Precision Irrigation with Cost-effective and Autonomic IoT Devices using Artificial Intelligence at the Edge

D5.2
Report on the deployment of the OSIRRIS system

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The deployment of the OSIRRIS system for optimizing water use efficiency of winter wheat under deficit irrigation (Site I. CHERFECH).

Abstract

In the context of water restriction, the adoption of innovative technology and water saving strategies is a key to sustainable agriculture production, Thus, we sought to emphasize the contribution of precision irrigation based on Internet of Things (IoT) technology and smart sensors for optimizing irrigation water use. The effects of different drip irrigation regimes on total dry matter (TDM), grain yield (GY) and water use efficiency (WUE) of winter wheat grown on clay-loam soil under semi-arid conditions of Tunisia have been assessed for three consecutive growing seasons. The trial included fully irrigated crop FI 100% of crop evapotranspiration (ETc), two deficit irrigation treatments (DI1, DI2 corresponding to 75 and 60% of ETc, respectively) and rainfed treatment DI3, replicated three each. The results showed that TDM and GY increase with increasing irrigation amount. At harvest, the highest TDM and GY values were recorded under FI and DI1.

1- Introduction

Water resources along the southern Mediterranean area are limited and climate change is expected to worsen this scarcity, posing challenges for crop growth and productivity in the region (Brouziyne et al ,2018; Vodez, V et al., 2023). Durum wheat is considered as the major crops grown in the Mediterranean basin in terms of social importance and extent of cultivated area (FAO,2019). However, durum wheat production is mainly conditioned by water availability (Araus et al.,2003; Loss et al.,1994; Sabella et al., 2020; Xynias et al.,2020; Zampieri et al., 2020). Tunisia is a food-deficit country with a 121% increase in wheat imports between 1984 and 2016 (Khaldi et al 2017) with immense inter-annual fluctuations due to rainfall variation (WFP, 2011). As noted by (Nyakudya, I.W., Stroosnijder, 2014) when rainfall is lower and unevenly distributed, such as in Tunisia, irrigation is an increasingly important measure to sustain agricultural production in the region. It is important to highlight that the expansion of irrigated areas associated to water consumption without technical criteria by farmers, irrigation water is becoming increasingly lacking. Hence, urgent search for best agronomic practice for cultivation in terms of maximizing yield and saving water, as well as strategies of optimal use of water in irrigated agriculture is highly required (Alhaj Hamoud et al.,2019). The most effective way to improve water use efficiency is the precise control of irrigation based on soil or plant water status indicators (Rallo et al., 2017). Indeed, precision irrigation could reduce water consumption by 8–20% (Rallo et al 1991). (Rallo et al.,2023; Markovic, M., et al., 2024) noticed that effective monitoring of soil moisture content in the active rooting zone of the crop using soil moisture sensors (SMSs) is pivotal to ensure optimal irrigation scheduling. Therefore, a wide range of sensors were developed for measuring either volumetric soil moisture or soil water tension (SWT) (Zhang, K et al., 2019; Zhao et al., 2018; da Silva et al., 2018). When efficiently used, soil moisture sensors can reduce water use and energy costs while maintaining yields in irrigated fields (Allen et al., 1998). With the new technological development, Internet of Things (IoT) solutions that take the form of sensors connected to the internet allowed collecting several in field-measurements. It has led to establish a low-cost technology method that leads to enhance the control and real-time soil moisture monitoring (Sudesan et al.,2024; Obaideen et al., 2022). However, before any use, soil-specific calibration of the smart soil sensors is necessary to improve their performances (Pahuja, R ,2022). In this context, (Kumar et al., 2023) developed and assessed an IoT based irrigation system for sweet corn yield and other morphometric characteristics. They revealed that the IoT-SM43.5% irrigation increased water productivity over ETc-based and deficit irrigation (IoT-SM34.8%) treatments. Additionally, (Singh et al ., 2022 ; Kumar et al .,2024) found that Internet of Things (IoT)-based precision irrigation system has successfully enhanced irrigation water productivity. Therefore, the adoption of innovative solutions and technologies for irrigation water saving is primordial for the new agricultural strategy. In line with, the objectives of this study were (i) to investigate the response of winter wheat to different water regimes in a semi-arid region where government-controlled irrigation limits are used as a climate change mitigation strategy, (ii) to emphasize the importance of using smart sensors and IoT technology in enhancing irrigation water use efficiency and (iii) to determine thresholds for deficit irrigation, for winter wheat crop, that allowed enhancing WUE without affecting yield.

2. Materials, Methods and Plant Material

2.1. Description of the study site

Field experiments were carried out at the experimental station of the National Research Institute for Rural Engineering, Water and Forestry (INRGREF) of Cherfech, (Lat. 37.1◦N; Long. 10.5◦E, Alt. 328 m a.s.l) for three consecutive cropping seasons (2023-2024). The area is characterized by a Mediterranean semi-arid climate. The average annual evapotranspiration (ET0) is 1100 mm. The average annual precipitation is 450 mm, mainly concentrated in autumn and winter. The plant material was local winter durum wheat (Triticum turgidum) "Razek" cultivar. The crop was sown on December 05th 2023; the sowing technique used was a mechanical seed drilling, with a seeding rate of 150 kg ha−1. For each cropping season, 150 kg ha-1 Di-Ammonium Phosphate (DAP) was applied before seeding. The seasonal Ammonium-nitrate application was 150 kg ha-1, applied with a rate of 30%, 40% and 30% at 3 leaves, tillering and booting stages, respectively. Weeds and pests were managed following the usual criteria in the area. Soil samples were collected from three profiles (P1, P2, and P3) at 10 cm intervals to a depth of 60 cm. Soil chemical analysis for NPK (g kg^{-1} dry matter) and organic matter (OM %) was conducted for the 0 to 60 cm soil depth, yielding average values of 2% for nitrogen, 0.21% (as P2O5) for phosphorus, 0.5% (as K2O) for potassium, and 2.68% for organic matter. The soil texture is classified as clay loam and the moisture at field capacity and wilting point was measured using Richard's apparatus. The water content at field capacity (θfc) ranged from 42.9% to 45.9%, while the water content at wilting point (θwp) varied from 26.1% to 28.2%. The total plant available water (TAW) was 172 mm m^{-1}. The average bulk density ranged from 1.60 to 1.67 g cm^{-3} from the surface to a depth of 60 cm. Some key physical properties of the soil at the 0–60 cm depth are summarized in Table 1.

Table 1: Soil physical properties of the experimental site

Depth (cm)	Θ_{fc} (%)	Θ_{wp} (%)	TAW (mm)
0-10	43.2	26.1	17.1
10-20	42.9	26.2	16.7
20-30	43.1	28.2	16.9
30-40	43.7	27.5	16.2
40-50	45.6	27.8	17.8
50-60	45.9	27.7	18.2

Note : Θ_{fc} = water content at field capacity, Θ_{wp}= water content at wilting point, TAW= Total available water .

2.2. **Experimental design and treatments**

The experiment was set up as a randomized block design with four irrigation treatments, replicated three times each. Overall, 12 plots were considered, and each plot area was 60 m^2 (12 m length ×4 m width). Two meters interval band was maintained between the water regimes treatments. The irrigation water was applied by a drip system with 95% efficiency. Drip laterals were laid on the surface with a row spacing of 0.5m. The drippers were inline type, spaced 0.33m emitted 4 l h^{-1} with an operational pressure of 1 bar. The irrigation water is characterized with an electrical conductivity ECw = 3.12 dS m^{-1}. The irrigation regimes were Full irrigation (FI): irrigated at 100% of the Evapotranspiration ($ET_{c.}$), two sustained deficit irrigation (SDI) treatments D1 = SDI-75% and D2 = SDI-60%: irrigated at 75 and 60% of ETc, respectively, and D3 = rainfed treatment (RF). The ET_c, defined as crop water requirement, was calculated according to the FAO-56 single crop coefficient approach with K_c values during initial, mid-season, and end-season stages were 0.7, 1.15, and 0.3, respectively (Allen et al., 1998). The reference evapotranspiration (ET_0) was computed on a daily step using the Penman-Monteith model.

$$ET_c = K_c \times ET_0 \quad (1)$$

The irrigation amount is estimated with soil water balance equation as follows (Hillel, 1998):

$$I = ETc + U + R + D - P \pm \Delta S \quad (2)$$

For deficit irrigation treatments, cumulative ETc. (crop evapotranspiration) is reduced to water consumption (real crop evapotranspiration, ET_r) using a deficit irrigation coefficient "d" equal to 0.75 and 0.6 for D1 = SDI-75% and D2 = SDI-60% treatment, respectively. P is the effective precipitation (mm), I is the irrigation (mm), U is the upward capillary flow into the root zone (mm), R is the runoff (mm), D was the downward drainage out the root zone (mm) and ΔS is the change of soil water stored in soil layer of 0–60 cm (mm). The upward and downward flow was estimated using Darcy's law (Kar et al.,2007; De Medeiros et al., 2005). Results indicated that the two items (U and D) were insignificant at the experimental site. Runoff (R) was also insignificant during the three growing seasons. Soil water content was measured by smart tensiometer every fifteen minutes and each seven days with gravimetrically method. Soil water content data were collected for every 20 cm interval in soil depth. Some measurements were added before and after irrigation and heavy rain events.

2.3. **Measurement of soil water status**

During the growing season (2021-2022), soil water content was measured regularly every 7 days intervals using the gravimetric method, in fact, this method is widely adopted and recommended by the scientific communities. It doesn't require costly equipment and well-trained personnel. Thus, it is the standard reference method against which other techniques are normally calibrated. For each plot, soil samples were taken at three depths (20, 40 and 60 cm) from the soil surface, oven dried at 105°C for 24 h, then the soil water content was determined for the root zone. For the two following crop seasons (2022-2023) and (2023-2024), soil water matric potential in the root zone was monitored in real-time with four smart tensiometers "WaziSense". The smart tensiometers were installed in two fully irrigated plots at 20 and 40 cm depths and 15 cm away from the emitter. In addition to tensiometric records, gravimetric soil water contents were measured with soil profile from 0 to 60 cm taken in 20 cm, using the oven drying method. Data collected during the 2022-2023 crop season (soil matric potential and soil water contents) were used to create the soil water retention curve (SWRC).

2.4. **Smart tensiometers**

The smart tensiometer used in this study is the WaziSense model, developed within the framework of the Osirris TUNGER 2+2 project (bilateral collaboration between Germany (Waziup and INNOTEC 21) and Tunisia (INRGREF and INRAT). This model stands out in the field of embedded systems and IoT solutions due to its unique combination of state-of-the-art features. It integrates LoRa wireless communication technology, an MPPT solar charge controller and ATmega328P microcontroller programmed in C/C++ language (Figure 1). The WaziSense comprises a watermark sensor and temperature probe which are connected to an Arduino Pro-Mini microcontroller with a 3.3 V voltage and a frequency of 8 MHz. Sensor readings (soil matric potential and soil temperature) are recorded automatically at 15 minutes intervals by the WaziSense. The LoRaWAN communication module allows sending data wirelessly to the Gateway "WaziGate" for storage. Once the cloud connection is initialized, the WaziGate synchronizes all the data to the server "WaziCloud" where they can be securely stored, analyzed and managed. The WaziCloud platform allows users to view, manage, retrieve and share the collected data in real time. The whole device uses 4×AA rechargeable Li-ion 18650 cell batteries (4.2V and 2200 mAh), powered by a small solar panel delivering 6V at 166 mA.

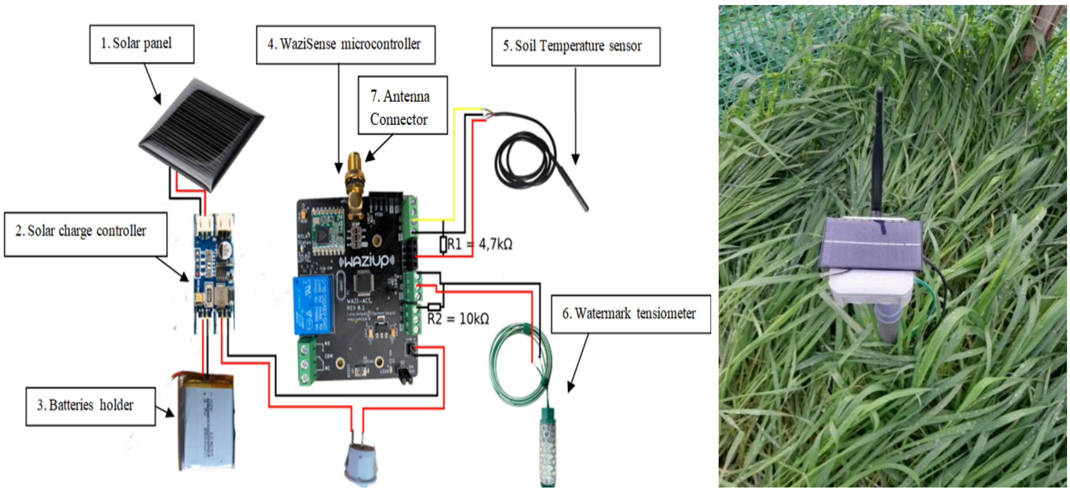


Figure 1. Smart tensiometer components.

