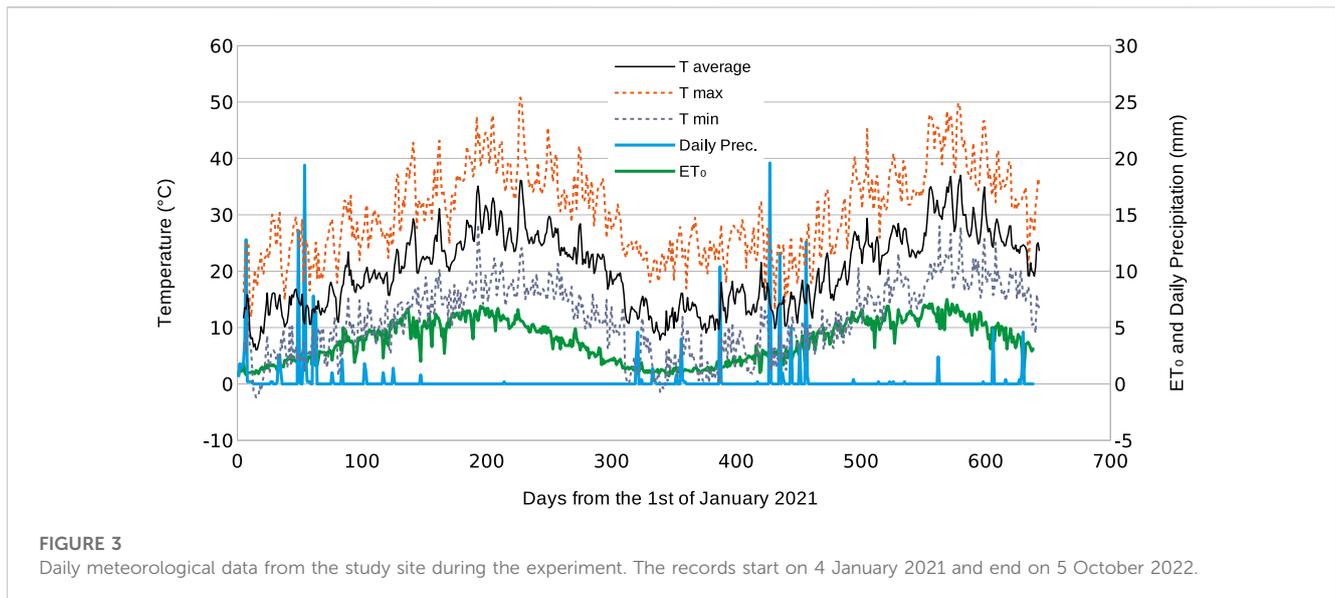
2 Materials and methods

2.1 Experimental site and olive orchards

An irrigation experiment was conducted in an olive orchard over 2 years, 2021 and 2022, to compare the effect of RDI and SDI at different phenological stages with fully irrigated (FI) trees. The study was carried out on 12-year-old trees of the Menara cultivar planted in 2011 at the research station of Saâda (31°37′33.6″ N, 8°08′45.6″ W, and 411 m a.s.l.) managed by the National Institute of Agronomic Research of Marrakech (Morocco). The trees are planted in a squared spaced scheme of 8 m of side length, under drip irrigation, with a density of 156 trees/ha, as shown in Figure 1. The experiment included seven different treatments replicated for two successive years on 18 trees per treatment. The soil at the experimental site had a clayey texture, pH of 7.82, and organic matter content of 2.33%. No fertilizers or pesticides were used, and weeding was performed manually.

2.2 Climate

The climate at the study site is Mediterranean, characterized by an arid or semi-arid climate with hot and dry summers, low rainfall, and spatiotemporal irregularity of precipitation (Er-Raki et al., 2010; Sebbar et al., 2011). These factors, along with climate change effects and water shortage, significantly limit the crop yield. According to the Köppen climate classification, the climate subtype at the study site is either "BSh" (hot semi-arid) or "BWh" (hot arid). Most of the annual rainfall occurs between late November and March, with very little precipitation during the summer period, as shown in the climatograph depicted in Figure 2.

The cumulative reference evapotranspiration (ET_o), which represents the climatic demand, between 1st January and 10th October, was 1295.7 and 1113.7 mm in 2021 and 2022, respectively. However, the cumulative precipitation (P) during the same period was only 112.6 and 75 mm in 2021 and 2022, respectively. This confirms that the second year (2022) of the experiment was affected by drought.

The irrigation requirements were calculated daily using the standard FAO56 formula for crop evapotranspiration ($ET_c = ET_o \cdot Kc \cdot Kr$), where the daily reference evapotranspiration ET_o was estimated using the Penman–Monteith equation (Allen et al., 1998, 2006). Daily ET_o values (Figure 3) were calculated using daily climatic data measured by a standard meteorological station (model iMETOS, Pessl instruments) installed on the experimental site. The crop coefficient Kc was estimated to be 0.65 in April and October; 0.6 in May and June; 0.55 from July to September; and 0.7 in November and December (Orgaz et al., 2007). The coefficient reduction Kr, which is related to the degree of orchard floor plant cover and applied to canopies that covered less than 50% of the ground, was calculated as Kr = 2C/100, where C is the percentage of canopy cover.

2.3 Irrigation treatments and experimental design

The control treatment, T0, involved full irrigation to meet the crop evapotranspiration (ET_c), demand throughout the irrigation season, which was divided into the sensitive period (SP) and normal period (NP). The first SP extended from flower differentiation to the beginning of pit hardening, the NP covered the phase of pit hardening, and the second SP spanned from oil accumulation to harvest.

