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Research Paper

Precision irrigation scheduling improves water productivity and economic indicators in young high-density apple orchards

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ABSTRACT

Water shortages in arid and semi-arid regions have caused traditional horticulture to move towards high-density orchards. While water productivity (WPc) in high-density orchards has been studied in various contexts, a comprehensive analysis of the key factors influencing it in a water-limited region, which also considers economic indicators, has been lacking. This research innovates by combining the effects of sensor-based precision irrigation and Deficit Irrigation (DI) and shading net on WPc, Economic crop Water Productivity (EWPc), and Economic Energy Productivity (EEP) indicators in high-density apple orchards. This experiment was carried out in northeastern Iran during two growing seasons in 2021–2022, in comparison to EvapoTranspiration-based Irrigation Scheduling (ETS) and Soil Moisture-based Irrigation Scheduling (SMS), as well as shading net treatment (with (S1) and without (S0) shading net) along with the irrigation strategies that included Full Irrigation (FI), Regulated Deficit Irrigation (RDI), and Sustainable Deficit Irrigation (SDI). FI applied 100 % of the crop water requirement at all growth stages, while RDI supplied 60 % of the water requirement between 55 and 105 days after full bloom, maintaining 100 % irrigation at other stages. In contrast, SDI provided 60 % of the water requirement throughout all growth stages. Results showed these techniques and strategies were able to increase WPc by varying amounts, such that the highest WPc was observed with SDI-S1 (11.5 kg/m^3) and SDI-SMS (12.7 kg/m^3) treatments in 2021 and RDI-SMS (15.9 kg/m^3) and RDI-S1 (10.8 kg/m^3) treatments in 2022. Similarly, under RDI-S1-SMS (1.3 \$/m^3 and 2.8 \$/m^3) treatments, the EWPc values reached in two years, respectively. These findings gained further insights into optimizing WPc and economic indicators for sustainability applications in horticultural development in water-limited regions.

1. Introduction

Water scarcity is an escalating challenge in arid and semi-arid regions, threatening the sustainability of horticultural production systems (Ghrab et al., 2015). Projected climate change is expected to exacerbate water shortages, necessitating a shift towards more efficient irrigation methods (Zakhem et al., 2019). Otherwise, severe negative consequences such as yield reduction, crop failure, and long-term degradation of horticultural systems may occur, particularly under increasing water scarcity scenarios (Fereres and Soriano, 2007). In response, one primary adaptive strategy in orchard management has been adopting high-density planting systems, which offer higher yields and early fruit production per unit area (Fernández et al., 2020). However, an increase in yield can lead to excessive water consumption, disrupting sustainable agricultural development, particularly in regions with water scarcity (Morante-Carballo et al., 2022). Therefore, improving water productivity (i.e., the yield produced per unit of water consumed) has become a crucial goal in water-limited environments. This can be achieved by implementing precision irrigation techniques and improved horticultural practices that optimize yield while minimizing water consumption (Arbizu-Milagro et al., 2022). High-density planting using dwarf and semi-dwarf cultivars offers additional advantages, including early fruiting, improved fruit quality, efficient labor management, and better input utilization, contributing to more sustainable orchard systems (Lordan et al., 2019). In this context, the apple (*Malus domestica* Borkh.), one of the most widely cultivated fruit crops globally, is particularly vulnerable to water scarcity, especially in countries like Iran, where temperate climatic conditions favor its production (FAO, 2023). In Iran, the apple represents the most economically significant horticultural crop; however, increasing water scarcity, particularly in the

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northeastern regions, has adversely impacted orchard productivity (Gohari et al., 2013). Precision irrigation technologies provide a potential solution by reducing water use while maintaining or enhancing fruit yield (Naor et al., 2008). When integrated with improved horticultural practices, these approaches can increase water productivity (WPc), a key objective for the sustainable intensification of high-density apple orchards in water-limited environments (Fernandez and Cuevas, 2010).

Water productivity (WPc), defined as the amount of crop yield per unit of water consumed (kg/m^3), is a key indicator for assessing irrigation and sustainability in horticulture (Heydari, 2014). Enhancing WPc is especially critical in arid regions, where water availability limits agricultural expansion (Panigrahi et al., 2023). Precision irrigation, primarily developed through sensor-based methods such as Time Domain Reflectometry (TDR), has significantly improved modern agriculture's water management and crop yield (Sui and Vories, 2020; Marek et al., 2023). The sensor-based approach thus allows for real-time monitoring of soil moisture to change irrigation scheduling and reduce variability in soil water status (Sui and Vories, 2020). Several studies have evaluated soil sensor-based irrigation scheduling for orchard systems (He et al., 2004; Osroosh et al., 2016; Arunadevi et al., 2024). A comparison between soil moisture-based and ET-based irrigation scheduling in a high-density apple orchard indicated that soil moisture-based methods used less water (Jiang and He, 2021).

Deficit irrigation (DI) refers to the strategic reduction of irrigation water below whole crop evapotranspiration (ETc) (English and Raja, 1996); among the DI strategies, Regulated Deficit Irrigation (RDI) applies water limitations only during selected phenological stages that are less sensitive to water stress (Selahvarzi et al., 2017). This selective application enhances the allocation of resources to reproductive growth and reduces unnecessary vegetative expansion (Chen et al., 2023). Initially adopted in Australia for managing vegetative and fruit competition in peach and pear orchards, RDI has since been successfully applied to apple trees, where it has been shown to reduce irrigation volumes while maintaining or improving yield and quality (Mpelasoka et al., 2001; Naor et al., 2008; Küçükyumuk et al., 2020). The effectiveness of RDI depends on precise knowledge of plant phenology and its physiological response to limited water availability (Selahvarzi et al., 2017). In contrast, sustainable Deficit Irrigation (SDI) imposes a consistent water deficit throughout the growing season, regardless of crop development stages) El Jaouhari et al., 2018(. This method induces gradual and uniform soil moisture depletion, influencing growth and quality parameters based on crop species, stress intensity, and site conditions (Atay et al., 2017; Zhong et al., 2019). Depending on cultivar and environmental interactions, SDI has shown varied effects in apple orchards. It provides a more stable but less targeted water-saving approach than RDI (Intrigliolo et al., 2013).

Historically used to protect fruit trees from hail (Do Amarante et al., 2011), shading nets have evolved into a multifunctional horticultural tool to mitigate environmental stresses. Recent studies have shown that these nets not only reduce excessive solar radiation, high temperatures, and water loss (Kalcsits et al., 2017; Lulane et al., 2022) but also protect against pests and insects (Mupambi et al., 2018; Kotilainen et al., 2018). In apple orchards, shading nets improve plant water status (Boini et al., 2021), protect fruits from sunburn, and support yield improvement by stabilizing the microclimate (Miller et al., 2015) and enhancing photosynthetic efficiency, thereby improving fruit development (Lopez et al., 2018).

In addition to WPc, economic indicators such as EWPc provide insight into profitability under limited water conditions. Physical water productivity refers to the quantity of crop yield per unit of water consumed, typically measured in kilograms per cubic meter (Heydari, 2014). In contrast, economic water productivity represents the net income or profit derived from each cubic meter of water used, making it a critical parameter in decision-making processes related to sustainable agriculture (Fernández et al., 2020).