Figure 2 shows the relationship between soil water content (%) and soil water potential (cbar) measured using smart tensiometer installed in the experimental field during the cropping season (2022-2023). A strong relationship between soil water content (%) and soil water potential (cbar) measurements was obtained with a coefficient of determination R^2 equal to 0.94.

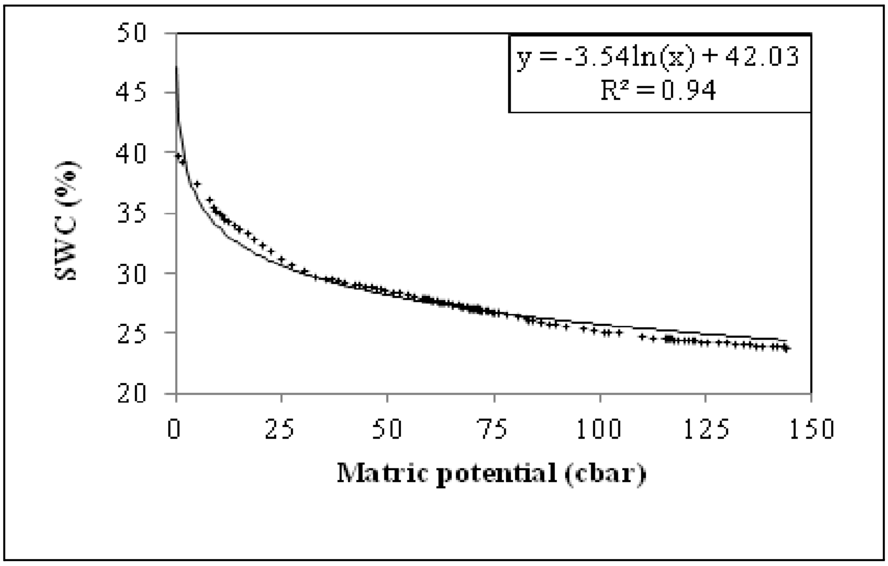


Figure 2. Soil matric potential values versus soil water content

2.5. **Plant sampling and measurement**

2.5.1. Total Dry Matter Production (TDM) and Grain yield (GY)

During the three growing seasons, a destructive sampling process was carried out to collect a representative plant sample. For each sub-plot, a 1 m^2 area of wheat was randomly selected as plant samples. Plant samples were separated into stems, leaves and spikes and their fresh weights were measured using a digitalized scale. Then, each plant part was put into kraft paper bags and oven-dried at 70°C for 48 h until a constant weight was achieved. The total dry matter was calculated as the sum of dry weights of each part. At harvest, wheat kernels were separated from spikes, weighted and converted into grain yield per hectare.

2.5.2. **Water Use Efficiency (WUE)**

The water use efficiency of total dry matter (WUETDM, kg m^{-3}) and grain yield (WUEGY, kg m^{-3}) were calculated as follows:

$$WUE_{TDM}\left(kg\ m^{-3}\right) = \frac{TDM}{ET_r} \qquad (3)$$

$$WUE_{GY}\left(kg\ m^{-3}\right) = \frac{GY}{ET_r} \qquad (4)$$

2.5.3. **Statistical analysis**

The effects of different degrees of deficit irrigation on TDM, GY and WUE, were assessed using one-way analysis of variance (ANOVA) after performing Shapiro-Wilk's Test for normality using IBM SPSS 20.0 Statistical package. Multiple comparisons between different irrigation treatments were performed using Tukey test at the significance level of $P \leq 0.05$.

3. Results and Discussion

3.1. **Agro-meteorological characterization of the study periods**

Figures 3(a-c) illustrates the dynamic of daily average air Temperature, (T_{avg}), reference evapotranspiration (ET_0) and precipitation (P) during the three consecutive winter wheat seasons. As shown in the figures, T_{avg} increased from 17 to 35°C; 15 to 23°C and from 13 to 26°C during the first, second and third crop season, respectively. In addition, daily ET_0 and T_{avg} followed approximately the same trend for the entire growing seasons showing the highest correlation between both climatic parameters. Cumulative precipitation over the winter wheat seasons was similar with totals equal to 187, 215 and 183 mm, mainly occurred during winter season.

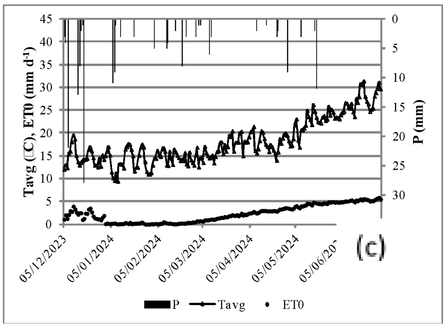
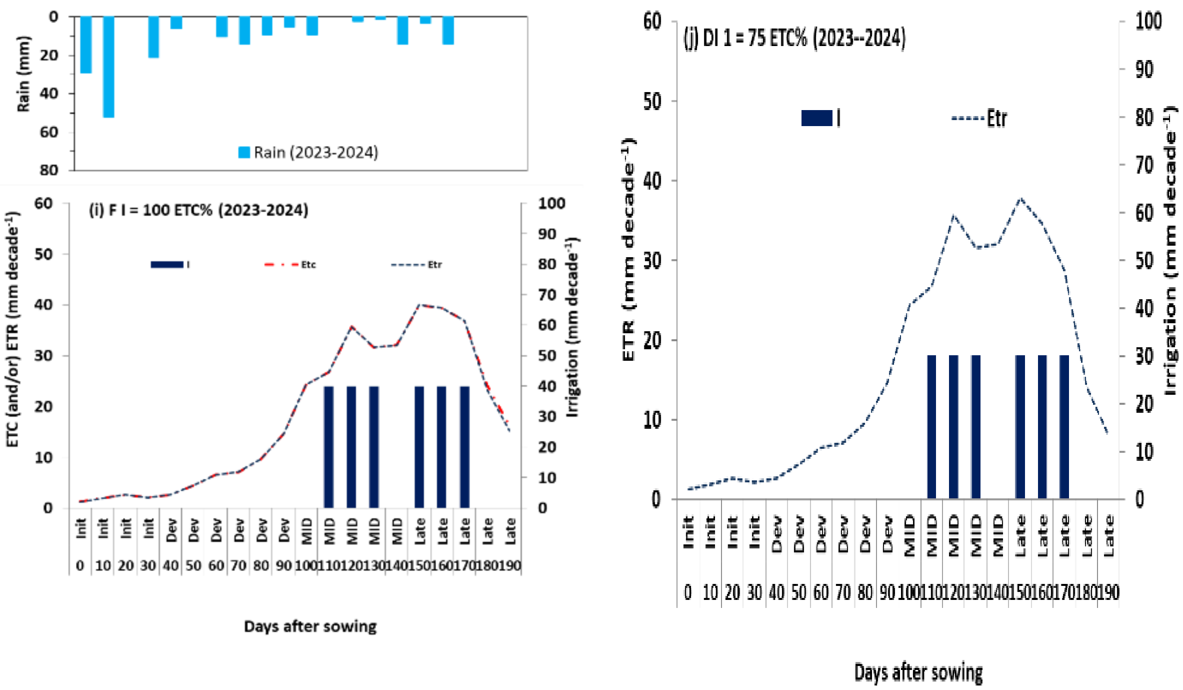


Figure 3. Daily patterns of average air temperature (T_{avg}), reference evapotranspiration (ET_0) and precipitation (P) during growth seasons (2023-2024)

3.2. **Evapotranspiration estimations and soil water balance**

Decadal patterns of crop evapotranspiration (ET_c) and water consumption (ET_r) as well as cumulative irrigation and precipitation of winter wheat crop cycle years is given in Figure 4.



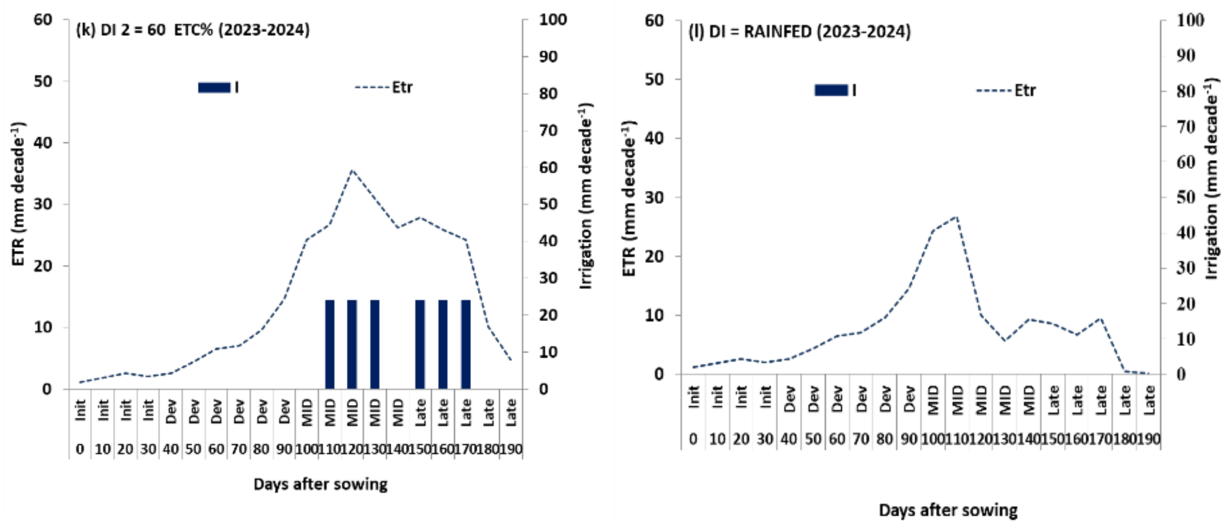


Figure 4. Decadal amounts of rainfall(R), irrigation (I), crop evapotranspiration (ET_c) and real evapotranspiration (ET_r) of winter wheat under different irrigation treatments for growing season (2023-2024).

For all treatments, winter wheat crop did not exhibit any water stress during initial and development stages. In fact, for the three crop seasons, precipitation amounts and frequency which occurred during these two periods were sufficient to meet the wheat water requirements. During the initial stage, decadal ET_c values were low and did not exceed 5 mm decade^{-1}. These low values might be attributed to the low atmospheric demand (ET_0) during the winter season. As the wheat crop grew and ET_0 increased, ET_c increased progressively to reach its maximum of about 40-mm decade^{-1} at mid-season. The increase of ET_c values is mainly due to the combined effect of high atmospheric demand in spring season and soil evaporation resulting from frequent irrigation and rainfall events (Nagaz et al.,2016). However, Waller and Yitayew (2016) reported that the majority of ET_c is due to evaporation from the soil surface while more than 90% of ET_c is due to crop transpiration when the crop fully covers the soil. At the late season, corresponding to the canopy senescence stage, decadal ET_c values tend to decrease progressively. For the whole growing seasons, cumulative ET_c was equal to 357.4 mm,.

For DI-75% and DI-60%, reductions in term of wheat evapotranspiration were observed starting from, approximately, the fifth and fourth decades of the mid-season stage (post-anthesis phase), respectively. This reduction was equal to 8.75% of ETc under DI-75% treatment, while, a reduction of about 19% was recorded under DI-60% treatment. For rainfed treatment, water stress was more severe and it was anticipated compared to the other treatments (around the first decade of mid-season stage) leading, therefore, to an important evapotranspiration reduction quantified as 57% of ET_c.