The study included four RDI treatments, which consisted of the following four water regimes: T1 (SP 100—NP 70% ET_c); T2 (SP 100—NP 60% ET_c); T3 (SP 80—NP 70% ET_c); and T4 (SP 80—NP 60% ET_c). Trees under T1 and T2 were fully irrigated during the SP, while they received 70% and 60% of ET_c during the NP, respectively. Trees under T3 and T4 received 80% of ET_c during SP and 70% and 60% of ET_c during the NP.

Two SDI treatments were also applied, which kept the plants irrigated throughout the season with a fixed percentage of the ET_c. The first regime, T5, maintained irrigation at 70% of the ET_c, while the second regime T6 maintained irrigation at 60% of the ET_c.

TABLE 1 Summary of different irrigation treatments and total water delivered in 2021 and 2022. The total water delivered may vary annually based on ET_c and phenological phases, as summarized in Table 2, and water deficits. The percentage of the total applied water relative to the control treatment for each year is shown in parentheses.

Category	Treatment	% of ET_c during SP	% of ET_c during NP	Total water delivered in (mm)	
				2021	2022
Control	T0	100	100	242 (100%)	279 (100%)
RDI	T1	100	70	218 (90%)	246 (88%)
RDI	T2	100	60	210 (87%)	235 (84%)
RDI	T3	80	70	185 (76%)	212 (76%)
RDI	T4	80	60	177 (73%)	201 (72%)
SDI	T5	70	70	169 (70%)	196 (70%)
SDI	T6	60	60	145 (60%)	168 (60%)

TABLE 2 Periods of different phenological phases characterizing the sensitive period (SP) and normal period (NP) in 2021 and 2022.

Phenological phase	Start	End	Duration (days)
Full flowering	06/04/2021	19/04/2021	13 (SP)
From flowering to fruit drop	19/04/2021	26/04/2021	7 (SP)
From fruit drop to the beginning of pit hardening	26/04/2021	15/06/2021	50 (SP)
From pit hardening to the beginning of oil synthesis	15/06/2021	16/08/2021	62 (NP)
From the beginning of oil synthesis to harvest	16/08/2021	06/10/2021	52 (SP)
Full flowering	05/04/2022	28/04/2022	23 (SP)
From flowering to fruit drop	28/04/2022	04/05/2022	6 (SP)
From fruit drop to the beginning of pit hardening	04/05/2022	01/06/2022	28 (SP)
From pit hardening to the beginning of oil synthesis	01/06/2022	03/08/2022	63 (NP)
From the beginning of oil synthesis to harvest	03/08/2022	05/10/2022	63 (SP)

Table 1 summarizes the total amount of water delivered to the Menara trees for each treatment. Irrigation amounts were adjusted based on weather conditions and effective water deficit.

2.4 Phenological assessment and growth monitoring

Phenological development, including mean budburst, full flowering, pit hardening, and maturity, was recorded in both years following the method described by Sanz-Cortés et al. (2002). The periods are given in Table 2.

To characterize the effect of different treatments on tree growth and development, vegetative growth was measured on six representative trees per treatment at weekly intervals during the vegetative growth season, from bud break until the beginning of July. Four current-year shoots per tree were selected for measurement at 1.5 m above the ground below the insertion of the first-year branch. Hence, productive-related parameters were monitored for each of the six selected trees per treatment, and 1-year old shoots were selected and marked. The following measurements were undertaken: shoot length (SL, cm), the number of buds (BUN, buds per shoot),

buds initiated (BI, inflorescences per buds), flowers per inflorescence at the white button stage just before flowering (FPI), and the number of fruits per shoot (FNS). The flowering rate (FR) was expressed as the percentage of buds developed into inflorescences. Additionally, fruit yield (FY, kg/tree), fruit weight (FW, g), fruit volume (FV, mL), and oil content (%) were measured for each treatment. FV was measured using the water displacement method, which consists of measuring the difference in the water volume in a graduated cylinder filled with water before and after fruit immersion. Oil content was measured using a laboratory scale system within 24 h of harvesting. Fruits were crushed using a hammer mill, and the resulting olive paste was homogenized and dried at 70°C; then, using a Soxhlet apparatus and 30°C hexane, the oil content was measured (Donaire et al., 1977).

2.5 Statistical analysis

Statistical differences among irrigation treatments for each season were estimated using ANOVA tests for all evaluated parameters. Tukey's test was used to identify significant differences between the means ($p < 0.05$). Descriptive statistics,

TABLE 3 Vegetative growth at the end of the growing period (7 July 2021 and 15 July 2022) (average and standard error (S.E.)) and its percentage of variation for each treatment compared to *T*0. The obtained results are statistically significant with $p < 0.001$. The measurements were taken on current-year shoots. Here, in Figure 4, and in Tables 5–8, the same letters indicate no significant differences between irrigation treatments within the group marked by the same letter, according to Tukey's test.

