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Use of smart tensiometers for monitoring different deficit irrigation strategies in two young apple cultivars in Tunisia: comparison of physiological and pomological behavior

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Under climatic change and water scarcity conditions, the use of a precision irrigation system and crop-adapted irrigation strategy that takes into account climatic conditions is a major objective for scientists and farmers. The current study investigated the effects of different irrigation strategies, using low-cost smart tensiometers, on the vegetative growth, relative water content, gas exchange, and fruit quality of two young apple cultivars (Galaxy and Richared) in dry climate. Four irrigation treatments were considered: Control Irrigation [CI, 100% crop evapotranspiration (ETc)], Continuous Deficit Irrigation (CDI at 50% ETc), and Partial Root-zone Drying (PRD75 and PRD50 irrigated at 75% and 50% ETc, respectively). Results showed that shoot growth significantly decreased under CDI50% and PRD50% with a reduction of approximately 31.65% and 38.63% for Galaxy and Richared, respectively. A slight decrease in gas exchange parameters was recorded during the fruit ripening period, especially for Richared under CDI50% and PRD50%, while under PRD75%, the decrease was negligible. Moreover, a significant improvement in fruit quality was reported by an increase in firmness, TSS, that reached 19.50 and 17.50°Brix in Galaxy and Richared, respectively, under PRD75% and a decrease in acidity mainly in Richared. In conclusion, the deficit irrigation strategy PRD75% based on smart tensiometers data is the most recommended strategy in the region of the present study, considering its moderate effect on tree physiology and improvement in fruit quality.

KEYWORDS

apple, smart tensiometers, partial root draying, gas exchange parameters, fruit growth

1 Introduction

The apple tree is one of the most important economical fruit trees in the world (He et al., 2023) with a global apple production that reaches 93.5 million tons per year, nearly half of which is harvested in China (Food and agriculture organization of the United nation (FAOSTAT), 2020). It is also the most cultivated fruit in Europe with an annual production higher than 12.6 million tons (Food and agriculture organization of the United nation (FAOSTAT), 2020). Apple cultivation occupies an important place in the tree-growing sector in Tunisia (Gara et al., 2019), with a national production that reached 127,000 tons in 2022 (Food and agriculture organization of the United nation (FAOSTAT), 2020). The Kasserine region is the main apple-producing region in Tunisia, with an area of 993 hectares and a production of nearly 60,000 tons in 2023. Sbiba and Foussana are particularly known for their apple trees, and the Sbeitla region has more recently become a new production area with 2,500 tons per year (CRDA Kasserine, 2024). In the Kasserine Governorate, two types of apple cultivars are grown: early cultivars (summer cultivars) such as Lorca, Anna, and Ain Chamir, and late cultivars (autumn cultivars): Golden Delicious, Starkrimson, and Richared (Gara et al., 2019). However, apple production in this region has seen a decline in area and production due to climate change, such as low rainfall, sudden changes in temperatures, and the decline in water resources (CRDA Kasserine, 2024). In fact, production was estimated at 75,000 tons in Kasserine in 2020, while it decreased to 60,000 tons by 2023 (CRDA Kasserine, 2024).

In recent decades, Tunisia has been facing water shortages, highlighting the urgent challenges associated with limited water availability in the country. The effects of climate change exacerbate the situation by increasing water scarcity problems (Gaaloul et al., 2021). This water shortage directly impacts yield and fruit quality, making efficient irrigation essential for maintaining optimal growth conditions. In fact, water requirement for apple trees is approximately 600 mm, and the usual rainfall (P) throughout the summer production season (June to August) is approximately 10 mm, which makes the majority of apple production irrigation-dependent. Regarding the lack of availability of water resources, deficit irrigation strategies are therefore a good choice to improve water use efficiency and fruit quality, including flavor profiles, along with their role in saving water and controlling vegetative growth.

Several water-saving techniques in irrigation were used in recent years to improve water productivity such as supplemental irrigation and deficit irrigation as well as the use of cultivars tolerant to water stress. With regard to this multitude of aforementioned techniques, some researchers have based their knowledge on plant-level physiological knowledge to develop a new irrigation technique by partial root drying ["Partial Root-zone Drying" (PRD)]. This PRD irrigation technique consists of reducing the irrigation water inputs to half compared to conventional irrigation. This reduction is very dependent on the type of crop and is generally accompanied by a non-significant reduction in yield while increasing water productivity (Ben Nouna and Rezig, 2016). This technique, now, is well adopted throughout the world in different fruit crops like citrus, pears, and peaches with promising results (Madhumala et al., 2019).

The efficient use of soil moisture sensors for irrigation requires an understanding of the soil's water retention capacity (Waldburger et al., 2025). It is also important to consider factors such as root water absorption variability, surface evaporation, and partial soil moistening prior to sensor installation (Shock and Wang, 2011). Soil moisture sensors provide an indirect measure of a plant's water status. It assesses either the volumetric soil water content or the soil water matric potential that is typically used to display soil moisture levels and provides information on the amount of water required for daily irrigation (Dursun and Ozden, 2019). Recent studies have shown that the use of innovative technologies, including Internet of Things (IoT) and sensor networks, facilitates agricultural land management. In particular, the adoption of IoT-based precision irrigation systems has proven effective in monitoring sensor data in real time, which optimizes water use and improves irrigation productivity (Vinod Kumar et al., 2024; Belkher et al., 2025). A recent study conducted by Seyar and Ahamed (2023) tested a drip irrigation LoRaWAN-based solution in outdoor conditions and showed easy management and robust controlling capability. Moreover, the smart irrigation can be used in an adverse situation through proper integration of the IoT module, sensors, and connection-less environments (Di Gennaro et al., 2024). IoT-based technologies make the irrigation easier and more precise by employing low-cost sensors and controlling modules (Seyar and Ahamed, 2023). Furthermore, it can help to obtain a precise measurement of soil moisture in the plant root zone and apply the required proportion of water at the right time, which helps the farmer to continuously monitor irrigation, save time, and economize water at a low cost.

The amount of water that is administered must be enough to prevent either too much or too little water from compromising the production and quality of the fruit (Thompson et al., 2007). Based on soil moisture data, pre-established thresholds that are based on knowledge of each crop and soil type help avoid both under- and over-irrigation. According to Domínguez-Niño et al. (2020), apples are among the crops for which the use of such irrigation systems can give reliable results.

In Tunisia, and especially under semi-arid climates, studies on the use of precise irrigation based on the control of water balance in the soil by intelligent tensiometers are very scarce, especially in the cultivation of fruit trees such as apple. Hence, this study focuses on evaluating the feasibility of using a low-cost automatic smart tensiometers to compare four irrigation strategies and define which is the effective strategy that saves water without affecting the physiology and the apple fruit quality. The effects of the irrigation strategies on plant shoot growth, water status, gas exchange, and fruit quality parameters were evaluated in two young apple cultivars cultivated in the Sbeitla region (west-central Tunisia).

2 Materials and methods

2.1 Experimental site and plant material

The experimental apple orchard (*Malus communis*) is located in west-central Tunisia in the Sbeitla region (35°14′ North, 9°08′ East, and an altitude of 525 m) (Figure 1). The study region belongs to the semi-arid bioclimatic zone, which is a large part of west-central Tunisia. Its climate is characterized by hot, dry summers and mild, rainy winters, and the rainfall average was approximately 254.8 mm. The experimental plot covered an area of 1 ha. The soil was sandy loam, with an average rooting depth of approximately 30 cm, a total available phosphorus (P_2O_5) content of 75.38 mg/kg, and an organic matter content of 0.97%. The soil sample had a pH of 7.85 and an electrical conductivity (EC) of 0.12 ms/cm. The experimental plot was arranged in blocks, and each block is divided into six rows for each cultivar. The plant distance in the apple orchard was 4 m between trees and 5 m between lines. The orchard was covered with a netting system to protect trees from hail and other physical attacks. In addition, soil tillage was involved in the autumn during the post-harvest period. Three-year-old trees of apple cultivars, Galaxy and Richared, were grafted on the rootstock "MM106" and both cultivars had a similar vigor. For statistical analyses, we studied 11 trees for each treatment, with three replicates in each cultivar (33 trees) for both cultivars. Indeed, for each measurement (leaves or fruit), more than three repetitions are considered.

2.2 Water needs, irrigation treatments, and soil water balance

2.2.1 Water needs and irrigation treatments

All trees were irrigated at control irrigation (100% ETc) until 01/07; then, for each cultivar, four different water regimes [Control Irrigation (CI), where trees were irrigated at 100% ETc; Continuous Deficit Irrigation (CDI at 50% ETc); Partial Root-zone Drying (PRD75 at 75% ETc); and Partial Root-zone Drying (PRD50 at 50% ETc)] were applied from the fruit growth to the fruit harvest period (from 01/07 to 04/09). Eleven trees for each treatment were followed, with three replicates in each cultivar. Irrigation was carried out using a drip irrigation system with two side ramps per row and four emitters per tree. Four different irrigation treatments were considered in this study:

- Control Irrigation (CI), where trees were irrigated at 100% ETc.
- Continuous Deficit Irrigation (CDI, 50% ETc).
- Partial Root-zone Drying (PRD75, 75% ETc).
- Partial Root-zone Drying (PRD50, 50% ETc).

