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Effects of partial root-zone drying and deficit irrigation on yield, quality and water productivity of Washington Naval orange

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ABSTRACT

Internet of Things (IoT) based precision irrigation system has proven to be promising tool for optimizing water use and crop production. In this study, two irrigation water-saving techniques, double-line drip irrigation (DI) and partial-root zone drying (PRD) were assessed on 27-year-old Washington Naval orange trees. Four strategies of irrigation based on crop water requirements (100, 75, 50, and 25% of ETc) were applied in the maturity stage of growth development (phase III). Soil water contents were monitored in real-time using 10HS sensors and the Zentra cloud IoT system. Results showed that the water availability in the soil approaches the TAW threshold for DI-50%, DI-25%, PRD-50%, and PRD-25% treatments, while it remains relatively higher than RAW for the other treatments. Deficit irrigation regimes did not significantly affect the final tree yield and the irrigation water productivity (WPirrig). Nevertheless, PRD mean values were slightly higher than those under DI treatments. Regarding fruit quality parameters, results revealed that the treatments PRD-75%, PRD-50% and PRD-25% yielded significantly higher fruit flesh firmness compared to fully irrigated and DI treatments. Despite the clear decline in titratable acid (TA) trait with increasing stress level, no significant difference among treatments was registered for maturity index (MI). Our results mirror a better adaptation of orange trees to water-saving irrigation under PRD than DI. However, further and deeper research in this direction is required for more efficient irrigation water use, enhancing citrus yield and organoleptic properties.

Keywords: precision irrigation; IoT, water saving, irrigation water productivity, citrus, fruit quality.

INTRODUCTION

In the Mediterranean area, the irrigated sector, which accounts for 30% of cultivated area, is the largest consumer of freshwater from the region [1]. In particular, in Tunisia, irrigated areas consume about 75% of the total available fresh water [2]. Citrus is one of the main fruit tree species cultivated under irrigation in Tunisia, with a surface total of 28.062 ha in 2020 (10% of total irrigated fruit tree areas), of which 69% are located in the Cap-Bon region (northern east of Tunisia). In addition, Cap-Bon is the main citrus producing region in Tunisia, with an average annual production of about 200,000 tons in 2023, which represents 73% of the national citrus production [3]. However, citrus production is ultimately related to the availability of water resources, which are severely affected by climate change [4]. In this context, several studies have shown that water scarcity would reduce citrus yield and quality [5, 6], resulting in drastic economic losses. Regarding the reduction and irregularity of precipitation associated with the increase in crop water requirements in the Cap-Bon region [7], farmers are highly interested in adopting efficient irrigation systems and optimal management of irrigation water to ensure the sustainability of water resources while maintaining near maximum agricultural production [8, 9, 10].

Good knowledge on plant-soil-water relationships is of paramount importance to enable efficient irrigation water use and management [11]. Therefore, quantification of crop water requirements (ETc) or full irrigation (FI), which is determined by multiplying the reference evapotranspiration by a pre-determined crop coefficient, is highly required [6, 12]. In fact, FI stands as the conventional method that allows maximizing crop yield per unit of land [13]. However, to overcome the problem of water scarcity, countries are looking to refine irrigation strategies and enhance water use efficiency (WUE) through shifting from full irrigation to more efficient strategies known as deficit irrigation (DI) [14]. In this regard, numerous studies have highlighted the importance of using localized irrigation techniques (surface and subsurface drip irrigation) in association with water-saving strategies, such as deficit irrigation (DI), which includes sustained deficit irrigation (SDI), regulated deficit irrigation (RDI), and partial root-zone drying (PRD), as effective alternatives for growers [15–19].

DI strategies consist of reducing the amount of irrigation water either uniformly during the entire growth season (SDI) or in specific phenological stages where trees are less sensitive to water stress (RDI), below the full crop water requirement for optimal plant growth [11, 14, 20, 21]. Different studies, considering various crops, highlighted the success and advantages of adopting the DI technique, particularly when properly applied [22]. In fact, application of RDI imposes a deep knowledge of the crop physiological response to water stress in order to know in which periods this technique can be applied, hence minimizing the undesirable impacts on crop yield and quality [23–25]. Previous study results point out that adoption of water restriction on citrus trees during the last phase of fruit growth and ripening reduces fruit weight and size, leading, therefore, to a yield decrease [26, 27]. However, Chen et al. [28] revealed that the physical and chemical quality of citrus fruit might be improved when DI is applied at the young fruit stage and maturation stage, respectively. On the other hand, Chen et al. [29] found that the increase in terms of fruit quality under deficit irrigation is mainly associated with a decrease in crop yield. Additionally, Obenland et al. [30] and Silveira et al. [31], for example, reported that the degree of water stress could significantly affect fruit quality. Depending on the species and the environments, adjusting irrigation amount during drought-tolerant stages reduces the effects on yield and fruit sizes and improves water productivity [6]. According to Jamshidi et al. [32], applying DI for citrus trees with 80% of ETc could result in water saving to 15% of the seasonal irrigation with no significant yield reduction, while a yield decrease up to 28% was recorded with 50% of ETc irrigation strategy.

Regarding PRD technique, it relies on alternating irrigation zones, with wetting one half of the plant roots whereas the other half is left dry [33]. It has been evidenced that the roots under dry soil trigger a root to shoot biochemical signals such as abscisic acid hormone (ABA) inducing stomatal conductance (gs) and plant transpiration reduction [16, 34]. Jovanovic and Stikic [35] and Chen et al. [6] have reported that implementing PRD can reduce crop water footprints and increase water productivity by 20–40% while maintaining or, in some cases, increasing yield. In addition, Mossad et al. [36] assessed the effect of using PRD and SDI techniques with 50% ETc on water status and growth of 'Valencia' orange trees grown in semi-arid conditions of Palermo-Italy. Their findings show that adoption of PRD-50% did not affect yield parameters, fruit size, or juice content compared to conventional irrigation. However, juice-soluble solids and acidity, vitamin C and carotenoid concentrations, as well as sugar productivity per unit of irrigation water, were increased.

Precision irrigation (PI) requires monitoring in real-time plant and/or soil water status to determine the exact time and depth of irrigation [37]. In this sense, several plant-based indicators have been adopted by scientists and proven to be appropriate for irrigation scheduling [19], among them the canopy temperature-driven crop water stress index (CWSI) suggested by Idso et al. [38]. CWSI has been identified to fit the irrigation amounts around mid-day hours [39], highly related to leaf water potential [40], stomatal conductance [41], and soil water depletion [42]. Besides, soil moisture sensors, for example, neutron probes, frequency domain reflectometry (FDR or capacitance probe), time-domain reflectometry (TDR) and fiber-optic sensors allowing direct soil water content measurement, have been extensively used in precise irrigation scheduling [24, 43]. However, site-specific calibration of sensors is an essential step that consists on adjusting the sensor readings to fit the specific conditions and properties of the soil to ensure accurate measure of soil moisture [85, 86]. In this sense, Kizito et al. [87] emphasized that variations in properties such as bulk density, mineralogy, salinity, and organic content can lead to inaccuracies in soil moistures measurements.

Recently, innovative technologies, including the IoT's, along with sensor networks, have been developed to facilitate agricultural field management. Particularly, adoption of Internet of Things (IoT's)-based precision irrigation systems has proven effective for monitoring real-time data from sensors, consequently optimizing water use and enhancing irrigation water productivity [44, 45]. Ndunagu et al. [81] designed a Smart Irrigation System controller (SIS) using drip irrigation technique. The system uses wireless sensor networks and an open-source Internet of Things (IoT) cloud computing. Irrigation decisions were made based on web resources like the weather predictions and sensor values from soil samples, while, the system is controlled and monitored by an android application edge or a web browser. The smart irrigation system showed a prediction capability of crop water need up to 98%. Kumar et al. [82], assessed and compared the performances of using sensors and IoT-based drip irrigation system against an ETc-based drip irrigation system for brinjal crops cultivated in planter beds. They found that the adoption of IoT-based system improved pump operating time, leaf length and width of brinjal plant and saved water to 35% during a period of 31 days compared to the ETc-based system. Lakshmiprabha and Govindaraju [83], proposed IoT-based smart irrigation systems for hydroponic systems by monitoring the water and nutrients supply to enhance their productivity. To precisely estimate crop water requirements, [84], compared four machine learning ET_O models (GNB, SVM, KNN, ANN) using real-time measurements of air temperature and relative humidity directly sensed by the proposed IoT architecture against the standardized FAO-56 Penman Monteith model. The authors revealed that the KNN model outperforms the other models, with a prediction accuracy of 92%.

Given the critical situation of water availability in the region, providing citrus growers with precise and technical knowledge on irrigation water-saving strategies and technologies is relevant to ensuring sustainable water and agricultural production. Integrating IoT technology into soil moisture sensors allows real-time irrigation data monitoring, contributing to optimize irrigation efficiency and agricultural production. In this context, this study seeks (i) to assess the effects of IoT-based DI and IoT-based PRD water saving techniques on soil water status, yield, and irrigation water productivity of citrus trees grown in semi-arid conditions of the Nabeul region; and (iii) to compare the response of citrus fruit quality traits to different irrigation water levels applied using double-line drip irrigation and PRD techniques.