Root zone water depletion, estimated by the SWB model using the spreadsheet program, for the four irrigation treatments of winter wheat, the total available water (TAW) as well as the readily available water (RAW) are presented in figure 5. During the crop season, both TAW and RAW curves present tendency to increase as consequence of increasing root depth which reached a maximum value of 0.50 m. During the period spanning from sowing to approximately 50 days after sowing (DAS), soil water content was maintained at field capacity. This is due to many factors including a high frequency of rainy days, low atmospheric demand associated with small plants with limited root zone leading to negligible water depletion. Following that period, crop water requirements increased, resulting in important soil water depletion from root zone. Thus, water depletion from root zone can be assumed as the net water requirement.

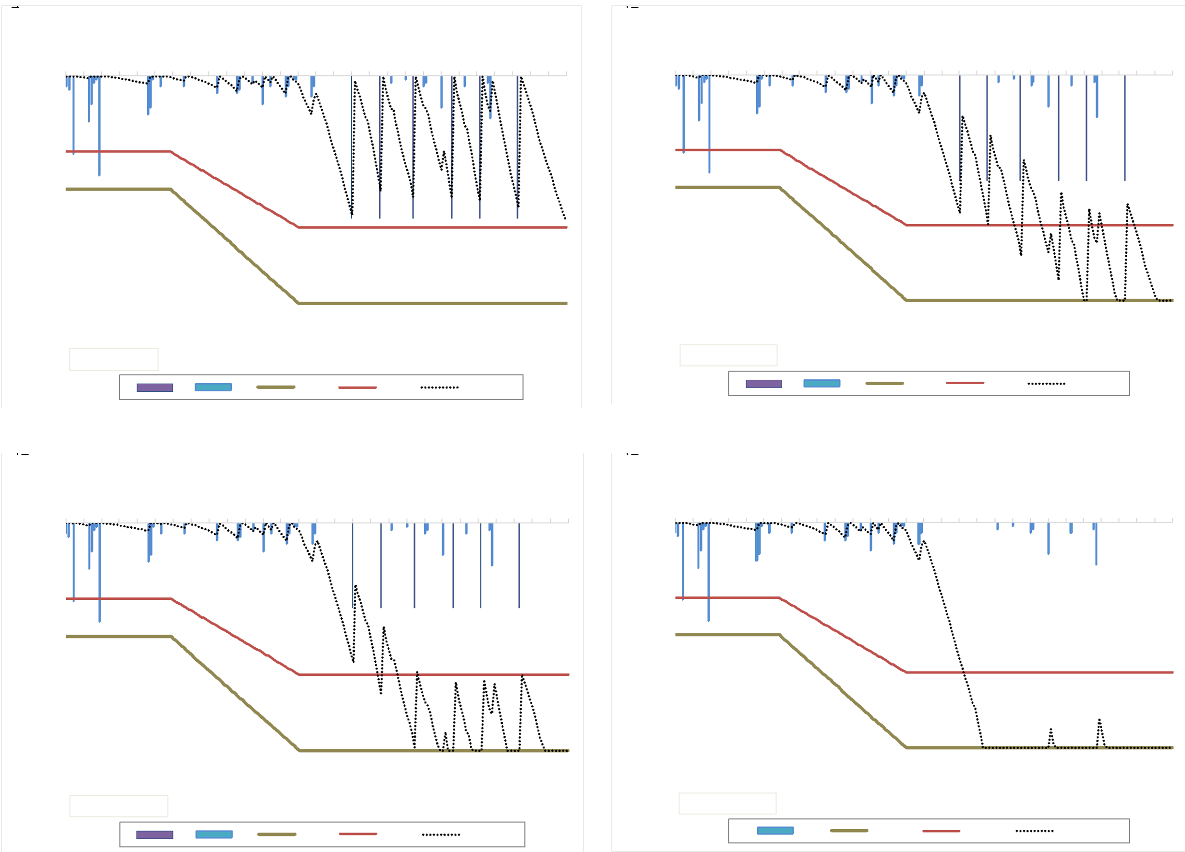


Figure 5. Daily dynamics of water depletion in the root zone (0–50 cm) under different irrigation treatments during 2023-2024 wheat cropping seasons (DAS: Days After Sowing, TAW: Total Available Water, RAW: Readily Available Water).

Under full irrigation treatment, root zone water depletion was always kept between field capacity and RAW threshold for the three growing seasons. In particular, for the entire 2023-2024 wheat growing season, root zone was replenished to field capacity following each irrigation or precipitation event. For DI1, DI2 and rainfed treatments, precipitation and irrigation amounts and frequency were insufficient to maintain water depletion between the threshold value and field capacity. In fact, starting from 136, 125 and 105 DAS, (corresponding to anthesis phase) until the end of the first and second crop season, water depletion exceeded RAW thresholds indicating that plants were subjected to sustained severe water stress conditions.

The irrigation application should vary with seasonal rainfall pattern and the soil moisture condition before sowing, thus, the depletion at the root zone was considerable in the ET components. The most important reason for durum wheat responses differently to irrigation water stress at its different growing stages. Zhang (2003) reported that the most sensitive stage of winter wheat to drought was from stem elongation to booting, followed by anthesis.

3.3. **Total Dry Matter (TDM) response to water amounts**

Temporal pattern of total dry matter of winter wheat (TDM) under various irrigation rates (FI, DI1, DI2, and DI3) for three cropping seasons is shown in figure 6. As depicted from the graph, total dry matter increases progressively from around 60g m^{-2} at 35DAS to reach a maximum value of 1482.94 g m^{-2} at harvest, under full irrigation for the cropping season 2023-2024. Relatively similar trend of TDM evolution has been recorded under DI1, DI2 and DI3. Among the crop season, the lowest TDM values were attributed to the rainfed treatment (DI3). However, from the beginning of post-anthesis phase, the impact of irrigation regime on TDM was clearly evidenced. At harvest, TDM achieved with DI2 and DI3 were significantly reduced by (19.7%; 14%) and (38%, 34.1%) in 2023-2024 when compared with FI and DI1, respectively. In this context, Akbari (2012) showed that biomass and yield components of wheat crop decline under water stress conditions. Furthermore, Feng et al. (2023) evidenced that water stress at the grain filling stage would reduce transportation of assimilates to the grain, hence, reducing the final yield. In the same context, Zhuang et al. (2024) showed that yield decline resulting from water shortage is related to the reduction in term of spikes number and kernels per spike.

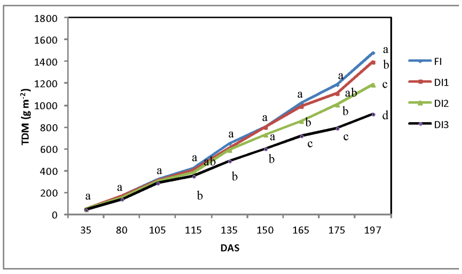


Figure 6. Temporal evolution of TDM (Total Dry Matter) under different irrigation regimes (DI1, DI2, and DI3) as a function of DAS (Days After Sowing); The different letters (a, b, c, and d) indicate statistically significant differences according to Tukey's Test ($p \leq 0.05$).

Response of TDM of winter wheat crop to cumulative water consumption (I+P) for the growing season (2023-2024) is presented in Figure 7. For irrigated treatments (FI, DI1 and DI2), linear relationship was observed between TDM and water consumption with slopes of regression lines forced through the origin, corresponding to WUE, varying from 3.67 to 4.29 for DI2 (2023-2024) and DI1 (2022-2023), respectively, and R^2 values close to 1. These results are in accordance with those reported by (Kang et al., 2002) who found a linear relationship between biomass and water consumption for winter wheat with a slope of regression line equal to 3.5 k gm^{-3} and an intercept of -992.24.

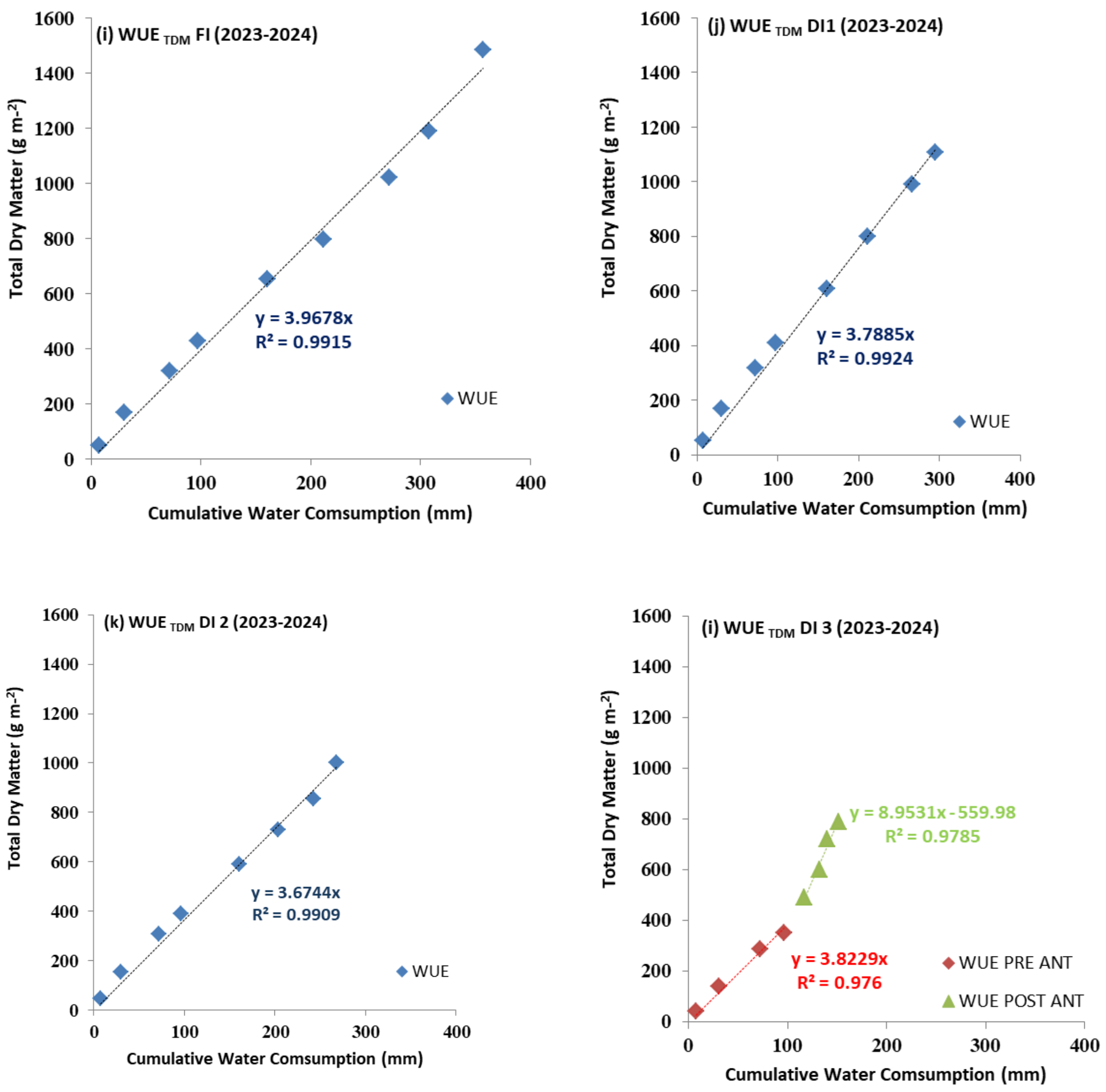


Figure 7. Winter wheat TDM (total dry matter) as a function of cumulative water consumption (ET_r).

Regarding rainfed treatment, TDM increases with increasing cumulative water consumption. Meanwhile, the increasing trend of TDM did not behave similarly for pre- and post-anthesis phases. Indeed, during pre-anthesis phase, slope of regression lines forced through the origin was equal to 3.82. This value was relatively similar to this achieved under irrigated treatments. This is justified by the fact that during pre-anthesis phase, irrigation events were limited and therefore, the consumed water was mainly provided from precipitation. However, during post-anthesis phase, slope of regression lines was equal 8.95 showing faster TDM increment rate. The achieved results suggest that water stress at post-anthesis phase did not affect biomass development. This result was consistent with the findings of Kang et al. (2002), who reported that higher WUE were gained under conditions of mild water deficit at seedling and stem-elongation stages and severe soil water stress in the maturity stage. In addition, AraMemon et al. (2021) revealed that tillering stage is the most critical and sensitive stage of wheat crop to water stress to achieve higher water use efficiency.

