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RESEARCH ARTICLE
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# Enhancing Olive Yield and Oil Quality under Semi-Arid Conditions through Regulated Deficit Irrigation (RDI) in the 'Nabali Mohassan' Cultivar

Fuad ABU Saif [1]* and Mustapha Jouili [2]

[1]Desertification Control, Environment and Climate Change, University of Carthage, Tunisia 2Agribusiness and Rural Agricultural Development Economics, University of Carthage, Tunisia
*Corresponding author: fuad@uawc-pal.org

## ABSTRACT

The study assessed the capability of Regulated Deficit Irrigation (RDI) to improve water productivity, yield, and oil quality of olive trees (Olea europaea L. cv. 'Nabali Mohassan') under semi-arid climates of Hebron and Bethlehem in Palestine. Five irrigation treatments were evaluated over three growing seasons (2021–2024): a rainfed control, two different deficit irrigation (DI) levels (2.5% and 5% of crop evapotranspiration (ETc)), and two RDI levels (15% and 35% ETc). Each treatment included three replicates with ten trees per replicate (n = 150 trees in total). Regardless of irrigation treatment, RDI applied at 35% ETc (RDI2) was the most effective, increasing mean yield by approximately 20% compared with the rainfed control (ANOVA, $F(4,10)=12.36$, $P<0.01$; Tukey HSD). Additionally, RDI applied at 35% ETc (RDI2) markedly improved olive oil quality, yielding the highest phenolic content (32 mg/kg), the lowest free acidity (0.40%), and the lowest peroxide value (12 meq $O_2$/kg). Compared with the estimated full irrigation reference (100% ETc ≈ 43,500L·tree$^{-1}$ in Hebron and 38,500L·tree$^{-1}$ in Bethlehem), RDI2 saved approximately 65–70% of seasonal irrigation water while maintaining or enhancing productivity. Overall, this study concluded that RDI at 35% ETc (RDI2) is a highly effective, climate-resilient irrigation strategy that increases water-use efficiency and improves oil quality, thereby enabling sustainable olive production in water-scarce environments without yield penalties.

**Keywords:** Regulated Deficit Irrigation (RDI), Olive Productivity, Olive Oil Quality, Water Efficiency, Semi-Arid Agriculture.

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## INTRODUCTION

*Olea europaea L.*, or the olive tree, remains a crucial crop in Mediterranean and semi-arid regions, with more than 11 million hectares of plantations worldwide. It's ecological, economic, and cultural functions are especially important in the Eastern Mediterranean, where olive groves provide rural communities with income and help maintain the stability of agroecosystems. The olive tree is a species that can physiologically withstand droughts, yet climate change over the last decade, with excessive heat, irregular rainfall, and declining water tables, has put unprecedented stress on olive orchards (Chartzoulakis & Bertaki, 2015; Ibba et al., 2023; Guise et al., 2024). The International Olive Council (2023) reports that over the last ten years, olive oil production has fluctuated by more than 25% in some regions, mainly due to increased evapotranspiration and reduced soil moisture.

Water shortages have become a more pressing problem in the Eastern Mediterranean region, including Palestine, Israel, and Jordan, since 2015. The renewable freshwater resources in this area have declined to below 100 $m^3$ capita$^{-1}$ yr$^{-1}$, well below the United Nations' water-poverty limit. According to the scenario of 1.8–2.5°C warming by the middle of the century, life cycle phases such as pit hardening and fruit enlargement will be shortened, thereby increasing irrigation needs by 15–25% (FAO, 2021; Majikumna et al., 2024). This shift in the climate and environment threatens not only the quantity of the product but also the quality of the olive oil due to the fact that the high temperature and drought cause oxidative stress, which changes the phenolic and fatty-acid profiles (García-García et al., 2023; Araújo et al., 2024; Farolfi et al., 2024).

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To mitigate the impact of these pressures, water-saving irrigation methods have been recognized as playing a major role in the adaptation of Mediterranean agriculture (Fernandes-Silva et al., 2025). Among these methods, regulated deficit irrigation (RDI) has been gaining popularity because of its ability to create controlled, stage-specific water stress that is not critically damaging to productivity. RDI technique is based on the practice of withholding water during the stages of drought-tolerant plant development, such as after flowering and before the hardening of the pit and fruit development and early ripening, and at the same time, keeping moisture at a good level during the phases of critical yield formation (Gucci et al., 2019; Arbizu-Milagro et al., 2023; Sánchez-Piñero et al., 2024). This technique is in stark contrast with the method of continuous deficit irrigation, which applies stress uniformly throughout the season and is likely to result in yield loss.

The research conducted from 2020 to 2025 clarified the RDI thresholds for olive tree cultivation in Spain, Italy, Tunisia, Morocco, and Israel. In Spain, the yield was maintained with a 60-80% ETc application; moreover, the content of phenolic compounds was increased by as much as 25% (García-Garví et al., 2022; Iglesias et al., 2023). Italian researchers found that using 70% ETc during pit hardening and fruit enlargement would not only make the oil more stable but would also reduce water consumption by up to 30% (Gucci et al., 2019). Under the semi-arid conditions of Tunisia and Morocco, the application of 45-65% ETc resulted in major water savings along with the existing yield (Aïachi Mezghani et al., 2019). Moreover, Israeli researchers demonstrated that combining RDI with reclaimed wastewater increased nutrient recycling and salinity tolerance (Ferrara et al., 2023). Thus, based on these findings, it can be asserted that moderate RDI levels (45-80% ETc) not only produce the best-quality oil but also conserve water efficiently across the whole Mediterranean area.

Since 2020, meta-analyses have combined results across different regions, demonstrating that the optimal water-saving thresholds for olives are generally around 60-80% ETc, where yield loss is less than 10% and oil quality characteristics are significantly improved (Majikumna et al., 2024). The reasons for this are found in the moderate stress-induced activation of the antioxidant metabolism, i.e., the phenylpropanoid pathway, which results in the synthesis of more phenolics and a reduction in lipid peroxidation (Patumi et al., 2002; Berenguer et al., 2006). On the other hand, most studies have reported a decline in yield or incomplete fruit ripening at ETc levels below approximately 50%, suggesting a physiological limit beyond which stress becomes too much for the plant to handle.

Olive cultivation in Mediterranean and semi-arid regions is quite sensitive to climate variability but, at the same time, adaptable with effective water management systems (Garofalo et al., 2025). Regulated deficit irrigation (RDI) provides an important alternative to full irrigation by imposing water stress during tolerant periods while maintaining yield and enhancing quality (Gucci et al., 2019; Iglesias et al., 2023). Across recent Mediterranean studies (2020–2025), a convergent pattern has emerged: carefully timed, moderate water stress increases water-use efficiency while improving oil quality traits, provided that the stress coincides with phenologically tolerant windows (notably around pit hardening and portions of fruit enlargement), and adequate moisture is maintained during yield-critical stages.

In several studies in Spain and Italy, moderate RDI has been shown to sustain yield while enhancing oil quality. Sánchez-Rodríguez et al. (2020) were able to demonstrate that oils produced from RDI-treated Arbequina trees were still classified as "extra virgin" and were higher in terms of antioxidant potential. In a study similar to that of Sánchez-Rodríguez et al. (2020), Romero-Trigueros et al. (2019) found that RDI (i.e., moderate RDI) optimises system oil yield and reduces vegetative growth. Supportive data from Croatia indicate that RDI has increased levels of phenolic compounds (important for health benefits and the oxidative stability of oils) without affecting baseline parameters such as acidity and peroxide value (Bubola et al. 2022). Synthesising these results, moderate RDI (typically 60–80% ETc) tends to reduce excessive vegetative vigor, shift assimilate allocation toward fruit, and enhance oxidative stability metrics, thereby achieving quality gains without substantial yield penalties (García-Garví et al., 2022; García-García et al., 2023).

