



Optimizing Jalapeño pepper growth and water use efficiency under deficit and partial rootzone drying irrigation in arid and semiarid regions

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Abstract

The delicate balance between water availability and demand has reached a critical point, with projections suggesting that future agricultural water demand will likely exceed available resources. Therefore, efficient water use is critical for sustainable agriculture in arid and semiarid regions. This study investigated the effects of deficit irrigation (DI) and partial rootzone drying (PRD) on the physiological performance, yield, and water use efficiency (WUE) of jalapeño pepper (*Capsicum annuum* L.) over two growing seasons. Six treatments were applied: full irrigation (FI), DI at 75% and 50% of FI (DI75, DI50), and PRD at 100%, 75%, and 50% of FI (PRD100, PRD75, PRD50), each with three replicates in a randomized complete block design. Despite yield reduction, DI75 (3.5%, 9.6%) and PRD75 (10%, 13.4%) were not significantly different from FI in yield during both growing seasons, 2022 and 2023, respectively. However, yield reduction of DI50 (54.6%, 54.4%) and PRD75 (62.1%, 43.6%) significantly differed from FI during both growing seasons 2022 and 2023, respectively. PRD treatments generally enhanced nutrient uptake and WUE compared to equivalent DI treatments. These findings suggest PRD75 is an effective water-saving strategy for jalapeño pepper production under water-limited conditions.

Keywords Partial rootzone drying · Deficit irrigation · *Capsicum annuum* L. · Water use efficiency · Arid agriculture

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1 Introduction

In numerous locations globally, the delicate equilibrium between water availability and demand has reached a critical juncture, with projections indicating that future water demand will likely surpass agricultural production (Mancosu et al. 2015). The prospect of regions competing for water supply becomes more plausible as the essential water resources for food production become increasingly scarce. Recognizing the pivotal role of irrigated agriculture in food security, it is imperative to acknowledge that it often results in higher crop yields than rain-fed conditions. To adequately meet the food needs, there is a necessity for an over 20% expansion in irrigated areas and a 40% increase in the output of irrigated crops. Consequently, there is a pressing need to enhance the productivity and efficiency of water resource utilization (Sepaskhah and Ahmadi 2010).

Jordan is among the most water-stressed countries globally. 2022 The Ministry of Water and Irrigation reported a 200 million cubic meter shortfall in drinking water (Mohawesh et al. 2022). Water allocations for agriculture

are routinely reduced to meet domestic needs, jeopardizing crop productivity and food security (Beithou et al. 2022; Mohawesh et al. 2022). In such contexts, advanced irrigation strategies are crucial. Techniques like drip irrigation have shown promise, yet further improvements are possible through methods that deliberately impose mild water stress to conserve water without significantly compromising yield.

Among the innovative strategies to improve irrigation efficiency, deficit irrigation (DI) and partial root zone drying (PRD) have received considerable attention. DI involves applying water below the full crop evapotranspiration (ET_c) demand, while PRD alternates irrigation between sides of the root system, allowing one side to experience drying and the other to receive water. This technique has induced physiological and molecular responses that enhance water use efficiency (WUE) without severely compromising yield (Chai et al. 2016; Iqbal et al. 2020). While PRD has been widely studied in crops such as tomato, maize, lettuce, and strawberry (Mattar et al. 2020; Kaman et al. 2023; Chen et al. 2023), there remains a notable lack of research focused on its application in jalapeño pepper (*Capsicum annuum* L.), particularly under arid and semiarid conditions. Most existing studies have emphasized vegetative or fruit-bearing crops with different root physiology and water requirements than hot peppers. Given the increasing economic importance of jalapeño peppers and their sensitivity to water stress, it is critical to understand how PRD affects their physiological responses, nutrient uptake, and yield performance compared to conventional DI. Moreover, little is known about the comparative WUE of jalapeño peppers under varying levels of PRD, which limits evidence-based irrigation strategies for optimizing production in water-limited regions. We hypothesized that PRD and DI would result in higher water use efficiency than FI; moderate water stress (PRD75, DI75) treatments would sustain yields comparable to FI; and severe water reduction (PRD50, DI50) would lead to significant declines in plant physiological performance, nutrient uptake, and yield. This study evaluates the effects of DI and PRD at varying irrigation levels (50%, 75%, and 100% of field capacity) on the physiological performance, yield, and WUE of jalapeño pepper grown under semi-controlled conditions.

2 Materials and methods

2.1 Study site and experimental setup

The experiment was conducted in the 2022 and 2023 growing seasons at the experimental field of the Faculty of Agriculture, University of Science and Technology, Jordan (32° 28' 01" N, 35° 58' 31.5" E, elevation 613.5 m) under controlled greenhouse conditions (9 m width × 50 m length) covered with white plastic sheets (200 µm). An automatic ventilation

system maintained the temperature and relative humidity inside the greenhouse between 24–27 °C and 50–70%, respectively. Jalapeño pepper (*Capsicum annuum* L.) (Sandia seed company, USA) was transplanted into 8 L pots (25 cm upper diameter, 19 cm lower diameter, and 20 cm height) after one month from sowing in the greenhouse on 27/5/2022 and 14/5/2023 in 2022 and 2023, respectively. The pots were divided into equal vertical compartments using a thick plastic sheet (400 µm) to prevent horizontal water movement between the two sides. Pots were filled with 9.75 kg of air-dried loamy soil (sand 35%, silt 47%, and clay 18%). Seedlings were transplanted to FI, DI75, and DI50 treatments. For PRD treatment, the roots of the seedlings were divided into two equal parts and transplanted, with each root side planted in each pot compartment. One seedling of jalapeño pepper (*Capsicum annuum* L.) was planted in each pot. Fertilizers NPK (20–20–20) were equally applied to all treatments at a rate of 520 kg/ha; it was applied once a month by dissolving 1.0 g of fertilizers in irrigation water for each pot. 0.5 g was dissolved in irrigation water for PRD treatment. At the same time, the remaining half was added with the next irrigation cycle to improve nutrient uptake and distribute the fertilizer equally between the two compartments (Mohawesh et al. 2022).