MATERIALS AND METHODS

Description of the study area and experimental layout

The experiment was conducted during 2023 at the agricultural experimental unit of the National Institute for Research in Rural Engineering, Water, and Forestry (INRGREF) of Oued Souhil, Nabeul, Tunisia (long. 32°37'03'' N; lat. 10°42'22'' E, altitude 25 m a.s.l.). The climate of the investigated area is Mediterranean semi-arid, with an average annual precipitation of about 440 mm and an average annual reference evapotranspiration (ETo) of 1350 mm. The experiment was performed on 27-year-old orange trees at Washington Naval (*Citrus sinensis* L., Osbeck). The field area is up to 0.26 ha, with trees planted at a spacing of 6.0 × 6.0 m. The trees are characterized by similar growth rates, with an average height of 2.5 m and a maximum rooting depth of 0.55 m. The highest root density is at 0.35 m depth. Irrigation water was pumped from a well located near the experimental site and characterized by electrical conductivity ECw = 2.77 $mS \cdot cm^{-1}$.

Data relative to the soil physical properties of the experimental site are summarized in Table 1. According to the United States Department of Agriculture (USDA) textural classification system, the soil texture in the experimental field is sandy loam (71.3% sand16% silt 11.7% clay). Average values of soil water contents at field capacity (SWCfc) and permanent wilting point (SWCwp) are equal to 0.26 and 0.06 cm^3cm^{-3}, respectively. The soil bulk density is 1.4 g cm^{-3}.

The experimental field was divided into two large adjacent plots defined according to irrigation technique (deficit irrigation "DI" and partial

Table 1. Soil physical properties of the experimental site

Depth (cm)	Θ_{fc} (%)	Θ_{wp} (%)	d_a (g cm^{-3})
0–20	27.80	5.06	1.37
20–40	24.76	6.16	1.42
40–60	26.55	5.85	1.51

root-zone drying "PRD"). Each plot (72 × 18 m) included four irrigation treatments with three adjacent rows each (three trees per row). In order to avoid border effect, observations were limited to the three trees of the middle row of each treatment. For each trees row, irrigation water was applied using two lateral pipes, one on each side of the tree, at 0.5 m from the trunks. Each lateral contains two auto-regulated emitters per tree with flow rate of 4 $l \cdot h^{-1}$ at a pressure of 100 kPa. On the head of each lateral a micro-valve was installed to control water supply.

The experimental irrigation treatments included: full irrigation (FI) with 100% of crop evapotranspiration (ETc), deficit irrigation (DI) with DI-75%, DI-50% and DI-25% of ETc, respectively, and PRD-100%, PRD-75%, PRD-50% and PRD-25% of ETc respectively. Flowering and fruitlet abscission have been widely stated as the most water stress sensitive stages in citrus [48–50]. These stages span from mid-February until the end of June in the region of study. Additionally, daily evaporative climatic demand (ETo) was very high in July. Hence, all tress were fully irrigated from February to July. The trees were subjected to the irrigation levels from August to December (DI-75%, DI-50%, DI-25% and PRD-75%, PRD-50% and PRD-25%, respectively of ETc). For PRD technique, irrigation was alternated between the two sides of tree every week. While one side of the root zone was wetted at the desired amount, the other side was kept dry. Irrigation was applied twice a week from early March to the end of December. Except for irrigation, all trees were treated similarly according to standard orchard pesticide management practices in the area.

Daily data of minimum and maximum air temperature, relative air humidity, global solar radiation, wind speed and precipitation were collected from a standard agro-meteorological station located within the experimental unit. These data were used to estimate daily reference evapotranspiration (ETo), according to the FAO-56 Penman Monteith model [12].

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma\left(\frac{900}{T_{avg} + 273}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where: Δ [kPa·°C^{-1}] is the slope of saturation vapor pressure curve, Rn [MJ·m^{-2}·d^{-1}] is the net radiation at the crop surface, G [MJ·m^{-2}·d^{-1}] is the soil heat flux density, $(e_s - e_a)$ [kPa] is the actual vapor pressure deficit, γ [kPa·°C^{-1}] is the psychrometric constant and U_2 [m·s^{-1}] is the wind speed measured at 2 m height.

Crop evapotranspiration (ETc) was computed using the FAO-single crop coefficient approach [12] as follow:

$$ET_c = Kc \times ET_o \quad (2)$$

Crop coefficient (Kc) values of 0.65 at the initial stage, 0.6 during the mid-season, and 0.65 during the late season [51] were considered based on the percentage of ground cover of the experimental field (50%). The experimental plots were irrigated on the same day. For fully irrigated treatment, the irrigation amount per time was calculated on 10 days intervals using the simplified water balance equation:

$$I = ET_c - P \pm \sum_{i=1}^{n}(\theta_2 - \theta_1)\,\Delta Z_i \quad (3)$$

where: I, irrigation (mm); P, precipitation (mm); θ_1 and θ_2 and are the volumetric soil water contents (SWC) at two consecutive measurements (cm^3·cm^{-3}); ΔZ is the thickness of soil layer (mm).

For deficit irrigation treatments, ETc is reduced to actual evapotranspiration (ETa) using a deficit irrigation coefficient (d) equal to 0.75, 0.5 and 0.25 for (DI-75%, PRD-75%), (DI-50%, PRD-50%) and (DI-25%, PRD-25%) treatments, respectively.

Soil water contents measurements

During the entire growing season, soil water content was measured gravimetrically at weekly intervals. For all treatments, soil samples were taken at depths of 0–20, 20–40, and 40–60 cm from the soil surface. Soil samples were immediately shifted to the laboratory for weighing before and after being dried in an oven at 105 °C for 24 hours. Starting from August, soil-water dynamic was assessed in real-time based on soil-water sensors and Internet of Things (IoT) system (ZL6 device from METER GROUPE). Twelve capacitive sensors 10HS (METER Group Inc., Pullman WA, USA), preliminarily calibrated, were used to monitor soil water content at 20 and 40 cm depth, with a time resolution of about 15 min. Two sensors were installed in each of treatments DI-100% and PRD-100%, while two sensors were positioned on each side of PRD-75% and PRD-50% treatments. Each set of six sensors was connected to one ZL6 data logger enclosed in a weather-proof casing. Records obtained from 10HS sensors are stored in the ZL6 data logger and, then, transferred to Zentra Cloud via IoT technology. The Zentra cloud platform web application allows visualizing, managing, and sharing the near-real-time measurements.

Fruits sampling and quality traits analysis

The crop load was measured from the harvested fruits at the end of the season (January 2024). For fruit characteristics, the three trees of the middle row of each treatment were considered, and five fruits per tree were collected to ensure a representative sample. In the laboratory, the following parameters were measured: fruit weight (g), polar and equatorial diameter (mm) (fruit size), form index (fruit shape), peel thickness (mm), and firmness ($kg \cdot cm^{-2}$).

The polar (length) and equatorial (width) diameters (mm) were measured using a caliper. The Shape Index was calculated by determining the length-to-width ratio, with a value of 1 indicating a spheroid shape. The Firmness was measured on three opposite fruit sides of the equatorial zone using a table penetrometer (Fruit Texture Analyser, GÜSS Manufacturing, South Africa) with an 11 mm diameter plunger tip connected to a computer and guided by software. Values are specified in $kg \cdot cm^{-2}$ (exerted force/surface).

Then, the fruits were sliced in the equatorial area and the peel thickness (in mm) was measured, at 3 equatorial points, by assessing the thickness of both the flavedo (outer part of the fruit) and the albedo (fibrous part of the fruit) using a digital caliper.

The fruits were juiced using electric citrus juices, and then the juice was stained through 1mm mesh sieve. The five juices of each tree were mixed and considered as a single sample for the juice quality analysis, to obtain 3 replications per treatment. The juice parameters analyzed in this study are: juice weight, total titratable acidity (citric acid content), total soluble solids, ascorbic acid (vitamin C) and maturity index. The maturity index (MI) was calculated as:

$$MI = \frac{TSS \times 10}{TA} \quad (4)$$

where: *TSS* ($g \cdot l^{-1}$) represents the content of total soluble solids (sugar) in the juice which was measured by using a digital refractometer (Atago) at 25 °C and *TA* ($g \cdot l^{-1}$) represents the titratable acidity, was determined by titration with NaOH and phenolphthalein indicator according to conventional methods [51].

The vitamin C has the raw formula C6H8O6, also known as ascorbic acid, is a water-soluble vitamin. The concentration of vitamin C can be determined by using a redox titration with a solution of 2, 6-dichlorophenol-indophenol (DCPIP). The titration is complete when the DCIPIP changes color to pale pink or purple, indicating the amount of ascorbic acid present in the solution. Vitamin C is indicated as mg ascorbic acid per 100 ml of juice [52].