Treatment	2021			2022		
	Vegetative growth (cm)	S.E.	%variation	Vegetative growth (cm)	S.E.	%variation
*T*0	9.31^d	0.32	(100 ± 3)%	8.88^b	0.69	(100 ± 8)%
*T*1	9.42^d	0.33	(101 ± 7)%	8.43^b	0.72	(95 ± 16)%
*T*2	8.50^{bcd}	0.22	(91 ± 5)%	7.25^{ab}	0.61	(82 ± 13)%
*T*3	8.88^{cd}	0.27	(95 ± 6)%	5.38^a	0.65	(61 ± 12)%
*T*4	8.02^{abc}	0.30	(86 ± 6)%	6.52^{ab}	0.57	(73 ± 12)%
*T*5	7.42^{ab}	0.14	(80 ± 4)%	6.60^{ab}	0.55	(74 ± 12)%
*T*6	7.23^a	0.12	(78 ± 4)%	5.13^a	0.53	(58 ± 10)%
ANOVA F$_{7,24}$	11.789***			4.84***		

such as the mean, standard deviation, and standard error, were calculated to explore variation in the measured variables obtained from different treatments. The coefficient of variation was also calculated to determine the amplitude of variation of the measured variables under different treatments, which is expressed as $100 \cdot \sigma/|\mu|$. To test for statistical differences between the treatments and measured variables, ANOVA was used, followed by Tukey HSD *post hoc* tests for inter-treatment comparisons with a significance level of $p = 0.05$.

To test for differences between the studied years, we conducted a *t*-test between the years and for each variable. Additionally, a variance decomposition analysis was conducted (Kassout et al., 2019) using R software to explore the four organizational scales within the experiment: 1) "years" (variation between different years); 2) "treatments" (variation between different irrigation treatments); 3) "inter-trees" (variation between different trees within the same treatment); and 4) "intra-trees" (variation between different parts of the same tree). The "lme" function in the "nlme" package (Pinheiro et al., 2018) was used to fit a general linear model using the restricted maximum likelihood (RMEL) method across the studied levels. Then, the "varcomp" function in the "ape" package (Paradis et al., 2004) was used to extract the variance expressed at each level. This approach was used to assess the variability for growth and phenological variables, which were measured at the tree level with multiple repetitions.

3 Results

## 3.1 Variation in vegetative growth

Table 3 summarizes the results showing that RDI, SDI, and the volume of applied water had a significant impact on vegetative growth. Differences in growth rates were observed during the vegetative growth season, which occurred from March to July. The shoot length of trees from *T*0 was approximately 9.3 cm in 2021 and 8.9 cm in 2022. ANOVA,

assuming $\alpha = 0.05$, demonstrated significant differences in the average vegetative growth between irrigation treatments in both years with $p < 0.001$. The most significant reduction in vegetative growth was observed for *T*6, where the final length of the shoots decreased by approximately 22% in 2021 and by 40% in 2022 compared to *T*0 and *T*1.

3.2 Variation in phenological and growth-related traits

The results showed that deficit irrigation had a significant effect on both the phenological and growth-related traits across all treatments. Significant differences were observed among the Menara trees for all studied parameters except for SL and BUN in the first year (2021), as shown in Figure 4. In 2022, the ANOVA test indicated significant differences in the studied parameters among treatments with $p < 0.001$. SL was higher in 2022 than in 2021 for both the control and RDI treatments, and this increase was attributed to the bud number per shoot. Overall, a significant difference in fruit number per shoot between irrigation treatments was observed in 2022. The fruits per shoot in FI and RDI treatments were significantly higher than in SDI treatments. Moreover, according to the findings given in Figure 4, in 2022, flowering parameters, notably, BUN, FPI, and FR, were found to be lower in trees under SDI than those subjected to RDI and FI.