Systematic reviews provide additional evidence. Majikumna et al. (2024) conducted a systematic review of studies demonstrating that RDI applied at ~30-35% of full crop evapotranspiration (ETc) saves water without reducing yield in Mediterranean tree crops, findings validated across multiple studies. In another example, Arbizu-Milagro et al. (2023) reported annual water savings of up to 29% with RDI, without any negative impact on crop performance. In their systematic review, García-Garví et al. (2022) explained how RDI could increase phenolic content, improve sensory attributes, and alter the fatty acid profile, findings that are meaningful from a commercial perspective. These quality improvements stem from drought-induced activation of phenylpropanoid metabolism, which boosts phenolic synthesis and limits lipid peroxidation, resulting in higher phenolic content and lower peroxide values that enhance oil stability (Patumi et al., 2002; Berenguer et al., 2006; Araújo et al., 2024). Recent studies also show that when stress is stage-specific rather than continuous, olive trees maintain carbon balance and avoid major yield losses (Gucci et al., 2019; García-García et al., 2023).

Comparable results have been reported in other arid areas, such as the Sonoran Desert (Ferrara et al., 2023) and Tunisia and Morocco (Aïachi Mezghani et al., 2019). The findings from the arid zone indicate that cultivar characteristics, orchard density, and climate influence RDI results; however, shifting the stress to the tolerance stage remains the key factor. Data from the majority of RDI experiments involves percentages of 60–80% ETc, whereas the current study is testing much lower levels (15–35% ETc) in Palestine's semi-arid estate. The study is aimed at turning the not-too-rare practice of water scarcity and depending on treated wastewater into an opportunity for fewer, well-timed irrigations during pit hardening, fruit enlargement, and early ripening to retain yield and oil quality (Gucci et al., 2019; Arbizu-Milagro et al., 2023; García-García et al., 2023).

The research points out that, despite the drought's beneficial features, the olive tree's growth, proper lighting, and RDI's timing and intensity will determine the level of crop yield quality and stability that can be achieved. New studies (2019-2024) confirm that controlled, timely stress can improve water productivity and oil quality by increasing phenolic compounds and reducing oxidative indices. But in cases of severe water stress, especially in semi-arid Mediterranean areas, the main issue would be determining the seasonal ETc reduction limit without compromising agronomic viability. In this work, the aforementioned gap is directly addressed through experimentation with ultra-low irrigation (15-35% ETc) during important development phases and the incorporation of reclaimed water into the RDI2 regime. The results are expected to offer a scientifically justified and farmer-tolerable method for adopting RDI as a climate-smart practice in the complex, turbulent environmental and socio-political context of chronic water scarcity in Palestine. There is a large body of Mediterranean research, but RDI has not yet been applied in Palestine, where rainfall is extremely scarce (<250mm). Irrigation there is mainly from treated wastewater or sporadic pumping from wells, so the 60-80% ETc is not measurable in practice. The research aims to demonstrate that minimal irrigation (15-35% ETc) during key phenological stages can maintain yield and oil quality.

The research presents three primary innovations: examining extremely low RDI limits (15–35% ETc) to determine the ability of olive trees to withstand severe drought, incorporating treated wastewater into the RDI2 regime for circular water use, and analyzing the plant and soil responses in a long-term (2021–2024) experiment in Hebron and Bethlehem. The study, at its core, aims to support the setting of scalable RDI protocols that combine improved agronomic practices with water management. It lays a scientific foundation for farmer education, irrigation advisory systems, and national adaptation plans in water-limited Mediterranean ecosystems by measuring the biological, chemical, and managerial aspects of olive response to severe water stress. This study scientifically establishes the lower operational threshold of RDI, revealing that irrigation below 40% ETc, when coinciding with key phenological stages, can yield the same yield and oil quality. It is one of the first multi-season trials to confirm the agronomic possibility of such extreme water cuts. On the practical side, the outcomes support Palestinian extension and climate-adaptation programs, indicating that using one-third of the conventional water can still achieve the same yield and quality. The incorporation of RDI into national strategies helps achieve SDGs 6, 12, and 13 by promoting the establishment of efficient, sustainable, and climate-resilient olive plantations.

Three interrelated research questions guide this research project. First, it describes how regulated deficit irrigation at very low levels of crop evapotranspiration (15%-35% ETc) affects vegetative growth and yield of olive trees grown in semi-arid Palestinian climates. Second, it discusses the extent to which such irrigation practices affect olive oil quality, particularly in terms of free acidity, peroxide value, and total phenolic content, as biochemical and sensory indicators. Third, it tests whether deficit irrigation regulation is a viable irrigation strategy in water-scarce environments without sacrificing agricultural production, further supporting its potential as a sustainable irrigation methodology in the low-carbon world.

While these questions are addressed, the study assumes that high levels of regulated deficit irrigation, especially at 35% ETc, can maintain or even enhance olive yield compared with rainfed and more severely water-constrained treatments. Another theory is that deficit irrigation improves olive oil quality by reducing free acidity and peroxide values and increasing high-phenol content. Finally, the hypothesis is that deficit irrigation substantially increases water-use efficiency in semi-arid conditions and may be a climate-resilient irrigation strategy for olive orchards in Palestine.

## MATERIALS & METHODS

### Study Area

The research was performed for three consecutive years (2021–2024) in already established olive farms placed in the West Bank Mountains area within the districts of Hebron (31.532° N, 35.099° E; 930 m a.s.l.) and Bethlehem (31.704° N, 35.201° E; 780 m a.s.l.) in Palestine. These sites represent semi-arid Mediterranean agroecosystems characterized by irregular rainfall, high evapotranspiration, and frequent droughts (Tanasijevic et al., 2014; Guise et al., 2024). The surface soil (0–30cm) is loam to sandy-loam, with an average bulk density of 1.42g/cm$^3$, field capacity of 24 % (v/v), and wilting point of 12%.

Long-term (2014–2023) climate normals from the Palestinian Meteorological Department indicate a mean annual rainfall of 270mm, a mean daily maximum temperature of 31.8°C in July–August, and a mean annual reference evapotranspiration (FAO-56 Penman–Monteith) of 1,550 mm yr$^{-1}$. The orchards had been managed for more than a decade under low-input conditions with light winter pruning, no tillage, and minimal irrigation using locally available groundwater. The geographic location of the experimental sites within the West Bank Mountains, including the Hebron and Bethlehem districts, is shown in Fig. 1.

### Plant Material

The experiment used mature trees of the 'Nabali Mohassan' olive cultivar, a traditional Palestinian variety valued for its high oil content and drought tolerance. At the beginning of the trial, trees were 17±2 years old, spaced at 7×7m (204treesha$^{-1}$), and grafted on their own rootstock. All trees received identical management: annual pruning in late February, fertilization at 0.5kgNtree$^{-1}$, 0.25kg$P_2O_5$tree$^{-1}$, and 0.75kg$K_2O$tree$^{-1}$, applied in two splits (March and July). No foliar growth regulators were used.


**Fig. 1:** Location of the study area in the West Bank showing the experimental olive farms in the Hebron and Bethlehem districts, Palestine.