The application of PRD consists of irrigating only one side of the root system of the apple tree. We changed the irrigation side every 10 days. Since 01/07, for 50% PRD and 75% PRD, the application has begun for the right side (dry period), and the left side received a certain amount of water (wet period).

*Irrigation doses are calculated to replace ETc (net of actual precipitation) by the following formula:

$$ETc = ET0 \times Kc$$

where

ET0: Reference evapotranspiration, computed on a daily step using the Penman–Monteith model.

Kc: a crop cultural coefficient adapted to apples for localized irrigation [initial $Kc_{(April\text{-}May)} = 0.5$, $Kc_{mid\text{-}season\ (June)} = 0.65$, $Kc_{(July\ until\ harvest)} = 0.8$, and $Kc_{end\ of\ season\ (after\ harvest)} = 0.5$].

Real crop evapotranspiration (ETr) was calculated using the soil water balance method, based on the water inputs and outputs in the root zone of the apple tree.

$$ETr = P + I + C - R - D - \Delta S$$

where P is the effective precipitation (mm), I is the irrigation (mm), C 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 in soil water stored in the 0–40 cm soil layer (mm).

2.2.2 Soil water balance

Soil water dynamics was assessed in real time based on soil water sensors and the IoT system (ZL6 device from METER GROUPE). Twelve capacitive 10HS sensors (METER Group Inc., Pullman WA, USA), preliminarily calibrated, were used to monitor soil water content in the root zone (30 cm from the tree trunk), at two depths (20 and 40 cm), with a time resolution of approximately 15 min. Two sensors were installed in each treatment, FI (100% ETc) and CDI (50% ETc), while two sensors were positioned on each side of PRD50% and PRD75% treatments. Each set of six sensors was connected to one ZL6 data logger enclosed in a weatherproof 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.

In this study we also used a smart tensiometer model, WaziSense V2, created as part of the Osirris TUNGER 2 + 2 project [a bilateral partnership 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 an ATMega328P microcontroller programmed in C/C++, an MPPT solar charge controller, and LoRa wireless communication technology (Supplementary Figure S1), equipped with a MPPT solar charge controller to the board.

This tensiometer (WaziSense) comprises a watermark sensor and a temperature probe connected to an Arduino Pro-Mini microcontroller with a frequency of 8 MHz and a voltage of 3.3 V. It automatically records sensor measurements (soil temperature and soil matric potential) every 15 min by the WaziSense. The LoRaWAN communication module allows data to be sent to the "WaziGate" gateway for storage. Once the cloud connection is initialized, the WaziGate synchronizes all the data and transferred them to the "WaziCloud" server, where it can be securely stored, analyzed, and managed. Customers can view, manage, retrieve, and share recorded data in real time via the WaziCloud platform. The whole device runs on four 18650 AA rechargeable Li-ion batteries (4.2 V and 2,200 mAh), powered by a small solar panel (6 V, 166 mA). The sensors were installed at sensitive and suitable locations in the plant's root zone.

We performed the calibration curves for the three smart tensiometers used in this study, in order to establish the calibration of the smart tensiometers, and transformed the tensions into water content. In fact, 12 soil moisture 10HS sensors were used to measure soil moisture at 20- and 40-cm depths throughout the growing season; moreover, the gravimetric moisture contents were used to develop a linear regression model and determined the calibration curve (Supplementary Figure S2).

The calibration of these smart tensiometers was carried out using the 10HS probes. The advantages and specificity of these smart tensiometers (OSIRRIS) are their reasonable cost and ease of use. In fact, the cost of the smart tensiometer including all the equipment did not exceed 90 euros. Moreover, installation is easy and does not require the intervention of a technician.

2.3 Vegetative growth

Lateral vegetative growth was assessed by measuring the extension of the shoots at different time intervals. At the beginning of vegetative growth, 12 shoots of the year were selected on the four sides and at the same height in each tree. Measurements were made every 15 days during the growing season. For each cultivar, monitoring was carried out on three trees per treatment (*n* = 12).

2.4 Relative leaf water content

Relative water content (RWC) was determined on mature leaves taken from the middle part of the shoot. For each treatment, we take four leaves from three different trees (*n* = 12). RWC was monitored during regular time intervals, every 15 days, and was calculated as follows: RWC = ((MF − MS)/(MFsat − MS)) *100.

where

- MF: mass of fresh matter at the time of harvest;
- MS: mass of dry matter;
- MFsat: mass of saturated fresh matter.

Leaves are weighed immediately after harvest (MF). MFsat represents the mass of leaves after rehydration in a humid atmosphere until saturation (Kramer, 1980) obtained in the dark and at room temperature in the laboratory, by soaking the basal part of the petiole in distilled water for 12 h. Then, the leaves are dried at 80°C for 48 h to determine the MS.

2.5 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 the CO_2 molar fraction in intercellular spaces (Ci) were measured on mature leaves with a portable gas exchange analyzer (LCpro + ADC Ltd. BioScientific, Hoddensdon, UK). These gas exchange parameters were measured under saturating sunlight during the day, with a photosynthetically active radiation (PAR) of approximately 1,700 μmol photons m^{-2} s^{-1}. After switching on the device, a 5-min wait was allowed to equilibrate the chamber with the surrounding atmosphere. Four leaves from three different trees were measured for each treatment (*n* = 12).

2.6 Fruit growth and fruit quality assessment

Fruit growth was assessed by measuring the increase in fruit size. For each cultivar, at the beginning of fruit development, in three different trees, we marked four fruits of the same age on all four sides for each irrigation treatment. Measurements were made every 15 days during the growing season until harvest.

For both studied cultivars, fruits were harvested at the corresponding commercial ripening stage. Each tree was harvested individually, and for each treatment, fruit yield (kg/tree) was calculated in three trees for three replications. Concerning fruit quality analysis, for both cultivars exposed to different water treatments, immediately after harvest, fruit diameter, weight, firmness, water content, soluble solids (TSS), titratable acidity (TA), pH, and NO_3^- content were determined on 10 fruits per tree considering three trees per replicate for each treatment and cultivar. The diameter (mm) of each fruit was measured using a vernier caliper (Mitutoyo, UK), while fresh weight was determined using a precision balance (AXIS-AGN 100 C, Poland). The color of the epicarp was measured with a Chroma Meter CR-400 trichromatic colorimeter. The parameters *a**, *b**, and *L** are determined, with *L** indicating the lightness or luminance and varies from 0 for black to 100 for white; *a** varies from −60 for green to +60 for red, and *b** varies from −60 for blue to +60 for yellow.

2.7 Statistical analyses

Statistical analyses were performed using SPSS software (version 17.0 for Windows, SPSS, Chicago, IL, USA). Analysis of variance (ANOVA) was used. Duncan's test was used to compare means between treatments for each cultivar, and Student's *t*-test was used to compare the two cultivars for each water treatment. Values were presented as mean ± standard deviation.

3 Results

3.1 Climatic condition and water consumption estimations

The analysis of meteorological conditions and crop evapotranspiration (ETc) during the study period indicated that precipitation did not exceed 63 mm during the followed period (Figure 2B). Furthermore, rainfall was mainly confined to early spring and autumn, and no characteristic rain was observed during the summer. In contrast, the accumulated ETc during the growth period was 646 mm; the maximum value was found in the mid-late vegetative period, especially in July and August. The results also revealed significant differences in ETr as a function of the irrigation strategies. Under CI, ETr followed ETc very closely, but under deficit irrigation regimes, ETr decreased sharply from the fourth decade of the mid-season stage, approximately 130 days after bud burst (DABB) (Figure 2B).