2.2 Soil analysis

Soil texture was determined using the hydrometer method (Gee and Bauder 1986). The core method measured soil bulk density (BD) (Klute and Dirksen 1986). Field capacity (FC) and permanent wilting point (PWP) were estimated using a pressure plate apparatus at −0.33 bar and −15 bar, respectively (Klute and Dirksen 1986). Soil pH and EC were determined by pH meter and EC meter, respectively. Total nitrogen was determined using the Kjeldahl nitrogen apparatus's Kjeldahl method (UDK 149 Automatic Kjeldahl Nitrogen Protein Analyzer, Italy) (Kalra 1970). Phosphorus was analyzed quantitatively using a UV/visible Spectrophotometer (PhotoLab 7600 UV–VIS, WTW GmbH, Germany) (Watanabe and Olsen 1965), potassium by flame photometer (BWB XP 5 Channel Flame Photometer, UK) (Kirnak et al. 2001), and calcium by flame photometer (BWB XP 5 Channel Flame Photometer, UK) (Klute and Dirksen 1986). Table 1 summarizes the physical and chemical properties of the soil.

2.3 Irrigation treatments

This experiment used three water irrigation levels (100%, 75%, and 50%) and two irrigation methods (DI and PRD) with FI as the control. Six treatments, with three replicates for each treatment, resulted in 18 pots organized in a Randomized Complete Block Design (RCBD). The treatments

Table 1 Physical and chemical properties of the experimental soil

Soil texture	BD (g/cm ³)	FC (%)	PWP (%)	AW/pot (mm)	pH (-)	EC (dS/m)	N (N)	P (mg/kg)	K (mg/L)	Ca (mg/L)
Loam	1.36	40.0%	20.0%	40	7.99	1.99	0.072	182.9	61.6	418.5

BD Bulk density, *FC* Field capacity, *PWP* Permanent wilting point, *AW* Available water, *pH* Alkalinity, *EC* Electrical conductivity

comprised: (1) Full irrigation (FI), (2) partial rootzone drying 100% (PRD100) where irrigation water was alternated between the two root compartments at the same volume as in FI, (3) partial rootzone drying 75% (PRD75) involving 75% of FI alternately applied to the two sides of the root system, (4) partial rootzone drying 50% (PRD50) with 50% of the irrigation water of FI applied alternately to the two sides of the root system, (5) deficit irrigation 75% (DI75) entailing 75% of the irrigation water of FI, and (6) deficit irrigation 50% (DI50) with 50% of the irrigation water of FI. Irrigation scheduling was managed by monitoring the weights of FI pots and using time domain reflectometry (TDR). The pots were irrigated to FI for two weeks after transplanting. Then, the irrigation commenced when 50% of the available water was depleted from FI treatment (readily available water (RAW)=50% of available water (AW)). The 75% and 50% of FI irrigation amounts were adjusted as a percentage of FI. Volumetric water content (Θ) was measured before and after 2 h of irrigation using a handheld time domain reflectometer (ThetaProbe, ML2x; Delta-T Devices, Cambridge, UK). Measurements were taken for FI, DI75, and DI50 on both sides for PRD100, PRD75, and PRD50. Irrigation interval depended on water consumption during the growing season, ranging from 2 to 4 days. The irrigation ended 120 days after transplanting.

2.4 Plant parameter measurements

Plant height and chlorophyll content were determined every two weeks during the experiment. Plant height was determined using a measuring tape. A chlorophyll meter (SPAD-502; Konica Minolta Sensing, Osaka, Japan) was used to determine the amount of chlorophyll in each plant's fully expanded, healthy leaf in triplicate. Leaf Area (LA) was measured every two weeks during the experiment (one leaf/plant/replicate) for each treatment. LA was determined using a portable LI-3100 Area Meter (LI-COR Inc., Nebraska, USA). The Leaf relative water content (RWC) of jalapeño pepper was measured every two weeks during the experiment (one leaf/plant/replicate) for each treatment for the same leaf of LAI. The leaf water potential (LWP) measurements were taken biweekly during the growth cycle. LWP was evaluated using a pressure chamber (one leaf/plant/replicate) for each treatment (Model 600-EXP Super Pressure Chamber, PMS instrument, Albany, OR, USA). At the end of the

experiment, jalapeño pepper plants (one plant/replicate) were harvested for each treatment. The harvesting process was done carefully to keep the plant and roots intact and ensure no part of the plant was lost. Jalapeño pepper plant parameters were estimated after shoot and root systems were separated, including shoot fresh weight (SFW), root fresh weight (RFW), shoot height (SH), shoot dry weight (SDW), and root dry weight (RDW). SFW and RFW were measured directly after harvesting using a weighing balance. SDW and RDW were determined after drying the shoots and roots in the oven at 70 °C for at least 48 h until they reached constant weight. Fruit yield was estimated by summing up the harvested plant production at maturity every 3–4 days. WUE was calculated as the ratio between yield (kg) and irrigation water applied for each treatment (m³) during the growing season.