Irrigation water productivity

Irrigation water productivity (WPirrig) is defined as the total yield produced per unit of irrigation water [53, 54].

$$WP_{irrig}\ (kg \cdot m^{-3}) = \frac{Y}{I} \quad (5)$$

where: *Y* – total harvestable fresh yield ($kg \cdot ha^{-1}$);
I – total amount of irrigation water ($m^3 \cdot ha^{-1}$).

Statistical analysis

The data collected were statistically analyzed using IBM SPSS 20.0 Statistical package. One-way analysis of variance (ANOVA) followed by Tukey's multiple test (P < 0.05) were performed to assess differences between treatments. Before ANOVA, the normality of data was checked using the Shapiro-Wilk test.

RESULTS AND DISCUSSION

Site agro-environmental characteristics and soil water status

Agro-climatic characterization

Daily meteorological variables (average temperature, vapor pressure deficit (VDP), reference ETo and precipitation (P) for the entire growing period are depicted in Figure 1. Initial analysis of the data shows that the air temperatures were cool in the first two months of the year, with values lower than 15 °C. Progressively, Tavg increases to reach maximum values during the initial fruit enlargement phase (July-August), then, gradually decrease until harvesting. The VPD values follow the same pattern as Tavg.

The seasonal variation of reference evapotranspiration is typical of a semi-arid climate. The calculated daily FAO-56 PM ETo data did not exceed 2 mm d-1 during winter season, while, values higher than 5 mm·d^{-1} were reached in summer. The cumulated ETo was equal to 1092 mm; indicating high evaporative demand, and while, total precipitation was limited to 390 mm.

Soil water status

During the experiment, the cumulated precipitation was 390 mm. The lowest and highest monthly precipitation values were registered in July (0.2 mm) and December (144.6 mm), respectively. For the entire growth season, irrigation was applied at 10 days intervals with amounts estimated based on the FAO-56 approach [12]. Total available water (TAW) and readily available water (RAW) in the root zone were equal to 80 mm and 54 mm, respectively. Daily patterns of root zone water depletion under different irrigation

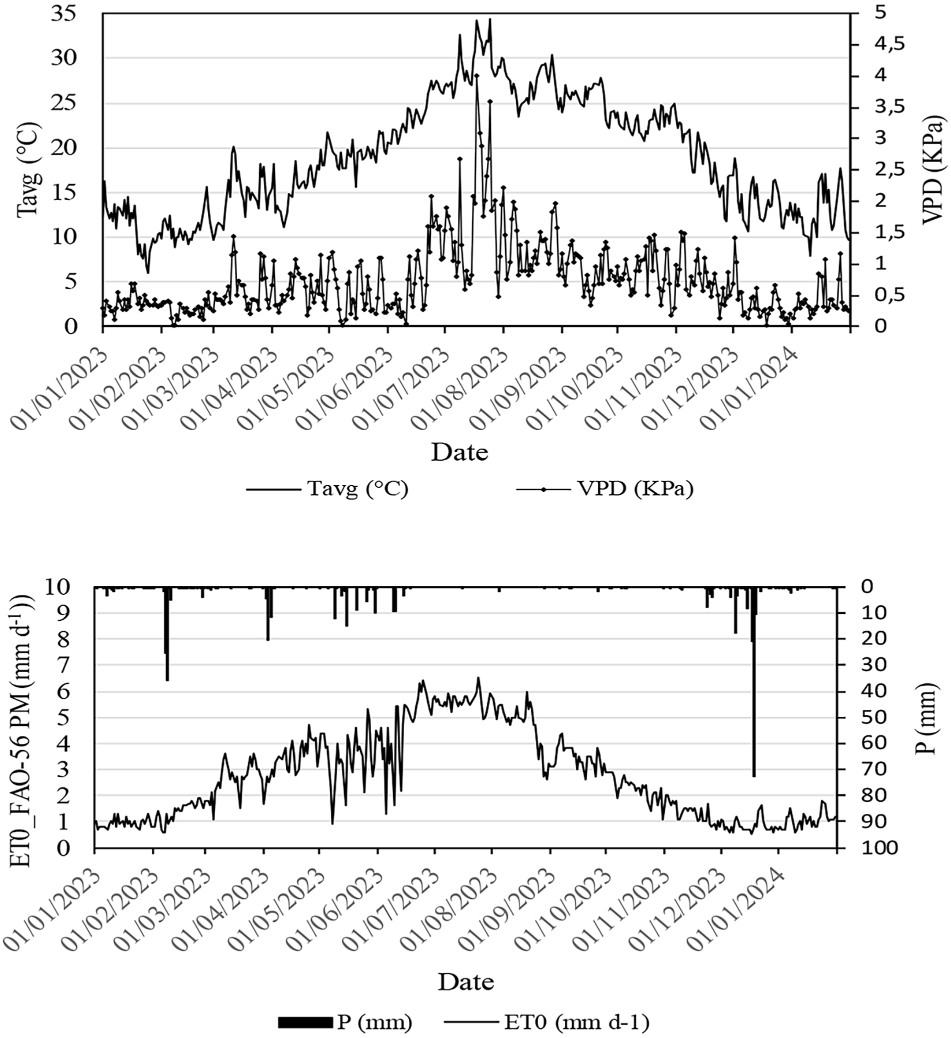

Figure 1. Dynamics of daily average air temperature (Tavg), vapor pressure deficit (VPD), reference ETo and precipitation along the study period

regimes and for the entire fruit growth season are depicted in Figure 2. During the initial and second stages, all plots were fully irrigated (100% ETc) and no water deficit treatment has been applied. Therefore, all plots were characterized by relatively similar daily water depletion patterns remained always higher than RAW threshold (54 mm), reflecting well watering conditions during that period. As shown in the Figure 2, applied irrigation depth was not always sufficient to refill soil to field capacity, as the irrigation dose was calculated indirectly according to ETc and not based on the actual soil water content [22, 55]. For the remaining period of fruit growth, soil water depletion values exhibited different patterns in response to irrigation treatments. It was clear that the depleted water was the lowest in the FI treatment followed by the DI-75% and PRD-75%,