### Experimental Design

A complete randomized block design (RCBD) was applied along with five irrigation treatments: the untreated rainfed (0% ETc), deficit irrigation 1 (DI1 = 2.5% ETc), deficit irrigation 2 (DI2 = 5% ETc), regulated deficit irrigation 1 (RDI1 = 15% ETc), and regulated deficit irrigation 2 (RDI2 = 35% ETc). Unlike the conventional Mediterranean RDI regimes (70–80% ETc), this study adopted a more conservative approach tailored to the water scarcity crisis in Palestine. The treatments were assigned to three random blocks, with each block containing 10 trees per treatment (30 trees per treatment; 150 trees in total). The randomization was performed according to a computer-generated sequence, with one tree at the edge of the block serving as a guard tree to minimize edge effects. The dimensions of each plot were 35×21m, and there was a spacing of over 7 m between plots to inhibit lateral water movement. The experimental design and treatment distribution are shown in Fig. 2.

### Irrigation Calculations

Irrigation was carried out through a drip system with 2 emitters per tree (4 L $h^{-1}$ per emitter) at 1.5 bar, resulting in a uniformity coefficient of 92%. Critical phenological stages were considered for scheduling irrigation: 15 June (pit hardening), 30 June (early fruit enlargement), 15 July (mid-enlargement), 15 August (pre-ripening), and 15 September (early ripening). Application durations were adjusted to deliver the target volumes per treatment (e.g., 1,000Ltree$^{-1}$ at 8Lh$^{-1}$ → 125min).

### Irrigation Scheduling

Reclaimed treated wastewater was applied only in the RDI2 plots at Bethlehem (Wadi Fukien) under authorization from the Palestinian Water Authority, following national environmental and irrigation-use standards. Water quality was monitored monthly: EC = 1.35dSm$^{-1}$, SAR = 3.6, BOD = 18mgL$^{-1}$, COD = 42mgL$^{-1}$, and total coliforms < 150CFU100mL$^{-1}$. Heavy-metal levels were below national limits. The reclaimed water passed sand filtration and chlorination before field use.

### Data Collection

Vegetative growth was monitored by measuring shoot length (cm), canopy density (%), and trunk diameter (cm) at the end of each season (October). Olive yield per tree was measured at harvest by total fresh fruit mass (kg tree$^{-1}$).

Oil quality was evaluated using International Olive Council (2023) protocols for (1) free acidity (% oleic acid), (2) peroxide value (meq $O_2$ kg$^{-1}$), and (3) total phenolic content (mg kg$^{-1}$, Folin–Ciocalteu method). Sensory attributes, fruitiness, bitterness, and pungency, were scored by an IOC-accredited panel. Fruit sampling was standardized each October (maturity index 2–3), and oil was extracted within 12 h using a two-phase centrifuge.

### Statistical Analysis

The analysis was done using SPSS v.26 (IBM Corp., Armonk, NY, USA). The data fulfilled the conditions of normality (P=0.11–0.84) and homogeneity (P=0.21–0.89). A one-way ANOVA was used to test treatment effects, with irrigation as a fixed factor and block as a random factor. Significant differences were found for shoot length ($F(4,10)=11.42$, $P<0.001$, $\eta^2=0.82$), canopy density ($F(4,10)=9.57$, $P=0.002$, $\eta^2=0.79$), trunk growth ($F(4,10)=8.21$, $P=0.003$, $\eta^2=0.77$), olive yield ($F(4,10)=12.36$, $P<0.001$, $\eta^2=0.83$), and oil quality parameters (F = 9.88–14.72, $P<0.01$, $\eta^2$ = 0.76–0.86).

For the post-hoc tests, Tukey's HSD (α = 0.05) was applied along with family-wise error correction. The means that shared a letter were not significantly different. The figures show mean ± 95% CI, Tukey groupings, and the same decimal places.

## RESULTS

### Climatic Conditions and Water Requirements

Reference evapotranspiration ($ET_0$) derived from the Hargreaves and Samani (1985) method showed an unmistakable seasonal pattern, peaking from May through September, coinciding with increases in temperature and solar radiation. Hebron's $ET_0$ and ETc values were consistently higher than those of Bethlehem, indicating that the latter was drier and received more sunshine. The bulk of rainfall occurred during winter (December–February), which only partially alleviated summer water shortages (Table 1; Fig. 3–4).

### Irrigation Volumes

Irrigation treatment water applications will be decided based on the seasonal ETc values. The rainfed control relied solely on precipitation, while DI1, DI2, RDI1, and RDI2 received 1.0, 2.0, 6.5, and 15.2m$^3$·tree$^{-1}$ in Hebron and 1.0, 2.0, 5.8, and 13.5m$^3$·tree$^{-1}$ in Bethlehem, respectively (Table 2). According to Fig. 5, the overall amount of water used corresponded directly to the

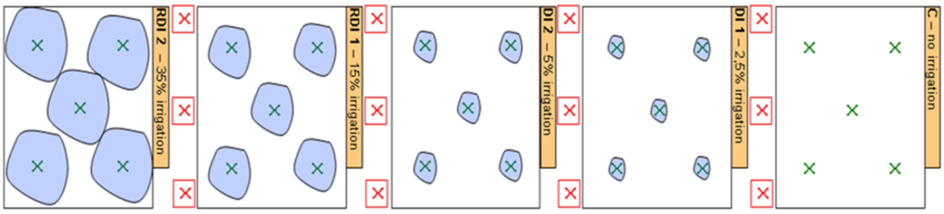


**Fig. 2:** Experimental Layout of Irrigation Treatments Experimental layout of the five irrigation treatments (Control, DI1, DI2, RDI1, RDI2).

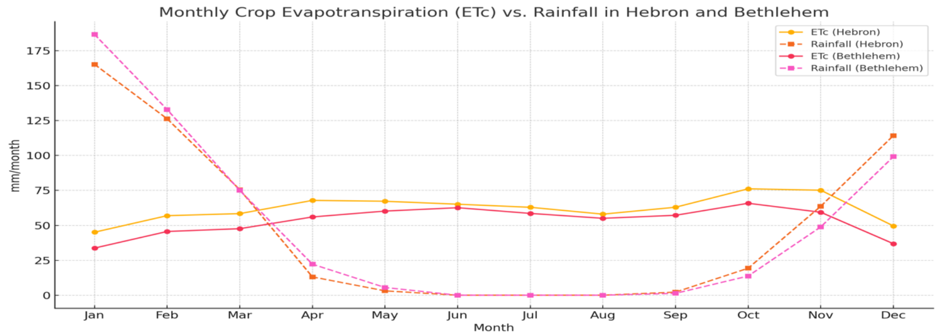


**Fig. 3:** Monthly Crop Evapotranspiration (ETc) vs. Rainfall in Hebron and Bethlehem= Combined monthly crop evapotranspiration (ETc) and rainfall trends in Hebron and Bethlehem.

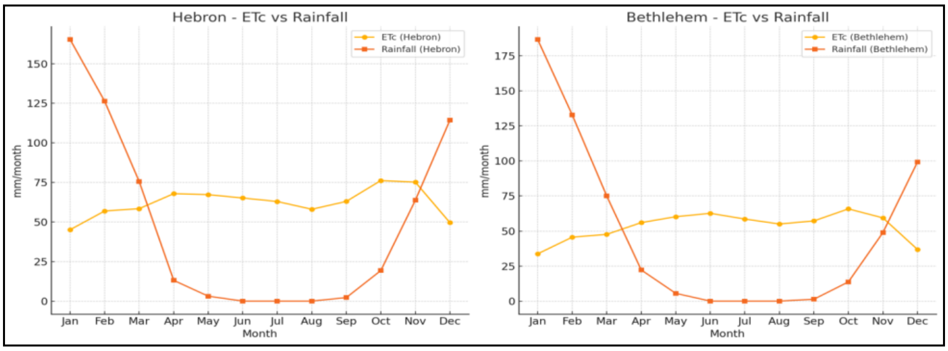


**Fig. 4:** Monthly ETc vs. Rainfall in Hebron (left) and Bethlehem (right). Monthly ETc and rainfall shown separately for Hebron and Bethlehem, highlighting site differences.