3.2 Dynamics of water depletion

The soil water depletion dynamics under different irrigation treatments, shown in Figure 3, provide important information about the water use of the two apple cultivars (Galaxy and Richared). In fact, the water depletion curves were similar for both cultivars, likely due to their similar age, vigor, phenological development, and uniform irrigation management. This is consistent with varietal influence on water uptake being minimal under the conditions of this study. Under CI treatment (Figure 3A), both cultivars maintained optimal water status throughout the growing season. Soil water content was within the comfort range (80–120 mm), and no water stress was detected. In fact, for the CI treatment, ETc was 646 mm, and ETr was 641 mm, during the whole study period. Deficit irrigation was started 123 DABB. For the CDI treatment (at 50% ETc), there was a net decrease for the water stock from 123 DABB, and WS reached the wilting point at 146 DABB. The irrigation doses were not sufficient to reach the readily available water. Furthermore, for this treatment, ETr was 521 mm, while the irrigation quantity received was 460 mm (Figure 3A). Concerning the PRD75% treatment, asymmetrical moisture distribution was observed. On the left side of the root zone, water was depleted rapidly and soil water content dropped to the permanent wilting point within 10 days of withholding water. On the right side, which continued to receive water, soil water content was sufficient to support physiological activity until approximately 140 DABB (Figures 3B, C). For these strategies, there was some period of recovery, where WS reached the readily available moisture (RAM), especially during the period from 160 to 170 DABB. In contrast, the continuous deficit irrigation treatment (50% ETc), caused a uniform decline in soil water content. In fact, RAM was reached at 130 DABB and depletion continued to the permanent wilting point by 140 days (Figure 3A). A similar trend was observed under PRD50% treatment. Both sides of the root zone showed a sharp decline in soil water content from 10 days after the start of the deficit period (Figures 3B, C). Moreover, for information purposes only, the increase in water stock 188 DABB in the root zone is due to significant amounts of rain in the study area as shown in Figure 2B.

3.3 Shoot growth

The shoot growth variation of the two apple cultivars subjected to four different water regimes (irrigation strategies) is shown in Figures 4A, B. The results showed that Richared had a higher shoot growth than Galaxy, where the branches reached 99 cm while those of Galaxy did not exceed 89 cm under control irrigation treatment. Furthermore, there was a significant reduction rate in shoot growth for Galaxy and Richared cultivars exposed to deficit irrigation (Figures 4A, B). In fact the effect of water stress was clear 148 DABB. The two deficit water regimes CDI (50% ETc) and PRD50% had significantly decreased shoot growth in the two cultivars studied. Indeed, our results showed that the Galaxy cultivar was the most affected, especially by the PRD50% treatment where shoot growth did not exceed 61 cm. However, trees exposed to the PRD75% water deficit treatment were less affected and the shoot growth was 79.25 and 80.83 cm for Galaxy and Richared, respectively (Figures 4A, B).

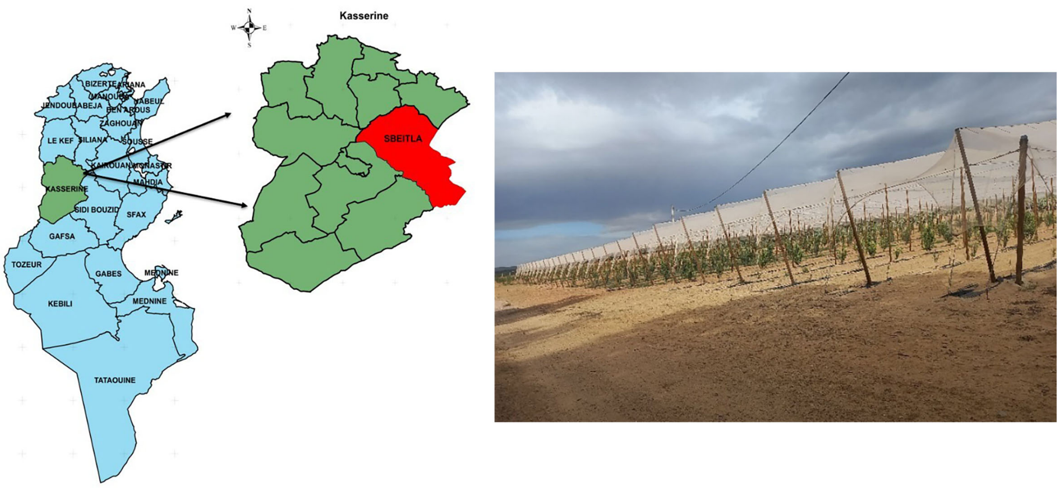

FIGURE 1
Location of the experimental orchard (Sbeitla Tunisia).

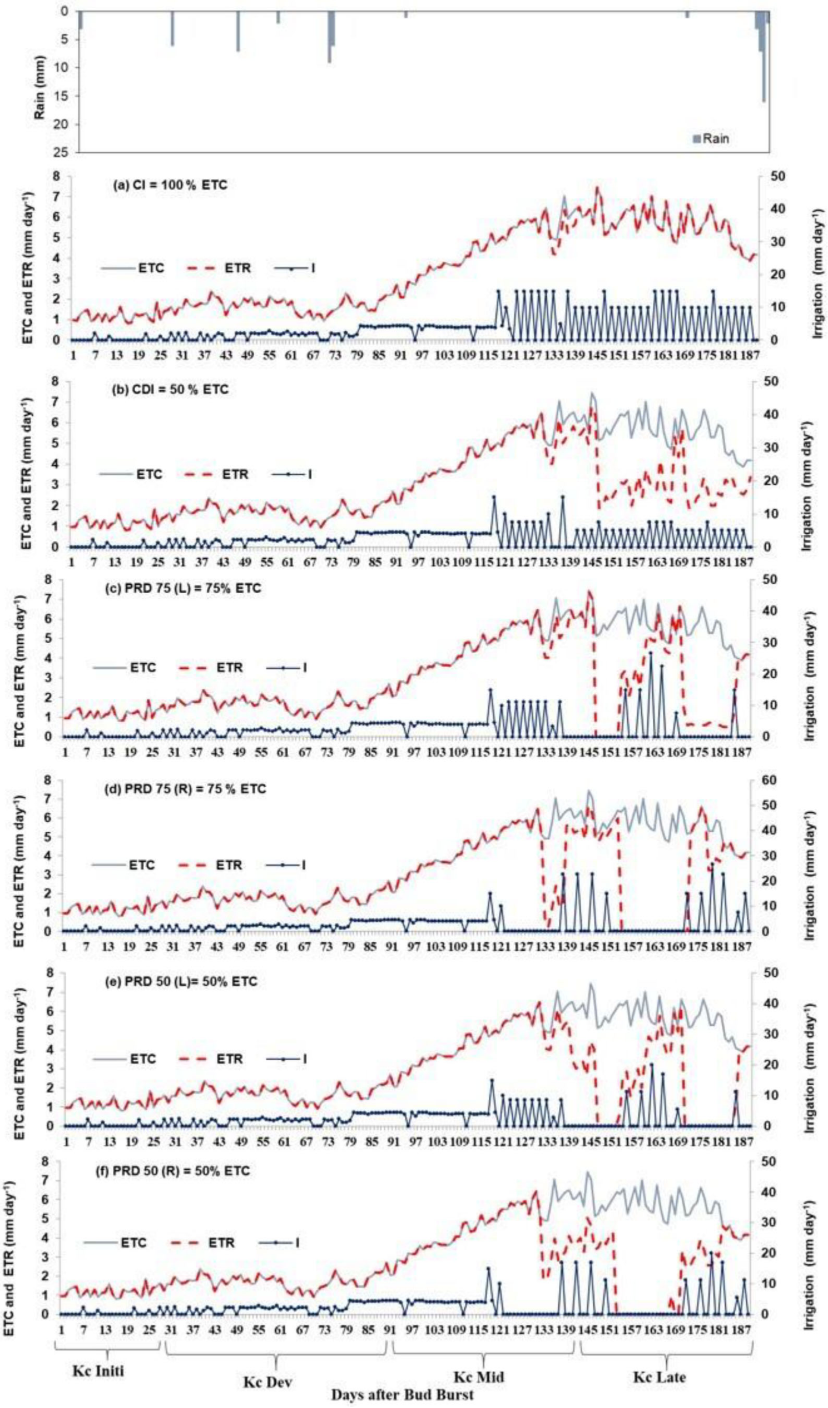

FIGURE 2
Rain (mm), crop evapotranspiration (ETc mm day^{-1}), real evapotranspiration (ETr mm day^{-1}), and irrigation (mm day^{-1}) of two apple cultivars (Galaxy and Richared) growing under dry climate, during the studied period. I, irrigation; CI, control irrigation; CDI, continuous deficit irrigation; Kc, crop coefficient; Kc Init, crop coefficient initial; Kc Dev, crop coefficient; Kc MID, crop coefficient of mid-season period; Kc Late, crop coefficient late season; PRD, partial root draining; PRD at 50% ETc (R), right side; PRD at 75% ETc (L), left side.