2.5 Plant and fruit nutrient content analysis

The elemental contents of both shoot (one plant/replicate) and fruit samples (three fruits/plant/replicate) were measured for each treatment. The samples were dried at 70 °C until constant weight was reached. The total nitrogen content was determined using the Kjeldahl method by the Kjeldahl nitrogen apparatus (UDK 149 Automatic Kjeldahl Nitrogen Protein Analyzer, Italy), following the method described in (Bremner and Jenkinson 1960). The phosphorus (P) content was determined following the Vanadate Molybdate yellow color method using a spectrophotometer (PhotoLab 7600 UV-VIS, WTW GmbH, Germany) (Kirnak et al. 2001). A flame photometer (BWB XP 5 Channel Flame Photometer, UK) was used to measure the Potassium (K) and Calcium (Ca) content (Kirnak et al. 2001).

2.6 Statistical analysis

Differences among the treatments were analyzed using the R software program. Firstly, analysis of variance (ANOVA) was performed to confirm the significant differences among the treatments. Then, at a 95% confidence level, Fisher's protected least significant differences (LSDs) were used. Data from the two years were included; the year x treatment interactions were insignificant.

3 Results and discussion

3.1 Soil water content variation

Changes in volumetric soil water content during the 2022 and 2023 growing seasons are shown in Figs. 1 and 2. As expected, soil water content was higher under FI than DI75, DI50, PRD75, and PRD50 during the 2022 and 2023 growing seasons. The highest soil water content was recorded in FI (39.1 and 40.1 m³/m³) during the 2022 and 2023 growing seasons, respectively, while the lowest soil water content was recorded in PRD50 (27.7 m³/m³) and DI50 (26.2 m³/m³) treatments during the 2022 and

2023 growing seasons, respectively. PRD treatment values related to soil water content depended on the wetting and drying cycle (Fig. 1c).

3.2 Plant parameter measurements

3.2.1 Physiological and morphological parameters

As indicated in Fig. 3, it is evident that plants irrigated with 50% or 75% of FI were shorter than those irrigated with FI and PRD100. For example, the tallest jalapeño pepper plant measured FI (56.8 cm) at 100 DAT, while the shortest plant was DI50 (49.7 cm) during the 2022 growing season. Our

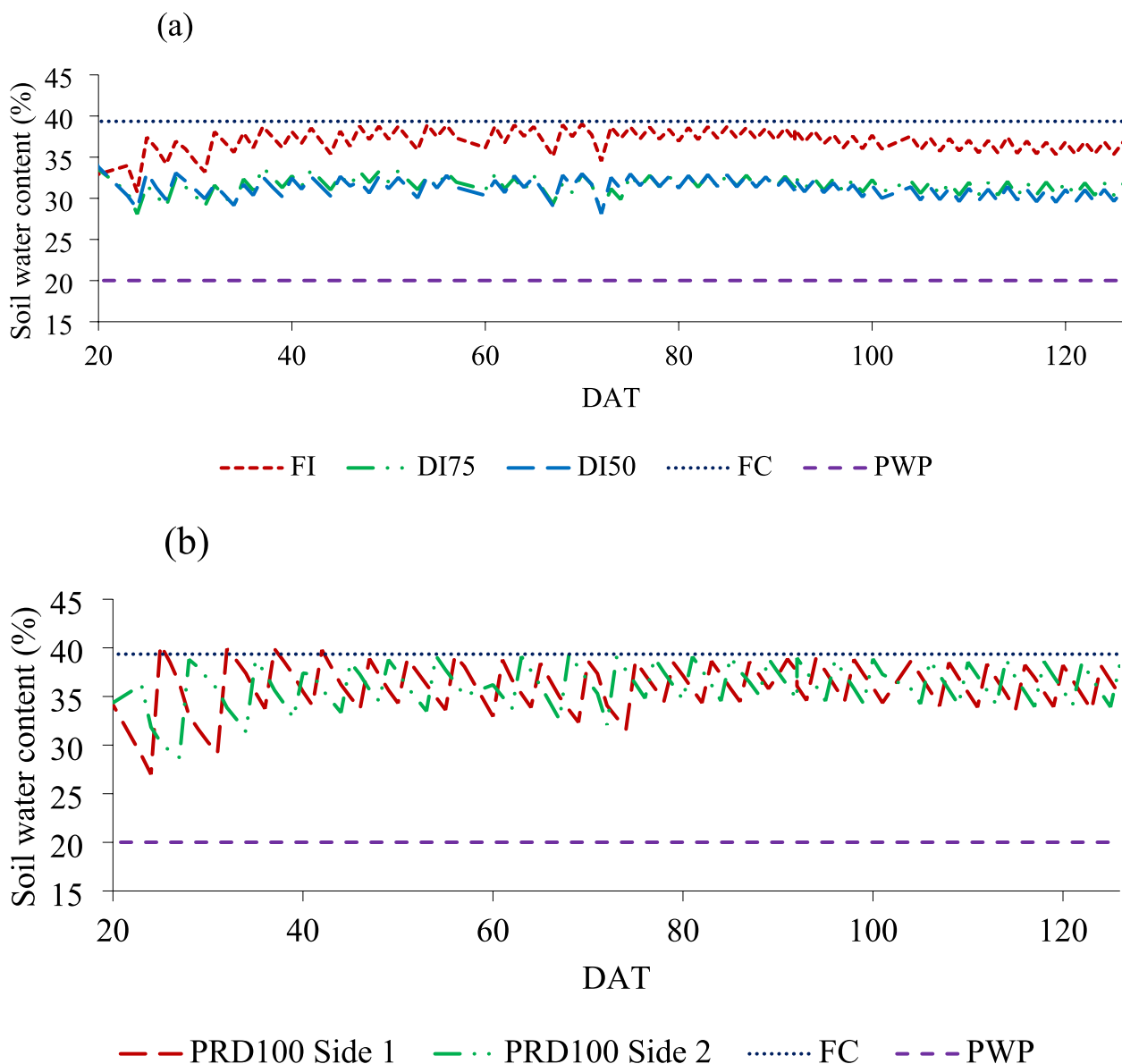


Fig. 1 Volumetric soil water content dynamics: (a) FI and DI treatments, (b) PRD100, (c) PRD75, and (d) PRD50 during 2022 growing season