Generally, the percentage variance was high at the intra-tree level for all variables, ranging from 39.54% to 65.81% (Table 4). Shoot length explained the highest proportion of variance between years (25.11%); meanwhile, the flowering rate expressed the lowest value (1.42%). In addition, flowers per inflorescence (FPI) exhibited an important proportion of variance at the inter-tree level (25.13%), between years (18.42%), and at the treatment level (9.89%). In addition, the flowering rate (FR) and fruit number per shoot (FNS) explained an important amount of variance at the inter-tree level, with 15.97% and 17.30%, respectively.
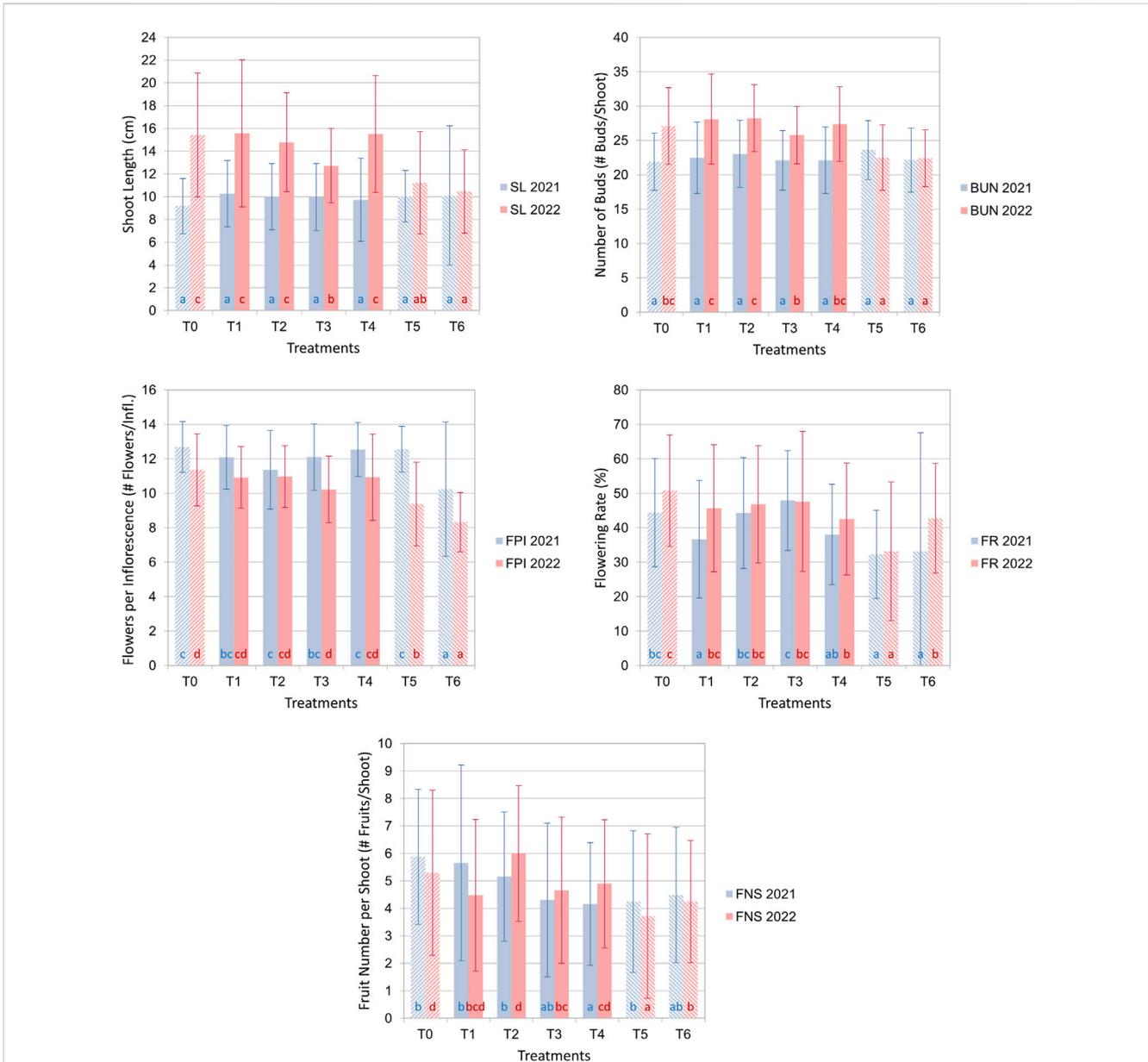
FIGURE 4
Plots of the average values of the investigated parameters, with error bars representing the standard deviation. In 2022, the ANOVA test indicated highly significant differences in the studied parameters among treatments with $p < 0.001$. The same letters indicate the absence of significant differences between irrigation treatments within the group marked by the same letter, according to Tukey's test. Fully irrigated ($T0$) and SDI ($T5$ and $T6$) treatments are represented with different bar textures.

3.3 Variation in agronomical parameters

3.3.1 Fruit yield

Table 5 shows that the applied irrigation treatments significantly influenced the fruit yield in terms of Kg/tree. In 2021, the parameter decreased significantly in the range of 10%–25%, but it later increased significantly for $T1$ and $T2$ and decreased significantly for $T5$ and $T6$ in 2022. In 2022, it is worth mentioning that fruit yield was not significantly affected for $T3$ and $T5$ treatments, despite implementing water saving by 20% during the SP, 30% during the NP in $T3$, and 30% throughout the growing season in $T5$ compared to FI treatment in 2021. The ANOVA test, assuming that $\alpha = 0.05$,

showed a significant variation in the average fruit yield between irrigation treatments in 2021 with $p < 0.01$ and an extremely significant difference in 2022 with $p < 0.001$. This difference can be attributed to the fact that 2022 was drier than 2021.

3.3.2 Fruit volume

The fruit volume was significantly affected by the RDI and SDI treatments. ANOVA, assuming that $\alpha = 0.05$, showed an extremely significant variation in the average fruit volume between irrigation treatments in both years with $p < 0.001$, as shown in Table 6. It is interesting to note that for $T1$, although the yield per tree increased, the average fruit volume decreased.

TABLE 4 Estimated percentage of variance across the studied hierarchical levels included in the experimental design of the study for growth and phenological parameters. Maximum values are in bold.

Variable	% of variance				
	Year	Treatment	Inter-trees	Intra-trees	Residual
Shoot length (cm)	25.11	6.93	10.53	**49.50**	7.93
Bud number	16.66	8.43	7.72	**58.20**	8.99
Flowers per inflorescence	18.42	9.89	25.13	**39.54**	7.02
Flowering rate (%)	1.42	5.92	15.97	**65.81**	10.88
Fruit number per shoot	7.58	5.17	17.30	**60.33**	9.61

TABLE 5 Fruit yield (average and standard error (S.E.)) and its percentage of variation for each treatment compared to *T*0. The ANOVA test indicated a significant difference among treatments with $p < 0.01$ in 2021 and $p < 0.001$ in 2022.

Treatment	2021			2022		
	Yield (kg/tree)	S.E.	%variation	Yield (kg/tree)	S.E.	%variation
*T*0	90.8^b	1.6	$(100 \pm 2)\%$	114.4^c	6.8	$(100 \pm 6)\%$
*T*1	73.9^{ab}	4.8	$(81 \pm 7)\%$	123.3^c	3.8	$(108 \pm 10)\%$
*T*2	70.4^a	7.4	$(78 \pm 10)\%$	112.5^{bc}	3.7	$(98 \pm 9)\%$
*T*3	$82.1^{ab.}$	5.3	$(90 \pm 9)\%$	99.6^{bc}	6.5	$(87 \pm 11)\%$
*T*4	69.2^a	4.8	$(76 \pm 8)\%$	88.3^b	4.9	$(77 \pm 9)\%$
*T*5	80.0^{ab}	3.6	$(88 \pm 7)\%$	53.5^a	9.7	$(47 \pm 11)\%$
*T*6	68.3^a	3.2	$(75 \pm 6)\%$	55.8^a	5.5	$(49 \pm 8)\%$
ANOVA $F_{7,12}$	3.15**			22.35***		

TABLE 6 Fruit volume (average and standard error (S.E.)) and its percentage of variation for each treatment compared to *T*0. The obtained results are statistically significant with $p < 0.001$.