3.4. Grain yield, WUE_{TDM} and WUE_{GY}

Results of total precipitation and applied irrigation, water consumption ETr, Grain yield, WUE_{TDM} and WUE_{GY} at harvest for the winter wheat cropping cycle are summarized in Table 2. For the growing season, cumulative precipitation was equal to 189-mm. Irrigation volumes applied for FI treatments fall within the range of variability of wheat water requirements reported by Steduto et al. (2012). As presented in table 2, the irrigation regime significantly affects the wheat grain yield. Compared with the other irrigation treatments, FI allowed obtaining higher grain yield with values equal to 667.45 g m^{-2}. The lowest grain yield was recorded under rainfed treatment. This outcome aligns with different previous published studies including Othmani et al. (2020) and Zhuang et al. (2024). It is worth noting that, in our case, achieved grain yields were slightly lower than those recorded by Othmani et al. (2020). For winter wheat in Kef region (Tunisian semi-arid conditions) where rainy days were frequent throughout the crop cycle that reduce the negative effect of water stress, in particular, during critical growth stages. Several studies have evidenced that grain yield decline depends strongly on the timing and severity of water stress. For example, Zeng et al., (2023) showed that severe water deficiency before flowering reduce grain filling duration which result in significant yield decrease. In our study, across all adopted treatments, water stress was mainly occurred for the entire post-anthesis phase which would justify the yield reduction.

Results presented in table 2 highlight that, in overall, WUE_{TDM} and WUE_{GY} were significantly affected by water regimes. As expected, the highest WUE_{TDM} values were registered with rainfed treatment since it achieved higher TDM with lower water consumption. However, across irrigated treatments, no significant difference was observed between WUE_{TDM} values. Regarding WUE_{GY}, the highest values (1.95 kg m^{-3}) was recorded under mild water stress treatment (DI1). These values are comparable to the maximum achievable efficiency (2.2 kg m^{-3}) suggested by Steduto, P. et al. (2012) . It is important to highlight that the highest WUE_{GY} values were associated with important grain yield. Contrarily to WUE_{TDM}, the lowest values of WUE_{GY} were observed under rainfed treatment. This is probably due to the fact that under rainfed treatment the wheat crop experienced a severe water shortage during the grain filling period reducing, therefore, the final yield as the kernel number per spike declines. In our study, even though statistically different, acceptable WUE_{GY} were achieved in all treatments and seasons. Indeed, obtained values were in the same order of magnitude as those reported by Kharrou et al. (2011) who found that wheat WUE may vary from 0.40 to 1.83 kg/m^3. However, WUE_{GY} relative to DI2 and DI3 treatments were associated with low grain yield. These results suggest that these two irrigation strategies are not suitable for recommendation.

Table 2. Seasonal precipitation (P), Irrigation (I), Water consumption (ETr), Grain yield, WUE_{TDM} and WUE_{GY} for winter wheat under different irrigation regimes for the growing season (2023-2024)

Treatment	**P + I (mm)**	**ETr (mm)**	**Grain yield ($g\ m^{-2}$)**	**WUE_{TDM} ($kg\ m^{-3}$)**	**WUE_{GY} ($kg\ m^{-3}$)**
			2023-2024		
FI	189 + 240	357.4	655.1^a	4.15^b	1.83^a
DI1	189 + 180	326.1	635.8^b	4.29^b	1.95^a
DI2	189 + 144	289.5	455.7^c	4.11^b	1.57^b
DI3	189	153.9	208.6^d	6.00^a	1.36^c

The different letters (a, b, c and d) indicate statistically significant differences according to Tukey's Test ($p \leq 0.05$).

The deployment of the OSIRRIS system for optimizing water use efficiency of Apple under deficit irrigation (Site II. SBEITLA)

1. Experimental Site

The experimental apple orchard (Malus communis) is located in the Sbeitla region, in central Tunisia (35° 14′ North, 9° 08′ East, at an altitude of 525 m). The study area belongs to the semi-arid bioclimatic stage, characteristic of much of central-western Tunisia. The experimental plot is organized into blocks, each divided into six rows. The studied varieties, Galaxy and Rich-a-Red, are three years old and grafted onto the MM106 rootstock.

2. Calculation of Water Requirements

Soil water content monitoring tools:

- **Time-Domain Reflectometry (TDR) Probes:** These probes were installed on April 1, 2024. A total of 10 probes were installed for the Galaxy variety (8 probes for the PRD 50% and 75% treatments and 2 probes each for the control and 50% ETc treatments). Monitoring was conducted twice a week.
- **10HS Probes:** Installed at two depths (20 cm and 40 cm) within the root zone (30 cm from the tree trunk). Ten probes were placed for the Rich-a-Red variety (8 for PRD 50% and 75% treatments and 2 each for the control and 50% ETc treatments). After installation, the probes were connected to ZL6 data loggers to record soil moisture data. Data collection was carried out via the ZENTRA Utility application.
- **Smart Tensiometers (OSIRRIS):** Two smart tensiometers were also installed for the Rich-a-Red variety under the PRD 75% treatment.

In addition to tensiometers, gravimetric soil moisture content was measured at soil depths ranging from 0 to 1.20 m. Soil samples were oven-dried at 105–110 °C until constant weight to quantify the soil water content in the root zone. Irrigation doses were calculated based on the measured values.

Note: Soil moisture monitoring results and water balance calculations are in progress.

3. Application of Controlled Irrigation

Four different water regimes were applied to each variety from fruit set to fruit maturation.

Irrigation Treatments:

Three types of deficit irrigation and one control irrigation were applied to each variety (11 trees per treatment with three repetitions). Irrigation was conducted using a drip irrigation system with two lateral lines per row and four emitters per tree. Four irrigation treatments were considered in this study:

Control Irrigation (CI): 100% ETc

Continuous Deficit Irrigation (CD): 50% ETc

Partial Root Drying (PRD): 75% ETc

Partial Root Drying (PRD): 50% ETc

Irrigation doses were calculated to replace ETc (net of effective precipitation) using the following formula:

$$ETc = ET0 \times Kc$$

Where:

ET0: Reference evapotranspiration

Kc: Crop coefficient adapted for apples under localized irrigation:

Initial Kc (April-May): 0.5

Mid-season Kc (June): 0.65

Late-season Kc (July to harvest): 0.8

Post-harvest Kc: 0.5

4- Monitoring of Physiological and Pomological Parameters

- Phenological Stages Monitoring The work began with the monitoring of phenological stages for two apple tree varieties (*Galaxy* and *Rich a Red*).
- Physiological Parameters Monitoring Physiological parameters were monitored during the fruit development period and the post-harvest period.

Vegetative Growth

Lateral vegetative growth was evaluated by measuring the extension of shoots at different time intervals. At the beginning of vegetative growth, 12 one-year-old shoots were selected on all four sides and at the same height of each tree. Measurements were taken every 15 days during the growth season. Monitoring was conducted on three trees per treatment (n = 12).

Relative Water Content (RWC)

The relative water content was determined on mature leaves collected from the middle section of the shoot. RWC was monitored at regular time intervals, every 15 days. RWC was calculated as follows:

$$RWC = ((MF-MS) / (MFsat-MS)) * 100$$

Where:

- **MF**: Fresh weight at the time of sampling.
- **MS**: Dry weight.
- **MFsat**: Saturated fresh weight.

Leaves were weighed immediately after sampling (**MF**). **MFsat** represents the weight of leaves after rehydration in a humid atmosphere until saturation (Kramer, 1980), achieved in darkness at room temperature by immersing the basal part of the petiole in distilled water for 12 hours. The leaves were then dried at 80 °C for 48 hours to determine the **MS**.

Gas Exchange Variables

The photosynthetic assimilation rate (pn, µmol CO_2 m^{-2} s^{-1}), stomatal conductance (gs, mmol H_2O m^{-2} s^{-1}), transpiration rate (Tr, mmol H_2O m^{-2} s^{-1}), instantaneous water use efficiency (**WUEinst** = pn / Tr), and intercellular CO_2 molar fraction (**Ci**) were measured on mature leaves using a portable gas exchange analyzer (LCpro+ ADC Ltd. BioScientific, Hoddensdon, UK). These gas exchange parameters were recorded under daylight-saturating solar light. After starting the device, a 5-minute waiting period was allowed to ensure equilibrium between the chamber and the surrounding atmosphere.

Fruit Growth

Fruit growth was assessed by measuring four fruits per tree at different time intervals. At the onset of fruit development, four fruits of the same age were marked on all four sides of the tree. Measurements were taken every 15 days during the growth season until harvest.

Fruit Quality Analysis for Two Varieties under Different Water Treatments

Immediately after harvest, fruit diameter, weight, firmness, water content, total soluble solids (TSS), titratable acidity (TA), pH, and nitrate content (NO_3^-) were determined on 10 fruits per tree, considering three trees per repetition for each treatment and variety. The diameter (mm) of each fruit was measured using a caliper (Mitutoyo, UK), and fresh weight was determined using a precision balance (AXIS-AGN 100 C, Poland).

The epidermis color was measured with a Chroma Meter CR-400 colorimeter. The parameters **a***, **b***, and **L*** were determined as follows:

- **L***: Indicates brightness or luminance, ranging from 0 (black) to 100 (white).
- **a***: Ranges from -60 (green) to +60 (red).
- **b***: Ranges from -60 (blue) to +60 (yellow).

Statistical Analyses

Statistical analyses were conducted using SPSS software (version 17.0 for Windows, SPSS, Chicago, IL, USA). Analysis of variance (ANOVA) was used, and Duncan's test was employed to compare treatment means for each variety. A Student's t-test was applied to compare the two varieties under each water treatment. Values were represented as the mean ± standard deviation.

Results

- Effect of Different Water Regimes on the Physiology of Two Apple Varieties

Phenological Stages: The phenological stages were determined based on the reference stages defined by Bernard Bloesch and Olivier Viret. Our observations showed that the two varieties are characterized by staggered bud break and flowering periods. Apple tree bud break begins with the bud swelling and the appearance of a green tip. For the Galaxy variety, this stage began on March 15, and full bloom occurred on April 1. The Rich Red variety was later, with bud break starting in mid-April, and flowering lasting from May 7 to May 25.

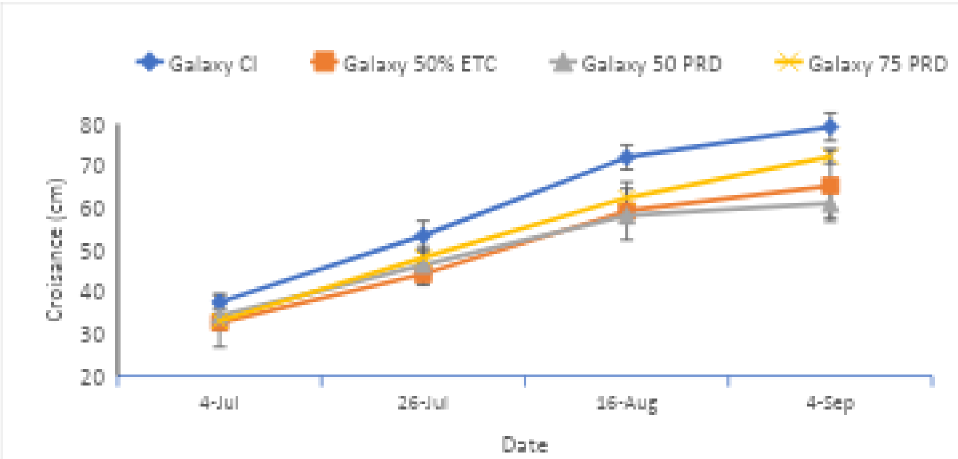
A B C

Photo 1: Phenological stages of the Galaxy variety (A): Bud swelling, (B): Beginning of flowering, (C): Full flowering.

Vegetative Growth

The analysis of shoot growth results for the two apple varieties subjected to four different water regimes, illustrated in Figure 1, showed a significant decrease in trees exposed to water deficit for the Galaxy variety. However, for the Rich Red variety, the water-deficit regime PRD75% did not affect vegetative growth. Water-deficit regimes, ETC 50% and PRD 50%, significantly reduced shoot growth in both studied varieties. Notably, the Galaxy variety was most affected by water deficit, particularly under the PRD 50 treatment, where growth did not exceed 61 cm.