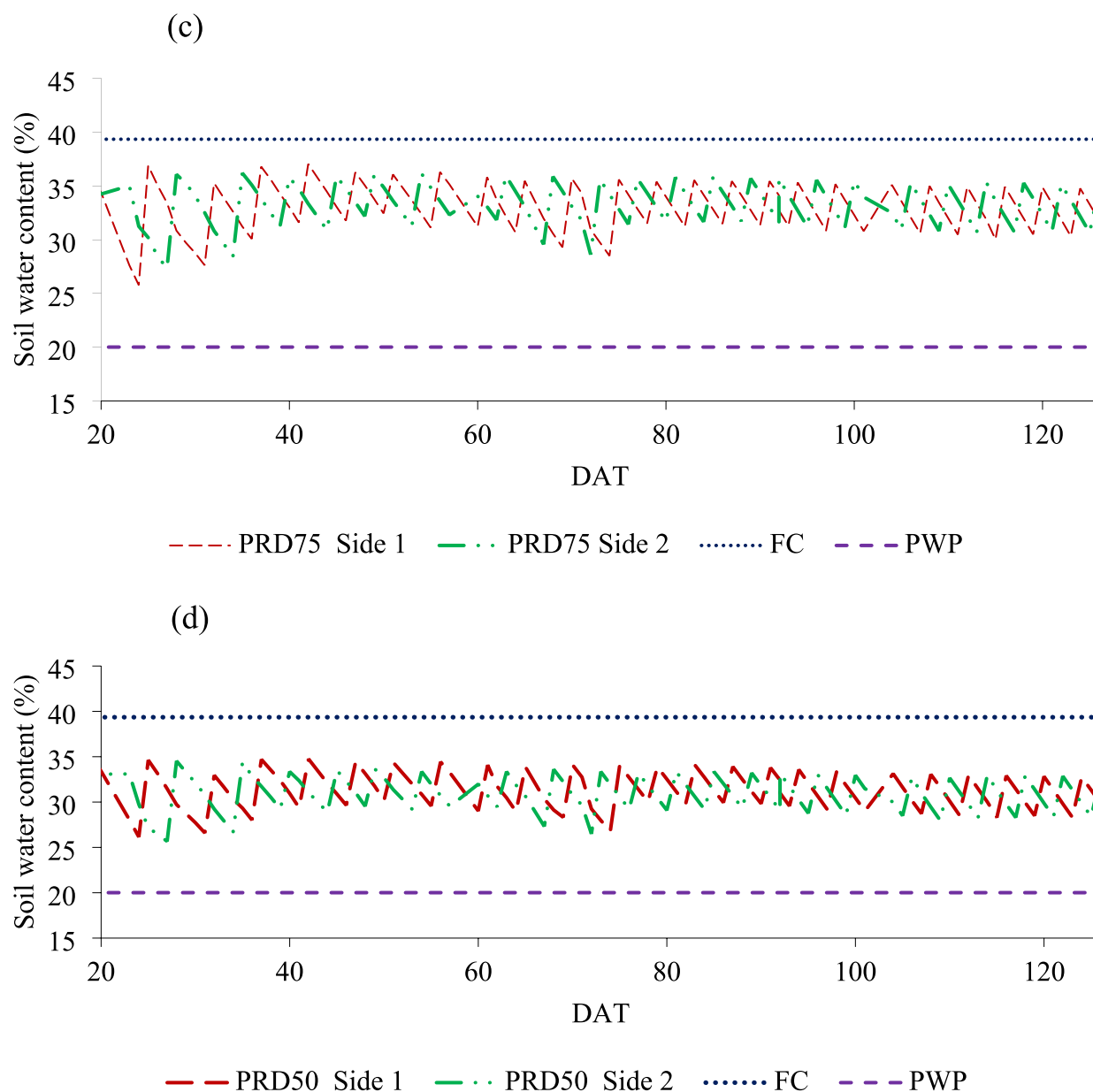


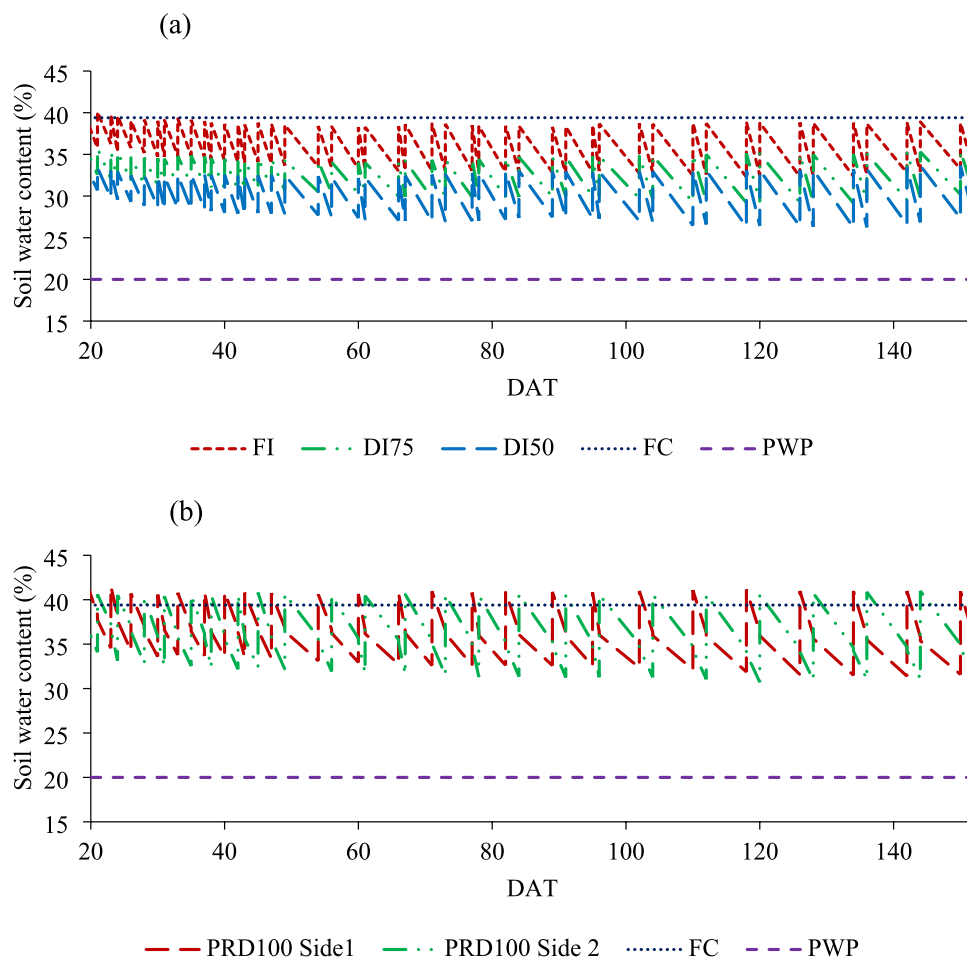
Fig. 1 (continued)

results are consistent with the results of Shao et al. (2008), who indicate that DI and reduced PRD at various growth stages of hot pepper statistically decreased plant height. Mattar et al. (2020) also observed that the plant height of tomatoes was reduced under DI and reduced PRD treatments.

The effect of irrigation treatment on chlorophyll content in jalapeño pepper during the growing season is illustrated in Fig. 4. FI, PRD100, and PRD75 showed significantly lower SPAD values during both seasons than other treatments. In contrast, DI50 had elevated SPAD values compared to all treatments. During the 2022 growing season, PRD50 was the second-highest chlorophyll content value from 87 DAT

until the end of the season, while during the 2023 growing season, it was higher than FI, PRD100, and PRD75 (Fig. 4). Water deficit can influence jalapeño pepper photosynthesis, which causes an increase in SPAD readings. Also, chlorophyll content in jalapeño pepper leaves under PRD treatment