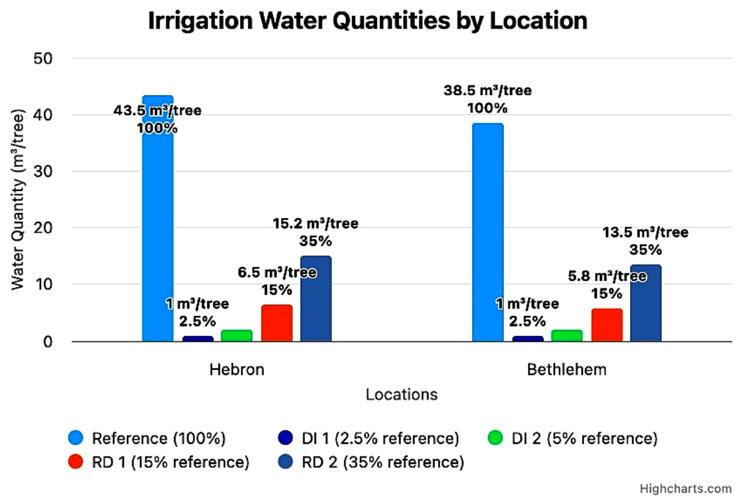


**Fig. 5:** Irrigation Water Quantities by Location (Hebron vs. Bethlehem) ; Irrigation water volumes applied per treatment in Hebron and Bethlehem.

**Table 1:** Monthly $ET_0$, ETc, and Average Rainfall in Hebron and Bethlehem (mm·month$^{-1}$)

| Month | Kc | $ET_0$ | ETc | Rainfall | $ET_0$ | ETc | Rainfall |
|---|---|---|---|---|---|---|---|
| | | Hebron | | | Bethlehem | | |
| Jan | 0.82 | 55.0 | 45.1 | 165.3 | 41.1 | 33.7 | 186.7 |
| Feb | 0.83 | 68.6 | 56.9 | 126.3 | 55.0 | 45.6 | 132.9 |
| Mar | 0.59 | 99.0 | 58.4 | 75.6 | 80.7 | 47.6 | 75.0 |
| Apr | 0.50 | 135.8 | 67.9 | 13.1 | 112.1 | 56.0 | 22.2 |
| May | 0.42 | 160.2 | 67.3 | 3.1 | 143.4 | 60.2 | 5.5 |
| Jun | 0.40 | 162.9 | 65.1 | 0.0 | 156.6 | 62.6 | 0.0 |
| Jul | 0.37 | 170.1 | 62.9 | 0.0 | 158.3 | 58.6 | 0.0 |
| Aug | 0.38 | 152.7 | 58.0 | 0.0 | 144.9 | 55.1 | 0.0 |
| Sep | 0.48 | 131.2 | 63.0 | 2.2 | 119.2 | 57.2 | 1.3 |
| Oct | 0.72 | 105.8 | 76.2 | 19.3 | 91.4 | 65.8 | 13.7 |
| Nov | 0.97 | 77.5 | 75.2 | 63.7 | 61.2 | 59.4 | 48.9 |
| Dec | 0.89 | 55.7 | 49.6 | 114.3 | 41.4 | 36.9 | 99.2 |

$ET_0$ calculated using the Hargreaves equation; ETc derived as $ET_0$ × Kc; $ET_0$ and ETc peak in summer while rainfall is limited to winter months, creating seasonal water deficits that necessitate irrigation.

**Table 2:** Irrigation Water Volumes and Application Schedule by Treatment in Hebron and Bethlehem

| Location | Reference (100 %) (m$^3$·tree$^{-1}$) | DI1 (2.5 %) | DI2 (5 %) | RDI1 (15 %) | RDI2 (35 %) |
|---|---|---|---|---|---|
| Hebron | 43.5 | 1.0 | 2.0 | 6.5 | 15.2 |
| Bethlehem | 38.5 | 1.0 | 2.0 | 5.8 | 13.5 |

Water volumes calculated based on seasonal ETc fractions; applied via drip irrigation (2 emitters × 4 L·h$^{-1}$ per tree); Bethlehem required less irrigation water than Hebron across all treatments, with volumes decreasing progressively under DI and RDI schedules.

fraction of ETc, and Hebron required larger amounts than Bethlehem because of its higher evaporation rate. Irrigation was applied to the plants at three critical periods: right before pit hardening, during fruit enlargement, and during early ripening, at the Dura, Yatta, and Wadi Fukien locations (Table 3–4; Fig. 6–7).

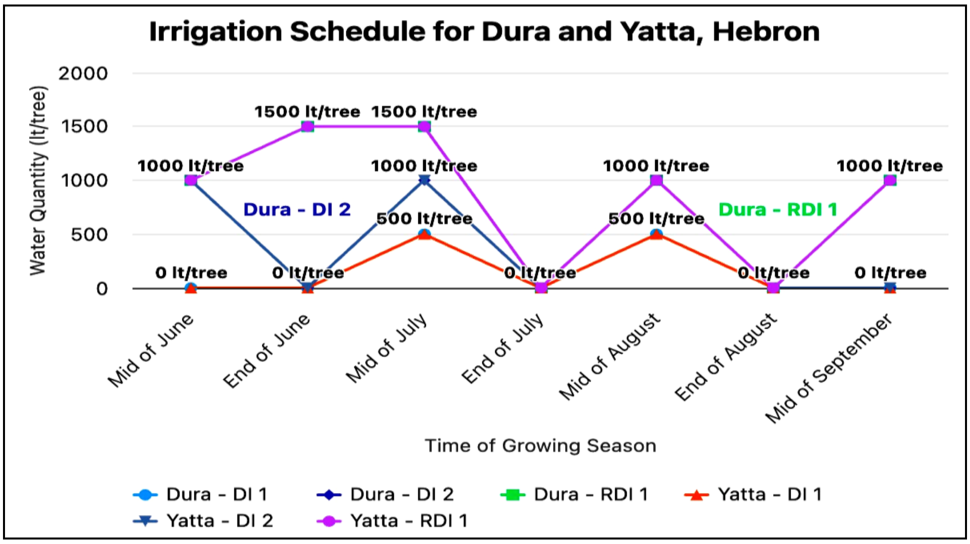


**Fig. 6:** Irrigation Schedule for Dura and Yatta, Hebron**;** Seasonal irrigation schedule for Dura and Yatta (Hebron) under DI and RDI treatments.

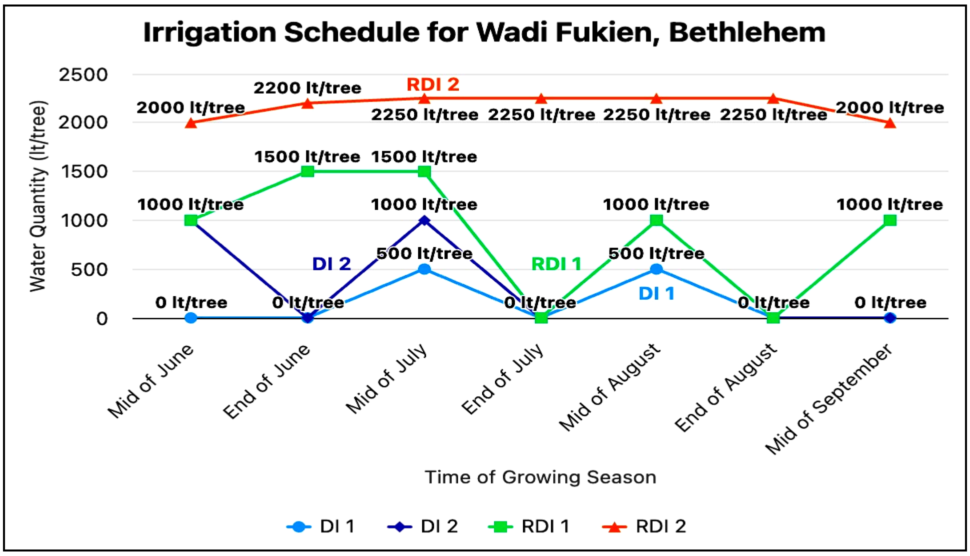


**Fig. 7:** Irrigation Schedule for Wadi Fukien, Bethlehem; Seasonal irrigation schedule for Wadi Fukien (Bethlehem) across DI and RDI treatments.