3.4 Relative water content

RWC was used as an indirect criterion to examine tree water status. The results presented in Figures 5A, B showed a slight decrease in RWC under the control irrigation treatment, particularly between 161 and 179 DABB, in both cultivars. However, the intensity of this reduction depended on the cultivar. In fact, RWC in the leaves of the Galaxy cultivar decreased more than that of the Richared cultivar. Furthermore, a significant difference was recorded between the control (100% ETc) and

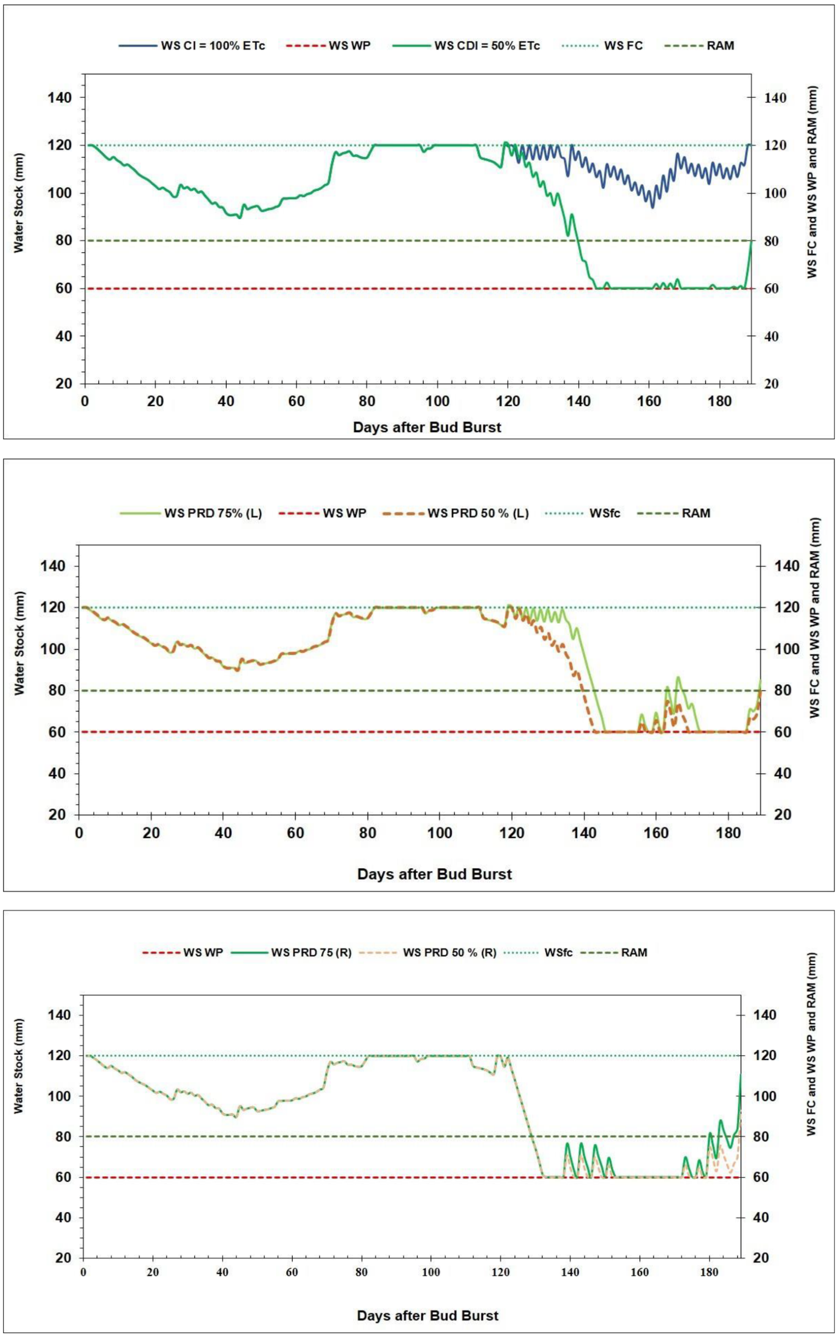

FIGURE 3
Dynamics of water depletion in the root zone (0–40 cm) under different irrigation treatments during the study period of the two apple cultivars Galaxy and Richared. WS, water stock; RAW, readily available water; WP, wilting point, fc, field capacity; CI, control irrigation; CDI, continuous deficit irrigation, PRD, partial root draining; PRD at 50% ETc (R), right side; PRD at 75% ETc (L), left side.

deficit irrigation treatments (75% PRD, 50% PRD, and CDI). There was a significant decrease in RWC in trees exposed to continuous (CDI, 50% ETc) and PRD50%; this reduction was more pronounced in Galaxy, where RWC fell to 37.4% under CDI 50% ETc. The decrease in leaf water content was smallest for trees exposed to the 75% PRD water deficit, and for both cultivars, RWC did not drop more than 49% (Figures 5A, B).

3.5 Gas exchange parameters

The evolution of Pn, illustrated in Table 1, showed that under control irrigation treatment, the Richared cultivar had higher Pn values compared to Galaxy, during all the studied periods. However, Galaxy leaves exhibited higher values of gs. Furthermore, for both cultivars, the highest values were recorded during the fruit growth

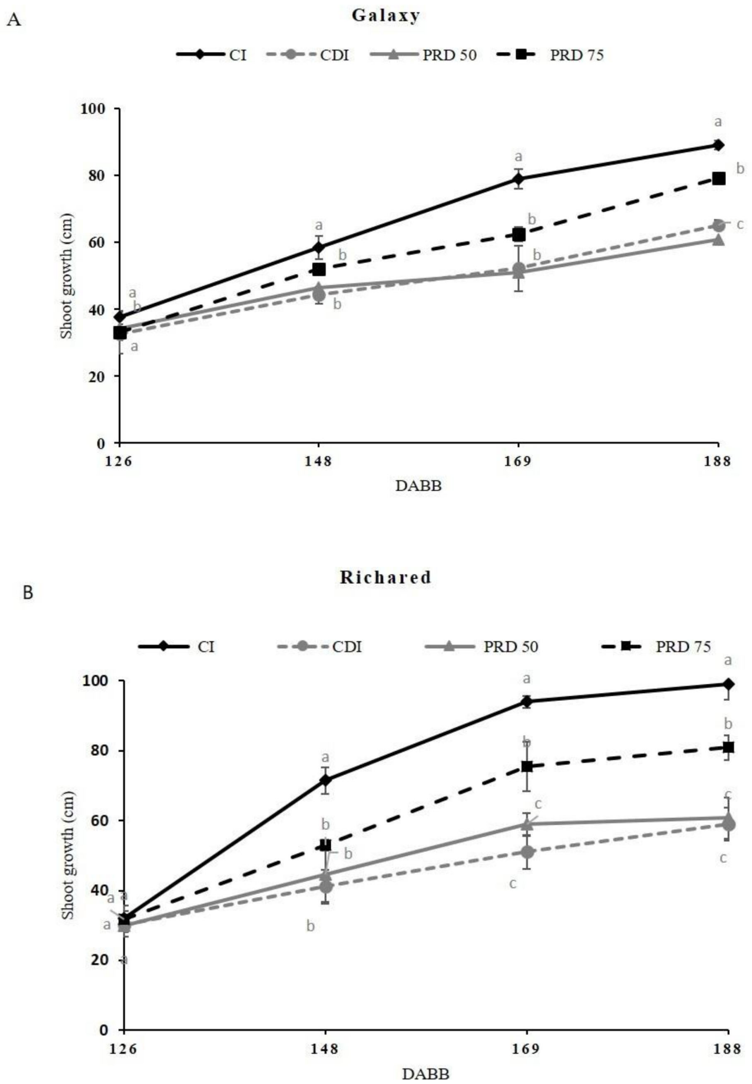

FIGURE 4
Variation of shoot growth in the two apple cultivars Galaxy **(A)** and Richared **(B)** under different water regimes. The values are the means of 12 samples (n = 12) ± standard deviation. Letters a, b, c, and d indicate significant differences (p < 0.05) between the four treatments for each cultivar separately. DABB, days after bud burst; CI, control irrigation; CDI, continuous deficit irrigation, PRD, partial root draining; PRD50%, partial root draining at 50% ETc; PRD75%, partial root draining at 75% ETc.