is less affected than in DI treatments with the same irrigation water. As shown by SPAD readings, the jalapeño pepper's photosynthesis in PRD is less affected by water stress. The results of this research can be explained by the fact that elevated water stress often leads to increased chlorophyll concentration in jalapeño pepper leaves (Fig. 4) (Chen et al. 2023). Chlorophyll fluorescence results from red and far-red

Fig. 2 Volumetric soil water content dynamics: **(a)** FI and DI treatments, **(b)** PRD100, **(c)** PRD75, and **(d)** PRD50 during 2023 growing season



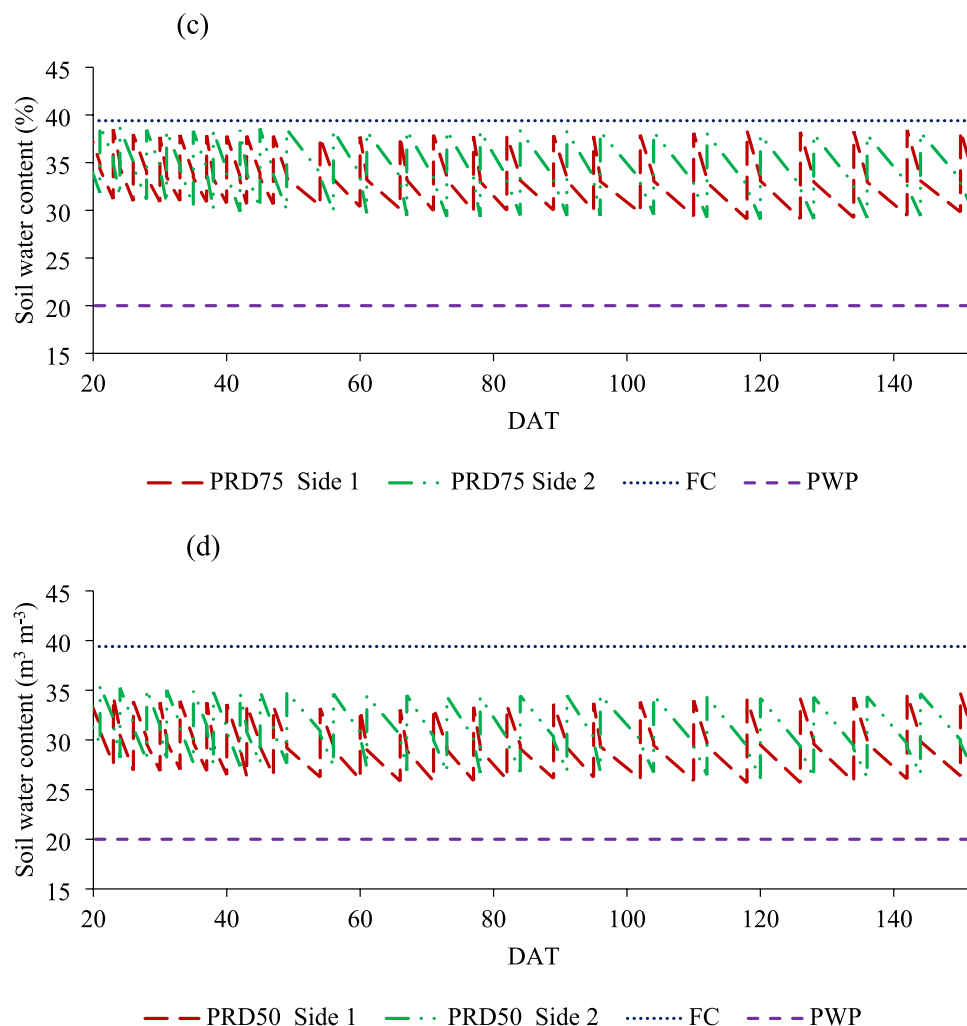
light released by photosynthetic plants in response to photosynthetically active light. Then, during photosynthesis, light energy is captured in the chloroplast and handled by two photosystems, which create energy and oxygen through oxidation–reduction reactions. Consequently, chlorophyll fluorescence’s reaction to light intensity and quality may be a sensitive indicator of a water deficiency and may be used to manage irrigation water in the PRD method (Alemu 2020).