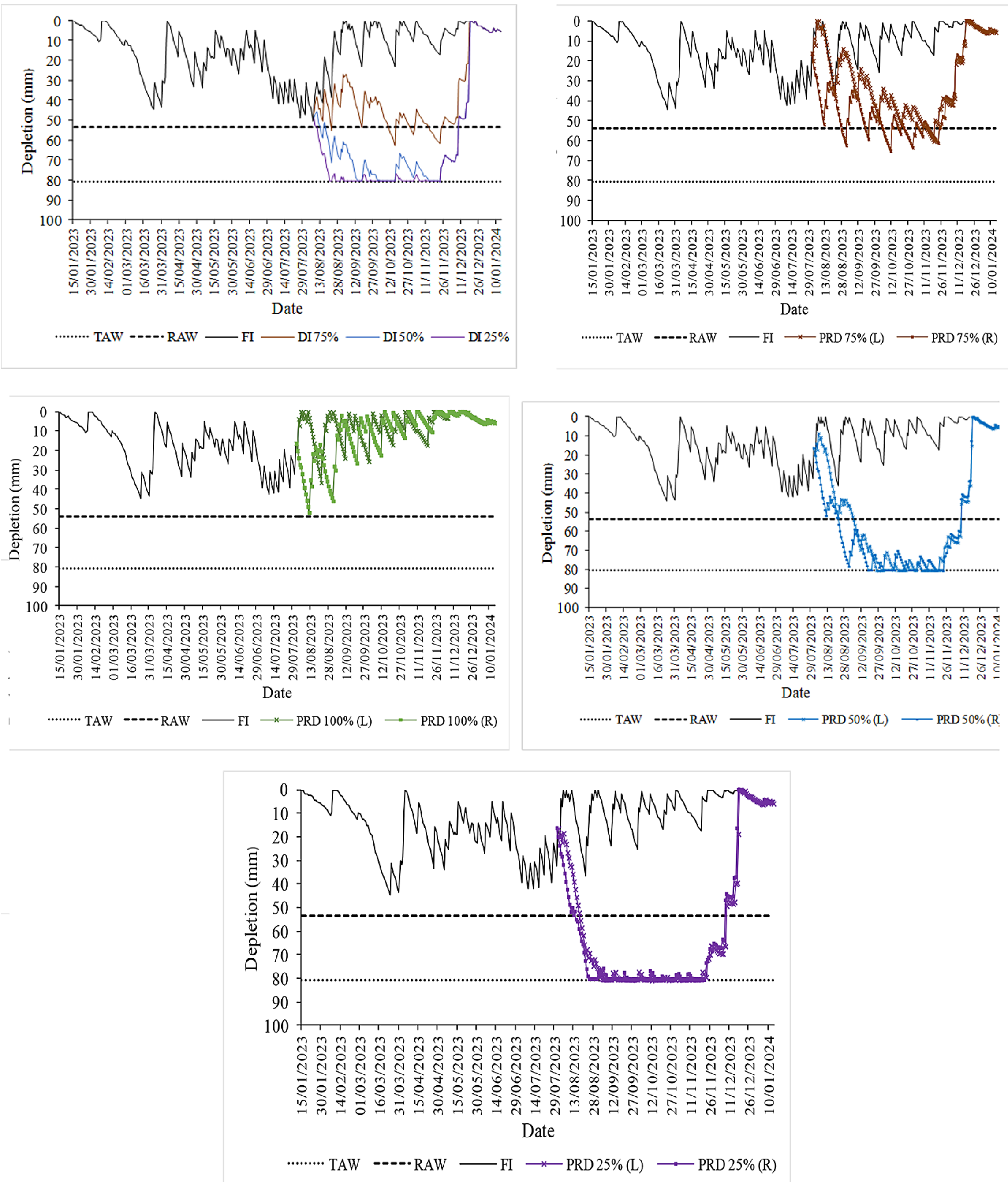

Figure 2. Daily patterns of soil water depletion (mm) in the root zone under full irrigation (FI), deficit irrigation with 75%, 50% and 25%ETc (DI-75%, DI-50%, DI-25%), and partial root-zone drying with 25%, 50% and 75% ETc (PRD-75%, PRD-50%, PRD-25%) alternating at 10 days, treatments. TAW: total available water, RAW: readily available water

DI-50% and PRD-50%, and then DI-25% and PRD-25%. This result aligns with the finding of Nagaz et al. [56] who found that the soil water depletion values decrease with increasing irrigation amounts. Similarly, Du et al. [58] stated the soil water content recorded for RDI and PRD treatments were lower than those of the fully irrigated treatments.

More detailed analysis showed that soil water depletion values of both treatments DI-50% and DI-25% increased immediately after treatment initiation and remained approaching TAW limit till mid-December indicating that the trees were subjected to a severe water stress condition. Meanwhile, DI-75% treatment was characterized with intermediate water depletion values, rarely exceeding the RAW threshold. Our results are in accordance with those achieved by Nagaz et al [56], who found that adoption of DI-75% treatment allowed intermediate soil water depletion values close to the RAW limit at the end of growing season. In addition, Piug-Sirera et al. [19] showed that the lowest values of soil water contents as well as the predawn (PLWP) and midday (MLWP) leaf water potential of mandarin trees, grown in Mediterranean semi-arid climate, were achieved when DI-25% of ET treatment is applied in the stages II and III of fruit growth.

Particularly in PRD treatments, an alternate increase and decrease of soil water depletion was observed for the two PRD lines as a result of alternate wetting and drying cycles. Furthermore, a clear difference in term of amplitude of depleted water between the wet and dry sides were reached. For example, in the second cycle of PRD-75% treatment, soil water depletion on the wetted side was equal to 15 mm, meanwhile, it reached approximately 60 mm on the side of trees row subjected to drying which correspond to a depletion of 12% below the RAW threshold. It is noteworthy that soil available water on the dry side of each PRD treatment presents a slight tendency to increase following each watering event. This behavior might be explained by either the existence of lateral movement of water from the wet to the dry side after each irrigation or water redistribution through the root zone [22, 57, 58]. Although the considerable difference in depleted water between the left and right sides of the PRD, their average values were relatively comparable to their corresponding obtained in DI treatment, confirming that the amounts of consumed water were the same for the two treatments (PRD and DI).

Effects of irrigation water saving strategies on yield components, water productivity and fruit quality

Yield and water productivity response to PRD and DI

Results of the effects of irrigation level and practices on the harvested fruit weight, yield and irrigation water productivity of Washington Naval orange trees are summarized in (Table 2). Concerning fruit weight, some difference among treatments was observed. Unfortunately, the fruit weight did not show any clear relationship with the irrigation level. The DI-75% and PRD-100% trees yielded the highest fruit weight with values equal to 259.86 g and 252 g, respectively. These values were significantly higher than those obtained under DI-25% and PRD-50% treatments. Although these differences in fruit yield, no statistically significant difference in term of tree yield was recorded among studied treatments. When considering DI and PRD treatments separately, it was possible to identify a response of fruit yield per tree to irrigation level. As shown in Table 2, the tree yield tends to increase with increasing irrigation level, when, unexpectedly, the tree yield under PRD-50% was higher than that achieved

Table 2. Fruit weight, yield and water productivity of Washington Naval orange trees under different irrigation treatments

Treatment	Irrigation (mm)	Fruit weight (g)	Fruit yield (kg tree^{-1})	WP_{irrig} (kg m^{-3})
FI	505	226.13^{b,c}	123.56^{a}	6.80^{a}
DI-75%	439	259.86^{a}	81.26^{a}	5.14^{a}
DI-50%	380	231.6^{a,b,c}	86.2^{a}	6.31^{a}
DI-25%	310	218.4^{c}	70.56^{a}	6.33^{a}
PRD-100%	515	252^{a,b}	111.82^{a}	6.03^{a}
PRD-75%	451	239.53^{a,b,c}	85.6^{a}	5.28^{a}
PRD-50%	390	209.33^{c}	120.5^{a}	8.6^{a}
PRD-25%	327	236.43^{a,b,c}	81.25^{a}	6.9^{a}

under PRD-100%. This positive correlation between yield and irrigation amount corroborates the findings of Panigrahi [59]. In addition, Wang et al. [61] affirmed that irrigating citrus trees with PRD-50% ETc resulted in higher yield compared to DI-75% ETc strategy.

Furthermore, the yields under PRD treatments were slightly higher than their corresponding obtained under DI treatments. That behavior might be related to alternating wetting and drying cycle under PRD, which stimulates abscisic acid (ABA) synthesis and its root-to shoot transport. However, the fact that concentration of ABA is higher in trees subjected to PRD compared to those under DI is not always true [62]. Jamshidi et al. [18] pointed out that ABA synthesis and effects is more pronounced with higher water stress level. In our study, PRD-25% water saving strategy produced lower yield compared to PRD-50%, emphasizing that PRD-50% can be considered as the optimum strategy for simulating ABA synthesis in citrus trees. With regard to FI treatment, a clear reduction of tree yield was registered under DI-25% and PRD-25% treatments with values equal to 43% and 34.2%, respectively. However, these reductions were not statistically significant. Our results are in accordance with those reported by Saitta et al. [25]. The authors showed that adoption of RDI, SDI-75% and PRD-50% ETc irrigation strategies did not significantly affect the final yield of orange tree as compared to full irrigated conditions with final yield values ranging from 26.6±1.7 to 31.7±1.6 $t \cdot ha^{-1}$ and from 29.9±2.1 to 34.5±2.4 $t \cdot ha^{-1}$ respectively under PRD-50% and SDI-75% treatments in 2019 and 2020. Similarly, Agado et al. [62] and Puglisi et al. [63], found that the final yield of citrus trees subjected to DI treatments were not statistically different from normally irrigated trees. In this sense, Adu et al. [47] reported that crop species and soil texture are the main determinant factors in crop yield response to water-saving irrigation strategies.

The irrigation water productivity values varied from 5.14 to 8.6 $kg \cdot m^{-3}$ under DI-75% and PRD-50% treatments, respectively, which are clearly higher than those obtained by Nagaz et al. [56] for citrus trees conducted in arid conditions in Tunisia. Except for FI and PRD-100%, irrigation water productivity "WPirrig" values achieved under PRD treatments were higher than their corresponding in DI treatments. However, there were no significant differences among all studied treatments. In accordance with our results, Consoli et al. [64] found that IWP in citrus trees increases under PRD technique and justified this response by the lower wetted soil volume. In fact, the higher WPirrig under PRD-50% is explained by the higher final yield with less applied water compared to other treatments. Our finding is strengthened by that reported by Consoli et al. [65] who revealed that PRD-50% ETc water saving strategy allows increase in WUE of a young orange orchard with no yield reduction. Similarly, Zapata-Sierra and Manzano-Agugliaro [66,] showed that adoption of DI in mature orange orchard did not affect WUE and yield.