period (17.35 and 18.32 µmol m^{-2} s^{-1}, for Galaxy and Richared, respectively). No significant difference was recorded during this stage for the four irrigation treatments, while a clear decrease was noted during the fruit ripening stage where Pn varied between 13.53 and 14.20 m^{-2} s^{-1} for Galaxy and Richared, respectively. In addition, a significant decrease was recorded under deficit irrigation strategies, mainly under the 50% PRD and CDI 50% ETc treatments where it dropped to 9.82 µmol m^{-2} s^{-1} for Richared. No significant reduction was noted for trees exposed to PRD75% ETc. In both cultivars, during the post-harvest period, no significant variation was reported for photosynthetic assimilation rate (Pn), under the four water regimes. Furthermore, the variation in transpiration rate (Tr) is similar to that observed for Pn. In fact, we also found that the application of water deficit treatments did not induce a significant difference in leaf transpiration (Tr) during fruit growth for Galaxy and Richared cultivars (Table 1). However, during fruit ripening and post-harvest stages, a significant decrease was recorded, under water shortage mainly under 50% PRD and CDI 50% ETc. It dropped to 1.62 and 2.04 mmol m^{-2} s^{-1} in Richared and Galaxy trees, respectively, during the fruit ripening period under 50% PRD strategy. Our results illustrated that there is no significant reduction of the transpiration rate (Tr) in trees exposed to PRD75%. Leaf transpiration rate in the Richared cultivar was the most affected by water deficit treatment compared to the Galaxy cultivar. Moreover, our findings showed that the variation in stomatal conductance (gs, mmol H_2O m^{-2} s^{-1}) exhibited the same pattern as Pn and Tr (Table 1). Indeed, the fruit development period presented the highest gs values (175.50 and 169.18mmol H_2O m^{-2} s^{-1}, for Galaxy and Richared, respectively). Nevertheless, there was a clear decrease during the fruit harvest and post-harvest period especially for Richared cultivars. In fact, deficit irrigation treatments resulted in a remarkable decrease in gs in both

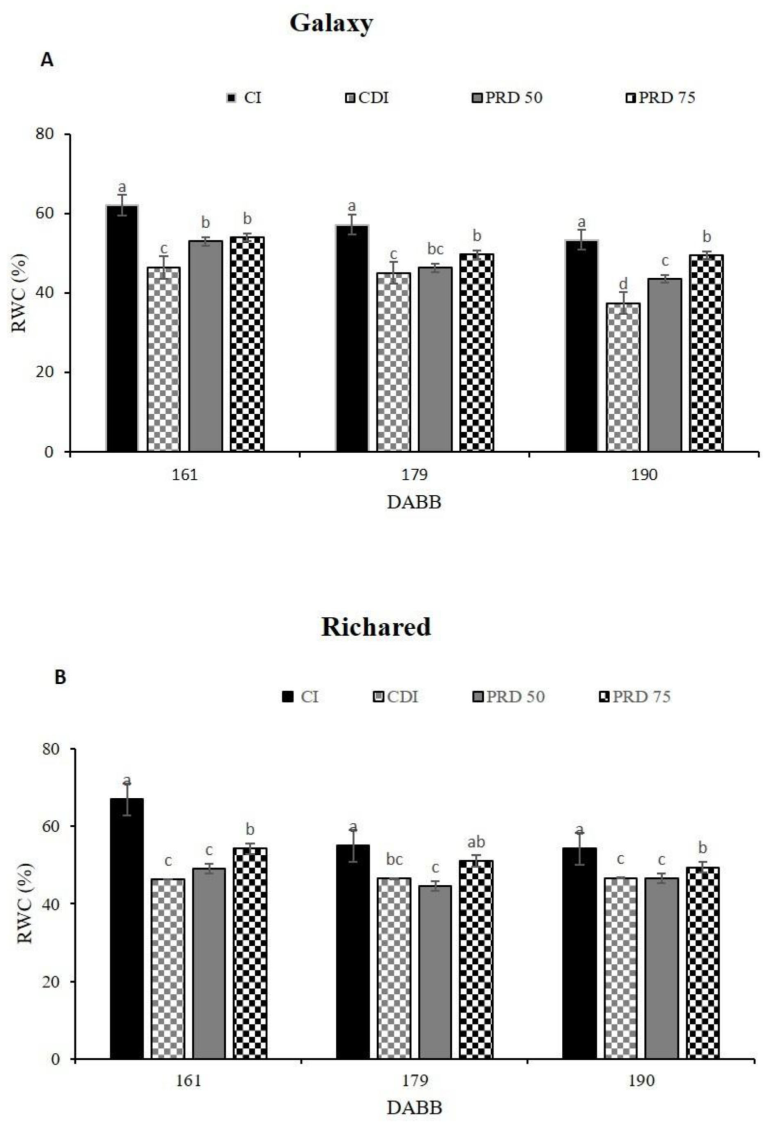

FIGURE 5
Dynamic of water depletion in the root zone (0–40 cm) under different irrigation treatments during the studying period of the two apple cultivars Galaxy and Richared. **(A)**: WS CI and CDI 50% ETC; **(B)**: WS PRD 75% (L) and PRD50% (L); (C): WS PRD 75% (R) and PRD 50% (R). WS, water stock; RAW, readily available water; WP, wilting point, fc: field capacity; CI, control irrigation; CDI, Continuous deficit irrigation, PRD, Partial Root Draining; PRD 50% ETC (R)) right side; PRD 75% ETC (L), left side.

cultivars studied mainly under the CDI 50% ETc and 50% PRD treatments compared to the control and the 75% PRD water regime. It seems that Tr and gs were more sensitive to deficit irrigation strategies (CDI 50% ETc and 50% PRD).

The variation of instantaneous water use efficiency (WUEins) was slightly affected by the irrigation treatment as shown in Table 1, during the fruit harvest and post-harvest period. Indeed, in both cultivars, there was a slight increase recorded for WUEinst values under water deficit regimes (PRD50% and CDI at 50% ETc). The application of water stress affected the two apple cultivars differently. In fact, the Richared cultivar was the less affected by the water deficit. and WUE has reached 6.06 µmol $mmol^{-1}$ under PRD50%, compared to Galaxy.

3.6 Impact of different irrigation regimes on fruit quality

3.6.1 Fruit growth assessment

The results of the evolution of fruit growth under different irrigation treatments are shown in Figures 6A, B. For both cultivars, the most significant growth occurred 148 DABB. Under control irrigation treatment, the Richared cultivar had greater fruit growth, reaching a size of 129.98 mm, whereas Galaxy had fruit that did not exceed 84.93 mm. The water deficit regimes had significantly reduced fruit growth in both Galaxy and Richared cultivars. Indeed, growth of fruits exposed to the CDI 50% ETc and PRD50% treatments was the most affected (a reduction of 25%

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TABLE 1 Gas exchange parameters in the two apple varieties subjected to four irrigation treatments during the stages of development, fruit ripening, and post-harvest.

Cultivars	Treatments	Fruit development				Fruit ripening				Post-harvest			
		Pn (µmol m^{-2} s^{-1})	Tr (mmol m^{-2} s^{-1})	gs (mmol H_2O m^{-2} s^{-1})	WUE (µmol $mmol^{-1}$)	Pn (µmol m^{-2} s^{-1})	Tr (mmol m^{-2} s^{-1})	gs (mmol H_2O m^{-2} s^{-1})	WUE (µmol $mmol^{-1}$)	Pn (µmol m^{-2} s^{-1})	Tr (mmol m^{-2} s^{-1})	gs (mmol H_2O m^{-2} s^{-1})	WUE (µmol $mmol^{-1}$)
Galaxy	CI	17.35 ± 3.64^{aw}	3.92 ± 0.10^{aw}	175.50 ± 3.05^{aw}	$4,52 \pm 0.39^{aw}$	13.53 ± 1.53^{aw}	2.99 ± 0.27^{ax}	165.50 ± 5.31^{awx}	4.52 ± 0.19^{aw}	13.07 ± 0.31^{aw}	2.77 ± 0.19^{ax}	158.98 ± 2.50^{ax}	4.71 ± 0.20^{aw}
	CDI	17.08 ± 1.67^{aw}	3.86 ± 0.39^{aw}	168.07 ± 8.98^{aw}	4.43 ± 0.43^{aw}	11.39 ± 1.09^{ax}	2.18 ± 0.20^{bx}	152.14 ± 3.47^{aw}	$5.22 \pm 0.37^{a\ w}$	11.09 ± 0.57^{bx}	2.51 ± 0.23^{ax}	148.15 ± 2.65^{bw}	5.25 ± 0.17^{aw}
	PRD75%	15.67 ± 2.75^{aw}	3.88 ± 0.41^{aw}	169.38 ± 9.64^{aw}	4.11 ± 0.47^{aw}	12.87 ± 0.58^{aw}	2.68 ± 0.11^{abx}	159.29 ± 6.87^{aw}	4.81 ± 0.14^{aw}	13.12 ± 1.05^{aw}	2.68 ± 0.54^{ax}	155.87 ± 5.87^{aw}	4.88 ± 0.06^{aw}
	PRD50%	16.22 ± 3.96^{aw}	4.22 ± 0.56^{aw}	164.77 ± 9.64^{aw}	3.81 ± 0.46^{aw}	11.35 ± 1.91^{aw}	2.04 ± 0.12^{bx}	150.27 ± 8.36^{ax}	5.56 ± 0.54^{aw}	10.97 ± 0.85^{bw}	2.19 ± 0.24^{ax}	147.36 ± 5.87^{bx}	5.01 ± 0.26^{aw}
Richared	CI	18.32 ± 1.57^{AW}	3.98 ± 0.24^{AW}	169.18 ± 8.19^{AW}	4.60 ± 0.15^{AW}	14.20 ± 2.08^{AX}	2.97 ± 0.32^{AX}	140.18 ± 7.36^{AX}	4.78 ± 0.53^{AW}	14.06 ± 1.33^{AX}	2.79 ± 0.61^{AX}	136.25 ± 4.37^{AX}	5.08 ± 0.12^{AW}
	CDI	16.64 ± 0.47^{ABW}	3.50 ± 0.11^{AW}	166.30 ± 4.66^{AW}	4.74 ± 0.19^{AW}	10.36 ± 1.52^{BCX}	1.82 ± 0.41^{BX}	128.26 ± 5.72^{BX}	5.70 ± 0.24^{AW}	10.65 ± 1.36^{AX}	2.10 ± 0.31^{BX}	125.36 ± 2.98^{BX}	5.05 ± 0.18^{AW}
	PRD75%	16.48 ± 1.67^{BW}	3.79 ± 0.25^{AW}	165.02 ± 7.34^{AW}	4.34 ± 0.16^{AW}	13.69 ± 2.27^{ABW}	2.67 ± 0.35^{AX}	139.73 ± 10.5^{AX}	5.12 ± 0.67^{AW}	13.98 ± 0.85^{AW}	2.80 ± 0.23^{AX}	132.87 ± 4.87^{AX}	4.99 ± 0.19^{AW}
	PRD50%	17.67 ± 2.78^{ABW}	3.53 ± 0.35^{AW}	161.30 ± 5.24^{AW}	5.00 ± 0.43^{AW}	9.82 ± 3.30^{CX}	1.62 ± 0.35^{BX}	124.98 ± 7.85^{BX}	6.06 ± 0.26^{AW}	11.10 ± 2.49^{AX}	2.03 ± 0.12^{BX}	119.36 ± 1.15^{BX}	5.46 ± 0.07^{AW}