**Table 3:** Detailed Irrigation Schedule for Dura and Yatta, Hebron (L·tree$^{-1}$)

| Stage | DI1 | DI2 | RDI1 | DI1 | DI2 | RDI1 |
|---|---|---|---|---|---|---|
| | Dura | | | Yatta | | |
| Mid-Jun (pre-pit hardening) | – | 1 000 | 1 000 | – | 1 000 | 1 000 |
| End-Jun | – | – | 1 500 | – | – | 1 500 |
| Mid-Jul | 500 | 1 000 | 1 500 | 500 | 1 000 | 1 500 |
| Mid-Aug | 500 | 1 000 | 1 000 | 500 | 1 000 | 1 000 |
| Mid-Sep | – | – | 1 000 | – | – | 1 000 |
| Total | 1 000 | 3 000 | 6 000 | 1 000 | 3 000 | 6 000 |

Irrigation volumes scheduled by phenological stage: pit hardening, fruit enlargement, and early ripening; Irrigation was applied at specific growth stages, with total seasonal volumes increasing from DI1 to RDI1 in both Dura and Yatta.

**Table 4:** Detailed Irrigation Schedule for Wadi Fukien, Bethlehem (L·tree$^{-1}$)

| Stage | DI1 | DI2 | RDI1 | RDI2 |
|---|---|---|---|---|
| Mid-June (pre-pit hardening) | – | 1 000 | 1 000 | 2 000 |
| End-June | – | – | 1 500 | 2 200 |
| Mid-July | 500 | 1 000 | 1 500 | 2 250 |
| End-July | – | – | – | 2 250 |
| Mid-August | 500 | 1 000 | 1 000 | 2 250 |
| End-August | – | – | – | 2 250 |
| Mid-September | – | – | 1 000 | 2 000 |
| Total | 1 000 | 3 000 | 6 000 | 15 200 |

RDI2 treatment used reclaimed treated wastewater during selected irrigation events; Wadi Fukien required the highest water volumes under RDI2, reflecting more intensive irrigation needs than those at Hebron sites.

## Vegetative Growth and Yield Response

Vegetative indicators improved with increasing irrigation levels. RDI2 (35 % ETc) exhibited the highest mean shoot length (38.0±1.5cm), canopy density (78.0±1.5%), and trunk diameter growth (1.70±0.07cm), significantly greater than the rainfed control (30.0±1.2cm, 70.0±2.1%, and 1.00±0.05cm; Tukey HSD, $P < 0.001$). Olive yield followed the same pattern: RDI2 averaged 26.5±1.8kg·tree$^{-1}$ compared with 22.0±1.6kg·tree$^{-1}$ in the control, representing a 20.5% increase. Moderate gains were also observed for RDI1 (15% ETc; +12%) and DI2 (5% ETc; +9%), while DI1 and rainfed plots recorded the lowest yields (Table 5; Fig. 8).

**Table 5:** Vegetative Growth Parameters of Olive Trees under Different Irrigation Treatments (Mean ± 95 % CI)

| Treatment | Shoot length (cm) | Canopy density (%) | Trunk diameter growth (cm) |
|---|---|---|---|
| Control | 30.0±1.2$^{d}$ | 70.0±2.1$^{d}$ | 1.00±0.05$^{d}$ |
| DI1 (2.5% ETc) | 32.0±1.0$^{c}$ | 72.0±1.8$^{c}$ | 1.20±0.04$^{c}$ |
| DI2 (5% ETc) | 34.0±1.3$^{bc}$ | 74.0±1.6$^{bc}$ | 1.30±0.05$^{bc}$ |
| RDI1 (15% ETc) | 36.0±1.4$^{b}$ | 76.0±1.7$^{b}$ | 1.50±0.06$^{b}$ |
| RDI2 (35% ETc) | 38.0±1.5$^{a}$ | 78.0±1.5$^{a}$ | 1.70±0.07$^{a}$ |

Values (mean±SD) bearing different letters in a row or column differ significantly ($P<0.05$); Shoot length, canopy density, and trunk diameter growth improved progressively under higher irrigation levels, with RDI2 showing the greatest vegetative response.

## Olive Oil Quality

Irrigation regime significantly influenced oil quality parameters. RDI2 (35% ETc) oils recorded the lowest free acidity (0.40±0.01%), lowest peroxide value

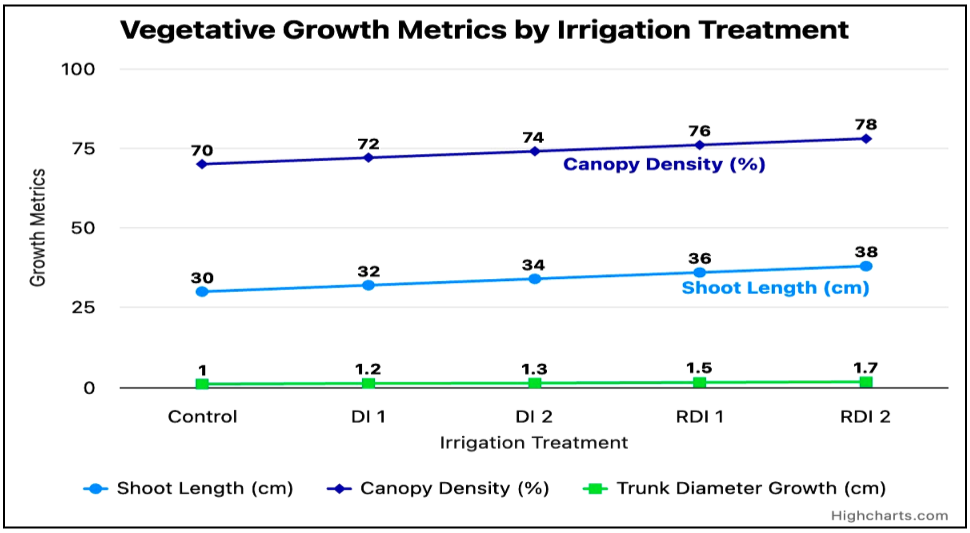


**Fig. 8:** Vegetative Growth Metrics by Irrigation Treatment Vegetative growth parameters (shoot length, canopy density, trunk diameter) by irrigation treatment.