Fruit quality parameters response to PRD and DI

Fruit shape, firmness, peel roughness and color are among the main attributes, of an agricultural food product, that should meet a minimum standard of visual acceptance or palatability to satisfy the consumer quality preferences [67,68]. Table 3 shows the effects of different irrigation practices and levels applied during phase III of fruit growth

Table 3. Fruit quality parameters of Washington Naval orange trees under different irrigation treatment

Treatment	PD (mm)	FI	PT (mm)	Firmness (kg cm^{-2})
FI	73.2^{b}	0.94^{a}	$4.58^{a,b}$	0.13^{b}
DI-75%	78.6^{a}	0.96^{a}	5.11^{a}	0.13^{b}
DI-50%	72.38^{b}	0.94^{a}	5.02^{a}	0.13^{b}
DI-25%	72.6^{b}	0.96^{a}	$4.78^{a,b}$	0.14^{b}
PRD-100%	$75.32^{a,b}$	0.94^{a}	$4.37^{a,b}$	0.14^{b}
PRD-75%	$76.1^{a,b}$	0.98^{a}	$4.83^{a,b}$	0.57^{a}
PRD-50%	71.66^{b}	0.96^{a}	3.77^{b}	0.5^{a}
PRD-25%	$74.21^{a,b}$	0.96^{a}	5.38^{a}	0.42^{a}

Note: PD, polar diameter; FI, form index; PT, peel thickness. Different letters within columns indicate significant differences by Tukey test at $P \leq 0.05$

on some fruit quality parameters. Polar diameter presents a slight tendency to decrease with increasing water stress level. As seen in Table 3, PD under DI-50%, DI-25% and PRD-50% were significantly lower than that under DI-75% treatment. Indeed, it was widely reported that citrus trees subjected to water stress yielded a smaller mean fruit diameter [16]. Additionally, Navarro et al. [23] noted significant decrease in fruit size when the trees experienced severe water shortage during Phase II. In spite of the existence of significant differences in polar diameter among treatments, the form index which is defined as the ratio between (Equatorial diameters) ED and (Polar diameter) PD was not significantly affected by irrigation treatment. For all treatments, the form index values were close to 1 showing that the fruits are characterized by a nearly spheroid shape.

Firmness, as an important sensory characteristic determining citrus fruit ripeness, was assessed in this study. Results showed that the treatments PRD-75%, PRD-50% and PRD-25% of ETc reached significantly higher fruit flesh firmness compared to FI, PRD-100% and DI treatments. This can be directly related to a loss of peel moisture, becoming dryer and consequently firmer, but not of the juice vesicles' content. It is well known that the fruit's water content is influenced by leaves transpiration which draws water from the fruit in addition to the fruit transpiration itself. Fruit moisture lost during these processes comes primarily from the peel where the juice vesicles, anatomically isolated from the vascular system compared to the peel, do not change water status as rapidly [69]. In addition, application of PRD technique enhances ABA hormone synthesis that works as metabolic inhibitor by inducing stomata closing and reducing transpiration rates [16,34], enhancing therefore fruit firmness. In apparent contradictions with our results, Kusakabe et al. [70] found that the application of PRD technique in grapefruit trees during phase II decreases citrus fruit firmness. In addition, Morianou et al. [71] observed that citrus fruit firmness significantly increases when DI strategy during is adopted during Phase II of different citrus cultivars.

Internal fruit quality parameters under PRD and DI

Figure 3 shows the response of internal fruit quality parameters (juice (%), Vitamin C contents (Tc), acidity and TSS) of Washington Navel orange tree to various irrigation levels and practices. Vitamin C is one of the important antioxidants reflecting the fruit nutritional quality [72]. It varied from 55 to 78.4 mg/100 ml under DI-75% and FI treatments, respectively. However, these differences among treatments were not statistically significant. Referring to the extracted fruit juice, obtained values were significantly higher than the minimum acceptable value (33%) recommended by UNECE [73] for navel oranges and was comparable to those reported for orange varieties in different studies. PRD-100% and PRD-75% produced significantly higher contents (54.3 and 51.7%) compared to PRD-50%. The reduction in juice content in citrus fruits with decreasing irrigation amounts was also reported by several authors among them [26, 74] and [75]. Furthermore, for the same irrigation level, no significant difference was observed between DI and PRD irrigation technique. In addition, it can be speculated that juice contents and TSS are negatively correlated. Relatively the same has been observed by Panigrahi [59]. The authors reported that juice percentage diminish is accompanied by an increment in the soluble solids concentrations in fruits.

Maturity index (MI), recognized as the main relevant fruit's internal quality indicator, is determined as the ratio between the total soluble solids (TSS) and the titratable acidity (TA) since TSS increases toward harvest while acid content declines because of catabolism of citric acid and dilution phenomena [71,67]. In our case study, reducing irrigation amount by 25, 50 and 75% of ETc during the stage III of fruit development of Washington Naval orange tree did not show any significant effect on MI. In overall, the MI values fall within the standard range (8–10) suitable for commercial harvest as suggested by UNECE [73]. Kusakabe et al [70] showed that the effect of DI strategy on MI depends widely on the crop variety. An increase of MI might be considered as an advantage for the market value of juice and the profit of an early harvest. However, higher MI values indicate late harvest and flavor loss as acids concentration declines toward harvest, whereas, sugars accumulate [67] which is the case under DI-50% and DI-25% treatments. With the regard to the effect of water irrigation level and practices on TSS feature, there were no significant differences among all adopted treatments, except for PRD-75% treatment in which a significant reduction is observed (Figure 3). This finding aligns with that reported by Saitta et al [25] and Gasque et al. [76] who found that TSS and MI in citrus fruit was not affected by DI. It is worth to note that in overall, FI

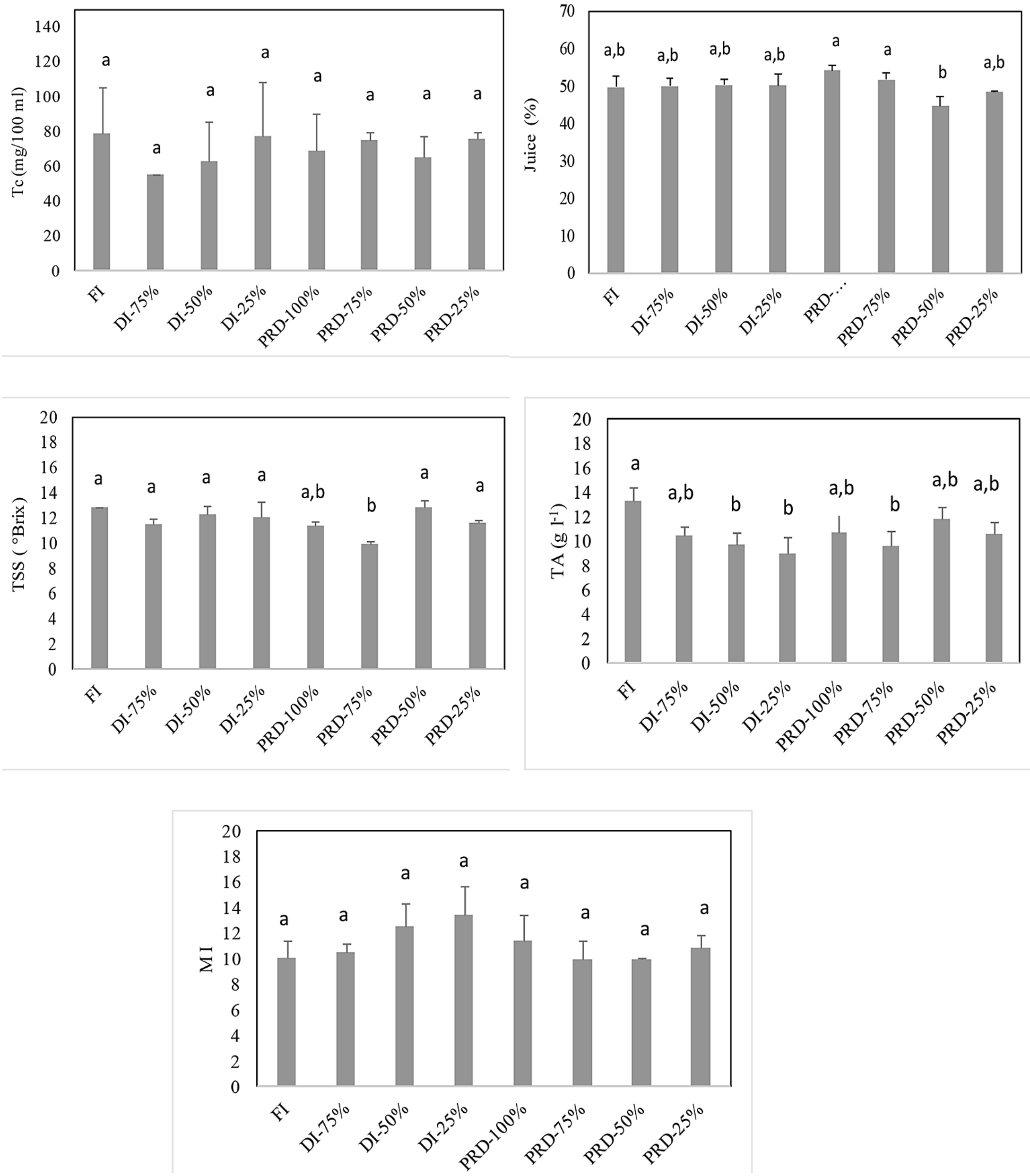

Figure 3. Effects of irrigation treatments on internal fruit quality parameters at harvest (Tc: ascorbic acid (vitamin C); Juice contents (%); TSS, total soluble solids; TA, titrable acidity; MI, maturity index) of irrigated Washington Navel orange trees. Different letters indicate statistically significant differences according to Tukey's test ($p \leq 0.05$)