Building on the above, this study aims to comprehensively assess the interactive effects of precision irrigation scheduling (sensor-based and ET-based), deficit irrigation strategies (RDI and SDI), and shading nets on both physical and economic water productivity in high-density apple orchards. Unlike previous research, which often focused on isolated practices in conventional orchards, this study provides an integrated evaluation of technical and economic dimensions to inform sustainable orchard management under water-limited conditions.

2. Materials & methods

2.1. Experimental condition and plant material

This field experiment was conducted for two consecutive growing seasons (2021–2022) in a high-density apple orchard located in Mashhad, Iran (59°43′N; 36°11′E). The orchard was planted in 2015 with (*Malus domestica* Borkh. cv. 'Golden Delicious'), grafted on M9 rootstock. It was planted at a high-density spacing of 3.2 m × 0.8 m; the trees were trained to be spindle-shaped canopies. The experimental design focused on the top 40 cm of the loam-textured soil layer, where the effective root system of M9 dwarf rootstock apple trees is typically concentrated. This soil layer comprised 25.2 % clay, 29.2 % silt, and 45.6 % sand. The average seasonal air temperature during the two experimental years was approximately 26.6 °C and 25.1 °C, respectively. Rainfall during the irrigation season (April to October) was 23.8 mm and 122 mm for the respective years (Fig. 1). The electrical conductivity (EC) of the saturated soil extract and the irrigation water in the orchard was 1.5 dS m^{-1} and 1.0 dS m^{-1} respectively, and an organic matter content of 2.1 %. The volumetric soil moisture content (Θ_v) at field capacity ($\Psi_m = -0.33$ MPa) and permanent wilting point ($\Psi_m = -15$ MPa) was determined using pressure plate apparatus in the soil physics laboratory. The values were 28.3 % and 9.1 %, respectively.

The orchard was equipped with a localized (dripper) irrigation system that included in-line drippers with a nominal flow rate of 1.7 liters per hour and a distance of 30 cm from each other, located inside the single lateral pipeline (16 mm). The shut-off valve was placed on each lateral line. Similarly, the manifold line (125 mm), the subline (125 mm), and the main line (160 mm) are indicated schematically (Fig. 2).

2.2. ET-based and soil moisture-based irrigation scheduling

In **E**vapo**T**ranspiration-based irrigation **S**cheduling (ETS), the reference crop evapotranspiration (ET_o) is obtained using pan evaporation (E_{pan}) measurements from two class A pans for treatments with and without shading net (Equation 1).

$$ET_o = K_p E_{pan} \frac{mm}{day} \quad (1)$$

The pan coefficient (Kp) was calculated daily from equation 2 (Allen et al., 1998).

$$K_p = 0.108 - 0.0286u_2 + 0.0422\ln(FET) + 0.1434\ln(RH_{mean}) - 0.000631[\ln(FET)]^2\ln(RH_{mean}) \quad (2)$$

The average daily wind speed at height (u_2) and average daily relative humidity (RH_{mean}) are taken from the weather station near the orchard daily. Also, the fetch, or distance of the identified surface type for two pans, was measured.

Then, the crop coefficient (K_c) was fitted and adjusted for stages of apple growth (the K_c curve), and the crop evapotranspiration (ET_c) was obtained from equation 3 (Allen et al., 1998).

$$ET_c = K_c ET_o \frac{mm}{day} \quad (3)$$

Subsequently, adjustments were made for dripper irrigation, and irrigation efficiency and effective rainfall were measured and estimated.

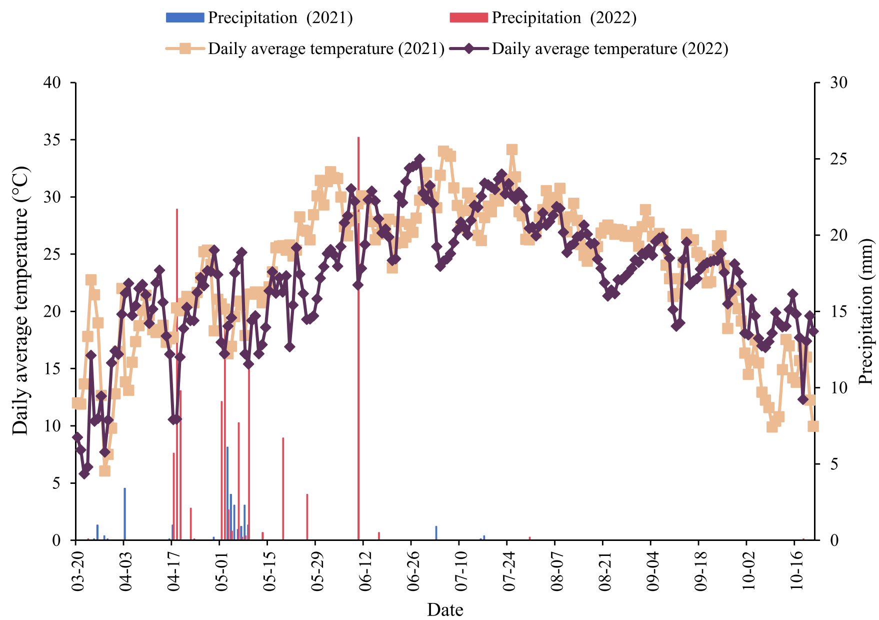

Fig. 1. Daily average temperature and precipitation in two growing seasons.

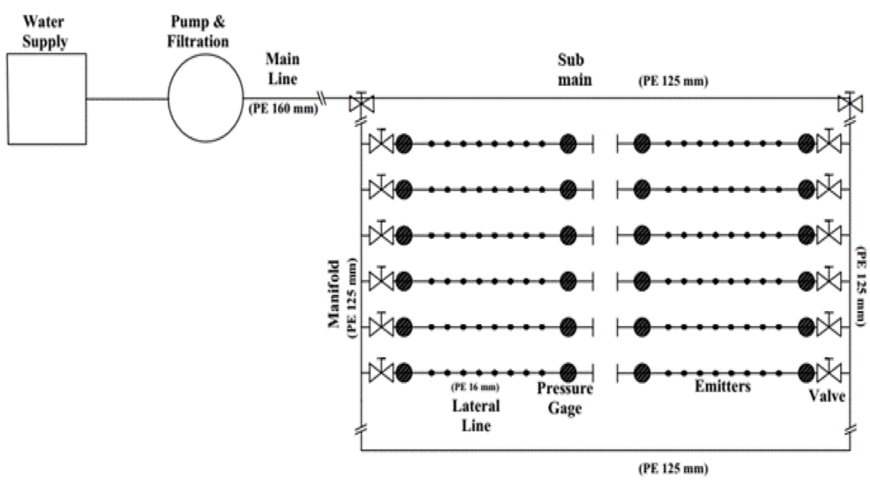

Fig. 2. The schematic layout of the drip irrigation system.

The leaching fraction was disregarded. Finally, the irrigation amount for each irrigation frequency was calculated and applied to the treatments within a set time.

Soil **M**oisture-based irrigation **S**cheduling (SMS) was measured using a FieldScout TDR 350 soil moisture meter (Spectrum Technologies, USA) based on the soil moisture content. Soil water potential points (the soil water characteristic curve) were acquired for orchard soil. Before each irrigation event, soil moisture content was measured for all SMS treatments. The irrigation required for each treatment was calculated based on the difference between the measured moisture and the target level, which was defined as a fraction of field capacity (FC) specific to each irrigation strategy. The irrigation duration was then determined accordingly for each treatment. The measurements in pre-irrigation soil moisture content under different SMS treatments are illustrated in Fig. 3.