The LWP of the jalapeño pepper plant under treatment during the 2022 and 2023 growing seasons is shown in Fig. 5. LWP was measured four times during the 2022 growing season and seven times during the 2023 growing season. The highest value of LWP during the 2022 and 2023 growing seasons was observed in FI (−6.8 bar) at 102 DAT and PRD100 treatment (−11.8 bar) at 85 DAT, respectively. There was no significant difference between FI and PRD100 during both growing seasons (Fig. 5). Generally, DI50 and PRD50 had significantly lower LWP than all treatments during the 2022 and 2023 growing seasons. The difference between PRD50 and DI50 was not statistically significant (Fig. 5). Fruits are stronger water sinks than plants’ vegetative parts; therefore, LWP may have decreased, especially in DI and PRD (50 and 75% FI), as a result of

competition for water from developing reproductive sinks and higher evaporative demand (Farah et al. 2021). Irrigation treatments significantly impacted the LWP values of jalapeño pepper; when water stress increased, LWP values significantly decreased compared to FI. Sezen et al. (2019) reported variations in the seasonal trends of LWP of red pepper leaf across various irrigation treatments; lower LWP values were observed with increasing water stress.

The highest RWC of the jalapeño pepper plant was recorded in FI and PRD100 treatments during the 2022 and 2023 growing seasons (90.0% and 90.2%, respectively) (Fig. 6). In contrast, the lowest value of RWC was recorded in DI50 and PRD50 treatments during the 2022 and 2023 growing seasons (49.8% and 48.6%, respectively). Under drought stress, DI50 and PRD50 had significantly lower RWC than other treatments due to limited water availability (Fig. 6). Water stress-induced reductions in leaf RWC indicate decreased plant tissue metabolism. Also, Kumar et al. (2017) reported that greater osmoregulation might result from a greater RWC in the grafted tomato plants under water stress. Yactayo et al. (2013) reported that plants under water stress had lower RWC than controls and that the RWC values of potatoes were significantly decreased

Fig. 2 (continued)