Treatment	2021			2022		
	Volume (mL)	S.E.	%variation	Volume (mL)	S.E.	%variation
*T*0	4.70^c	0.15	$(100 \pm 3)\%$	5.12^e	0.18	$(100 \pm 3)\%$
*T*1	4.64^c	0.13	$(99 \pm 6)\%$	3.88^{cd}	0.13	$(76 \pm 5)\%$
*T*2	3.41^b	0.13	$(73 \pm 5)\%$	4.32^d	0.18	$(84 \pm 6)\%$
*T*3	3.60^b	0.12	$(77 \pm 5)\%$	4.48^d	0.16	$(88 \pm 6)\%$
*T*4	3.49^b	0.13	$(74 \pm 5)\%$	3.20^b	0.13	$(63 \pm 5)\%$
*T*5	3.24^b	0.12	$(69 \pm 5)\%$	3.40^{bc}	0.10	$(66 \pm 4)\%$
*T*6	2.31^a	0.12	$(49 \pm 4)\%$	1.76^a	0.16	$(34 \pm 4)\%$
ANOVA $F_{7,25}$	42.50***			52.29***		

3.3.3 Fruit weight

Fruit weight was significantly influenced by irrigation treatments. ANOVA showed significant differences in the average fruit weight between irrigation treatments in both years with $p < 0.001$, as given in Table 7. Compared to *T*0, the fruit weight for almost all the other treatments decreased by 15%–25%, with the exception of *T*6 in 2022 where it decreased by an exceptional 45%.

3.3.4 Fruit oil content

The fruit oil content, measured as the percentage of dry weight, was significantly affected by water deficit. ANOVA, assuming that

TABLE 7 Fruit weight (average and standard error (S.E.)) of 100 drupes and its percentage of variation for each treatment compared to *T*0. The obtained results are statistically significant with $p < 0.001$.

Treatment	2021			2022		
	100 fruit weight (g)	S.E.	%variation	100 fruit weight (g)	S.E.	%variation
*T*0	405.48^b	10.04	$(100 \pm 2)\%$	398.88^c	10.62	$(100 \pm 3)\%$
*T*1	331.75^a	13.30	$(82 \pm 5)\%$	343.69^{bc}	6.03	$(86 \pm 4)\%$
*T*2	309.07^a	5.46	$(76 \pm 3)\%$	318.70^b	16.70	$(80 \pm 6)\%$
*T*3	298.53^a	9.35	$(74 \pm 4)\%$	344.81^{bc}	15.49	$(86 \pm 6)\%$
*T*4	320.31^a	19.34	$(79 \pm 7)\%$	320.60^b	12.22	$(80 \pm 5)\%$
*T*5	314.70^a	10.57	$(78 \pm 5)\%$	349.05^{bc}	17.28	$(88 \pm 7)\%$
*T*6	314.37^a	7.68	$(78 \pm 4)\%$	215.69^a	7.29	$(54 \pm 3)\%$
ANOVA $F_{7,6}$	9.52***			18.71***		

TABLE 8 Oil content over dry weight expressed as a percentage (average and standard error (S.E.)) and its percentage of variation for each treatment compared to *T*0. The obtained results are statistically significant with $p < 0.001$.

Treatment	2021			2022		
	Oil/dry weight (%)	S.E.	%variation	Oil/dry weight (%)	S.E.	%variation
*T*0	30.22^c	0.54	$(100 \pm 2)\%$	29.18^{ab}	0.73	$(100 \pm 2)\%$
*T*1	27.25^b	0.66	$(90 \pm 4)\%$	26.84^a	0.27	$(92 \pm 3)\%$
*T*2	24.89^a	0.34	$(82 \pm 3)\%$	27.45^a	0.75	$(94 \pm 5)\%$
*T*3	24.70^a	0.40	$(82 \pm 3)\%$	31.52^{bc}	0.74	$(108 \pm 5)\%$
*T*4	27.48^b	0.42	$(91 \pm 3)\%$	31.87^{bc}	0.63	$(109 \pm 5)\%$
*T*5	29.00^{bc}	0.34	$(96 \pm 3)\%$	33.40^c	0.56	$(114 \pm 5)\%$
*T*6	30.63^c	0.38	$(101 \pm 3)\%$	31.92^c	0.53	$(109 \pm 5)\%$
ANOVA $F_{7,18}$	27.49***			15.19***		

$\alpha = 0.05$, showed an extremely significant variation of the average fruit oil content between irrigation treatments in 2021 with $p < 0.001$. Compared to *T*0, the oil content decreased by 5% for *T*5, 10% for *T*1 and *T*4, and 20% for *T*2 and *T*3, but remained unchanged for *T*6. In contrast to 2021, in 2022, a significant increase in the oil content was observed for fruits from trees subjected to SDI treatment, as well as for *T*3 and *T*4 subjected to RDI treatment. The detailed results are given in Table 8.