2.3. Plant measurements

The weight and number of fruits per tree were measured at commercial maturity. For each treatment, five sound fruits were randomly selected from each of the four central trees in all four replications, resulting in a total of 80 fruits per treatment.

The fruit diameter was then determined at the midsection using a digital caliper, and the weight of each fruit was determined using a laboratory scale (precision 0.1 g) and fruit firmness was measured by penetrometer (kg/cm^3).

Vegetative and branch diameter growth were measured weekly throughout the current year for each replicate. Vegetative branch growth was assessed in the distal third of the previous year's branches. Measurements commenced in both years following the budburst. Fruit diameter growth was recorded for five fruits per central tree until harvest. Measurements were taken at weekly intervals using a digital caliper. Additionally, the relative growth rate of fruits was calculated for each major fruit growth stage in the studied treatments on a millimeter-per-day basis.

Measuring midday stem water potential (SWP), and stomatal conductivity (gs) was done on three fully expanded leaves in the shaded zones per replicate. Stomatal conductance (gs) was measured to evaluate the plant's response to water stress conditions .A pressure chamber (ELE, UK) was used to determine SWP, following the procedures outlined by Shackel et al. (1997). The leaf stomatal conductance was

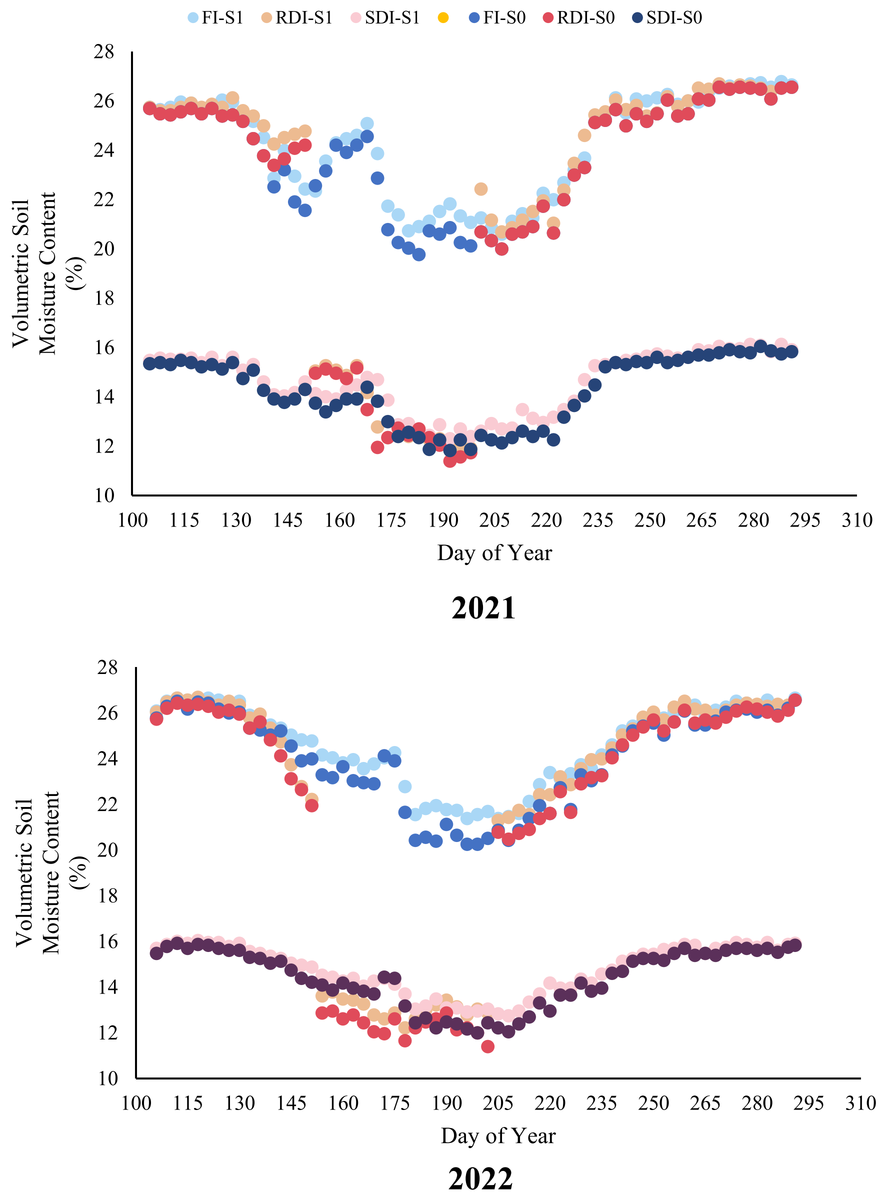

Fig. 3. The measurements in pre-irrigation soil moisture content under different SMS treatments for irrigation scheduling.

assessed using a calibrated porometer, SC-1 (Decagon Devices, Pullman, WA). The measurements for SWP and gs were taken every two weeks.

Total soluble solids (TSS) were measured using a handheld refractometer (Atago, Japan) and reported as°brix in the fruit juice. Titratable acidity (TA) was measured using a pH meter by titrating 5 mL of fruit juice with 0.1 N NaOH until a pH of 8.1 was reached and expressed as a percentage of malic acid (the predominant acid in apples). Then, the maturity index (MI = TSS/TA) was calculated (Laribi et al., 2013).

According to the local market appeal, apple fruits were classified and sorted based on their size and diameter. Class A apples had a diameter greater than 68 mm; Class B apples had a diameter between 60 and 68 mm; and Class C apples had a diameter <60 mm.

2.4. Water, energy productivity, and economic analysis

Water productivity (WPc) is calculated by determining the total marketable apple yield (Yield) and the total water involved in crop production (TWU). The latter is equal to the applied irrigation (I) plus the effective rainfall (Pe), which together represent evapotranspiration (ETc) (Equation 4).

$$WP_c = \frac{\text{Yield}}{\text{ETc}} \quad \frac{\text{kg ha}^{-1}}{\text{m}^3\text{ha}^{-1}} \tag{4}$$

All labor inputs, machinery, chemicals, and fertilizers are the same for the entire orchard at all points, and the only difference is in the amount of irrigation and electrical energy of the irrigation pump for different treatments. Therefore, the energy referred to is the electrical energy of the irrigation pump. The energy productivity of the irrigation pump (EP) is calculated as the ratio of the total marketable apple yield (Yield) to the energy consumed by the irrigation pump (E) (Jackson et al., 2010):

$$EP = \frac{\text{Yield}}{\text{E}} \quad \frac{\text{kg ha}^{-1}}{\text{kWh ha}^{-1}} \tag{5}$$

The energy consumed (E) is calculated by multiplying the irrigation pump's power consumption (P) by its operating time (T). To calculate the power consumption, use the following equation (Gulliver and Arndt., 1991):

$$P = \frac{\gamma QH}{1000\,\eta} \quad \frac{\text{Nm}^{-2}\ \text{m}^3\text{s}^{-1}\ \text{m}}{\%} \tag{6}$$

The specific gravity of water (γ) is 9810 N m^{-2}, and for each irrigation event, a pressure gauge was used on each irrigation lateral line to measure the head of the water pump (H), the capacity of flow rate (Q) in the drip irrigation system, and the efficiency of the irrigation pump (η).