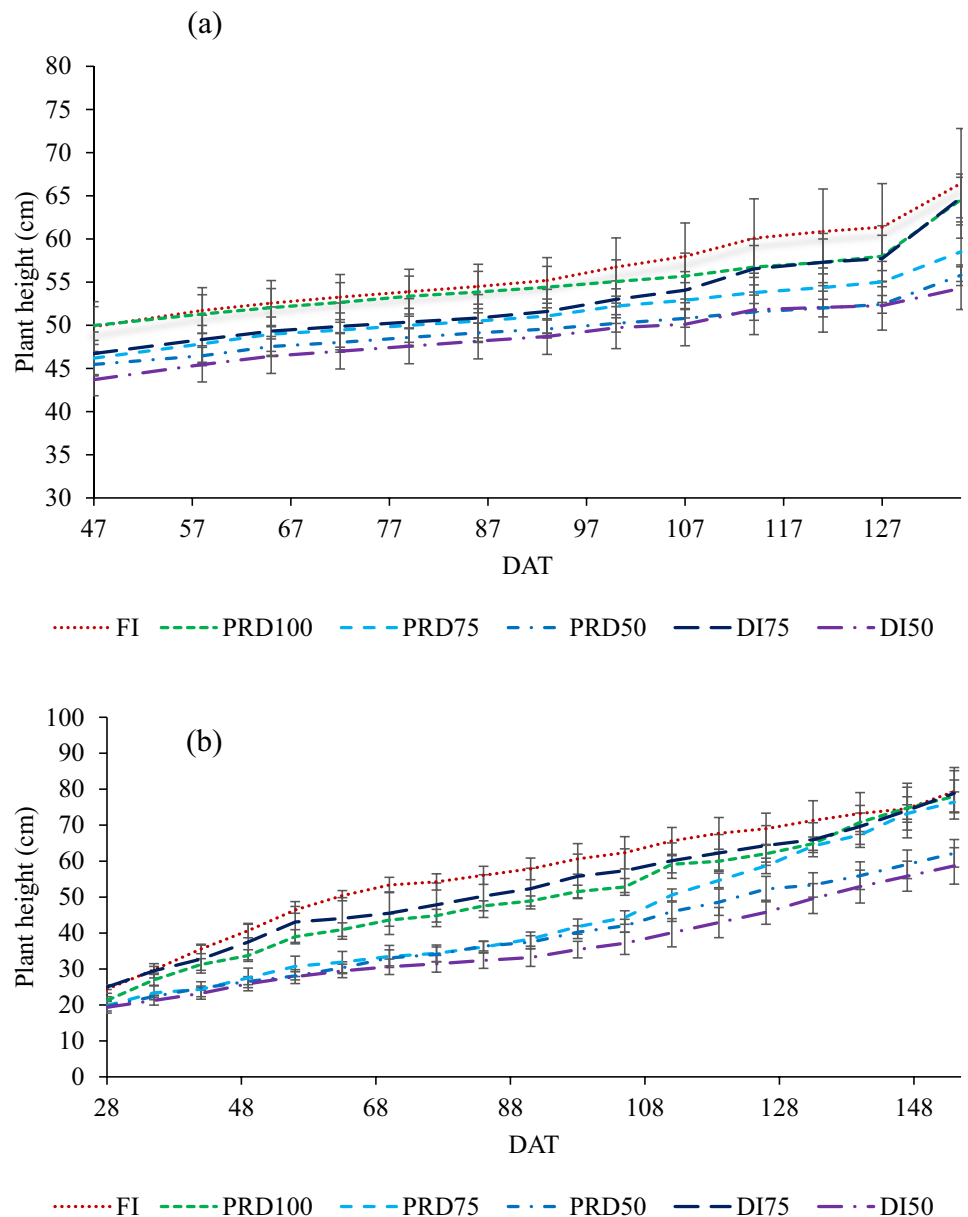


along the experimental phase. In this study, there was no statistical difference between DI and PRD in most measurements with the same amount of irrigation; however, DI and reduced PRD treatments had lower RWC values than FI. LA recorded high values when the jalapeño pepper plant was well watered (Fig. 7). It was apparent that FI was significantly higher than DI50 and PRD50 treatments (Fig. 7). The maximum and minimum LA values of the jalapeño pepper plant were recorded in FI (18.6 cm^2) and PRD50 (5.8 cm^2) treatments, respectively, during the 2022 growing season, and FI (12.9 cm^2) and PRD50 (2.5 cm^2) treatments, respectively, during the 2023 growing season (Fig. 7). Water stress inhibited leaf growth, limiting the canopy's development ability and resulting in low LA under highly stressed treatments. Several studies using PRD and DI (Davies et al. 2002; Liu et al. 2006; Zin El-Abedin et al. 2017) reported a corresponding rise in quantifiable Absciscic acid (ABA) levels when there is a water shortage in a portion of the root system. This increase in ABA quantitatively accounts for the decrease in leaf growth (Shao et al. 2008). Results obtained

from the experiment showed that irrigation treatment affects vegetative parts of jalapeño pepper plants (Table 2). The maximum SFW was obtained under FI in the 2022 and 2023 growing seasons (91.6 g and 137.9 g, respectively). FI was significantly higher than all treatments except PRD100 in the 2022 growing season and DI75, PRD75, and PRD100 in the 2023 growing season. Moreover, there was no statistical difference between DI50 and PRD50 in either growing season (Table 2). The minimum SFW was obtained under PRD50 and DI50 in the 2022 and 2023 growing seasons (52.7 g and 68.4 g, respectively).

The maximum RFW of the jalapeño pepper plant was observed in FI (46.5 g) in 2022 and DI75 (32.1 g) in 2023 (Table 2). The minimum RFW was obtained under PRD50 and PRD75 in the 2022 and 2023 growing seasons (28.6 g and 14.9 g, respectively). The maximum value of RDW of the jalapeño pepper plant was recorded in PRD100 (17.22 g) in the 2022 growing season. The minimum value of the same year was recorded in PRD50 (13.17 g), while in the 2023 growing season, the maximum value of RDW of the jalapeño pepper