3.4 Variation in oil production and water productivity

To evaluate water productivity (WP) in terms of fruit yield, measured in kg/mm, with respect to *T*0, fruit yield (FY) for each treatment was divided by the percentage of the total water delivered with respect to *T*0 (Table 1). The results obtained are shown in Table 9, which indicate that the applied irrigation treatments significantly influenced WP. The SDI strategy showed the highest

water productivity during the first season (2021), with significant water savings, whereas during the second season of the experiment (2022), this strategy reduced water productivity, which might be due to the prolonged effects of stress in perennial crops. Among the RDI treatments, *T*3 showed the highest water productivity, with an average increase of 17% over the 2 years of the experiment compared to *T*0.

4 Discussion

The results obtained from the experiment showed that different irrigation treatments significantly affect all the studied traits of the Menara olive cultivar, leading to an important variability at the intra- and inter-tree levels, and thus, across years (Table 4). Generally, the Menara cultivar responds quickly to RDI and SDI treatments in both years of the experiment. The response of the cultivar to treatment is characterized by a reduction in the fruit yield of around 20% and a reduction in the fruit oil content of 5% and 10%

TABLE 9 Variation of water productivity in terms of fruit yield compared to *T*0. "FY % *T*0" indicates the percentage variation of fruit yield with respect to *T*0. "Total water % *T*0" indicates the percentage of total water delivered according to *T*0, and "% Var. *WP*" indicates the percentage variation of water productivity.

Treatment	2021			2022		
	FY % T0	Total water (%)T0	%var. WP	FY % T0	Total water (%)T0	%var. WP
*T*0	(100 ± 2)%	100	(100 ± 2)%	(100 ± 6)%	100	(100 ± 6)%
*T*1	(81 ± 7)%	90	(90 ± 7)%	(108 ± 10)%	88	(122 ± 7)%
*T*2	(78 ± 10)%	87	(89 ± 12)%	(98 ± 9)%	84	(117 ± 7)%
*T*3	(90 ± 9)%	76	(119 ± 12)%	(87 ± 11)%	76	(115 ± 12)%
*T*4	(76 ± 8)%	73	(104 ± 11)%	(77 ± 9)%	72	(107 ± 10)%
*T*5	(88 ± 7)%	70	(126 ± 10)%	(47 ± 11)%	70	(67 ± 12)%
*T*6	(75 ± 6)%	60	(125 ± 11)%	(49 ± 8)%	60	(81 ± 12)%

in the first year, followed by an increase in value up to 15% in the second year. In contrast, other varieties evaluated over years in the RDI treatment showed no significant difference in fruit yield at the end of the third year (Pierantozzi et al., 2020).

Water deficit is a critical stressor that affects plant growth and development. It is also the most significant factor that limits olive yield (Brito et al., 2019). Our findings suggest that the Menara tree's response to RDI and SDI treatments was influenced by both the effect of treatments and varying seasons. The growth rate of Menara trees varied among treatments, with vegetative growth responding differently to applied water deficits. Analysis of the experimental years showed that deficit irrigation treatments significantly reduced shoot growth. Vegetative shoot growth started toward the end of winter and was significantly reduced by deficit irrigation (Pierantozzi et al., 2020). Water availability is a crucial limiting factor for trees, with significant consequences on ecophysiological processes, and the growth potential is substantially affected by water stress in trees, such as in the case of the olive tree (Pierantozzi et al., 2013; Steppe et al., 2015; Kassout et al., 2021). Therefore, shoot growth in Menara trees was significantly lower under DI treatment compared to FI trees. Furthermore, the growth capacity of trees subjected to RDI treatment was higher than those subjected to SDI treatment, indicating that the RDI strategy might be a more suitable irrigation method for promoting shoot growth in trees (Table 3). Correa-Tedesco et al. (2010) showed that fully irrigated trees subjected to a warm climate exhibited significant shoot growth. In the case of the studied Menara trees, analysis results of Student's t-test showed that after two consecutive years, vegetative growth was significantly affected by the enduring effects of treatments *T*3 and *T*4 under RDI and *T*6 under SDI, where olive Menara trees may not have enough water to support optimal vegetative growth (Supplementary Table S1). Trentacoste et al. (2019) observed a significant reduction in vegetative growth in the "Arbosana" olive cultivar subjected to different RDI treatments over three consecutive seasons compared to those with full irrigation. Nevertheless, these trees still yielded significant water savings and a substantial increase in fruit yield. Moreover, reduced vegetative growth can be beneficial in super-intensive olive orchards as it can improve canopy and fruit illumination (Gomez-del Campo et al., 2017; Trentacoste et al., 2019).

Our analysis of phenological variability at different hierarchical levels revealed significant intra-tree variability, ranging from 40% for FPI to 66% for FR (Table 4). This high variability between trees is not negligible and has been observed previously in leaf- (Kassout et al., 2019) and wood-related traits (Kassout et al., 2021) in wild olive trees in Morocco. This variability was attributed to differences in water availability at multiple scales, from regional to local. The substantial variability observed between the study years (Table 4) suggests that environmental conditions may also play a significant role in shaping the variability of the studied traits (Siefert et al., 2015). Therefore, the observed variability in phenological traits at different hierarchical levels could be attributed to the complex interactions between genetic and environmental factors (Kassout et al., 2021).