and DI treatments resulted in higher means of TSS compared to their corresponding achieved under PRD technique. According to Lado et al. [67], the increase in sugars is always associated with an increment in TSS. Hence, our result suggests that adoption of PRD techniques would decline sugar accumulation in the fruits. Further analysis shows that means of TSS increased under PRD-50% and PRD-25% compared to PRD-100%. However, in this study a clear decrease in TA trait with increasing stress level was registered. The higher TSS and lower acidity of fruits were observed in DI-50% and DI-25%. This is might be related to the boosted process of transformation of acids to sugars in dehydrated juice sacs responsible in maintaining the osmotic pressure of fruit cells [77]. The impacts of deficit irrigation on fruits qualitative parameters have been investigated in a large range of crop types. In fruit citrus, the increase of TSS and TA traits under water deficit applied either during the whole season or during fruit growth stages has been widely evidenced [15, 23, 26, 64]. Hutton and Loveys [16], reported that TSS and acid concentrations were higher in navel orange trees irrigated by PRD compared to normally irrigated trees. Adu et al. [78] showed that DI strategies improve TSS without significantly affecting TA or pH of fruits. However, Gasque et al. [76] noted that DI did not significantly affect the fruit quality of Navalina sweet orange grown in Spain. Barry et al. [79], showed that limiting water later in fruit development (January–March) did not increase TSS and TA traits. In the other hand, an increase in TSS associated with a decrease in acidity in citrus fruits under optimal DI strategy over FI was reported by Panigrahi et al. [80]. In the works of Romero-Trigueros [5] and Pérez-Pérez et al. [26], DI strategies increased the values of TSS and TA of citrus fruit juices without affecting MI. Therefore, it is important to note that the effects of deficit irrigation on the main organoleptic properties of citrus fruits depend widely on the cultivar, irrigation technique, timing, duration and severity, climatic and edaphic conditions of the study areas.

CONCLUSIONS

This study investigated the effects of various water-saving irrigation strategies, namely DI-100%, DI-75%, DI-50% and DI-25% of ETc and PRD-100%, PRD-75%, PRD-50% and PRD-25% of ETc, on yield, water productivity and fruit quality traits of Washingon Naval orange trees conducted in semi-arid conditions. Real time soil moisture was monitored using IoT-based sensors. Our results revealed that implementing deficit irrigation strategies during the maturity stage of growth development (phase III) using either double-line drip irrigation or PRD technique did not significantly affect the final tree yield. Mean values of irrigation water productivity "WPirrig" were higher for restricted PRD treatments compared to their corresponding with DI technique. However, no significant differences among all studied treatments were recorded. The highest WPirrig mean value (8.6 kg m^{-3}) was achieved under PRD-50% treatment. With the regard to the effect of irrigation techniques and watering level on orange fruit quality traits, no substantial differences were observed among treatments. Thus, the findings of this study suggest that PRD-50% strategy can be adopted by growers as useful alternative for Washingon Naval orange trees that allows irrigation water saving without affecting yield and fruit quality. Due the increasing restriction in irrigation water use in the study region, further trials should be conducted to assess the impact of water stress timing and severity on yield and fruit quality of orange trees.

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REFERENCES

1. Harmanny, K.S., Malek, Ž., (2019). Adaptations in irrigated agriculture in the Mediterranean region: an overview and spatial analysis of implemented strategies. *Regional Environmental Change, 19*(5), 1401–1416. https://doi.org/10.1007/s10113-019-01494-8
2. Chebil, A., Soula, R., Souissi, S., Bennouna, B., (2022). Efficiency, evaluation, and pricing of irrigation water in northeastern Tunisia. *Agricultural Water Management, 266*, 107577, 0378–3774. https://doi.org/10.1016/j.agwat.2022.107577
3. Regional Agricultural Development Commission, Nabeul – Tunisia, (2023). https://www.nabeul.gov.tn/fr/agriculture-et-peche/
4. IPCC (Intergovernmental Panel on Climate Change), (2018). Special Report: Global Warming of 1.5oC. https://www.ipcc.ch/sr15
5. Romero-Trigueros, C., Alarcon, J.J., Nortes, P.A., Bayona, J.M., Maestre-Valero, J., Nicolas, E., (2020). Mid-long term effects of saline reclaimed water irrigation and regulated deficit irrigation on fruit quality of citrus. *J. Sci. Food Agric. 100*(3). https://doi.org/10.1002/jsfa.10091
6. Chen, F., Cui, N., Jiang, S., Wang, Z., Li, H., Lv, M., Wang, Y., Gong, D., Zhao, L., (2023). Multi-Objective deficit drip irrigation optimization of citrus yield, fruit quality and water use efficiency using NSGA-II in seasonal arid area of Southwest China. *Agricultural Water Management, 287*, 108440.
7. Latrech, B., Hermassi, T., Yacoubi, S., Slatni, A., Jarray, F., Pouget, L., Ben Abdallah, M.A., (2024). Comparative analysis of climate change impacts on climatic variables and reference evapotranspiration in Tunisian Semi-Arid Region. *Agriculture, 14*, 160. https:// doi.org/10.3390/agriculture14010160
8. García-Tejero, I.F., Durán-Zuazo, V.H., Muriel-Fernández, J.L., (2014). Towards sustainable irrigated Mediterranean agriculture: implications for water conservation in semi-arid environments. *Water Int. 39*, 635–648.
9. Martínez-Gimenoa, M.A., Bonet, L., Provenzano, G., Badal, E., Intrigliolo, D.S., Ballester, C., (2018). Assessment of yield and water productivity of clementine trees under surface and subsurface drip irrigation. *Agricultural Water Management, 206*, 209–216. https://doi.org/10.1016/j.agwat.2018.05.011
10. Gomez-Bellot, M.J., Parra, A., Nortes, P., Alarcon, J.J., Ortuno, M.F., (2024). Searching for a deficit

irrigation strategy to save water and improve fruit quality without compromising pomegranate production. *Scientia Horticulturae, 324*, 112631.