The Economic Crop Water Productivity (EWPc), which is defined as follows, is recommended for a thorough economic analysis, as it must take into account the opportunity costs. EWPc is appropriate for making decisions regarding the irrigation management of woody crops, as the profit in equation. 7 is defined as the revenue minus the sum of the variable, fixed, and opportunity costs (Fernández et al., 2020):

$$\mathrm{EWP_c} = \frac{\text{Profit}}{\text{TWU}}\ \frac{\$\ \text{ha}^{-1}}{\text{m}^3\text{ha}^{-1}} \tag{7}$$

Economic energy productivity is calculated based on the profit and the energy consumed, according to equation. 8 (Kitani, 1999).

$$\mathrm{EEP} = \frac{\text{Profit}}{\text{E}}\ \frac{\$\ \text{ha}^{-1}}{\text{kWh ha}^{-1}} \tag{8}$$

2.4. Experimental design

This study was conducted as a split-split plot experiment based on randomized complete blocks with four replications in 2021 and 2022. Measurements were carried out on four central trees per replication, resulting in 16 observed trees per treatment ($n = 16$). This sampling scheme was applied consistently to physiological, growth, yield, and economic indicators in both years. The main plot was based on irrigation scheduling (ETS and SMS), the sub-plot was shading net treatments, and the sub-sub-plot was irrigation treatments. Irrigation treatments included a **F**ull **I**rrigation treatment (FI-100 % water requirement at all stages), a **R**egulated **D**eficit **I**rrigation treatment (RDI-60 % water requirement from 55 to 105 days after full bloom and 100 % water requirement at other stages), and a **S**ustained **D**eficit **I**rrigation treatment (SDI-60 % water requirement at all stages). Shading net treatments are included with shading net (S1) and without (S0); the Schematic representation of the experimental layout is used in each of the four replicates (Fig. 4).

2.5. Statistical analysis

The effects of irrigation scheduling, irrigation treatments, shading net, and the experimental year were analyzed by multifactorial analysis of variance (ANOVA) using JMP 16 software (SAS Institute, Cary, NC). Whenever the F statistic was at 0.05 or 0.01 levels of significance, differences between treatments were calculated using Tukey's HSD range test ($p \leq 0.05$). The standard error of the means was also determined. The data is shown as mean ± SE in the figures.

Fig. 4. Experimental layout of treatments and measured trees in one replicate (typical of the four replicates).

3. Results

3.1. Irrigation applied

In 2021, irrigation was applied to all treatments based on three factors: irrigation scheduling methods (ETS and SMS), shading net conditions (S0: without shading net, and S1: with shading net), and irrigation levels (FI: full irrigation, RDI: regulated deficit irrigation, and SDI: sustained deficit irrigation) and also effective rainfall was estimated and the drip irrigation system's efficiency was measured. The total irrigation volume in 2021 was approximately 13 % higher than in 2022. Treatments with deficit irrigation strategies RDI and SDI resulted in reductions of 15 % and 40 %, respectively, in comparison to FI. The amount of irrigation applied to ETS treatments was 11 % higher than SMS, and that of S0 was 13 % higher than S1 (Table 1).

3.2. Growth parameters

In 2021, SDI treatments significantly reduced both slow and rapid shoot growth rates compared to FI, with the reductions even more pronounced in 2022. During the slow-growth phase of 2021, the shoot length rate under RDI was approximately 23 % lower than that under FI; however, the average fruit diameter under RDI did not differ significantly ($p > 0.05$). This suggests that RDI effectively limited vegetative growth due to water restriction, without compromising fruit development (Table 2).

The underlying mechanism may be that RDI restricts excessive vegetative growth, thereby redirecting assimilates toward reproductive structures. As a result, fruit growth was maintained despite reduced vegetative vigor. These findings are consistent with previous studies on apple (Küçükyumuk et al., 2013) and mango (Zuazo et al., 2021), although they contrast with results in several studies, such as apple (Atay et al., 2019), where reduced shoot growth was associated with a decline in fruit size.

3.3. Plant water status

In 2021, stem water potential (SWP) for the ETS and FI-S0 treatments ranged from −0.77 to −1.36 MPa (Fig. 5a). The shading net positively affected SWP, increasing its range to −0.69 to −1.21 MPa. For SMS, SWP under FI-S0 ranged from −0.81 to −1.27 MPa, while under FI-S1 it ranged from −0.75 to −1.15 MPa (Fig. 5b). RDI-S0 and RDI-S1 initially showed similar patterns to their corresponding FI treatments, but under stress, SWP dropped further to −1.46 MPa and −1.30 MPa, respectively (Figs. 5c, 5d). After water stress relief, SWP increased and approached values observed under FI. SDI-S0 and SDI-S1 exhibited statistically lower SWP values from the beginning of the season, with minimum values of −2.46 MPa and −2.19 MPa, respectively, and these gaps widened over

Table 1
Estimated irrigation application depths (mm) for different treatments calculated using evaporation pan (for ETS) and soil moisture sensor (for SMS).

Irrigation	shading	2021		2022	
		ETS[1]	SMS	ETS	SMS
FI	S1	659.6	601.3	587.3	515.5
	S0	765.7	675.9	681.1	601.7
RDI	S1	559.6	509	499.2	439.6
	S0	649.6	568.7	578.8	512.9
SDI	S1	395.7	356.5	352.3	303.6

[1] ETS: EvapoTranspiration-based Scheduling; SMS: Soil Moisture-based Scheduling. Values are calculated and not statistically analyzed.

Table 2
Effect DI on growth parameters during 2021 and 2022.

Season	DI	Shoot diameter (mm week^{-1})		Shoot length (cm week^{-1})		Fruit diameter (mm d^{-1})	
		Slow fruit growth	Rapid fruit growth	Slow fruit growth	Rapid fruit growth	Slow fruit growth	Rapid fruit growth
2021	FI	0.82 a[1]	0.36 a	2.94 a	0.95 a	0.43 a	0.79 a
	RDI	0.79 a	0.33 a	2.47 b	0.91 a	0.41 a	0.75 a
	SDI	0.61 b	0.24 b	2.35 b	0.74 b	0.31 b	0.64 b
2022	FI	0.77 a	0.32 a	2.09 c	0.71 b	0.37 a	0.76 a
	RDI	0.58 b	0.32 a	1.85 d	0.55 c	0.36 a	0.74 a
	SDI	0.51 c	0.21 b	1.38 e	0.44 d	0.29 b	0.59 b

[1] Means followed by different letters within a column are significantly different at $P < 0.05$ according to Tukey's HSD range test.

time without full recovery. The trend was even more pronounced in 2022.

In 2021, the minimum stomatal conductance (gs) for FI-S1 plants was 165 mmol H_2O m^{-2} s^{-1}, while in 2022, it was 167 mmol H_2O m^{-2} s^{-1} (Fig. 6a and 6b). The shading net increased gs, especially during warmer periods. For SMS in 2021, the minimum gs was 81 mmol H_2O m^{-2} s^{-1}, and in 2022, it increased to 104 mmol H2O m^{-2} s^{-1} (Fig. 6c and 6d). Initially, gs in RDI plants did not significantly differ from FI. However, during the water stress period, the difference became significant. After the stress period ended, gs values in RDI plants approached those of FI plants again. SDI plants were different from RDI, showing a significant difference from FI plants from the beginning, and this discrepancy remained throughout the growing season (Fig. 6).