The influence of irrigation treatments included in our study on "Menara" tree fruit yield, fruit weight, and volume, as well as fruit oil content, has been well documented. Previous studies have reported that irrigated olive trees produce higher yields and better fruit characteristics than non-irrigated ones (Moriana et al., 2003; Lavee et al., 2007). In our research, Menara trees under RDI treatment exhibited a higher yield in 2022 than in 2021, while those under SDI treatment had a lower yield in 2022 than in 2021. The SDI treatments resulted in significant water savings, with the trees receiving only 70% and 60% of the water supplied to FI throughout the growing season, causing a decline in fruit yield by more than 50% in 2022. Correa-Tedesco et al. (2010) found that applying 66% ET_c over the growing season in a table olive cultivar Manzanilla fina led to mild water stress, which reduced fruit yield by 25% compared to well-watered trees. Fruit volume was significantly influenced by the irrigation treatments, with significant differences observed in both years. The fruit volume was directly related to the water status of the trees, with less water supplied leading to smaller olive fruit. For table olive cultivars, fruit size and yield are critical parameters (Alcaras et al., 2021). The individual fruit volume in trees under the *T*1 irrigation treatment was smaller in 2022 due to the high fruit load during that season. Grappadelli and Lakso (2004) reported that fruit size was influenced and regulated by water availability and crop load. Crop load can significantly decrease fruit size in well-irrigated or deficit-irrigated trees (Gucci et al., 2007). The fruit volume of Menara trees was also significantly influenced by the year, with $p < 0.0001$ in *T*1, *T*2, and *T*3 for the RDI strategy. Additionally, FV decreased significantly with $p < 0.01$

in $T6$ treatment with the poorest water status during the irrigation season (Supplementary Table S8). Significant differences were also found in fruit weight according to the applied DI treatments (Table 7). The year was a significant factor ($p < 0.0001$) influencing fruit weight (Supplementary Table S9) for $T6$ treatment. The volume of water applied significantly affected fruit oil content. The relationship between oil content and irrigation regimes was weak during the first year of the experiment (2021). However, in 2022, oil content increased significantly with decreasing irrigation water. Therefore, fruit oil content is assumed to be lower under irrigation due to competition between oil and water in cellular spaces because of their opposite polarity (Mazliak, 1968). The SDI, $T3$, and $T4$ irrigation regimes did not alter the oil accumulation process, confirming results from previous investigations (Gucci et al., 2007; Trentacoste et al., 2018, 2019). Furthermore, previous studies (Dag et al., 2009; Ben-Gal et al., 2021) have shown that increasing water stress could enhance oil quality. Therefore, the observed increase in oil content under water stress in olive cultivars is well documented (Gomez-del Campo, 2010; Ramos and Santos, 2010; Trentacoste et al., 2019). In fact, full irrigation was not required to achieve maximum fruit oil content in the "Menara" cultivar.

The studied parameters were significantly affected by the availability of water during sensitive stages. The Menara cultivar showed differences between RDI and SDI treatments regarding the intensity and timing of water deficit, particularly during sensitive phenological stages. Table 3 shows that Menara trees under SDI treatment exhibited less shoot growth capacity than trees under RDI treatment. Our observations indicate that trees subjected to RDI treatment suffered less from water stress during sensitive phenological stages (100% or 80% of estimated ET_c) in the spring–early summer period when growth performance is more critical. This trend can be explained by the stimulation of shoot growth under RDI treatment, which is an evident response caused by the increase in transpiration (Mahhou et al., 2005). Several reversible mechanisms, including an increase in cell division speed (Granier et al., 2000), elasticity of cellular wall, facilitated cell growth (Cosgrove, 2005), and increased cell turgor (Bouchabke et al., 2006), contribute to its occurrence. Providing full or elevated levels of water availability (100% or 75% of estimated ET_c) during the spring months, according to Pierantozzi et al. (2013), can protect photosynthetic pigments from oxidative degradation and significantly improve CO_2 assimilation rates. The tree growth and development and, consequently, the physiological functioning appeared to be maintained through these sensitive periods (Hernandez-Santana et al., 2017). However, previous studies have shown that water deficit during spring can reduce shoot growth (Palese et al., 2010; Hueso et al., 2021). Important physiological events determine shoot growth and various flowering parameters during spring, such as flower differentiation, flowering, and fruit number. During the second year of the experiment, non-significant differences were observed in shoot length and bud number as a result of reduced water application due to the RDI strategy. Rapoport et al. (2012) found that water deficit during inflorescence development led to a reduction in various flowering traits. In our study, we observed that water deprivation during sensitive periods through the SDI strategy resulted in reduced phenological traits and slowed down shoot growth. Hueso et al. (2021) reported significantly lower numbers of flower buds in rainfed and 40% ET_c of "Arbequina" trees than those in fully irrigated trees. However, we observed only a slight decrease when comparing RDI and FI treatments, which may be due to the set of flowering parameters before the reduction in irrigation during the normal period (Rapoport et al., 2012).

Conversely, Menara trees under SDI treatment experienced water stress, negatively affecting their flowering-related traits, even before the flower differentiation period, confirming the effect of RDI and irrigation scheduling on the studied parameters. Drought could highly impair fruit set and subsequent lower yield due to the increased presence of imperfect flowers in olive trees. In contrast, adequate irrigation during flower initiation and induction improved perfect flowers and, consequently, fruit yield in olive trees (Tadayon and Hosseini, 2023). Applying irrigation during early spring can prevent severe physiological disturbances such as low floral development (Cuevas et al., 1997; Crous, 2009) and significantly enhance fruit growth kinetics even during the stone-hardening period, where fruit growth is usually slowed (Manrique et al., 1997). These findings suggest that trees subjected to RDI treatment were more resilient to water stress than those under SDI treatment. Furthermore, trees can better tolerate deficit irrigation during periods when productivity-determining processes are less sensitive to water stress (Gucci et al., 2019). Trentacoste et al. (2019) reported that fruit number was reduced by water deficit when applying deficit irrigation from spring to early summer. According to Pierantozzi et al. (2013), trees that did not receive any irrigation experienced a delay in flowering, and this delay, coupled with a decrease in flowering intensity, resulted in lower oil yield in the moderately and severely water-stressed treatments compared to the well-irrigated trees. Reduced soil moisture during inflorescence formation and flower development resulted in fewer flowers per inflorescence, as reported by Hartmann and Panetsos (1961).