Values are the means of three different apple leaf samples ($n = 3$) ± standard deviation. Letters a, b, c, and d indicate significant differences ($p < 0.05$) between the four treatments for Galaxy. Letters A, B, C, and D indicate significant differences ($p < 0.05$) between the four treatments for Richared. Letters w, x, and y, and W, X, and Y indicate significant differences ($p < 0.05$) between three studied stages (fruit development, fruit ripening, and post-harvest) for Galaxy and Richared, respectively. CI, control irrigation; CDI, continuous deficit irrigation, PRD, partial root draining; PRD50%, partial root draining at 50% ETc; PRD75%, partial root draining at 75% ETc; Pn, net photosynthesis rate; gs, stomatal conductance; Tr, transpiration rate; WUEins, instantaneous water use efficiency.

and 33.93% for Galaxy and Richared, respectively, under CDI 50% ETc). However, this reduction was weak under PRD75%, where fruit diameters were 76.36 and 115.91 mm for Galaxy and Richared, respectively (Figure 6).

3.6.2 Fruit quality parameters

The analysis of yield shown in Table 2 revealed that, under CI treatment, Richared had a higher yield (5.70 kg $tree^{-1}$) compared to Galaxy (4.23 kg $tree^{-1}$). CDI and PRD50% significantly reduced fruit yield for both cultivars. However, for trees exposed to PRD75%, this effect was not observed in the Galaxy cultivar, while a slight decrease was recorded for Richared. In addition, our results also showed that the fruits of the Richared cultivar had the highest weight and size (127.47 g and 68.21 mm, respectively) compared to those of Galaxy (84.86 g and 57.39 mm, respectively) under control irrigation treatment. Our results also revealed a significant decrease in size (length and width) and weight of fruits for the two cultivars ($p < 0.05$) exposed to deficit irrigation treatments. Indeed, the irrigation strategies PRD50% and CDI induced the smallest fruits (59.49 and 88.19 g for Galaxy and Richared, respectively, under CDI 50% ETc). In contrast, the fruit of trees subjected to PRD75% irrigation are significantly heavier (79.32 and 113.27 g for Galaxy and Richared, respectively) and larger than those of CDI and PRD50%.

The results shown in Table 2 showed that under control irrigation treatment (100% ETc), the fruits of the Galaxy cultivar showed the highest values of firmness (6.57 kg cm^{-2}) compared to Richared fruit (5.53 kg cm^{-2}). In addition, firmness varied significantly with irrigation treatments. In fact, fruits of Galaxy and Richared cultivars exposed to deficit water treatment (PRD50% and CD) had the highest values of firmness, while those harvested from trees exposed to the PRD75% treatment showed a slight increase, not significant, in both cultivars (7.33 and 5.87 kg cm^{-2} for Galaxy and Richared, respectively) (Table 2). In addition, we found that fruits of the Richared cultivar showed the highest TSS values (16.42°Brix). In both cultivars, the application of deficit irrigation significantly increased the TSS values. Indeed, the fruits of trees exposed to deficit irrigation PRD75% have the highest TSS values (19.50 and 17.50°Brix for Galaxy and Richared, respectively).

Our results showed, as well, that deficit irrigation treatment had significantly increased fruit acidity for Galaxy under PRD50% and CDI 50% ETc. On the other hand, this was not the case for Richared fruits. Furthermore, the results illustrated in Table 2 had shown that the NO_3^- rate accumulated in the fruits decreased significantly with deficit irrigation.

Moreover, the variation of the epicarps color in the fruits of two apple cultivars under different water treatments is illustrated in Table 2. The results showed that the fruits of Galaxy and Richared are characterized by high values of L^* and b^*, which indicates the yellowish green coloring. Instead, the values of a^* are lower and vary from 30.25 to 37.28 in Galaxy and from 11.52 to 21.27 in the fruits of Richared under different water treatments. In addition, we found that under water deficit, there was a significant increase in a^* in both cultivars, but no significant variation was recorded for L^* and b^*.

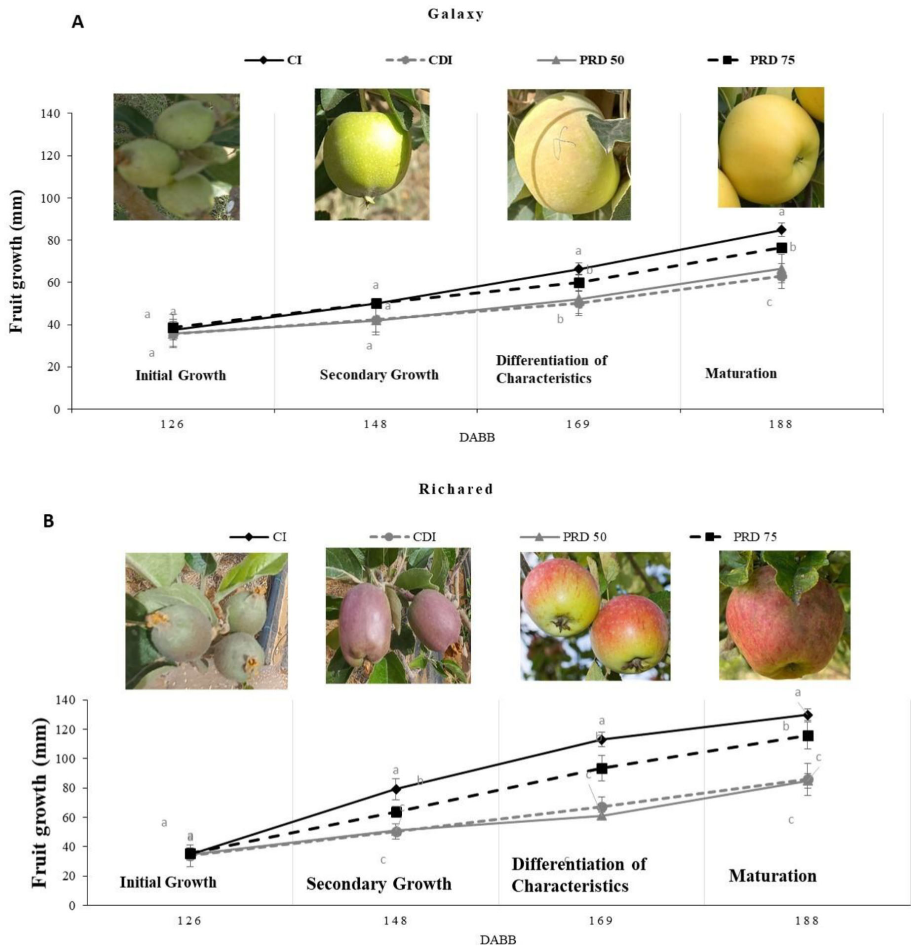

FIGURE 6
Impact of different water irrigation strategies on the evolution of fruit growth in the two apple cultivars Galaxy **(A)** and Richared **(B)**. Values are the means of four different apple fruits from three different trees (*n* = 12) ± standard deviation. Letters a, b, c, and d indicate significant differences ($p < 0.05$) between the four treatments for each cultivar separately. DABB, days after bud burst; CI, control irrigation; CDI, continuous deficit irrigation; PRD, partial root draining; PRD50%, partial root draining at 50% ETc; PRD75%, partial root draining at 75% ETc.