Stem water potential (SWP) and stomatal conductance (gs) are widely recognized as indicators of plant water status. SWP is an indirect physiological marker (Parkash and Singh, 2020). Stomatal conductance (gs) has also been suggested as a suitable plant-based indicator because stomatal closure belongs to the first response to water stress (Altieri et al., 2024; Plavcová et al., 2023). This study confirmed the relationship between SWP, gs, and irrigation, which has been well-documented in previous research. FI treatments maintained high SWP and gs, indicating adequate water availability and efficient gas exchange. Under water stress, SWP and gs declined concurrently, illustrating stomatal regulation as a water-conserving mechanism. Similar patterns have been reported in studies on apple (Plavcová et al., 2023), pomegranate (Selahvarzi et al., 2017), Olive (Shackel et al., 2021) and Citrus (García-Tejero et al., 2010).

3.4. Fruit properties

The RDI treatment did not result in a statistically significant difference in fruit weight compared to FI. In contrast, the SDI treatment led to a significant average reduction of 17 % in fruit weight. The shading net (S1) partially mitigated this reduction, resulting in an average 11 % increase in fruit weight compared to unshaded (S0) treatments(Table 3).

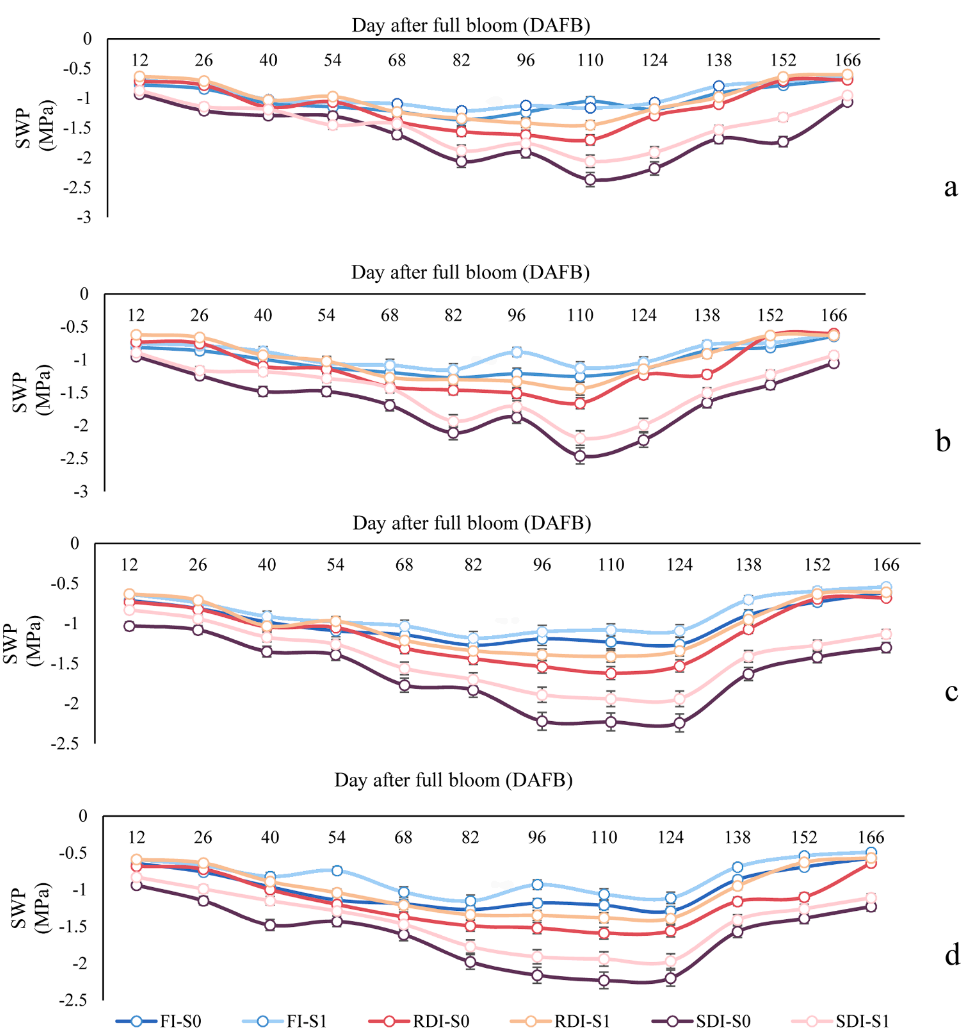

Fig. 5. Stem water potential in apple tree a) ETS-2021 b) SMS-2021 c) ETS-2022 d) SMS-2022 (Data are means ± SE, $n = 16$).