11. Tari, A.F., (2016). The effects of different deficit irrigation strategies on yield, quality, and water-use efficiencies of wheat under semi-arid conditions. *Agricultural Water Management, 167*. 1–10, https://doi.org/10.1016/j.agwat.2015.12.023
12. Allen, R.G., Pereira, S.L., Raes, D., Smith, M., (1998). *Crop evapotranspiration. Guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper 56. Rome, 300.
13. Zuazo, V.H.D., Garcia-Tejero, I.F., Rodriguez, B.C., Tarifa, D.F., Ruiz, B.G., Sacristan, P.C., (2021). Deficit irrigation strategies for subtropical mango farming. A review. *Agron. Sustain Dev. 41*(1), 13. https://doi.org/10.1007/s13593-021-00671-6
14. Galindo, A., Collado-González, J., Griñán, I., Corell, M., Centeno, A., Martín-Palomo, M.J., Girón, I.F., Rodríguez, P., Cruz, Z.N., Memmi, H., Carbonell-Barrachina, A.A., Hernández, F., Torrecillas, A., Moriana, A., Pérez-López, D., (2018). Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems. *Agricultural Water Management, 202*, 311–324, 0378–3774. https://doi.org/10.1016/j.agwat.2017.08.015
15. García-Tejero, I., Jiménez-Bocanegra, J.A., Martínez, G., Romero, R., Durán-Zuazo, V.H., Muriel-Fernández, J.L., (2010). Positive impact of regulated deficit irrigation on yield and fruit quality in a commercial citrus orchard [Citrus sinensis (L.) Osbeck, cv. salustiano]. *Agricultural Water Management, 97*(5), 614–622, 0378–3774, https://doi.org/10.1016/j.agwat.2009.12.005
16. Hutton, R.J., Loveys, B.R., (2011). A partial root zone drying irrigation strategy for citrus—Effects on water use efficiency and fruit characteristics. *Agricultural Water Management, 98*(10), 1485–1496. https://doi.org/10.1016/j.agwat.2011.04.010.
17. Martínez-Nicolas, J.J., Galindo, A., Grinan, I., Rodríguez, P., Cruz, Z.N., Martínez Font, R., Melgarejo, P. (2019). Irrigation water saving during pomegranate flowering nand fruit set period do not affect Wonderful and Mollar de Elche cultivars yield and fruit composition. *Agr. Water Manag. 226*, 105781.
18. Jamshidi, S., Zand-Parsa, S., Niyogi, D., (2021). Physiological responses of orange trees subject to regulated deficit irrigation and partial root drying. *Irrigation Science, 39*, 441–455. https://doi.org/10.1007/s00271-020-00709-9
19. Puig-Sirera, A., Provenzano, G., González-Altozano, P., Intrigliolo, D.S., Rallo, G., (2021). Irrigation water saving strategies in Citrus orchards: Analysis of the combined effects of timing and severity of soil water deficit. *Agricultural Water Management, 248*, 106773, 0378–3774, https://doi.org/10.1016/j.agwat.2021.106773
20. Laribi, A.I., Palou, L., Intrigliolo, D.S., Nortes, P.A., Rojas-Argudo, C., Taberner, V., Bartual, J., Pérez-Gago, M.B., (2013). Effect of sustained and regulated deficit irrigation on fruit quality of pomegranate cv. 'Mollar de Elche' at harvest and during cold storage. *Agricultural Water Management, 125*, 61–70, 0378–3774. https://doi.org/10.1016/j.agwat.2013.04.009
21. Yang, B., Fu, P., Lu, J., Ma, F., Sun, X., Fang, Y., (2022). Regulated deficit irrigation: an effective way to solve the shortage of agricultural water for horticulture. *Stress Biology, 2*, 28. https://doi.org/10.1007/s44154-022-00050-5
22. Mattar, M.A., Zin El-Abedin, T.K., Alazba, A.A., Al-Ghobari, H.M., (2020). Soil water status and growth of tomato with partial root-zone drying and deficit drip irrigation techniques. *Irrigation Science, 38*, 163–176. https://doi.org/10.1007/s00271-019-00658-y
23. Navarro, J.M., Botia, P., Perez-Perez, J.G., (2015). Influence of deficit irrigation timing on the fruit quality of grapefruit (Citrus paradise Mac.). *Food Chem. 175*, 329–336.
24. Rallo, G., Gonzalez-Altozano, P., Manzano-Juarez, J., Provenzano, G., (2017). Using field measurements and FAO-56 model to assess the eco-physiological response of citrus orchards under regulated deficit irrigation. *Agric. Water Manag. 180*, 136–147. https://doi.org/10.1016/j.agwat.2016.11.011
25. Saitta, D., Consoli, S., Ferlito, F., Torrisi, B., Allegra, M., Longo-Minnolo, G., Ramírez-Cuesta, J.M., Vanella, D., (2021). Adaptation of citrus orchards to deficit irrigation strategies. *Agricultural Water Management, 247*, 1–13. https://doi.org/doi.org/10.1016/j.agwat.2020.106734
26. Pérez-Pérez, J.G., Robles, J.M., Botía, P., (2009). Influence of deficit irrigation in phase III of fruit growth on fruit quality in 'lane late' sweet orange. *Agricultural Water Management. 96*, 969–974.
27. García-Tejero, I., Romero-Vicente, R., Jimenez-Bocanegra, J.A., Martínez-García, G., Dur´ an- Zuazo, V.H., Muriel-Fern´ andez, J.L., (2010a). Response of citrus trees to deficit irrigation during different phenological periods in relation to yield, fruit quality, and water productivity. *Agricultural Water Management, 97*, 689–699.
28. Chen, Q., Wang, D., Tan, C., Hu, Y., Sundararajan, B., Zhou, Z., (2020). Profiling of flavonoid and antioxidant activity of fruit tissues from 27 Chinese local Citrus cultivars. *Plants 9*, 196. https://doi.org/10.3390/plants9020196
29. Chen, J., et al. (2014). Modeling relations of tomato yield and fruit quality with water deficit at different growth stages under greenhouse condition. *Agricultural Water Management, 146*, 131–148.

30. Obenland, D., Campisi-Pinto, S., Arpaia, M.L., (2018). Determinants of sensory acceptability in grapefruit. *Sci. Hortic. 231*, 151–157. https://doi.org/10.1016/j. Scienta.2017.12.026
31. Silveira, L.K., Pavao, G.C., dos Santos Dias, C.T., Quaggio, J.A., Pires, R.C., de, M., (2020). Deficit irrigation effect on fruit yield, quality and water use efficiency: a long-term study on Pera-IAC sweet orange. *Agricultural Water Management, 231*. https://doi.org/10.1016/ j. agwat.2020.106019
32. Jamshidi, S., et al., (2020). Evapotranspiration, crop coefficients, and physiological responses of citrus trees in semi-arid climatic conditions. *Agricultural Water Management 227*, 105838.
33. Gil, P.M., Lobos, P., Durán, K., Olguín, J., Cea, D., Schaffer, B., (2018). Partial root-zone drying irrigation, shading, or mulching effects on water savings, productivity and quality of 'Syrah' grapevines. *Scientia Horticulturae, 240*, 478–483, 0304–4238. https://doi.org/10.1016/j.scienta.2018.06.050
34. 34- Gotur, M., Sharma, D.K., Joshi, C.J., Rajan, R., (2018). Partial root-zone drying technique in fruit crops: a review paper. *Int. J. Chem. Stud. 6*, 900–903.
35. Jovanovic, Z., Stikic, R., (2018). Partial root-zone drying technique: from water saving to the improvement of a fruit quality. *Frontiers in Sustainable Food Systems, 1*, 3. https://doi.org/10.3389/fsufs.2017.00003
36. Mossad, A., Farina, V., Lo, Bianco, R., (2020). Fruit yield and quality of 'Valencia' orange trees under long-term partial rootzone drying. *Agronomy, 10*, 164.
37. Anjum, M.N., Masud Cheema, M.J., Hussain, F., Wu, R.S. (2023). *Precision irrigation: challenges and opportunities*, Chapter 6 - Precision Agriculture, Academic Press, 85–101, 9780443189531. https://doi.org/10.1016/B978-0-443-18953-1.00007-6
38. Idso, S.B., Jackson, R.D., Pinter Jr, P.J., Reginato, R.J., Hatfield, J.L., (1981). Normalizing the stress-degree-day parameter for environmental variability. *Agric. Meteorol. 24*, 45–55.
39. Taghvaeian, S., et al. (2014). Conventional and simplified canopy temperature indices predict water stress in sunflower. *Agricultural water management 144*, 69–80.
40. King, B.A., et al. (2020). Data-driven models for canopy temperature-based irrigation scheduling. *Transactions of the ASABE 63*(5), 1579–1592.
41. Lena, B.P., Ortiz, B.V., Jimenez-Lope, A.F., Sanz-Saez, A., O'Shaughnessy, S.A., Durstock, M.K., Pate, G., (2020). Evaluation of infrared canopy temperature data in relation to soil water-based irrigation scheduling in a humid subtropical climate. *Trans. ASABE 63*(5), 1217–1231. https://doi.org/10.13031/trans.13912
42. Kullberg, E.G., DeJonge, K.C., Chavez, J.L., (2017). Evaluation of thermal remote sensing indices to estimate crop evapotranspiration coefficients. *Agric. Water Manag. 179*, 64–73. https://doi.org/10.1016/j.agwat.2016.07.007
43. Vera, J., Conejero, W., Conesa, M.R., Ruiz-S´anchez, M.C. (2019). Irrigation factor approach based on soil water content: a nectarine orchard case study. *Water 11*. https://doi.org/10.3390/w11030589
44. Singh, D.K., Sobti, R., Kumar Malik, P., Shrestha, S., Singh, P.K., Ghafoor, K.Z. (2022). IoT driven model for weather and soil conditions based on precision irrigation using machine learning. *Security and Communication Networks,* 1–10. https:// doi.org/ 10. 1155/ 2022/72839 75
45. Kumar, S.V., Singh, C.D., Ramana Rao, K.V., Rajwade, Y.A., Kumar, M., Jawaharlal, D., Asha, K.R. (2024). IoT-based smart drip irrigation scheduling and wireless monitoring of microclimate in sweet corn crop under plastic mulching. *Irrigation Science.* https://doi.org/10.1007/s00271-024-00945-3
46. Chakroun, H., Zemni, N., Benhmid, A., Dellaly, V., Slama, F., Bouksila, F., & Berndtsson, R. (2023). Evapotranspiration in semi-arid climate: Remote sensing vs. soil water simulation. *Sensors, 23*(5), 2823.
47. Adu, M.O., Yawson, D.O., Armah, F.A., Asare, P.A., Frimpong, K.A. (2018). Meta-analysis of crop yields of full, deficit, and partial root-zone drying irrigation. *Agric. Water Manag. 197*, 79–90.
48. García-Tejero, I.F. Durán Zuazo, V. & Arriaga-Sevilla, J., Muriel, J., (2011). Impact of water stress on citrus yield. *Agronomy for Sustainable Development, 32*. https://doi.org/10.1007/s13593-011-0060-y
49. Pérez-Pérez, J., Romero, P., Navarro, J., Botía, P., (2008). Response of sweet orange cv 'Lane late' to deficit-irrigation strategy in two rootstocks. II: Flowering, fruit growth, yield and fruit quality. *Irrigation Science, 26*, 519.
50. Doorenbos, J., Kassam, A.H., (1979). *Yield Response to Water, FAO- Irrigation and Drainage Paper, 33*. Food and Agricultural Organization, Rome.
51. Kimball, D. A. (2012). *Citrus Processing: Quality Control and Technology*. Springer Science & Business Media, New York, NY.
52. Ojukwu U.P., Nwobi, S.C., (2017). *Determination of Ascorbic Acid Content of Some Local Fruits in Nigeria*. 17, 1, Available from: https://www.tsijournals.com/articles/determination-of-ascorbic-acid-content-of-some-local-fruits-in-nigeria.html
53. Latrech, B., Ghazouani, H., Lasram, A., Douh M'hamdi, B., Mansour, M., Boujelben. A., (2019). Assessment of different methods for simulating actual evapotranspiration in a semi-arid environment. *Italian Journal of Agrometeorology*, (2), 21–34. https://doi.org/10.13128/ ijam-650
54. Leogrande, R., Vitti, C., Lopedota, O., Ventrella, D., Montemurro, F., (2016). Effects of irrigation

volume and saline water on maize yield and soil in Southern Italy. *Irrigation and drainage,* https://doi.org/10.1002/ird.1964