(A)



(B)

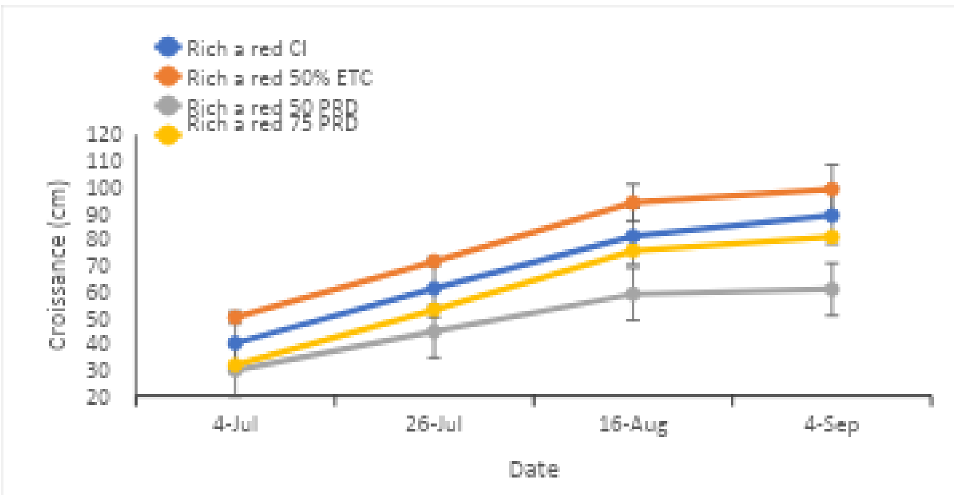
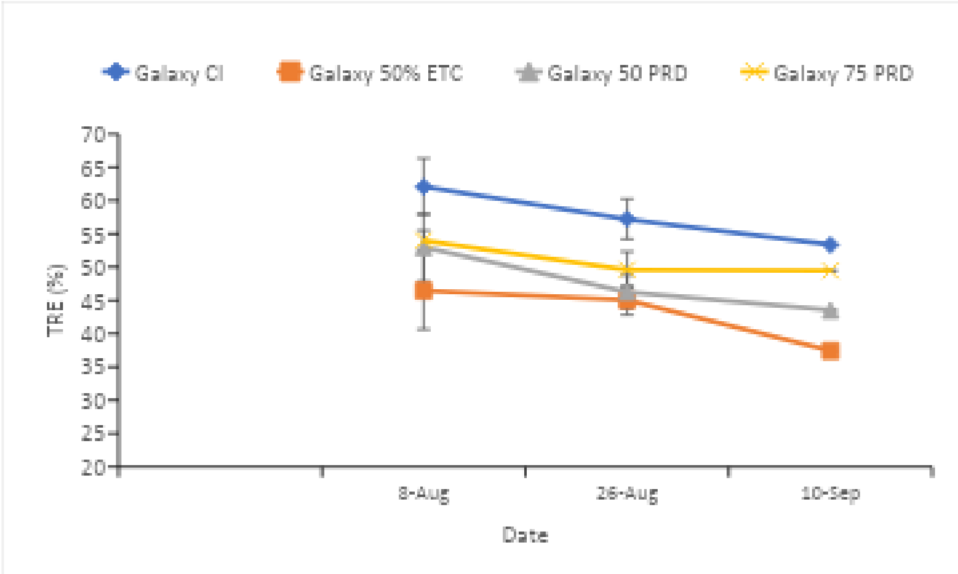


Figure 1: Influence of different water treatments on shoot growth in the two apple varieties, Galaxy (A) and Rich Red (B). Values represent the means of twelve samples (n = 12) ± standard deviation.

Relative Water Content

(A)



(B)

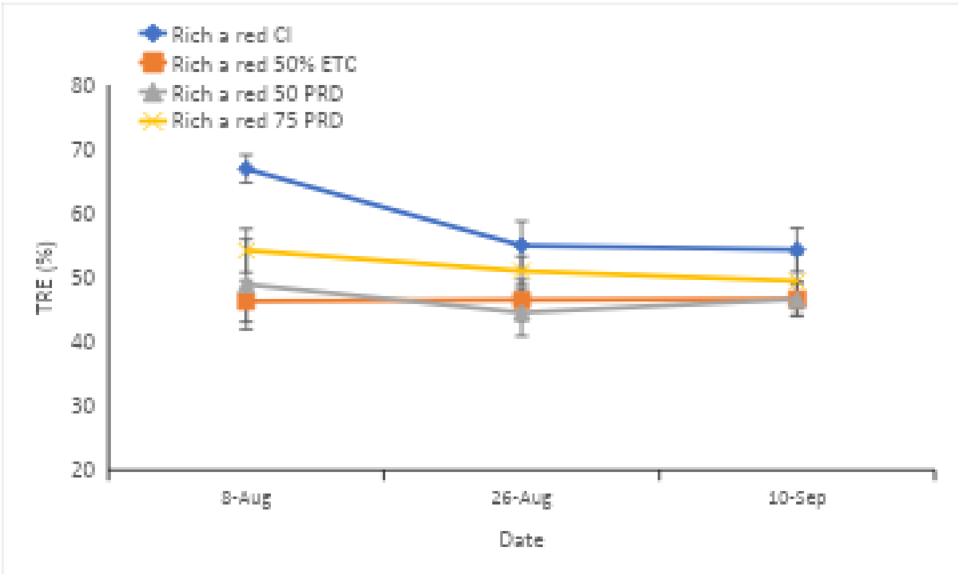


Figure 2: Variation in leaf relative water content (RWC) of two apple varieties (Galaxy (A) and Rich Red (B)) under different water treatments. Values represent the means of twelve samples (n = 12) ± standard deviation.

The relative water content (RWC) is used as an indirect criterion to assess leaf water status. The results showed a significant difference between the control water treatment (100% ETC) and the deficit treatments (PRD 75%, PRD 50%, and ETC 50%). For the control trees, leaf RWC gradually decreased during the fruit growth period, which can be explained by climatic conditions and increased evapotranspiration. Similarly, this reduction was minimal for trees exposed to the PRD 75% water deficit, where RWC did not decrease by more than 49% in both Galaxy and Rich Red varieties. Conversely, for the two deficit treatments, PRD 50% and

ETC 50%, the reduction was more significant, reaching 37.4% for the Galaxy variety under the ETC 50% treatment.

Effect of Water Deficit on Gas Exchange in the Galaxy and Rich Red Varieties

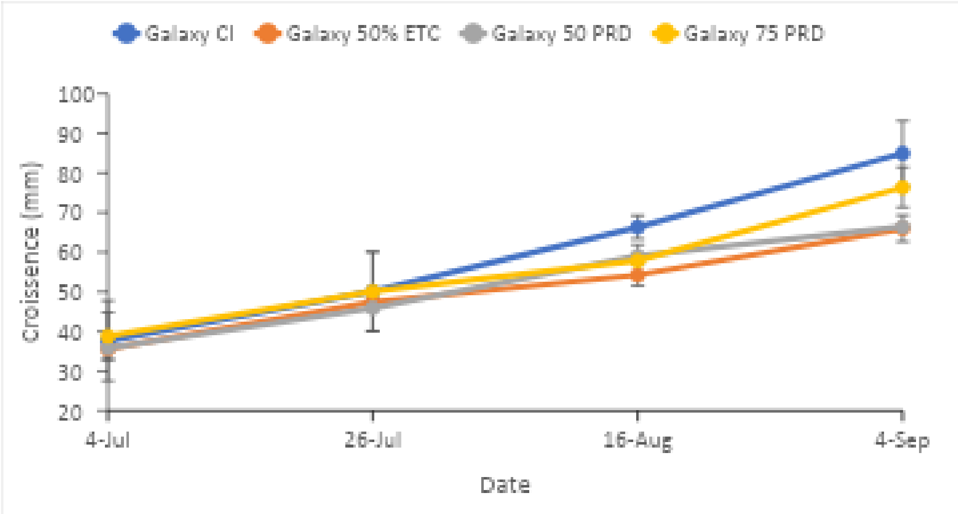
The evolution of Pn, as shown in Table 1, revealed that higher values were recorded during the fruit growth period for both Galaxy and Rich Red varieties. Similarly, no significant difference was recorded during this stage among the four water treatments. A marked decrease was observed during the fruit maturation stage, particularly for the Rich Red variety, where it reached 7.36 µmol m^{-2} s^{-1} under the 50% ETC treatment. For the Galaxy variety, the three water deficit treatments induced a significant reduction in Pn values. During the post-harvest period, a slight increase in Pn was noted for both varieties under all four irrigation regimes.

Our results also showed that for the Galaxy variety, the deficit irrigation treatments did not result in a significant difference in leaf transpiration (Tr) during the fruit growth and post-harvest stages (Table 1). However, during the fruit maturation stage, a significant reduction was recorded, especially under the PRD 75% treatment (2.40 mmol m^{-2} s^{-1}). Leaf transpiration in the Rich Red variety was affected by water deficit during the fruit growth stage, but no difference was observed during the maturation and post-harvest stages.

The results also showed that the irrigation strategies affected instantaneous water use efficiency (WUEinst), particularly during the fruit maturatn stage (Table 1). For both varieties, a significant increase in WUEinst values was recorded under the deficit irrigation regimes (PRD 50% and ETC 50%). The application of water stress affected the two apple varieties differently. The Galaxy variety was more efficient under water deficit condition

- Impact of Different Water Regimes on Fruit Quality
- Monitoring of Fruit Growth.

(A)



(B)

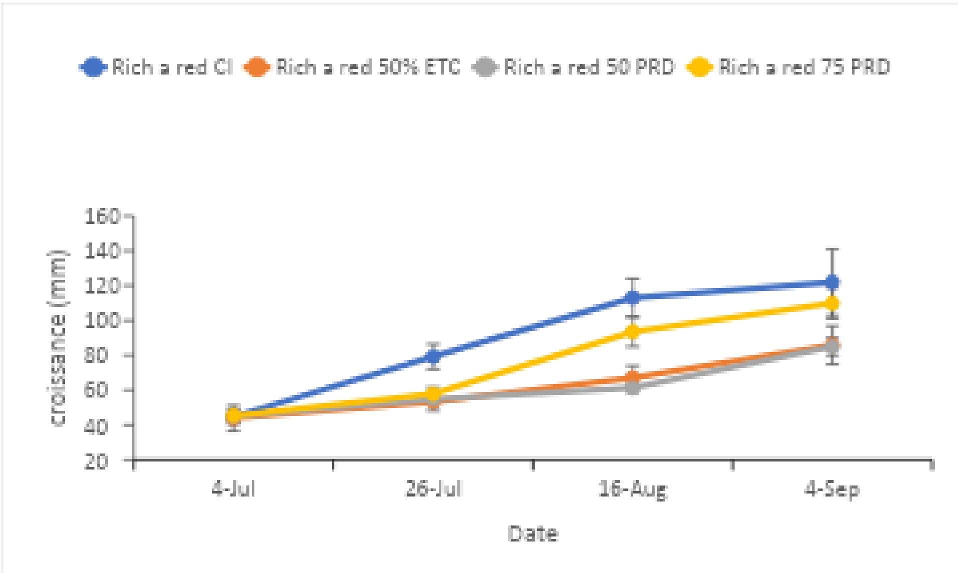


Figure 3: Influence of Different Water Regimes on Fruit Growth in the Two Apple Varieties Galaxy (A) and Rich Red (B).

Monitoring of fruit growth under the different water treatments revealed that deficit water regimes significantly reduced fruit growth in both the Galaxy and Rich Red varieties. In fact, fruit growth was most affected in fruits exposed to the 50% ETC and 50% PRD treatments. However, this reduction was much less significant under the PRD 75% treatment.

The fruit was harvest on 05/09 for both varieties. Biometric and pomological analyses were performed to study the impact of different water regimes on fruit quality.