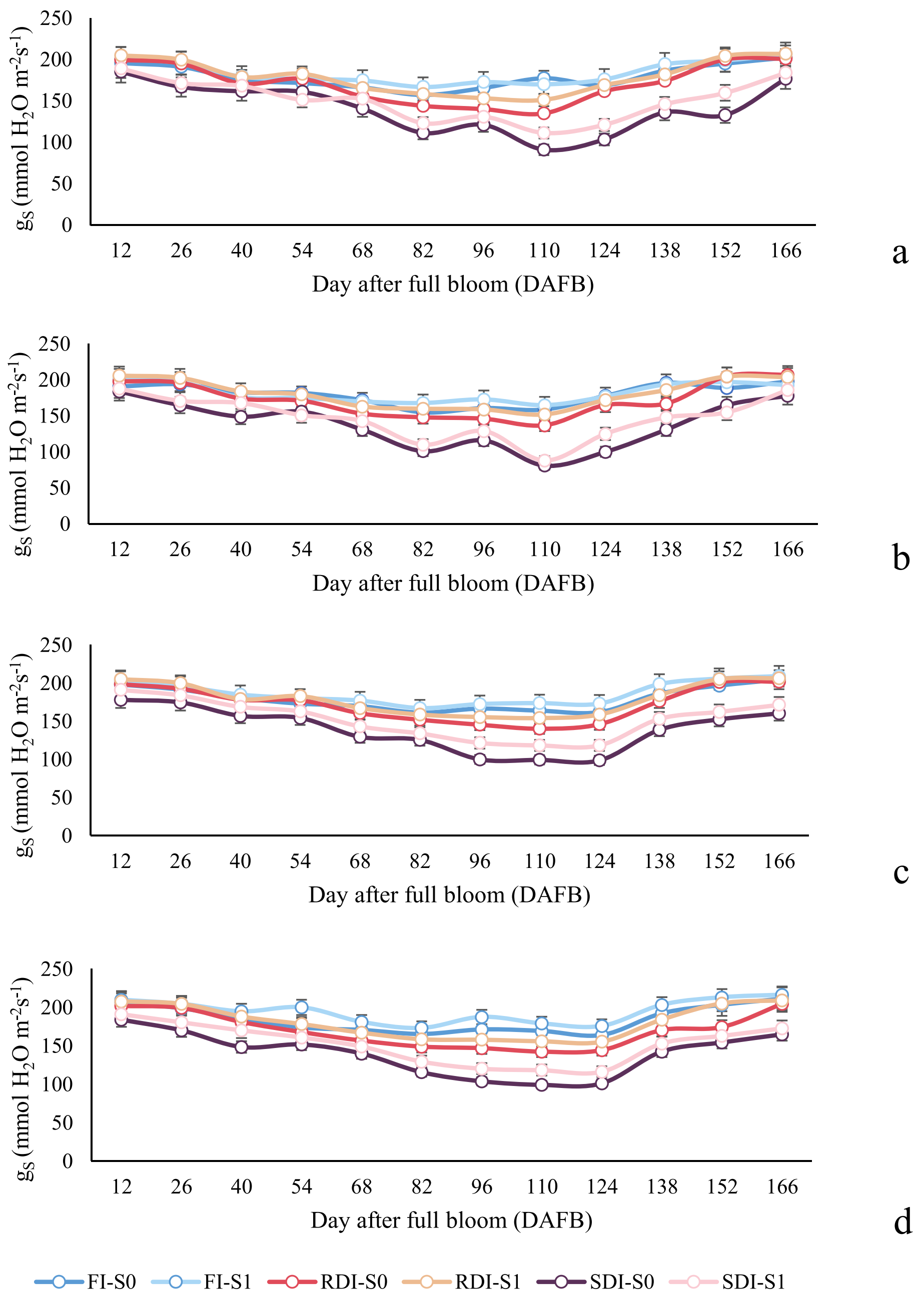

Fig. 6. Stomatal conductance in apple tree a) ETS-2021 b) SMS-2021 c) ETS-2022 d) SMS-2022 (Data are means ± SE, $n = 16$).

These findings are consistent with previous research (Do Amarante et al., 2011; Miller et al., 2015; Narjesi et al., 2023).

Deficit irrigation (DI) increased both firmness and the TSS/TA ratio in comparison with FI in both years. On average, RDI and SDI treatments (regardless of shading) resulted in 30 % and 28 % higher firmness, and 22 % and 11 % higher TSS/TA ratios, respectively. Conversely, shading reduced firmness by approximately 7 %, and TSS/TA was 5 % lower under FI. These results show that DI improved fruit quality by increasing firmness and TSS/TA. The findings are supported by previous studies (Zhong et al., 2019; Faghih et al., 2019; Lu, 2022; Tao et al., 2023), although some contradictions exist (Marsal et al., 2012; Keivanfar et al., 2019).

Table 3
Effect DI and shading net on fruit properties.

Irrigation	Shading net	Weight (gr)	Firmness (kg/cm^3)	TSS/TA
FI	S1	144 a[1]	4.2 d	14.5 d
	S0	132 b	4.6 c	14.2 d
RDI	S1	141 a	5.5 ab	17.9 a
	S0	126 b	5.9 a	17.1 b
SDI	S1	122 b	5.2 b	16.8 b
	S0	108 c	5.6 ab	15.3 c

[1] Means followed by different letters within a column are significantly different at $P < 0.05$ according to Tukey's HSD range test.

3.5. *Yield and water productivity*

In 2022, the number of fruits increased by an average of 27 % in the FI treatment and by an average of 29 % in the RDI treatment, in comparison with a low increase of 8 % in the SDI treatment (Table 4). The treatments of RDI and SDI caused yield reductions of 11 % and 26 %, respectively, in 2021, whereas RDI and SDI caused yield declines of 3 % and 34 %, respectively, in 2022. The maximum yield was recorded for FI-S1, 20.2 kg, and RDI-S1, 19.5 kg, although this was not significant at the statistical level. On the other hand, the lowest yield was found for SDI-S0: 11.6 kg. Based on input applied irrigation and yield per each treatment, RDI-S1 showed the highest WP: 10.8 kg/m^3. Interestingly, even SDI-S1 had a relatively high value of WP: 10.3 kg/m^3. Water stress lowers photosynthesis, nutrient uptake, and overall metabolism, all of which are responsible for plant yield (Azzeddine et al., 2019). In reducing photosynthesis, nutrient uptake, and overall plant metabolism, there is a resultant effect on yield reduction (Küçükyumuk et al., 2020). RDI maintained yield when applied during plant stages less sensitive to drought stress, while improving fruit quality. The shading net significantly enhanced yield and improved water productivity (WP), while reducing water consumption by mitigating the effects of deficit irrigation (Table 4).

In 2021, the FI treatment showed the highest yield (16.8 kg under ETS and 16.5 kg under SMS) and fruit number (123), while RDI and SDI treatments produced lower yields, with RDI-SMS showing 15.2 kg and SDI-ETS showing 12.3 kg (Table 5). WP was highest under SDI-SMS (12.7 kg/m^3). In 2022, fruit number increased across all treatments, with RDI-SMS producing 152 fruits. The highest yield was recorded for FI-SMS (18.3 kg), while RDI-SMS achieved 17.8 kg. SDI-SMS showed the highest WP (15.9 kg/m^3), followed by RDI-SMS (13.1 kg/m^3) and FI-SMS (12.4 kg/m^3).

3.6. Marketable yield

The yield was sorted into three marketable classes: A, B, and C. In both years, the SMS treatments (right side) outperformed the ETS treatments (left side) in terms of marketability and classification (Fig. 7). This classification of two growing seasons indicates SMS treatments that FI-S1 (88 %, 84 %)and RDI-S1 (90 %, 91 %) produced the highest amount of class A and B fruits. On the other hand, the SDI-S0 (71 %, 65 %) treatment produced the lowest amount of it. Also, in ETS treatments, RDI-S1 (88 %, 89 %) recorded the highest grade.

3.7. Economic indicators

The SMS, S1, and RDI treatments achieved the highest EWPc (1.3 \$/m^3, 2.8 \$/m^3) and EEP (2.2 \$/kWh, 4.7 \$/kWh) for both years of this study, respectively, according to economic analysis (Table 6). In contrast, the ETS, S0, and FI treatments in 2021 observed the lowest EWPc (0.7 \$/m^3) and EEP (1.3 \$/kWh), while the ETS, S0, and SDI treatments in 2022 recorded the highest EWPc (1.4 \$/m^3) and EEP (2.7 \$/kWh). Application of SMS, S1, and RDI techniques can, on the one hand, reduce water consumption and, on the other hand, increase net profit for gardeners by preserving or even improving yield.

Table 4
Effect DI and shading net on productivity.

Year	Irrigation	Shading	Fruit n.	Yield (kg)	WP$_c$ (kg/m^3)
2021	FI	S1	123 c[1]	17.6 b	9.3 c
		S0	119 cd	15.4 c	7.2 e
	RDI	S1	114 d	15.8 c	10.3 b
		S0	116 d	13.6 d	8.1 d
	SDI	S1	107 e	13.2 d	11.5 a
		S0	103 f	11.1 e	8.4 d
2022	FI	S1	156 a	20.2 a	10.2 b
		S0	153 a	17.9 b	8.1 bc
	RDI	S1	151 ab	19.5 a	10.8 ab
		S0	146 ab	17.4 b	8.6 d
	SDI	S1	118 cd	13.6 d	10.3 b
		S0	109 e	11.6 e	7.6 e

[1] Means followed by different letters within a column are significantly different at $P < 0.05$ according to Tukey's HSD range test.

Table 5
Effect DI and scheduling on productivity.