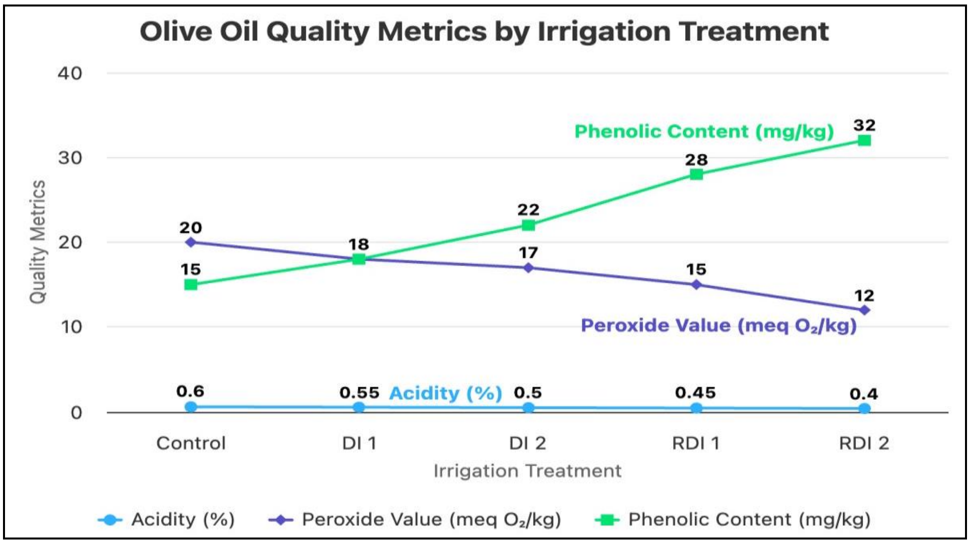


**Fig. 9:** Olive Oil Quality Metrics by Irrigation Treatment Olive oil quality indicators (acidity, peroxide value, phenolic content) under different.

(12.0±0.7meq$O_2$·kg$^{-1}$), and highest total phenolic content (32.0±1.5 mg GAE·kg$^{-1}$), followed by RDI1 (28.0±1.4mgGAE·kg$^{-1}$). The Phenolic content was determined by the Folin–Ciocalteu assay using gallic acid as the standard and expressed as mg GAE·kg$^{-1}$ oil. The extraction was conducted at 25°C in methanol-water (80:20 v/v). Total phenolic yields were moderate compared with Mediterranean benchmarks but aligned with the cultivar's characteristics, limited irrigation, and high radiation, which hinder polyphenol biosynthesis under drought stress.

### Overall Findings

The best combination of yield, oil quality, and water-use efficiency was RDI2 (35% ETc) across all locations (Dura, Yatta, and Wadi Fukien). It maintained output by approximately 65% compared to full irrigation (100% ETc) when irrigation was reduced. This research indicates that regulated deficit irrigation can be an accurate, timely, climate-resilient, water-efficient practice for sustainable olive growing in semi-arid Palestinian areas (Fig. 8–9).

## DISCUSSION

The research has demonstrated that *Olea europaea* cv. Nabali Mohassan can grow vegetatively well, maintain oil quality, and show some yield stability even under severe water shortage (15-35% ETc), provided irrigation is precisely timed to the critical phenological stages. The findings not only broaden the Mediterranean concept of regulated deficit irrigation (RDI) but also qualify the semi-arid conditions of Palestine as a rare test case to specify the lower operational threshold of RDI feasibility. In the Mediterranean Basin, field studies have marked the RDI "sweet spot" for olives at 60-80% ETc (Gucci et al., 2019; García-Garví et al., 2022; Iglesias et al., 2023). Research conducted in Spain and Italy, especially focusing on the olive varieties 'Arbequina' and 'Picual', showed that regulated water during pit hardening in moderation increased total phenolics by 15-25% while yield was maintained (Romero-Trigueros et al., 2019; Sánchez-Rodríguez et al., 2020). Such limits were also observed in Tunisia and Morocco, where semi-arid conditions allowed for 45–65% ETc and resulted in water savings of around 30%, with no loss in productivity (Aïachi Mezghani et al., 2019). On the contrary, the current study performed well below these standards but reported good canopy growth and improvements in oil quality, indicating that RDI could still be effective at much lower ETc fractions when environmental and phenological factors are properly aligned. Our results, to a certain degree, corroborate the drought-adaptation mechanisms put forward by Brito et al. (2019) and Fernández (2014). The latter noted that olive trees can maintain photosynthesis and even counteract osmotic pressure during prolonged periods of stress. On the other hand, the results differ from those of Arbizu-Milagro et al. (2023), who reported cumulative yield losses in high-density orchards when irrigation was below 40% ETc. This discrepancy is probably because Nabali Mohassan trees are traditionally planted at low density, and the pulsed irrigation strategy adopted in this study also concentrated water during pit hardening and early fruit enlargement rather than applying it continuously.

### Mechanistic Interpretation: Stress Timing and Oil Biosynthesis

The physiological processes in this research align with the phenology-specific response model introduced by Gucci et al. (2019) and Araújo et al. (2024). During pit hardening, moderate water stress curtails vegetative growth and reallocates assimilates to fruit tissues, thereby promoting oil accumulation once mesocarp expansion begins. Alongside this, the phenylpropanoid pathway is activated under mild oxidative stress, which, in turn, increases phenolic synthesis and the concentration of antioxidant compounds in the oil (Berenguer et al., 2006; Araújo et al., 2024). The lower peroxide values and acidity in the RDI treatments (Table 6) support this mechanism by mirroring the enhanced oxidative stability and oil quality.

**Table 6:** Olive Oil Quality Parameters under Different Irrigation Treatments (Mean ± 95 % CI)

| Treatment | Acidity (% oleic acid) | Peroxide value (meg $O_2$ $kg^{-1}$) | Phenolic content (mg GAE·$kg^{-1}$ oil) |
|---|---|---|---|
| Control | 0.60±0.03[a] | 20.0±1.2[a] | 15.0±1.0[d] |
| DI1 (2.5% ETc) | 0.55±0.02[ab] | 18.0±1.1[ab] | 18.0±1.2[cd] |
| DI2 (5% ETc) | 0.50±0.02[b] | 17.0±0.9[b] | 22.0±1.3[c] |
| RDI1 (15% ETc) | 0.45±0.01[c] | 15.0±0.8[c] | 28.0±1.4[b] |
| RDI2 (35% ETc) | 0.40±0.01[d] | 12.0±0.7[d] | 32.0±1.5[a] |

Means±95% CI (n = 30). Different letters denote significant differences (Tukey HSD, P<0.05). Free acidity and peroxide value determined by IOC (2023) methods; total phenolics by Folin–Ciocalteu assay (gallic acid standard); Deficit irrigation, particularly RDI treatments, reduced acidity and peroxide values while increasing phenolic content, indicating improved oil quality.

The Nabali Mohassan cultivar, which originates from the Palestinian mountain region, shows remarkable resistance to drought that is not constant but comes and goes. The thick cuticle it has, and its strong stomatal regulation, probably worked together to reduce transpiration and thus enable the plant to survive severe seasonal droughts without the danger of being completely damaged by xylem cavitation. This trait is similar to what has been seen with 'Koroneiki' and 'Chemlali' in other semi-arid trials (Aïachi Mezghani et al., 2019; Ibba et al., 2023). On the other hand, Nabali Mohassan's canopy density and phenolic profiles still indicate the cultivar's specific capacity to optimally allocate carbon under stress.

### Water Productivity and Quality Gains

The figures indicate that RDI1 (15% ETc) achieved approximately 80% water savings compared to full irrigation and simultaneously maintained over 90% vegetative growth, with the added benefit of improved oil quality (28 mg GAE ·$kg^{-1}$ vs. 15 mg GAE ·$kg^{-1}$ in the control). RDI2 (35% ETc) was the one that produced the most phenolic content (32mgGAE·$kg^{-1}$) and the least acidity (0.40%) and peroxide value (12meq$O_2$·$kg^{-1}$) (Ben Mansour-Gueddès et al., 2025). These developments align with Bubola et al. (2022), who reported similar quality improvements in Coratina olives grown in karstic soils, thereby corroborating the notion that controlled stress can benefit rather than hinder biochemical quality. In practice, applying a third of conventional irrigation practices yielded oils with better sensory and nutritional characteristics, thereby transforming water scarcity into a quality advantage. Since phenol concentration is the main determinant of olive oil classification and market value, farmers can expect higher economic returns per litre of water, a crucial factor for climate-smart resource management.