4 Discussion

Conventionally, farm managers using traditional irrigation provide a uniform amount of water during the growing season, based on their experiences, without taking into account plant water requirements, phenological stages, and climatic fluctuations. In contrast, appropriate irrigation scheduling promotes benefits such as saving water, decreasing environmental impacts, and generating sustainable agriculture (Domínguez-Niño et al., 2020). The use of smart tensiometers play a crucial role in precision irrigation, ensuring that crops receive the optimal amount of water while minimizing waste. In this study, we examine the effect of deficit irrigation strategies controlled by a precision tensiometer on Galaxy and Richared apple varieties by examining their physiological and pomological parameters.

In fact, we used smart moisture sensors to acquire real-time soil moisture data. These data enabled us to monitor the dynamics of water depletion in the root zone of apple trees and can serve as a reliable reference for determining the appropriate irrigation strategy and monitoring water consumption in the root zone. Our findings revealed that the ETc reached its maximum, 72 and 61 mm decade^{-1} during the mid and late development stage of the apple tree, respectively. ETc varies with climatic conditions and is also dependent on the tree including vegetative growth, tree height, leaf area, and cover rate. These changes in vegetation result in variations in ETc and, hence, variations in the crop coefficient (Kc). In addition, Ben Aïssa et al. (2000) found that tree transpiration depends positively on the amount of foliage. Indeed, the ratio (Tr/ET_0) increased over the days during the growing season, which was also reported by Zhang et al. (2024). Concerning the dynamics of water depletion, our results showed that under the CI treatment (Figure 3A), the soil water content for the two studied cultivars was in the comfort range in the root zone between 80 and 120 mm, and no water stress was detected during the whole study period. This is consistent with previous findings that control irrigation keeps root zone moisture stable and tree function optimal during critical phenological stages (Hao et al., 2025). After the application of water deficit (123 DABB), we found that, under PRD75% treatment, water was depleted rapidly and soil water content dropped to the permanent wilting point within 10

TABLE 2 Fruit yield, physicochemical characteristics, and skin color variation of the two apple cultivar fruits subjected to four irrigation treatments.

Cultivar	Treatment	Yield (kg tree^{-1})	Firmness (kg cm^{-2})	TSS (°Brix)	pH	Acidity (% malic acid)	NO^{3-} (ppm)	Weight (g)	Length (mm)	Size (mm)	*L**	*a**	*b**
Galaxy	CI	4.23 ± 0.56^{a}	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}	84.86 ± 1.82 ^{a}	54.25 ± 1.47 ^{a}	57.39 ± 2.61 ^{a}	81.75 ± 15.08^{a}	30.25 ± 1.08^{b}	102.25 ± 12.36^{a}
	CDI	3.26 ± 0.28^{b}	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}	52.49 ± 3.02^{d}	40.68 ± 2.55^{c}	44.86 ± 2.54^{b}	94.18 ± 10.75 ^{a}	35.28 ± 1.15 ^{a}	92.16 ± 11.69^{a}
	PRD75%	4.10 ± 0.36^{a}	7.33 ± 0.71^{a}	19.50 ± 0.12^{a}	3.70 ± 0.03^{a}	8.53 ± 0.47^{b}	142.00 ± 2.00^{b}	79.32 ± 3.85^{b}	50.28 ± 1.14^{b}	54.11 ± 3.80^{a}	92.81 ± 9.14 ^{a}	32.52 ± 1.58^{b}	93.42 ± 5.65 ^{a}
	PRD50%	3.09 ± 0.18^{b}	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}	59.11 ± 2.31^{c}	40.49 ± 3.74^{c}	45.18 ± 4.95^{b}	87.55 ± 11.72 ^{a}	37.25 ± 1.34 ^{a}	99.13 ± 11.35^{a}
Richared	CI	5.70 ± 0.35^{A}	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}	127.47 ± 7.47 ^{A}	59.87 ± 1.71 ^{A}	90.19 ± 4.10 ^{A}	79.47 ± 22.14 ^{A}	11.52 ± 0.95 ^{C}	83.19 ± 5.56 ^{A}
	CDI	3.85 ± 0.47^{C}	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}	88.19 ± 5.76^{C}	48.19 ± 4.41^{C}	51.73 ± 1.24^{D}	83.13 ± 19.36 ^{A}	20.35 ± 7.61 ^{A}	81.31 ± 3.06 ^{A}
	PRD75%	5.13 ± 0.28^{B}	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}	113.27 ± 4.64^{B}	57.28 ± 3.81^{B}	63.11 ± 2.26^{B}	89.90 ± 20.84 ^{A}	14.24 ± 0.69 ^{B}	76.74 ± 8.59 ^{A}
	PRD50%	4.12 ± 0.11^{C}	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}	90.19 ± 6.31^{C}	47.68 ± 2.36^{C}	57.28 ± 2.64^{C}	84.82 ± 18.98 ^{A}	21.27 ± 6.09 ^{A}	74.96 ± 12.56 ^{A}

Values are the means of six different fruit samples ($n = 6$) ± standard deviation. Letters a, b, c, and d indicate significant differences ($p < 0.05$) between the four treatments for Galaxy. Letters A, B, C, and D indicate significant differences ($p < 0.05$) between the four treatments for Richared. CI, control irrigation (100% ETc); CDI, continuous deficit irrigation (at 50% ETc); PRD, partial root draining; PRD50%, partial root draining at 50% ETc; PRD75%, partial root draining at 75% ETc.
The symbol * is for a*, L* and b* which expresses color as three values: L* for perceptual lightness and a* and b* for the four unique colors of human vision: red, green, blue and yellow.

days of withholding water, in the left side of the root zone; however, on the right side, soil water content was sufficient to support physiological activity until approximately 140 DABB (Figures 3B, C). This is consistent with the mechanism of PRD where alternating wet and dry zones stimulate partial stomatal closure without compromising overall plant water status. Under CDI (50% ETc), there was a decline in soil water content. Indeed, RAM was reached 130 DABB and depletion continued to the WP at 140 DABB (Figure 3A). This gradual and balanced decline suggests that roots were uniformly affected by the reduced water supply and potentially limited the tree's adaptability (Hao et al., 2025).

Our results showed that shoot growth (Figure 4) was the most sensitive to the irrigation regime and decreased significantly under PRD50% and CDI, with a reduction of shoot growth approximately 31.65% and 38.63% for Galaxy and Richared, respectively. This knowledge aligns with findings from other previous studies in apple (Reid and Kalcsits, 2020). In addition, the vegetative growth of the branches is less affected under the PRD75% treatment compared to other deficit treatments and in both varieties. This was also confirmed by Ben Messaouda et al. (2017) in the "Starkrimson" apple cultivar, cultivated in the Northwest of Tunisia. In fact, according to Lo Bianco (2013), shoot growth reductions are often considered as a result of water shortages, but they can also be seen as an adaptive mechanism and a water-saving strategy through reductions in the transpiration surface. Vegetative growth reductions for apples are also documented under regulated deficit irrigation by Mills et al. (1997), whereas contrasting expectations and results have been observed for trees under PRD.

Regarding relative leaf water contents, our results showed a slight decrease of this parameter in both cultivars even in trees treated with 100% ETc (CI). The increase of evaporative demand, under high temperature and lack of precipitation, may explain this reduction. Furthermore, the reduction of RWC in apple leaves under deficit irrigation has been proven in many other species such as pomegranate (Pourghayoumi et al., 2017), peach (Guizani et al., 2019), and plum (Hajlaoui et al., 2022). The effect of PRD75% treatment was moderate, and the trees were able to maintain high leaf water content (approximately 49% during 190 DABB) in both cultivars. This can be explained by the fact that in the PRD system, the roots on the irrigated side absorb enough water to maintain a high water potential while those on the non-irrigated side produce abscisic acid (ABA), which, in turn, regulates stomatal conductance and optimizes water use (Kang et al., 2000; Ahmadi et al., 2010). In addition, in the present study, the results of gas exchange showed that no significant difference was recorded during the fruit growth period under all irrigation treatments. This may be explained by the fact that since the water deficit was not very severe, the trees are able to absorb their needs from the water stock in the soil. However, during fruit ripening, there was a significant decrease of these parameters (transpiration and stomatal conductance) mainly in the Richared cultivar under 50% PRD (from 2.97 to 1.62 mmol m^{-2} s^{-1} for Tr and from 140.18 to 124.98 mmol H_2O m^{-2} s^{-1} for gs). Similar findings have been reported by Azzeddine et al. (2019). In fact, the reduction of net CO_2 assimilation (Pn) was probably elucidated by the closure of stomata when the leaf water potential fell below a given threshold (Centritto et al., 2002). However, the absence of a significant reduction of Pn and gs for trees exposed to PRD75% ETc may be explained by the fact that during a light PRD deficit irrigation, the wet part captures water to maintain the water balance of plants, while the dry part causes a partial closure of the stomata. This reduces their transpiration losses due to the production of ABA. However, a small amount of water is evacuated via the stomata, which causes the absorption of CO_2 and thus the production of glucose during the photosynthesis process. The fluctuations in stomatal opening and closing influence the photosynthetic rate and stomatal conductance (Iqbal et al., 2020). According to Raza et al. (2017), mild water stress does not influence the photosynthetic rate as much as leaf enlargement.