Year	Irrigation	Shading	Fruit n.	Yield (kg)	WP$_c$ (kg/m^3)
2021	FI	ETS	123 d[1]	16.8 b	9.3 f
		SMS	121 d	16.5 b	10.1 e
	RDI	ETS	118 e	15.6 c	10.2 e
		SMS	113 e	15.2 c	11.1 d
	SDI	ETS	108 f	12.3 e	11 b
		SMS	103 f	11.9 e	12.7 c
2022	FI	ETS	146 b	18.5 a	11.5 d
		SMS	148 ab	18.3 a	12.4 cd
	RDI	ETS	145 b	17.6 ab	11.8 d
		SMS	152 a	17.8 ab	13.1 c
	SDI	ETS	133 c	14.3 d	14.5 b
		SMS	121 d	13.8 d	15.9 a

[1] Means followed by different letters within a column are significantly different at $P < 0.05$ according to Tukey's HSD range test.

4. Discussion

High-density orchards have emerged as a dominant horticultural system worldwide due to their potential to maximize yield per unit area and improve fruit quality. However, in regions facing water scarcity, reduced irrigation allocations present serious challenges to the sustainability and expansion of these systems. Compared to traditional orchards, high-density systems demand more precise and efficient irrigation strategies to ensure optimal resource consumption. As such, a deeper understanding of their specific water requirements and adaptive management practices is essential. Identifying and implementing agronomic interventions that maintain or improve yield while minimizing water consumption has become a major research priority, particularly in arid and semi-arid regions (Narjesi et al., 2023; Tao et al., 2023).

In many apple-producing regions, the use of protective shading net has become a common practice to mitigate various environmental stresses (Bastías et al., 2012). These shading nets serve multiple purposes: they protect fruits from hail damage, reduce sunburn incidence, and shield crops from strong winds and pests such as birds and insects (Kotilainen et al., 2018). Moreover, in arid and semi-arid areas, shading nets are increasingly deployed to decrease solar radiation on the canopy, thereby reducing canopy temperature and improving fruit quality (Mupambi et al., 2018). The implementation of shading nets not only safeguards the crops but also contributes to creating a more favorable microclimate within the orchard, which can lead to improved water productivity.

Despite the increasing use of shading nets in orchards, detailed understanding of tree water relations under shading nets remains limited (Lopez et al., 2018). It is often assumed that shading net reduces tree transpiration and improves water productivity (WP); however, this assumption requires validation through direct measurements. Techniques such as the heat ratio sap flow method (Lulane et al., 2022) and orchard-scale evapotranspiration estimation using evaporation pans have been utilized for this purpose. In this study, irrigation requirements under ETS were estimated by placing an evaporation pan beneath the shading net, integrating all climatic effects into a single measure. In contrast, SMS treatments relied on soil moisture dynamics and environmental inputs for scheduling. As shown in Table 1, SMS and S1 treatments resulted in approximately 11–13 % lower irrigation volume than ETS and S0. These reductions were attributed to the shading net's effect in lowering solar radiation, air temperature, and wind speed, thereby reducing reference evapotranspiration.

In addition to reducing irrigation volume, shading nets contribute positively to plant physiological performance by mitigating heat stress and regulating canopy microclimate.Excessive solar radiation and high temperatures can trigger stomatal closure, limiting carbon dioxide uptake and subsequently reducing photosynthetic activity (Narjesi et al., 2023). By lowering leaf temperature and decreasing the vapor pressure deficit between the leaf and the surrounding air, shading promotes

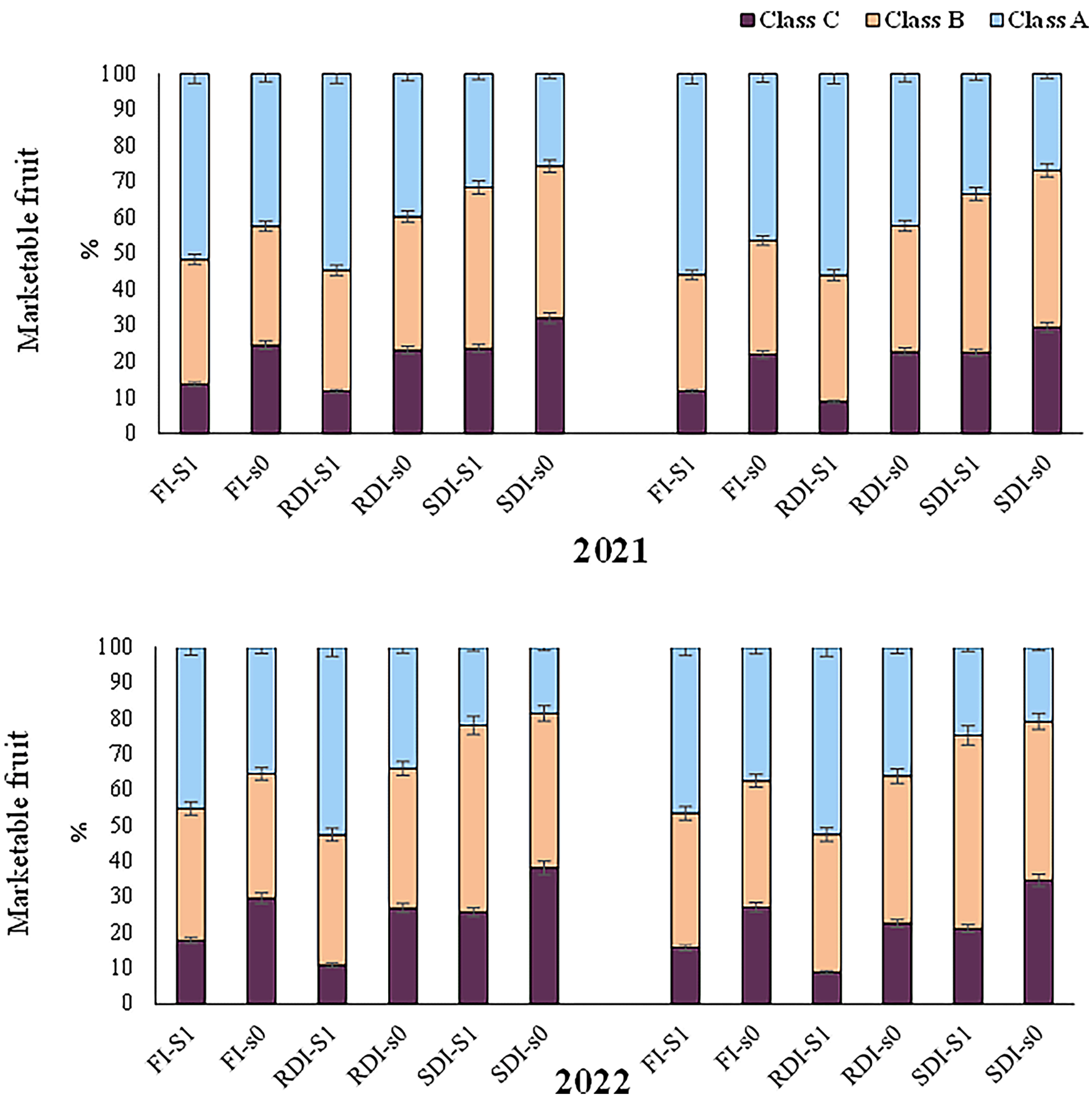

Fig. 7. Marketable fruit classification (Classes A–C) under different treatments in 2021 and 2022.

Table 6
Economic analysis of treatments in 2021 and 2022.