55. Patanè, C., Cosentino, S.L., (2010). Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. *Agric Water Management, 97*, 131–138. https ://doi.org/10.1016/j.agwat.2009.08.021
56. Nagaz, K., El Mokh, F., Ben Hassen, N., Masmoudi, M.M., Ben Mechlia, N., Baba Sy, M.O., Belkheiri, O., Ghiglieri, G., (2017). Impact of deficit irrigation on yield and fruit quality of orange trees (Citrus Sinensis, L. Osbeck, CV. Meski Maltaise) in Southern Tunisia. *Irrigation and drainage, 69* (Suppl. 1), 186–193.
57. Hashem, M.S., Zin El-Abedin, T.K., Al-Ghobari, H.M., (2019). Rational water use by applying regulated deficit and partial root-zone drying irrigation techniques in tomato under arid conditions. *Chile J Agric Res 79*(1), 75–88. https ://doi.org/10.4067/S0718 -58392 01900 01000 75
58. Du, T., Kang, S., Zhang, J., Li, F. (2008). Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of northwest China. *Irrig Sci., 26*, 147–159. https ://doi.org/10.1007/s0027 1-007-0081-0
59. 59- Panigrahi, P. (2023). Impact of deficit irrigation on citrus production under a sub-humid climate: a case study. *Water Supply, 23*(3), 1177. https://doi.org/10.2166/ws.2023.074
60. Consoli, S., Stagno, F., Roccuzzo, G., Cirelli, G.L., Intrigliolo, F., (2014). Sustainable management of limited water resources in a young orange orchard. Agric. *Water Manag. 132*, 60–68. https://doi.org/10.1016/j.agwat.2013.10.006
61. Wang, M., et al., (2021). Citrus flavonoids and the intestinal barrier: Interactions and effects. Comprehensive Reviews in Food Science and Food Safety 20.1 225–251.
62. Aguado, A., Frías, J., García-Tejero, I., Romero, F., Muriel, J.L., Capote, N., (2012). Towards the improvement of fruit-quality parameters in citrus under deficit irrigation strategies. *ISRN Agron*.
63. Puglisi, I., Nicolosi, E., Vanella, D., Lo Piero, A.R., Stagno, F., Saitta, D., Roccuzzo, G., Consoli, S., Baglieri, A., (2019). Physiological and biochemical responses of orange trees to different deficit irrigation regimes. *Plants 8*, 423.
64. Consoli, S., Vanella, D., Cassiani, G., Roccuzzo, G., Boaga, J., Stagno, F., (2016). Partial root-zone drying irrigation in orange orchards: effects on water use and crop production characteristics. *Eur. J. Agron. 82*, 190–202. https://doi.org/10.1016/j.eja.2016.11.001
65. Zapata-Sierra, A.J., Manzano-Agugliaro, F., (2017). Controlled deficit irrigation for orange trees in Mediterranean countries. *J. Clean. Prod. 162*, 130–140. https://doi.org/10. 1016/j.jclepro.2017.05.208
66. Lado, J., Rodrigo, M.J., Zacarías, L., (2014). Maturity indicators and citrus fruit quality. *Stewart Postharvest Rev.*
67. Shao, G.C., Deng, S., Liu, N., Wang, M.H., She, L.D., (2015). Fruit quality and yield of tomato as influenced by rain shelters and deficit irrigation. *J Agric Sci Technol 17*, 691–704.
68. Albrigo L.G., (1975). *Water Relations and Citrus Fruit Quality. Proceedings of the Second International Citrus Short Course: Water Relations*. University of Florida, Gainesville, FL. October 13–17, 1975.
69. Kusakabe, A., Contreras-Barragan, B., Simpson, C., Enciso, J., Nelson, S. & Melgar, J., (2016). Application of partial rootzone drying to improve irrigation water use efficiency in grapefruit trees. *Agricultural Water Management 178*, 66–75.
70. Morianou, G., Ziogas, V., Kourgialas, N.N., Karatzas, G.P., (2021). Effect of irrigation practices upon yield and fruit quality of four grapefruit (*Citrus paradisi* Mac.) cultivars. *Water supply, 21*(6). https://doi.org/10.2166/ws.113
71. Yang, L., Qu, H., Zhang, Y., Li, F., (2012). Effects of partial root-zone irrigation on physiology, fruit yield and quality and water use efficiency of tomato under different calcium levels. *Agric Water Management, 104*, 89–94. https ://doi.org/10.1016/j.agwat.2011.12.001
72. UNECE., (2018). UNECE Standard FFV-14 concerning the marketing and commercial quality control of Citrus Fruit. United Nations Economic Comission for Europe, New York and Geneva.
73. Gasque, M., Martib, P., Graneroc, B., Gonzalez-Altozanod, P., (2016). Effects of long-term summer deficit irrigation on 'Navelina' citrus trees. *Agricultural Water Management 169*(8), 140–147 https://doi.org/10.1016/j.agwat.2016.02.028
74. Aydinşakir, K., Uluca, E., Dinç, N., Küçükcoşkun, S., (2021). Effects of different irrigation levels on fruit yield and quality of valencia late orange under northern Cyprus conditions. *Journal of Agricultural Sciences (Tarim Bilimleri Dergisi), 27*(3), 276–284.
75. Gasque, M., Granero, B., Turégano Pastor, J.V., González-Altozano, P., (2010). Regulated deficit irrigation effects on yield, fruit quality and vegetative growth of 'Navelina' citrus trees. *Spanish Journal of Agricultural Research 2*, 40–51.
76. Navarro, J.M., Pérez-Pérez, J.G., Romero, P., Botía, P., (2010). Analysis of the changes in quality in mandarin fruit, produced by deficit irrigation treatments. *Food Chemistry, 119*, 1591–1596.
77. Adu, M.O., et al., (2019). Does water-saving irrigation improve the quality of fruits and vegetables? Evidence from meta-analysis. *Irrigation Science, 37*, 669–690.

78. Barry, G.H., W.S. Castle, F.S., Davies., (2004). Rootstocks and plant water relations affect sugar accumulation of citrus fruit via osmotic adjustment. *J. Amer. Soc. Hort. Sci., 129*(6), 881–889.
79. Panigrahi, P., et al. (2014). Deficit irrigation scheduling and yield prediction of 'Kinnow'mandarin (Citrus reticulate Blanco) in a semiarid region. *Agricultural Water Management, 140*, 48–60.
80. Ndunagu, J.N., Ukhurebor, K.E., Akaaza, M., Onyancha, R.B., (2022). Development of a wireless sensor network and IoT-basedsmart irrigation system, *Applied and Environmental Soil Science*. 7678570, 13.
81. Kumar S,V., Singh, C.D., K.V. Rao, R., Kumar, M., Rajwade, Y.A., (2022). Development of a smart IoT-based drip irrigation system for precision farming. *Irrigation and Drainage. 72*(1), 21–37. https://doi.org/10.1002/ird.2757
82. Lakshmiprabha K.E., Govindaraju, C., (2019). Hydroponic-based smart irrigation system using Internet of Things, *Int. J. Commun. Syst*., e4071.
83. Hu, Z., Bashir, R.N., Rehman, A.U., Iqbal, S.I., Shahid, M.M.A., Xu, T., (2022). *Machine learning based prediction of reference evapotranspiration (ET 0) using IoT*, IEEE Access, 10, 70526–70540.
84. Spelman, D., Kinzli, K.D., Kunberger, T., (2013). Calibration of the 10HS Soil Moisture Sensor for Southwest Florida Agricultural Soils. *Journal of irrigation and drainage engineering. 139*, 965–971.
85. Zawilski, B.M., Granouillac, F., Claverie, N., Lemaire, B., Brut, A., and Tallec, T., (2023). Calculation of soil water content using dielectric-permittivity-based sensors – benefits of soil-specific calibration, Geosci. *Instrum. Method. Data Syst., 12*, 45–56, https://doi.org/10.5194/gi-12-45-2023, 2023
86. Kizito, F., et al. (2008). Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor. *J. Hydrol., 352*(3–4), 367–378.