(A)

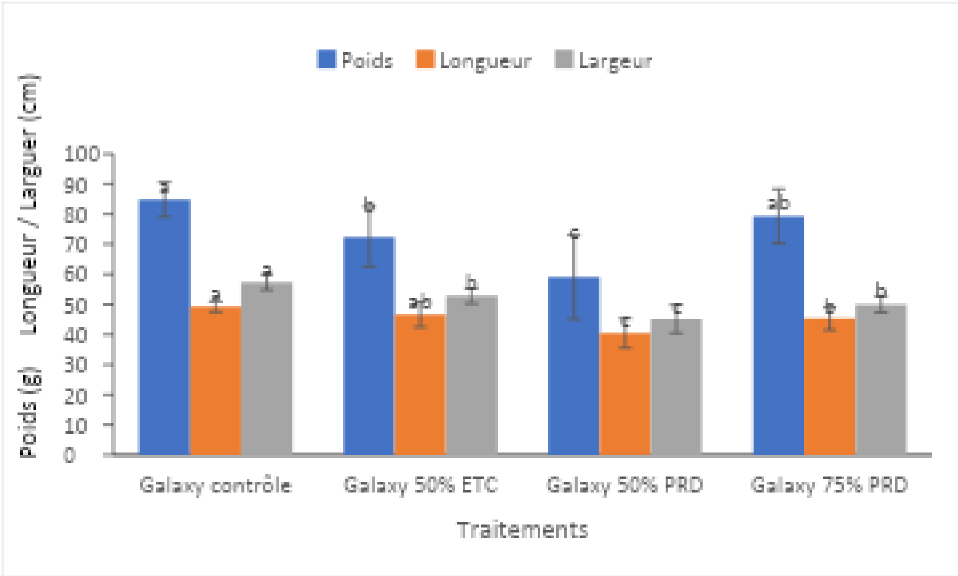
(B)

Photo 2: Fruits of the two apple varieties Galaxy (A) and Rich a red (B) subjected to four irrigation treatments.

Biometric analysis

The analysis of Figure 4 (A) and (B) showed a significant difference in size (length and width) and weight of fruits between the water treatments for the two varieties ($p < 0.05$). Indeed, the deficit treatments, mainly PRD 50% irrigation, resulted in a significant decrease in the weight, length and diameter of fruits. The fruits of trees subjected to PRD75% irrigation are significantly heavier and have a larger caliber than those of ETC 50% and PRD50% irrigation. Our results also showed that the fruits of the Rich a red variety are characterized by the highest weight (127g) compared to those of Galaxy (84g).

(A)



(B)

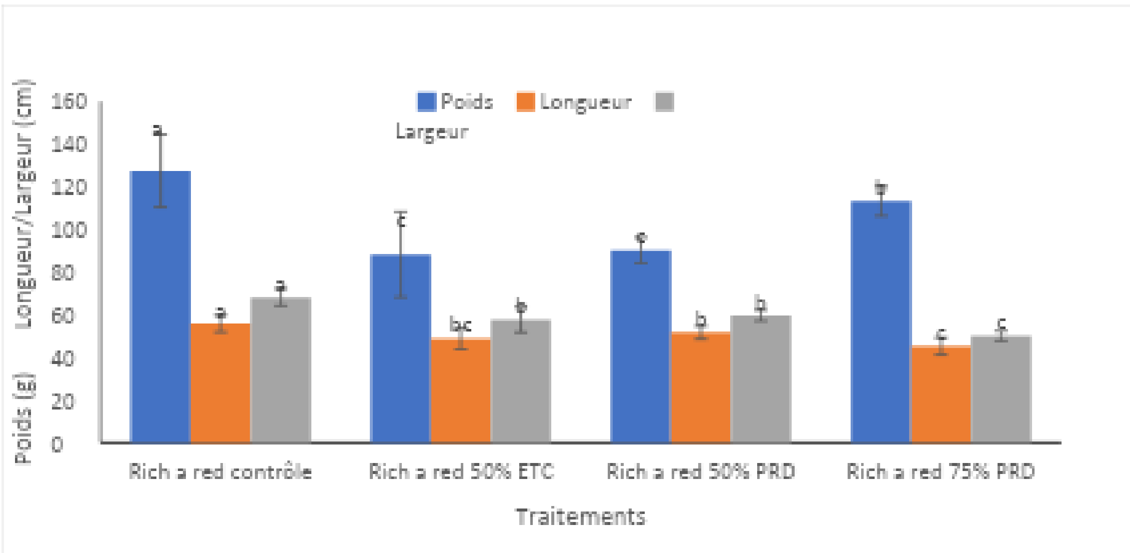


Figure 4. Biometric analysis of fruits of two apple varieties Galaxy (A) and Rich a red (B) subjected to different water regimes.

Pomological quality

Table 2: Physicochemical characteristics of the fruits of two apple varieties subjected to four irrigation treatments.

Variety	Treatment	Firmness	TSS (° Brix)	pH	acidity	NO3-
Galaxy	Control	6,57 ± 0,81^{b}	14,90 ± 0,10^{d}	3,45 ± 0,04^{d}	7,10 ± 0,10^{c}	150,33 ±0,57^{a}
	50% ETC	8,50 ± 0,26^{a}	16,37 ± 0,11^{c}	3,54 ± 0,01^{c}	9,60 ± 0,26^{a}	132,00 ± 2,00^{c}
	50% PRD	8,16 ± 0,73^{a}	17,40 ± 0,10^{b}	3,64 ± 0,02^{b}	9,90 ±0,10^{a}	141,66 ± 2,08^{b}
	75%PRD	7,33 ± 0,41^{ab}	19,50 ± 0,12^{a}	3,70 ± 0,03^{a}	8,53 ± 0,47^{b}	142,00 ± 2,00^{b}
Rich a red	Control	5,53 ± 0,25^{b}	16,46 ± 0,25^{b}	4,32 ± 0,01^{a}	7,38 ± 0,16^{a}	274,00 ± 4,00^{a}
	50% ETC	7,27 ± 0,24^{a}	17,17 ± 0,15^{a}	3,98 ± 0,03^{bc}	6,75 ± 0,05^{c}	179,33 ± 4,51^{c}
	50% PRD	7,70 ± 0,75^{a}	16,03 ± 0,25^{b}	3,92 ± 0,06^{c}	7,15 ± 0,05^{b}	182,33 ± 2,08^{c}
	75%PRD	5,87 ± 0,40^{b}	17,50 ± 0,30^{a}	4,04 ± 0,05^{b}	7,20 ± 0,10^{ab}	240,33 ± 2,52^{b}

Values are the means of six different fruit samples (n = 6) ± standard deviation. Letters (a, b, c, d) indicate significant differences ($p < 0.05$) between the four treatments for each variety separately.

The results of the variation in fruit quality based on water regimes showed that firmness varied significantly with the irrigation treatments. Indeed, in both Galaxy and Rich Red varieties, fruits exposed to the deficit irrigation treatments (PRD 50% and 50% ETC) were the firmest. Similarly, the PRD 75% treatment resulted in a slight increase in firmness in both varieties. Under the control irrigation treatment, fruits from the Galaxy variety showed the highest firmness values (Table 2). Significant differences were also observed for the total soluble solids (TSS) content, as indicated in Table 2. In the control trees, fruits from the Rich Red variety had the highest TSS values (16.42 °Brix). In both varieties, the application of deficit irrigation increased TSS values significantly. In fact, fruits from trees exposed to the PRD 75% deficit irrigation treatment had the highest TSS values (19.50 and 17.50 °Brix for Galaxy and Rich Red, respectively). Moreover, the results showed that acidity increased significantly for Galaxy fruits under PRD 50% and ETC 50%. However, this was not the case for Rich Red fruits. The NO3- content accumulated in the fruits decreased significantly with deficit irrigation (Table 2).

Table 3: Variation in the Coloration of the Fruit Epicarp in Two Apple Varieties under Four Irrigation Treatments.

Variety	Treatment	L*	a*	b*
Galaxy	Control	81,75 ± 15.08^{a}	30,25 ± 1,08^{b}	102,25 ± 12,36^{a}
	50% ETC	94,18 ± 10,75^{a}	35,28 ± 1,15^{a}	92,16 ± 11,69^{a}
	50% PRD	87,55 ± 11,72^{a}	37,25 ± 1,34^{a}	99,13 ± 11,35^{a}
	75%PRD	92,81 ± 9,14^{a}	32,52 ± 1,58^{b}	93,42 ± 5,65^{a}
Rich a red	Control	79,47 ± 22,14^{a}	1,52 ± 0,95^{c}	83,19 ± 5,56^{a}
	50% ETC	83,13 ± 19,36^{a}	20,35 ± 7,61^{a}	81,31 ± 3,06^{a}
	50% PRD	84,82 ± 18,98^{a}	21,27 ± 6,09^{a}	74,96 ± 12,56^{a}
	75%PRD	89,90 ± 20,84^{a}	4,24 ± 0,69^{b}	76,74 ± 8,59^{a}

The values are the means of six different peach fruit samples (n = 6) ± standard deviation. The letters (a, b, c, d) indicate significant differences ($p < 0.05$) between the four treatments for each variety separately.

The analysis of the results regarding the variation in the color of the fruit epicarp in two apple varieties under different water treatments is illustrated in Table 3. The results showed that fruits from both Galaxy and Rich Red varieties were characterized by high values of L* and b*, indicating a yellow-green coloration. However, the a* values were lower and ranged from 30.25 to 37.28 in Galaxy and from 1.52 to 21.27 in Rich Red fruits under the different water treatments. Under water deficit conditions, a significant increase in a* was observed for both varieties. Furthermore, no significant variation was recorded for L* and b*.

Conclusion

The results of applying four water regimes to the two apple varieties (Galaxy and Rich Red) led to the conclusion that the deficit irrigation strategy PRD 75% is the most recommended in the region of the present study, given its moderate effect on branch growth as well as on gas exchange parameters. Additionally, this irrigation strategy increased sugar content and firmness without altering the weight and size of the fruits.

The deployment of the OSIRRIS system for optimizing water use efficiency of of Washington Naval orange under deficit irrigation (Site III. Nabeul).

Abstract

Internet of Things (IoT) based precision irrigation system has proven to be promising tools 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%, DI25%, 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.

1. Introduction

Given the critical situation of water availability in the region, providing citrus growers with precise and technical knowledge on irrigation water-saving strategies 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 to diverse irrigation water levels applied using double-line drip irrigation and PRD techniques.

2. Materials and Methods

2.1. Description of the study area and Experimental layout

The experiment was conducted at the agricultural experimental unit (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 average annual precipitation of about 440 mm and average annual reference evapotranspiration (ET0) of 1350 mm. The trial was accomplished on 27-year- orange 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 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 cm^{-1}. The soil texture in the experimental field is sandy loam (71.3% sand16% silt 11.7% clay). The water contents at field capacity (SWCfc) and permanent wilting point (SWCwp) are equivalent to 0.26 and 0.06 cm3cm^{-3}, respectively. The soil bulk density is 1.4 g cm^{-3} (Table 1).

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

The experimental field was divided into two large adjacent plots defined according to irrigation technique (DI and 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 h^{-1} at a pressure of 100 kPa.

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 were widely quantified as the most water stress sensitive stages in citrus (García-Tejero et al., 2011; Pérez-Pérez et al., 2008; Doorenbos et al.,1979). These stages span from mid-February until the end of June. 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 deficit irrigation since 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 air temperature, 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 (Allen et el.,1998).

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

Δ [kPa °C^{-1}], Rn [MJ m^{-2} d^{-1}], G [MJ m^{-2} d^{-1}], (es–ea) [kPa], γ [kPa °C^{-1}] and U2 [m s^{-1}].

Water needs by crop ETc were calculated via the FAO approach (Allen et el., 1998) as follow:

$$ET_c = Kc \times ET_o$$

Crop coefficient (Kc) values of 0.65 at the initial stage, 0.6 during the mid-season, and 0.65 during the late season (Doorenbos et al.,1979) 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:

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

Where: I, irrigation (mm); P, precipitation (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.

2.2. 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 dried at 105°C up to constant weight. Additionally, starting in August, soil-water dynamics were assessed in real-time based on soil-water sensors and the 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 DI100% and PRD100%, while two sensors were positioned on each side of PRD75% 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.