Irrigation	Shading	2021				2022			
		EWP_c ($/m^3)		EEP ($/kWh)		EWP_c($/m^3)		EEP ($/kWh)	
		ETS	SMS	ETS	SMS	ETS	SMS	ETS	SMS
FI	S1	1	1.2	1.7	2	2.1	2.4	3.6	4.2
	S0	0.7	0.9	1.3	1.6	1.5	1.8	2.7	3.2
RDI	S1	1.1	1.3	1.9	2.2	2.3	2.8	3.9	4.7
	S0	0.7	0.9	1.3	1.6	1.7	2.1	2.8	3.4
SDI	S1	0.9	1.2	1.8	2.2	2.1	2.4	3.7	4.4
	S0	0.7	0.8	1.4	1.7	1.4	1.7	2.7	3.2

higher stomatal conductance and sustained photosynthetic rates (Prins, 2018). Moreover, improved plant water status under shaded conditions helps maintain open stomata, supporting transpiration and indirectly enhancing carbon assimilation (Lopez et al., 2018).These physiological improvements have been associated with increased fruit yield and quality, ultimately leading to enhanced water productivity.

Global water resources for agriculture are declining due to increasing demand and climate variability, limiting the ability of farmers to meet the full irrigation requirements of their crops. As a result, they are often forced to either reduce the cultivated area or irrigate the entire area with suboptimal water volumes. Under such constraints, improving water productivity)defined as the ratio of yield to water consumption(has become a critical objective. Agronomic and horticultural strategies aimed at enhancing WP typically involve either reducing the amount of irrigation while maintaining yield, or increasing yield with the same or lower water input. The goal is to optimize the balance between water input and yield output to achieve efficient resource use without compromising productivity (Fereres and Soriano, 2007).

Among the various irrigation management practices, deficit irrigation (DI) has been widely recognized as an effective strategy to improve water productivity under limited water availability. As noted by Fereres and Soriano (2007), DI enables the optimization of water productivity by reducing irrigation inputs while sustaining acceptable yield levels. In the present study, both RDI and SDI significantly reduced irrigation water productivity) by approximately 15 % and 40 %(, respectively, compared to FI. While RDI maintained marketable yield at a level statistically similar to FI, SDI led to a noticeable reduction. Nevertheless, both treatments resulted in improved water productivity (WP), particularly in RDI treatments, where yield stability was achieved alongside WP.

Both RDI and SDI treatments resulted in higher water productivity (WP) compared to the full irrigation (FI) treatment. The choice between these strategies should be based on management priorities. For instance, SDI achieved approximately 40 % water savings but was associated with an estimated 25 % reduction in yield. In addition to enhancing WP, deficit irrigation also improved fruit quality indicators such as firmness and the total soluble solids to titratable acidity ratio (TSS/TA). Water stress under DI conditions limits cell expansion and delays enzymatic degradation of the cell wall, leading to firmer fruit texture (Zhong et al., 2019). Furthermore, reduced water availability promotes starch degradation and sugar accumulation, which in turn enhances TSS/TA (Reid and Kalcsits, 2020). These physiological responses contribute to the improvement of fruit quality under DI conditions. DI has been shown to reduce vegetative growth, which facilitates greater sugar accumulation in fruits, thereby increasing total soluble solids (TSS). This effect, combined with enhanced anthocyanin synthesis, contributes to improved fruit quality under water-limited conditions (Tao et al., 2023;Faghih et al., 2019;El Jaouhari et al., 2018).

Stomatal closure acts in water conservation for the plant. This is considered a protective and defensive system, reducing the release of water vapor from leaves through stomata, thus reducing carbon dioxide uptake for photosynthesis accordingly (Brodribb and McAdam, 2017). The reduction of stomatal conductance by water deficit is, therefore, an adaptation that plants have to resist water stress and maintain water balance (Zhao et al., 2021).

In water shortage conditions, plants respond by closing their stomata to reduce transpirational water loss. However, this adaptive response also restricts carbon dioxide uptake, which is essential for the photosynthetic process, ultimately leading to a reduction in photosynthesis rate. Water deficit conditions reduce the rate of photosynthesis primarily by limiting stomatal conductance and transpiration, both of which are critical for CO_2 uptake. Prolonged or severe water stress can further lead to cellular damage and oxidative stress, exacerbating photosynthetic inhibition. However, the extent of this impact varies depending on the duration and severity of the stress, plant species, and environmental conditions. In apple trees, deficit irrigation has been shown to significantly reduce stomatal conductance and transpiration rates. Additionally, studies have reported a decline in photosynthetic rate and Rubisco activity under water-limited conditions, indicating a reduced capacity for carbon fixation (Al-Absi and Archbold, 2016). In apple trees, stem water potential (SWP) values below −1.2 MPa are commonly associated with moderate water stress, while values lower than −1.5 MPa indicate severe stress conditions (Plavcová et al., 2023). These thresholds provide valuable context for interpreting the physiological responses observed under different irrigation treatments in the present study.

Economic factors play a critical role in farmers' decision-making, often determining the adoption of irrigation strategies. Among the key economic indicators are Economic Water Productivity (EWP) and Economic Energy Productivity (EEP), which represent the net profit obtained per unit of water (m^3) and energy (kWh) used, respectively. These indicators are inherently interrelated, as increased water use typically leads to higher energy consumption for pumping. While fixed costs remain constant across treatments, variable costs (primarily water and electricity) and marketable yield are the primary determinants of profitability.

RDI and SDI treatments led to substantial reductions in irrigation water consumption by approximately 13 % and 40 %, respectively (Table 1), thereby decreasing electrical energy consumption. While both strategies improved fruit quality attributes such as firmness and the TSS/TA ratio (Table 3), RDI outperformed SDI in maintaining a higher quantity and quality of marketable yield (Fig. 6). Additionally, the SMS method required less water than ETS, particularly when combined with shading nets, which further enhanced water savings and improved yield and fruit quality (Tables 3 and 4). As confirmed by economic indicators (Table 6), the integrated application of RDI, SMS, and shading nets resulted in the highest net profit. This demonstrates their combined effectiveness as a sustainable and economically viable irrigation strategy for high-density apple orchards.

5. Conclusion

This study demonstrated that the integration of precision irrigation technologies, including sensor-based irrigation (SMS), deficit irrigation strategies (RDI and SDI), and shading nets, can significantly improve water productivity and economic indicators in high-density apple orchards. SMS reduced irrigation water consumption by 10.2 % in 2021 and 13.7 % in 2022 compared to ETS, while also lowering pump operation hours and energy costs. Shading nets contributed to an additional 13 % reduction in water consumption and enhanced fruit quality and yield. Among the evaluated approaches, the integration of RDI, SMS, and shading net consistently enhanced yield, quality, and profitability while reducing irrigation water and energy consumption. RDI reduced irrigation volume by approximately 13 % while maintaining fruit weight, diameter, stomatal conductance, and overall yield. In contrast, SDI achieved higher water savings (approximately 40 %) but resulted in significant reductions in yield and quality. Overall, the results support the implementation of RDI combined with SMS and shading nets as a sustainable and economically viable precision irrigation strategy for high-density apple orchards in water-limited regions.

CRediT authorship contribution statement

Mahdi Selahvarzi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hossein Ansari:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization. **Ali Naghi Ziaei:** Resources, Methodology, Formal analysis, Conceptualization. **Seyed Mohammadreza Naghedifar:** Writing – review & editing, Validation, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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