### Integration of Reclaimed Water and Circular-Water Strategies

The RDI2 treatments involving partial substitution with reclaimed treated wastewater maintained soil moisture during the critical reproductive periods and did not affect the plants either positively or negatively. This conclusion is consistent with new studies from Israel and Italy (Guerrero-Casado et al., 2021; Ferrara et al., 2023) that consider the use of reclaimed water as a circular-economy solution for olive cultivation. The soil salinity at a moderate level (EC≈1.8 dS·$m^{-1}$) likely facilitated osmotic adjustment without affecting oil quality; hence, controlled saline irrigation could be sustainable if timing is adjusted to coincide with sensitive phenological phases. However, there are still some issues related to infrastructure and governance. In Palestine, the distribution of reclaimed water is limited, and the quality standards set by the different municipalities vary. The coordination between the Palestinian Water Authority and the local councils needs to be strengthened to expand access to water. Furthermore, on-farm storage and filtration systems are necessary to stabilize intermittent supplies, a critical step under the ongoing political and hydrological constraints.

### Cultivar-Specific and Environmental Considerations

The impressive results from Nabali Mohassan highlight the essential role of the interaction between genotype and environment in RDI's success (Souali et al., 2025). Nabali's slow growth and conservative water-use strategies, in contrast to fast-maturing European cultivars like 'Arbequina', give it good drought tolerance. The same modifications were observed in 'Menara' in Morocco (Ibba et al., 2023) and in Iberian landraces (Guise et al., 2024), firmly concluding that cultivars suitable for local conditions are the only ones that can survive in mediocre conditions in the semi-arid RDI programs.

### Adoption Constraints and Policy Implications

The reasons large-scale adoption is not affected by the positive outcomes are fragmented irrigation systems, limited emitter density, difficulties in reclaiming water quality monitoring (FAO, 2021; IOC, 2023) and small farmers' unawareness of phenology-based scheduling. The solution to all these problems is provided through farming advice programs, decision-support calendars with Kc curves and phenological cues, and also giving financial support for drip retrofits and reclaimed-water access. The integration of RDI with remote sensing and soil moisture telemetry would also improve precision and adaptive management (Ramírez-Cuesta et al., 2025).

**Broader Scientific and Environmental Relevance**

From an academic standpoint, the research in this paper sets the experiment's lowest RDI limits for olives that could be applied in real-life situations. This makes a significant contribution to climate adaptation models across the entire Eastern Mediterranean region. The fact that productive and qualitative performance remains within the 15–35% ETc range is an important reference point for areas with water scarcity, such as Jordan, southern Tunisia, and northern Egypt. Furthermore, the results indicate that adopting the circular-water system pond-dry method for irrigation of high-value perennial crops aligns with the UN SDGs 6, 12, and 13.

The multi-year experiment has shown that combining phenology-specific stress, resilient local varieties, and selective use of reclaimed water can stabilise agronomic practices and improve oil quality under extreme dry conditions. It is demonstrated that it is the regulated, not the continuous, stress which brings about the maximums in both water productivity and biochemical efficiency. Since then, the development of an irrigation strategy specific to the cultivar, based on physiological thresholds and incorporating carbon assimilation, enzyme activity, and isotopic analysis, has been advocated for future research.

**Conclusions**

- Efficacy of RDI under extreme shortage: The olive trees of the Nabali Mohassan cultivar, which were linked with the RDI technique, sustained more than 90% of vegetative growth and consistent yield even under the 15–35% ETc irrigation restriction, thus confirming the strong physiological resilience of the species and the feasibility of ultra-low RDI in semi-arid Palestine.
- Oil quality improvement: Moderate, stage-specific stress conditions were so effective that they managed to lower the free acidity to 0.40% and peroxide value to 12meq$O_2$·$kg^{-1}$ while raising the phenolic content to 32 mgGAE·$kg^{-1}$ oil, which pointed out that water limitation can gradually push the products towards oxidative stability and nutritional value.
- Water-use efficiency: By the time of its application, RDI2 had approximately reduced water consumption by 65–80% compared to conventional full irrigation (~100% ETc) without compromising yield, thus serving as a practical model for sustainable water allocation in drought-prone areas.
- Cultivar and timing significance: Performance depended on the timing of irrigation pulses that matched pit hardening, fruit enlargement, and ripening; thus, the stress tolerance was maximized while the efficiency of oil biosynthesis was preserved.

**Recommendations**

- Adoption focus: Farmers in semi-arid zones should prioritize RDI near 35% ETc with properly timed irrigation events, rather than continuous watering, to optimize yield and oil quality under limited resources.
- Extension support: Local agricultural services should develop phenology-based irrigation calendars and demonstration plots to train growers on RDI scheduling and monitoring.
- Water resource integration: Controlled use of treated wastewater can be safely incorporated into RDI regimes after quality verification, supporting circular water and climate adaptation goals.

**Limitations and Future Work**

The absence of a full-irrigation (100% ETc) control restricts direct calculation of relative water-productivity indices. Economic analyses and farmer-led multi-year trials are needed to evaluate profitability, quality premiums, and long-term soil–water interactions. Future studies should also quantify carbon assimilation and enzyme responses to identify physiological thresholds for cultivar-specific RDI optimization.

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**Conflict of Interest:** None.

**Data Availability:** All the data is available in the article.

**Ethics Statement:** This study involved plant-based field experiments only, complied with local agricultural and environmental regulations, included authorized use of reclaimed treated wastewater, and required no institutional ethical approval.

**Author's Contribution:** F.A.S. designed the study and analyzed data. M.J. supervised the work and revised the manuscript. Both authors approved the final version.

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## REFERENCES


Aïachi Mezghani, M., Mguidiche, A., Allouche Khebour, F., Zouari, I., Attia, F., & Provenzano, G. (2019). Water status and yield response to deficit irrigation and fertilization of three olive oil cultivars under the semi-arid conditions of Tunisia. *Sustainability, 11*(17), 4812. https://doi.org/10.3390/su11174812

Araújo, M., Rodrigues, N., Santos, C., Pinto, D.C.G.A., Pereira, J.A., Silva, A.M.S., & Dias, M.C. (2024). Effects of summer water deficit stress on olive fruits and oil quality. *Horticulturae, 10*(12), 1349. https://doi.org/10.3390/horticulturae10121349

Arbizu-Milagro, J., Castillo-Ruiz, F.J., Tascón, A., & Peña, J.M. (2023). Effects of regulated, precision and continuous deficit irrigation on the growth and productivity of a young super-high-density olive orchard. *Agricultural Water Management, 286,* 108393. https://doi.org/10.1016/j.agwat.2023.108393

Ben Mansour-Gueddès, S., Bchir, A., Saidana-Naija, D., Mulla, D.J., Hidri, Y., & Braham, M. (2025). Impact of water regimes on the chemical composition, antioxidant activity, and quality of olive oil (*Olea europaea* L.) under semi-arid conditions in Tunisia. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 53*(2), 13466. https://doi.org/10.15835/nbha53213466

Berenguer, M.J., Vossen, P.M., Grattan, S.R., Connell, J.H., & Polito, V.S. (2006). Tree irrigation levels for optimum chemical and sensory properties of olive oil. *HortScience, 41*(2), 427–432. https://doi.org/10.21273/HORTSCI.41.2.427

Brito, C., Dinis, L.T., Moutinho-Pereira, J., & Correia, C.M. (2019). Drought stress effects and olive tree acclimation under a changing climate. *Plants, 8*(8), 290. https://doi.org/10.3390/plants8070232