The results of Student's t-test analysis for shoot length and fruit yield revealed significant differences across the years for all RDI treatments and $T5$ treatments in the SDI treatment, as presented in Supplementary Tables S2, S7. In 2022, fruit yield significantly increased for the RDI treatments but decreased significantly for $T5$, indicating that olive production decreased significantly under water stress during the sensitive period. Furthermore, across seasons, all RDI regimes had a significant effect on bud number, as presented in Supplementary Table S3. Similar findings were reported by Moriana et al. (2003), who showed that RDI treatment increased the yield compared to SDI, where the latter showed a significant reduction in agronomical parameters. Likewise, moderate RDI was found to increase the fruit yield in high-density orchards (Rosecrance et al., 2015) and provide similar or greater production than full irrigation with less water usage, resulting in significant water savings (Fernández-Escobar et al., 2013). However, negative effects of RDI have been observed in other fruit trees after two to three consecutive seasons of deficit irrigation, where negative carryover effects on the yield of peach trees were observed after 3 consecutive years of RDI treatment (Girona et al., 2003). The negative effects were due to a reduction in floral density and fruit set, resulting from a decreased accumulation of reserves in RDI trees. Hence, optimizing irrigation is crucial for maximizing crop productivity while minimizing water usage. In 2022, reducing irrigation volumes by 30% during the normal period resulted in fruit weight similar to control trees, while deficit treatments at 60% of crop evapotranspiration during the NP significantly decreased the fruit weight compared to $T0$. This result could be due to differences in water stress intensity, which was slight in $T1$. Lavee et al. (2007) suggested that irrigation influenced fruit characteristics and recommended supplying all the water volume after pit hardening. Additionally, Lodolini et al. (2011) reported that different olive fruit tissues and components respond differently to water stress, depending

on their different sensitivities in the phases in which deficit irrigation is applied and their capacity to recover once the olive tree is fully irrigated. Water stress during the first phase of fruit growth produced smaller pits that could lead to higher pulp-to-pit ratios but could also reduce fruit size and number (Lavee and Nir, 1986; Rapoport et al., 2004). However, the endocarp size of the stressed plants was similar to the control plants once the stress was relieved, as reported by these authors. Under more prolonged stress, the endocarp size remained smaller. Therefore, the problems in deficit irrigation of perennial crops may be the prolonged effects of stress that last longer than the current season and often become detrimental in the following years (Gucci et al., 2019).

An irrigation strategy should aim to balance high crop production with high water productivity. For olive oil producers practicing deficit irrigation, measuring crop water productivity (WP), which is the fruit yield per unit of water consumed, is a useful indicator for assessing the impact of irrigation scheduling protocols. Table 9 shows that the T3 and T4 treatments were the most suitable strategies for maximizing water productivity in both studied years. However, WP was reduced with the SDI strategy in 2022. It is important to note that attempting to maximize WP through SDI, in which trees received only 70% and 60% of the water supplied to fully irrigated trees throughout the growing season, resulted in a significant reduction in crop yield. Therefore, although improving water use efficiency is critical for producers, it should not be at the expense of yield as it is the primary determinant of producers' income (Gucci et al., 2019). Additionally, Trentacoste et al. (2019) reported higher productivity in some deficit treatments in the spring.

5 Conclusion

In conclusion, this study investigated the effects of two different irrigation strategies (RDI and SDI) on the growth and yield of Menara olive trees over 2 years. The results indicated that RDI treatment was a viable strategy for improving the acclimation of trees to water stress, as evidenced by the better performance of trees under RDI treatment in terms of vegetative growth, bud number, and fruit yield. However, prolonged exposure to deficit irrigation can have a cumulative negative effect on crop performance, as observed in T6 under SDI treatment. These findings highlight the importance of the careful management of irrigation strategies and consideration of long-term effects on crop performance. Moreover, these findings can provide valuable insights for farmers and policymakers in implementing effective irrigation management practices for sustainable crop production. Future research should aim to optimize irrigation strategies to improve both short-term and long-term crop performance while also taking into account environmental and economic sustainability. Hence, further research is required to better understand the ecophysiological mechanisms underlying the response of olive trees to deficit irrigation and to identify the optimal irrigation strategies for maximizing crop yield and quality while minimizing water use.

5.1 Limits of the study and further developments

The limitations of this study are primarily related to the short observation period, which does not provide a complete understanding of the long-term adaptation and productivity of the plant beyond 2 years. Extending the study period to observe the adaptation of the plant to the irrigation regime is a natural progression of this research. Although there are studies on different cultivars, they are limited to 2 or 3 years of observation. Therefore, it is essential to conduct long-term studies to fully comprehend the effects of deficit irrigation on the agronomic productivity and adaptation of olive cultivars.

Data availability statement

The data supporting the conclusion of this article will be made available by the authors under reasonable request.

Author contributions

KI, SE, SO, LM, AB, and RH contributed to the conception and design of the study. KI, AB, LS, and RH collected the data and organized the database. KI, JK, and VB performed the statistical analysis. KI, JK, VB, and RH wrote the first draft of the manuscript. KI, AB, SE, RH, JK, and VB wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

Acknowledgments

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1100552/full#supplementary-material

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