Similarly, we used smart tensiometer (prototype 2, Figure 1) is the WaziSense model, developed within the framework of the Osirris TUNGER 2+2 project (bilateral collaboration between Germany (Waziup and INNOTEC 21) and Tunisia (INRGREF and INRAT). This model stands out in the field of embedded systems and IoT solutions due to its unique combination of state-of-the-art features. It integrates LoRa wireless communication technology, an MPPT solar charge controller and ATmega328P microcontroller programmed in C/C++ language (Figure 1). The WaziSense comprises a watermark sensor and temperature probe which are connected to an Arduino Pro-Mini microcontroller with a 3.3 V voltage and a frequency of 8 MHz. Sensor readings (soil matric potential and soil temperature) are recorded automatically at 15 minutes intervals by the WaziSense. The LoRaWAN communication module allows sending data wirelessly to the Gateway "WaziGate" for storage. Once the cloud connection is initialized, the WaziGate synchronizes all the data to the server "WaziCloud" where they can be securely stored, analyzed and managed. The WaziCloud platform allows users to view, manage, retrieve and share the collected data in real time. The whole device uses 4×AA rechargeable Li-ion 18650 cell batteries (4.2V and 2200 mAh), powered by a small solar panel delivering 6V at 166 mA

Figure 1. Smart tensiometer VII

2.3. Fruits sampling and quality traits analysis

The yield was measured after harvest in January. 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), form index, peel thickness (mm), and firmness (Kg cm^{-2}).

The polar diameter (mm) was measured using a caliper and the fruit height (mm) was recorded as the pistil-peduncle distance. The Form Index was calculated by determining the height-to-diameter ratio, with a value of 1 indicating a spheroid shape. The Firmness (Kg cm^{-2}) was determined using a GUSS Manufacturing Ltd penetrometer, connected to a computer and guided by software, which measures the firmness of the 3 sides of each fruit.

Then, the fruit were sliced in the equatorial area and the peel thickness (in mm) was measured, at 3 point, 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 1-mm mesh sieve. The five juices of each tree were mixed and treated as a lone taster for the juice quality examination, to obtain 3 replications per treatment. The juices measurement analyzed in this study are: juice volume, weight of the juice, TA (citric acid content), TSS, AA (vit C) and MI.

Juice volume (ml) was determined by using a 1000 ml graduated beaker and the weight of the juice (g) was measured with the help of a precision balance of the Kern type CB12K1N.

Maturity Index (MI) was calculated by:

$$MI = \frac{TSS \times 10}{TA}$$

Where; TSS (g 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 l^{-1}) was achieved according to conventional techniques (Kimball et al., 201).

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 with the DCIPIP changes color the pale pink or purple, indication the amount of ascorbic acid present in the solution. Vitamin C is showed as mg AA per 100 ml of liquid (Ojukwu et al., 2017).

2.4. Irrigation Water productivity (WPirrig)

WP irrig the total yield produced per unit of irrigation water (Latrech et al., 2019;

Leogrande et al., 2016).

$$WP_{irrig}\,(kg\,m^{-3}) = \frac{Yd}{Irr}$$

Yd: total fresh yield (Kg ha^{-1}); Irr: total amount of irrigation (m^3 ha^{-1}).

2.5. Data analysis

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

3. Results

3. 1. Site agro-environmental characteristics and soil water status

3.1.1. Agro-climatic characterization

Daily meteorological variables (average temperature, vapor pressure deficit (VDP), ET0 and P for the all cycle are depicted in Fig 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 ET0 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 ET0 was equal to 1092 mm; indicating high evaporative demand, and while, total precipitation was limited to 390 mm.

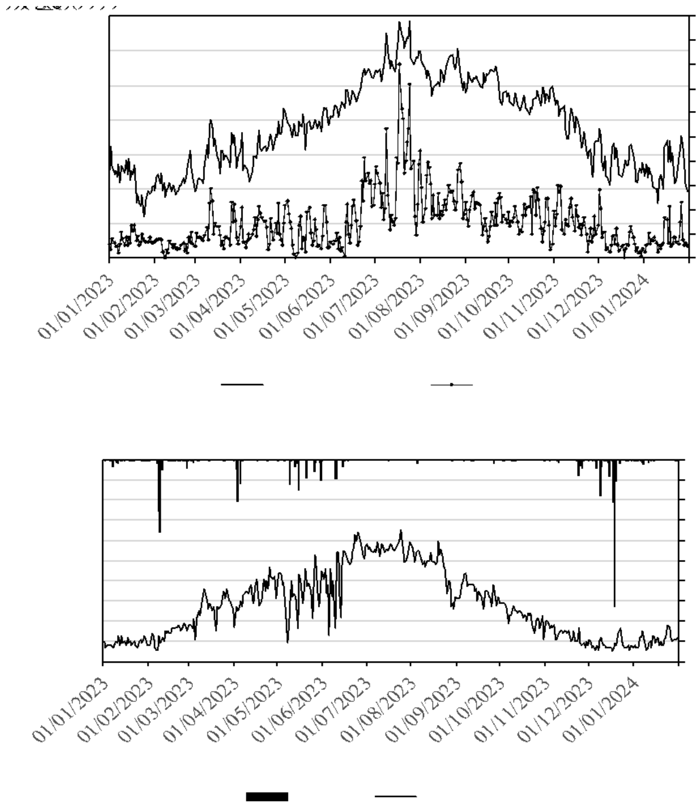


Figure 12: Dynamics of daily Tavg, VPD, ET0 and P.

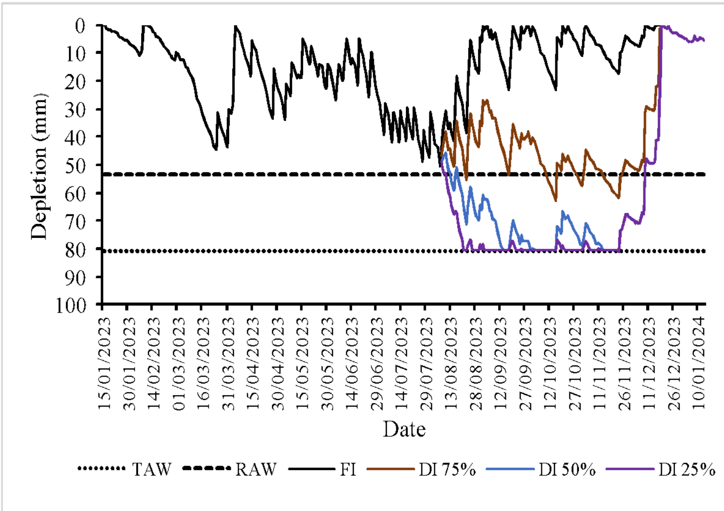
3.1.2. Soil water status

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 (Allen et al., 1998). Total available water (TAW) and readily available water (RAW) in the root zone were 80 and 54 mm, respectively. Daily patterns of root zone water depletion under different irrigation 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 (Patanè et al.,2010; Mattar et al.,2020). 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%, DI50% and PRD-50%, and then DI-25% and PRD-25%. This result aligns with the finding of (Nagaz et al.,2017) who found that the soil water depletion values decrease with increasing irrigation amounts. Similarly, (Du et al.,2008) stated the soil water content recorded for RDI and PRD treatments were lower than those of the fully irrigated treatments.

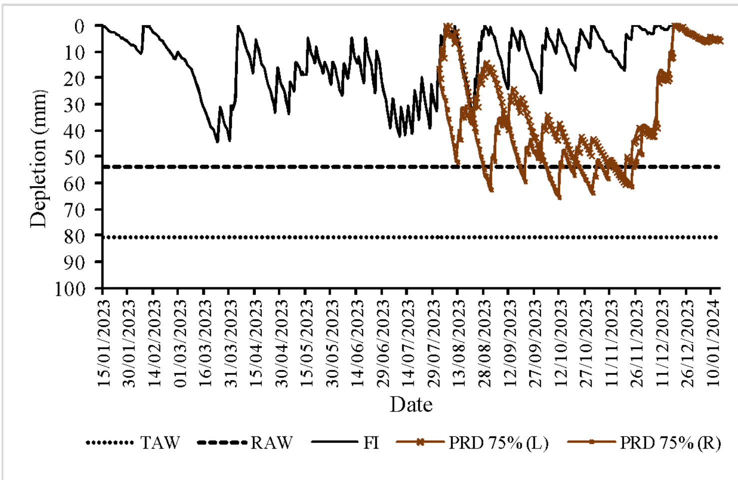
More detailed analysis showed that soil water depletion values of both treatments DI-50% and DI-25% increased immediately after treatment initiation and remained approaching TAW limit till mid-December indicating that the trees were subjected to a severe water stress condition. Meanwhile, DI-75% treatment was characterized with intermediate water depletion values, rarely exceeding the RAW threshold. Our results are in accordance with those achieved by (Nagaz et al.,2017) 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, (Puig-Sirera et al.,2021) showed that the lowest values of soil water contents as well as the predawn and midday (LWP) of mandarin trees, grown in Mediterranean semi-arid climate, were achieved when DI-25% of ET treatment is applied in the two phases II and III of fruit development.

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 two sides wet and dry. For example, during 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 worth to note 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 (Mattar et al.,2020; Hashem et al.,2019; Du et al., 2008). 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).

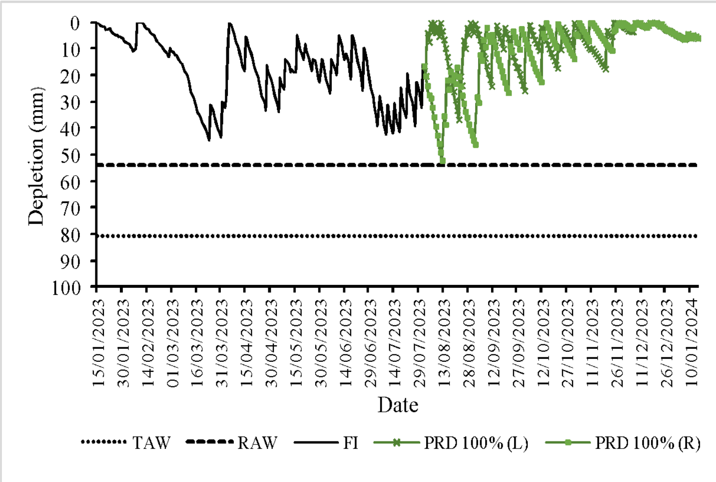
(a)



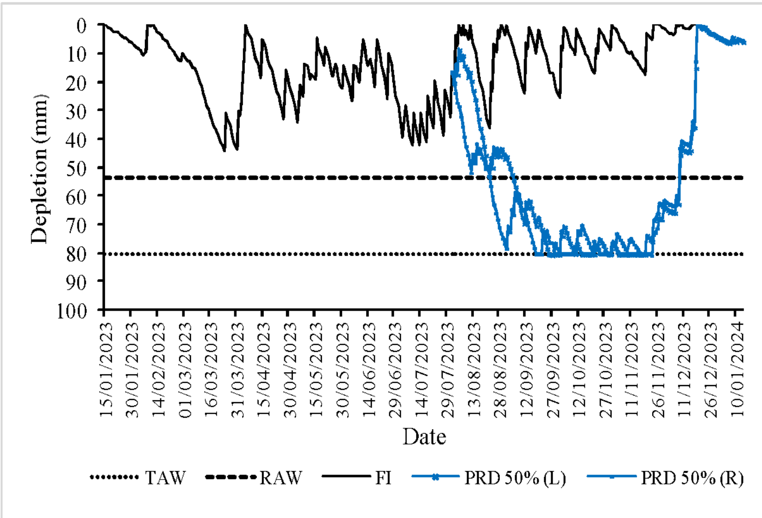
(b)



(c)


Depletion (mm)
Date
TAW
RAW
FI
PRD 100% (L)
PRD 100% (R)

(d)


Depletion (mm)
Date
TAW
RAW
FI
PRD 50% (L)
PRD 50% (R)

(e)

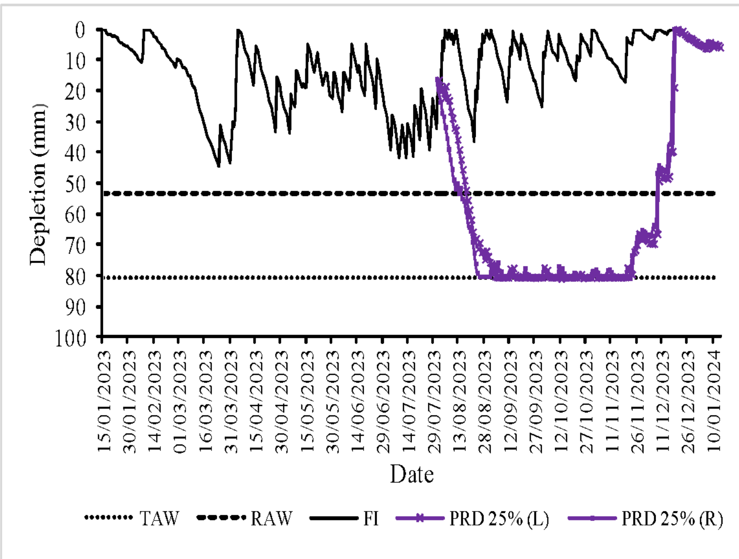

Depletion (mm)
Date
TAW
RAW
FI
PRD 25% (L)
PRD 25% (R)

Figure 13 (a, b, c, d, e): Daily patterns of soil water depletion (mm) in the root zone under Full irrigation (FI), Deficit irrigation with 75%, 50% and 25%ETc (DI75%, DI50%, DI 25%), and partial root-zone drying with 25%, 50% and 75% ETc (PRD75%, PRD50%, PRD25%) alternating at 10 days, treatments. TAW: total available water, RAW: readily available water.