Bubola, K.B., Kolega, Š., Marcelić, Š., Šikić, Z., Pinto, A.G., Zorica, M., Klisović, D., Novoselić, A., Špika, M.J., & Kos, T. (2022). Effect of different watering regimes on olive oil quality and composition of Coratina cultivar olives grown on karst soil in Croatia. *Foods, 11*(12), 1767. https://doi.org/10.3390/foods11121767

Chartzoulakis, K., & Bertaki, M. (2015). Sustainable water management in agriculture under climate change. *Agriculture and Agricultural Science Procedia, 4,* 88–98. https://doi.org/10.1016/j.aaspro.2015.03.011

FAO (2021). *The state of the world's land and water resources for food and agriculture*. Rome, Italy: Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb9910en

Farolfi, C., Tombesi, S., Lucini, L., Capri, E., & García-Pérez, P. (2024). Influence of fruit load and water deficit on olive fruit phenolic profiling and yield. *International Journal of Plant Biology*, 15(3), 895–913. https://doi.org/10.3390/ijpb15030064

Fernandes-Silva, A.A., Ben-Gal, A., Miranda Fernandes, R.D., Gucci, R., Imrak, B., Andima, D.K., Paço, T.A., & Garcia-Tejera, O. (2025). Water productivity in olive trees: Current advances and new perspectives. *Agricultural Water Management*, 322, 109988. https://doi.org/10.1016/j.agwat.2025.109988

Fernández, J.E. (2014). Understanding olive adaptation to abiotic stresses as a tool to increase crop performance. *Environmental and Experimental Botany, 103,* 158–179. https://doi.org/10.1016/j.envexpbot.2013.12.003

Ferrara, R., Bruno, R.M., Campi, P., & Camposeo, S. (2023). Water use of a super high-density olive orchard subjected to regulated deficit irrigation in Mediterranean environment over three contrasted years. *Irrigation Science.* Advance online publication. https://doi.org/10.1007/s00271-023-00892-5

García-García, J.M., Noguera-Artiaga, L., Hernández, F., Pérez-López, A.J., Burgos-Hernández, A., & Carbonell-Barrachina, Á.A. (2023). Quality of olive oil obtained by regulated deficit irrigation. *Horticulturae, 9*(5), 557. https://doi.org/10.3390/horticulturae9050557

García-Garví, J.M., Sánchez-Rodríguez, L., Hernández, F., Sendra, E., Corell, M., Moriana, A., Burgos-Hernández, A., & Carbonell-Barrachina, Á.A. (2022). Effect of regulated deficit irrigation on the quality of 'Arbequina' extra virgin olive oil produced on a super-high-intensive orchard. *Agronomy, 12*(8), 1892. https://doi.org/10.3390/agronomy12081892

Garofalo, P., Gaeta, L., Vitti, C., Giglio, L., & Leogrande, R. (2025). Optimizing water footprint, productivity, and sustainability in southern Italian olive groves: The role of organic fertilizers and irrigation management. *Land, 14*(2), 318. https://doi.org/10.3390/land14020318

Gucci, R., Caruso, G., Gennai, C., Esposto, S., Urbani, S., & Servili, M. (2019). Fruit growth, yield and oil quality changes induced by deficit irrigation at different stages of olive fruit development. *Agricultural Water Management, 212,* 88–98. https://doi.org/10.1016/j.agwat.2018.08.022

Guerrero-Casado, J., Carpio, A.J., Tortosa, F.S., & Villanueva, A.J. (2021). Environmental challenges of intensive woody crops: The case of super high-density olive groves. *Science of the Total Environment, 798,* Article 149212. https://doi.org/10.1016/j.scitotenv.2021.149212

Guise, I., García-García, M., & García-León, D. (2024). Climate change is expected to severely impact protected-area olive cultivation in the Iberian Peninsula. *Science of the Total Environment, 1000,* 152012. https://doi.org/10.1016/j.agsy.2024.104108

Hargreaves, G.H., & Samani, Z.A. (1985). Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture, 1*(2), 96–99. https://doi.org/10.13031/2013.26773

Ibba, K., Kassout, J., Boselli, V., Er-Raki, S., Oulbi, S., Mansouri, L.E., Bouizgaren, A., Sikaoui, L., & Hadria, R. (2023). Assessing the impact of deficit irrigation strategies on agronomic and productive parameters of Menara olive cultivar: Implications for operational water management. *Frontiers in Environmental Science, 11,* 1100552. https://doi.org/10.3389/fenvs.2023.1100552

Iglesias, M.A., Rousseaux, M.C., Agüero Alcaras, L.M., Hamze, L., & Searles, P.S. (2023). Influence of deficit irrigation and warming on plant water status during the late winter and spring in young olive trees. *Agricultural Water Management, 275,* Article 108030. https://doi.org/10.1016/j.agwat.2022.108030

International Olive Council (IOC) (2023). *Trade standard applying to olive oils and olive-pomace oils: Chemical and sensory analysis methods*. Madrid, Spain.

Majikumna, K.U., Zineddine, M., & Alaoui, A.E.H. (2024). Olive tree drought stress: A systematic review. *Journal of Water and Climate Change, 15*(12), 5741–5760. https://doi.org/10.2166/wcc.2024.158

Patumi, M., d'Andria, R., Marsilio, V., Fontanazza, G., Morelli, G., & Lanza, B. (2002). Olive and olive oil quality after intensive monocone olive growing with different irrigation regimes. *Food Chemistry, 77*(1), 27–34. https://doi.org/10.1016/S0308-8146(01)00317-X

Ramírez-Cuesta, J.M., Martínez-Gimeno, M.A., Badal, E., Tasa, M., Bonet L. & Pérez-Pérez, J.G. (2025). UAV-based multispectral and thermal indexes for estimating crop water status and yield on super-high-density olive orchards under deficit irrigation conditions. *Precision Agriculture, 26*, 47. https://doi.org/10.1007/s11119-025-10240-6

Romero-Trigueros, C., Vivaldi, G.A., Nicolás, E.N., Paduano, A., Salcedo, F.P., & Camposeo, S. (2019). Ripening indices, olive yield and oil quality in response to irrigation with saline reclaimed water and deficit strategies. *Frontiers in Plant Science, 10,* 1243. https://doi.org/10.3389/fpls.2019.01243

Sánchez-Piñero, M., Corell, M., de Sosa, L.L., Moriana, A., & Castro-Valdecantos, P. (2024). Assessment of water stress impact on olive trees using an accurate determination of the endocarp development. *Irrigation Science*, 42, 461–476. https://doi.org/10.1007/s00271-024-00914-w

Sánchez-Rodríguez, L., Kranjac, M., Marijanović, Z., & Sendra, E. (2020). "Arbequina" olive oil composition is affected by the application of regulated deficit irrigation during pit hardening stage. *Journal of the American Oil Chemists' Society, 97*(2), 157–167. https://doi.org/10.1002/aocs.12332

Souali, H., Ibba, K., Ahrouch, H., Zahiri, A., El Issaoui, K., Rabi, B., Choukrane, B., Boselli, V.A., Hadria, R., Er-Raki, S., Oulbi, S., Hsissou, D., Ater, M., & Kassout, J. (2025). Functional trait-based responses of the Moroccan Menara cultivar to deficit irrigation. *Sustainability, 17*(23), 10614. https://doi.org/10.3390/su172310614

Tanasijevic, L., Todorovic, M., Pereira, L.S., Pizzigalli, C., & Lionello, P. (2014). Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. *Agricultural Water Management, 144,* 54–68. https://doi.org/10.1016/j.agwat.2014.05.019