Moreover, the reduction of gs under water deficit conditions is related to the plant's ability to withstand drought conditions. The linear correlation of gs and Pn that is documented in previous studies (Šircelj et al., 2007; Guizani et al., 2019) confirms that gs controls Pn, and the limitation of gs induces a decrease in photosynthetic assimilation. On the other hand, the variation of photosynthesis rate from the fruit development, fruit ripening, and post-harvest stage was also reported by Laužikė et al. (2020), who mentioned that photosynthetic indices of apples are most affected by development stages during the season. This variation is related to physiological changes of metabolite transport and distribution during fruit ripening and leaf senescence. For both varieties, a significant reduction of gs was also noted under continuous and PRD (50%) deficit irrigation compared to control irrigation. Previous studies confirmed these findings under different environmental conditions (Lo Bianco, 2013). In fact, this decrease reflects the crop's sensitivity to water deficit. Similarly, other studies have shown that photosynthesis is significantly affected by PRD irrigation. According to Zegbe et al. (2004), cultivar type and environmental conditions significantly affect the results of PRD irrigation.

Our results displayed that during the first days of the application of deficit irrigation, shoot growth and photosynthetic parameters were not significantly affected by water shortage. However, a few days later and especially under deficit water regimes (CDI and PRD50%), with soil water content below the readily available water until the wilting point (Figure 3), physiological traits were gradually affected. Similar results were mentioned by Lawlor and Cornic (2002) and Bhusal et al. (2019) in apple trees. In contrast, our work also revealed that there was an increase in instantaneous water use efficiency (Pn/Tr) in trees subjected to PRD50% (5.56 and 6.06 µmol mmol^{-1}, for Galaxy and Richared, respectively, during fruit ripening). In fact, according to Kang et al. (2000), WUE increases under PRD irrigation compared to CI treatment. This increase can be explained by the fact that under PRD irrigation, less water is required to maintain yield, which leads to a reduction in overall water consumption although inducing some degree of water stress in the plant, which can improve WUE.

Fruit quality analysis showed that Richared exhibited the highest yield and the best fruit (in terms of weight and size) and even TSS, despite both cultivars undergoing the same irrigation, fertigation, and climatic conditions. This may be related to the varietal effect. It is important to mention that even for control irrigation conditions, the yield is considered low, because the trees are still young (3 years) and are not in full production. The application of deficit irrigation strategies (CDI and PRD50%) during the last phase of fruit development significantly reduced yield. This was not the case for trees exposed to PRD75%; this treatment does not have a depressive effect on physiological parameters and especially gas exchange parameters. According to Wen et al. (2024), apple is sensitive to severe water deficit during this period because it can lead to the loss of elasticity in plant cell walls, damage to leaves, and reduced photosynthetic capacity, causing a reduction in yield.

In addition, no significant impact was recorded on fruit diameter under diverse water deficit treatment during the beginning of application. However, we noted a remarkable decrease of fruit growth under PRD and continuous 50% treatments compared to control treatment. It is important to indicate that the fruit diameter was greater under 75% PRD treatment, and even fruit size was less affected. These results are in agreement with Goldhamer et al. (2006) and Badiee et al. (2023) who found that continued daily application of deficit irrigation during the rapid fruit growth phase would most likely decrease apple and almond fruit growth. During the experiment, the irrigation treatments had significantly affected fruit quality in the two varieties studied. In fact, there was a significant decrease in the yield, size, and weight among the fruits exposed to deficit irrigation; however, those exposed to PRD75% were the least affected. These results are in accordance with previous studies in different crops, including apple (Badiee et al., 2023), peach (Guizani et al., 2019), and plum (Maatallah et al., 2015).

According to the results of this study, a significant improvement in fruit quality was reported by the PRD75% water regime, despite the slight decrease in size and weight, which does not generally affect commercial quality. According to Hao et al. (2025), PRD irrigation improved leaf photosynthetic efficiency, which increased the transport of photosynthetic products to the fruit and enhanced nutritional content and market quality. In fact, fruit flesh firmness was shown to be significantly affected by the deficit irrigation treatments. The greatest values of firmness were recorded under PRD50% for Richared (7.70 kg cm^{-2}) and under CDI (50% ETc) for Galaxy (8.50 kg cm^{-2}). These findings are in agreement with previous results in the apple fruit (Mpelasoka et al., 2001; Küçükyumuk et al., 2013). Moreover, there was a significant increase of TSS under deficit irrigation strategies. The high values of TSS may be explained by the conversion of starch into sugars (Wan Zaliha and Singh, 2010). Indeed, fruit exposed to PRD75% recorded the highest level of TSS (17.50 and 19.50°Brix in Richared and Galaxy, respectively). Similar results were reported by Leib et al. (2006) and Mpelasoka et al. (2001). On the other hand, Ben Messaouda et al. (2017) found opposite results, and they showed that PRD50% treatment did not alter soluble solids and firmness. Generally, controlled irrigation PRD75% had no negative impact on apple quality, but instead increased water use efficiency. In this context, Zegbe and Behboudian (2008) reported that an increase of WUE by 120% allowed a reduction of 0.14 megaliters of water per hectare, which increased the farmer's economic profits.

In addition, our results showed that fruit skin color varied significantly among irrigation strategies. In fact, red skin color (a^*) increased significantly with deficit irrigation. The study's findings, regarding skin color, were consistent with those of previous studies (Kilili et al., 1996; Mills et al., 1997; Wan Zaliha and Singh, 2010), which found that redness increased as a result of insufficient watering. In fact, according to Wan Zaliha and Singh (2010), the improvement in fruit color can be attributed to the higher concentration of total anthocyanins on the apple skin. This could be associated with better sunlight penetration into the canopy and onto the fruits, due to sparse leaf abscission induced by water deficit. Furthermore, Küçükyumuk et al. (2013) explained the impact of deficit irrigation on skin color by the shoot length reduction, where the lowest shoot length values were correlated with the highest red color values.

Besides the important role of deficit irrigation strategies (PRD) in saving water and improving fruit quality, recent studies on the chemical and biological fertility of orchard soils have demonstrated that sustainable and innovative soil management systems are based on water management (Futa et al, 2024; Sofo et al., 2012). According to our results, PRD75% can establish an ideal nutrient balance for the plant and avoid nutrient accumulation, soil salinization, and the risk of leaching. In addition, optimized irrigation efficiency can prevent soil erosion and root asphyxiation. The use of smart irrigation based on smart tensiometers, which have a low environmental impact, can restore or increase soil fertility levels in fruit agro-ecosystems.

5 Conclusion

Accurate smart irrigation scheduling is essential for estimating the real need of the plants without excess or deficit. In this study, we investigated the irrigation scheduling techniques under four different irrigation treatments. The results illustrated that deficit irrigation strategies save water, but at higher levels of stress, the plant's physiology and fruit quality were affected. However, under PRD75%, the plants reached the RAM after irrigation for the two cultivars Galaxy and Richared. This allowed us to conclude that the PRD75% strategy controlled by smart tensiometers seems to be the most recommended in the region of the present study, given its moderate effect on the shoot growth as well as on the parameters of gas exchanges. Similarly, this irrigation strategy increased the sugar level and firmness and did not alter the weight and size of the fruits. The irrigation strategy PRD75% saves water, promotes physiological stability, improves fruit quality, and preserves soils for better sustainability of fruit production. Therefore, it could be a good choice for orchards of apple trees in areas with frequent rainfall. Furthermore, Richared seems to be the most suitable choice for this climate, given its fruit quality and the best physiological behavior under deficit irrigation treatments.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

MB: Conceptualization, Data curation, Validation, Writing – original draft. MG: Conceptualization, Data curation, Validation, Writing – original draft. SM: Writing – review & editing. OE: Writing – review & editing. MR: Conceptualization, Funding acquisition, Investigation, Methodology, Software, Supervision, Validation, Writing – review & editing.

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Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fagro.2025.1666801/full#supplementary-material

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