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

3.2.1. 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 8). 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 8), the tree yield tends to increase with increasing irrigation level, when, unexpectedly, the tree yield under PRD-50% was higher than that achieved under PRD-100%. This positive correlation between yield and irrigation amount corroborates the findings of Panigrahi, P. (2023). In addition, (Wang et al.,2021) , 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 (Aguado et al.,2012). Jamshidi (2021) 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., 2021) who 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. Similarly, Puglisi et al., (2019), found that the final yield of citrus subjected to DI were not statistically different from normally irrigated trees. In this sense, (Adu et al.,2018) reported that crop species and soil texture are the main determinant factors in crop yield response to water-saving irrigation strategies.

Table 8: 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}

The irrigation water productivity values varied from 5.14 to 8.6 kg m-3 under DI-75% and PRD-50% treatments, respectively, which are clearly higher than those obtained by (Nagaz et al.,2017) 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. Nevertheless, insignificant differences between all studied treatments. In accordance with our results, (Consoli et al.,2017) 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.,2016) 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 ,2017) showed that adoption of DI in mature orange orchard did not affect WUE and yield.

3.2.2. 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 (Lado et al.,2014; Shao et al.,2015). Table 9 shows the effects of different irrigation practices and levels applied during stage III on some quality fruit 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 (Hutton, and Loveys, 2011) Additionally, (Navarro et al., 2015) noted significant decrease in fruit size when the trees experienced to deficit irrigation under stage II. In spite of the existence of significant differences in polar diameter among treatments, the form index which is defined as the ratio among ED and PD was insignificantly modified by irrigation. The form index values were close to 1 showing that the fruits are characterized by a nearly spherical shape.

Table 9: 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}

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

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. However, no significant difference was observed between FI and DI treatments. Even it is not statistically different, fruit firmness decreases with increasing stress level when PRD technique is adopted. In fact, water loss driven by transpiration reduces turgor pressure, triggering cells to contract leading the fruit to lose firmness (Gidado et al.,2024). Meanwhile, as stated by different authors, application of PRD technique enhances ABA hormone synthesis that works as metabolic inhibitor by inducing stomata closing and reducing transpiration rates (Hutton, and Loveys, 2011; Gotur et al.,2018), enhancing therefore fruit firmness. In apparent contradictions with our results, (Kusakabe et al., 2016) found that PRD technique in stage II decreases grapefruit firmness. In addition, (Morianou et al., 2021) observed that citrus fruit firmness significantly increases when DI strategy during is adopted during Phase II of different citrus cultivars.

3.2.3. Internal fruit quality parameters under PRD and DI

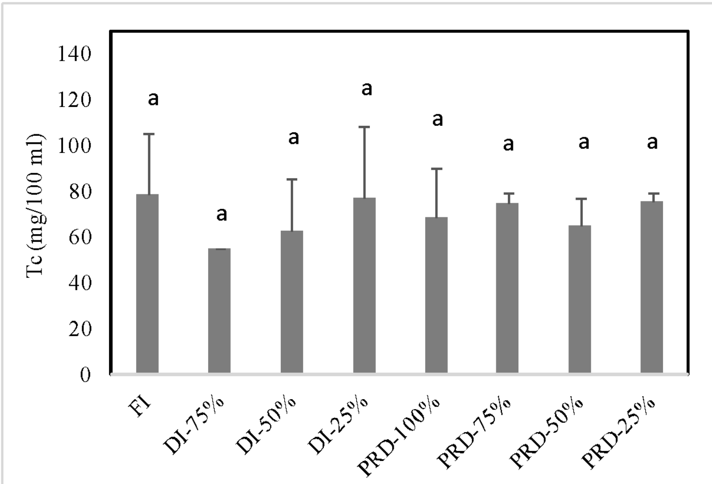
Figure 14 shows the response of internal fruit quality parameters (juice (%), Vitamin C contents (Tc), acidity and TSS) of citrus to different irrigation amount and techniques. Vitamin C is one of the important antioxidants reflecting the fruit nutritional quality (Yang et al.,2012). It varied from 55 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 greater than the lowest value mentioned by (UNECE, 2018), for navel and was similar to those testified for orange varieties. PRD-100% and PRD-75% produced significantly higher contents (54.3 and 51.7%) compared to PRD-50%. The decrease in juice content in citrus with reducing irrigation amounts was also reported by several authors among them (Gasque et al., 2016) and (Gasque et al., 2010). 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, P. (2023). The authors reported that juice percentage diminish is accompanied by an increment in the soluble solids concentrations in fruits.

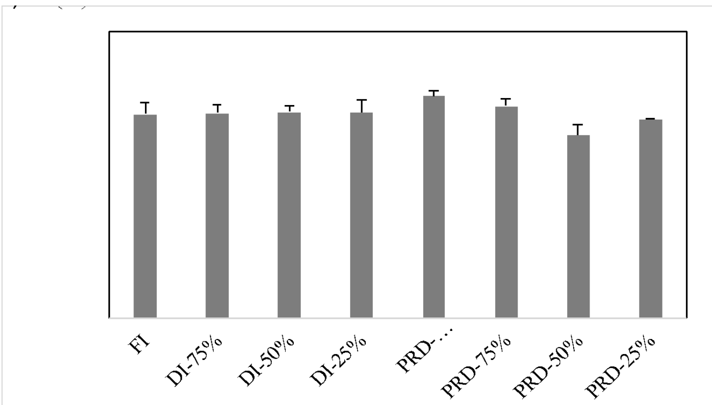
Maturity index (MI), recognized as the main relevant fruit's internal quality indicator, is determined as the ratio between TSS and TA since TSS increases toward harvest while acid content declines because of catabolism of citric acid and dilution phenomena (Morianou et al.,2021; Lado et al.,2014). In 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 typical kind (8-10) suitable for harvest as suggested by UNECE, (2018). Kusakabe (2016). 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 (Lado et al.,2014) 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 14-C). This finding aligns with that reported by (Rallo et al., 2017) and (Gasque et al., 2010) who found that TSS and MI in orange was unaffected by DI. It is worth to note that in overall, FI and DI treatments resulted in higher means of TSS compared to their corresponding achieved under PRD technique. According to (Lado et al.,2014), 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 greater TSS and minor acidity of fruits were marked 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 force of fruit cells (Navarro et al.,2010).

In fruit citrus, the amplification of TSS and TA traits during deficit irrigation either through the all season or during fruit growth phase has been widely evidenced (Consoli et al., 2017; García-Tejero et al., 2010; Pérez-Pérez et al., 2009). Hutton (2011), reported that TSS and acid concentrations were higher in navel orange trees irrigated by PRD compared to normally irrigated trees. Gasque et al. (2010) noted that DI did not significantly affect the fruit quality of Navalina. Barry (2004) showed that limiting water later in fruit development (January–March) did not increase TSS and TA traits. In the other hand, Panigrahi et al. (2014) reported that an increase in TSS associated with a decrease in acidity in orange during ideal DI strategy. In the works of Romero-Trigueros et al., (2020) and (Pérez-Pérez et al. (2009), DI strategies augmented TSS and TA of orange 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.

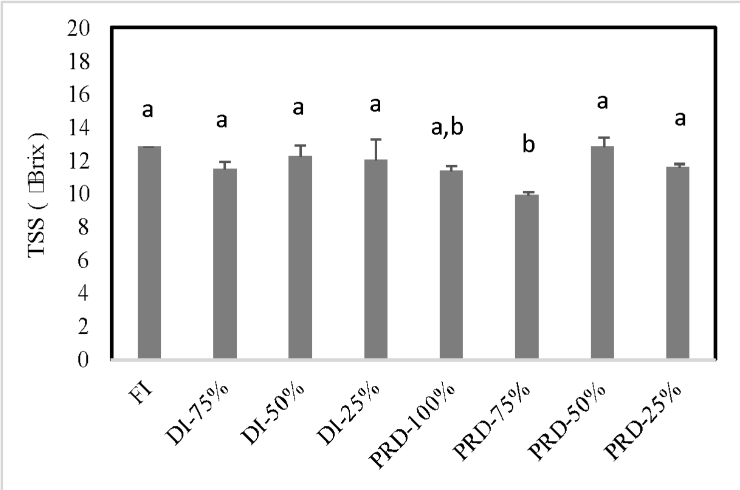
(A)



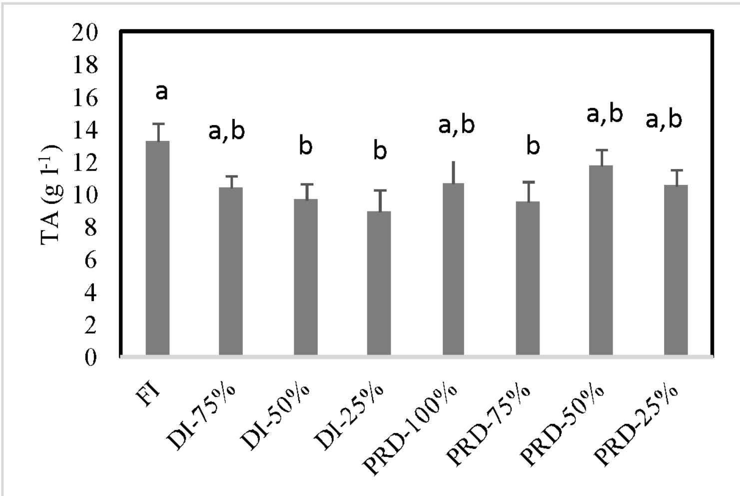
(B)



(C)


TSS (□Brix)
20
18
16
14
12
10
8
6
4
2
0
a
a
a
a
a,b
b
a
a
FI
DI-75%
DI-50%
DI-25%
PRD-100%
PRD-75%
PRD-50%
PRD-25%

(D)


TA (g l-1)
20
18
16
14
12
10
8
6
4
2
0
a
a,b
b
b
a,b
b
a,b
a,b
FI
DI-75%
DI-50%
DI-25%
PRD-100%
PRD-75%
PRD-50%
PRD-25%

(E)

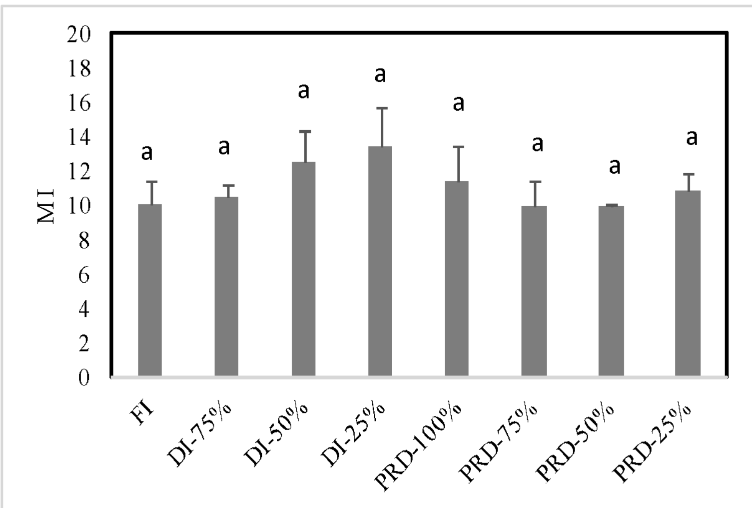

MI
20
18
16
14
12
10
8
6
4
2
0
a
a
a
a
a
a
a
a
FI
DI-75%
DI-50%
DI-25%
PRD-100%
PRD-75%
PRD-50%
PRD-25%

Figure 14 (A, B, C, D, E): Effects of irrigation treatments on internal fruit quality attributes 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 ($p \leq 0.05$).

Conclusion

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.