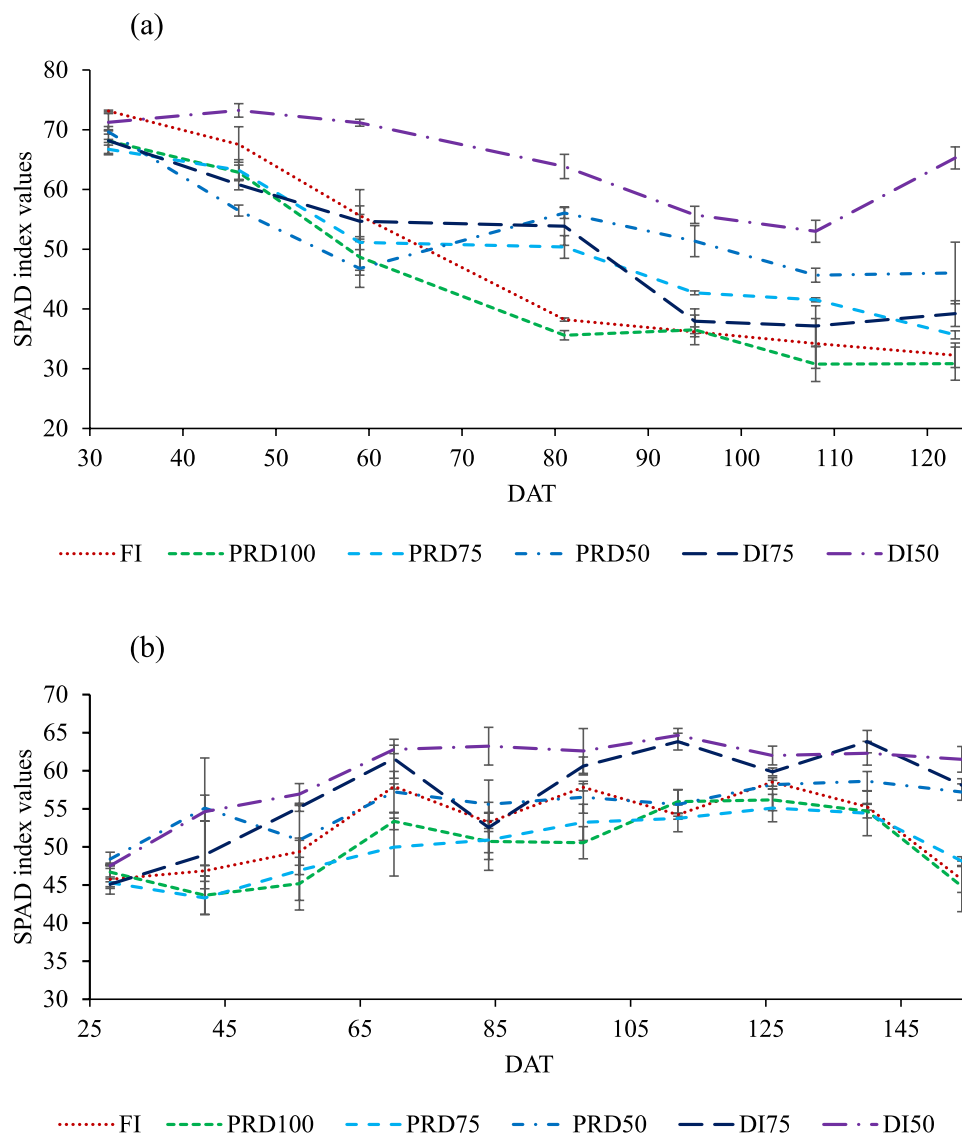
Fig. 3 Plant height for jalapeno plant under FI, DI, and PRD treatments during the growing season (a) 2022 and (b) 2023. The data points represent mean $\pm$ SE ($n=3$)



plant was recorded in DI75 (20.31 g). The minimum value of the same year was recorded in DI50 (8.35 g). However, there was no statistical difference between treatments in terms of RDW in both growing seasons (Table 2). Reducing the irrigation water level appears to increase the plant's water availability for physiological processes and decrease the amount of water content in its tissues (Hooshmand et al. 2019). Several studies have documented a decline in shoot development under DI and reduced PRD (Shao et al. 2008; Ahmed et al. 2014; Hooshmand et al. 2019). PRD75 surpassed DI75 in terms of shoot and root biomass; however, it is less than the treatments of FI. PRD aims to introduce soil moisture heterogeneity purposefully (both spatially and temporally) inside the plant root zone to modify root-to-shoot signaling and, in turn,

shoot physiology (Marsal et al. 2008; Mohawesh et al. 2022). However, it is not always possible to distinguish between physiological changes specific to PRD; this could be because a heterogeneous distribution of soil moisture is not always achieved (Dodd et al. 2008). The dry vegetative components in the PRD50 and DI50 treatments were the lowest among the DI and PRD treatments. The soil water depletion reduced the vegetative development in the DI50 and PRD50 treatments in the soil-root contact area, which was significantly reduced in these treatments. Valerio et al. (2017) reported that the dry matter of tomatoes decreased considerably when water stress increased. Mohawesh and Karajeh (2014) recorded that RDW and SDW of eggplant and tomatoes significantly decreased under water deficit irrigation. Therefore, under deficit irrigation regimes,

Fig. 4 Seasonal change of chlorophyll content for jalapeno plant under FI, DI, and PRD treatments during the growing season **(a)** 2022 and **(b)** 2023. The data points represent mean $\pm$ SE ($n=3$)



root and stem weight are likely to be reduced in response to water stress. Liu et al. (2020) observed that the dry biomass of vegetative organs of tomatoes under DI and reduced PRD was significantly lower than in the control. Shao et al. (2008) showed that hot pepper shoot and root dry weight were significantly less under DI and reduced PRD treatments than the control. The results obtained in this study show that the decrease in vegetative organs of plants occurs under DI and reduced PRD; nevertheless, plants can tolerate a mild reduction of irrigation water and remain viable.

4 Yield and water use efficiency

The highest jalapeño pepper fresh fruit weight was obtained during the 2022 and 2023 growing seasons under PRD100 (206.8 and 158.6 g, respectively), with significant

differences compared to all treatments (Table 3). Yield reduction under DI50 and PRD50 treatments was 54.6% and 62.1%, respectively, while the yield reduction during the 2023 growing season under DI50 and PRD50 was 54.4% and 43.6%, respectively, compared to FI (Table 3). Although 3.5% and 10% yield reductions were evident under the DI75 and PRD75, respectively, it was not statistically different from the FI treatment in 2022 (Table 3). Despite yield reduction, DI75 and reduced PRD75 treatments were not significantly different from FI in yield during both growing seasons. This result agrees with the finding of Farah et al. (2021), who indicated that increasing tomato's WUE may be achieved by lowering the irrigation volume. DI50 and PRD50 yields were significantly lower than FI during both growing seasons (Table 3); this can be attributed to a decrease in the mean soil water content and a decrease in the rate of photosynthetic activity (Shao

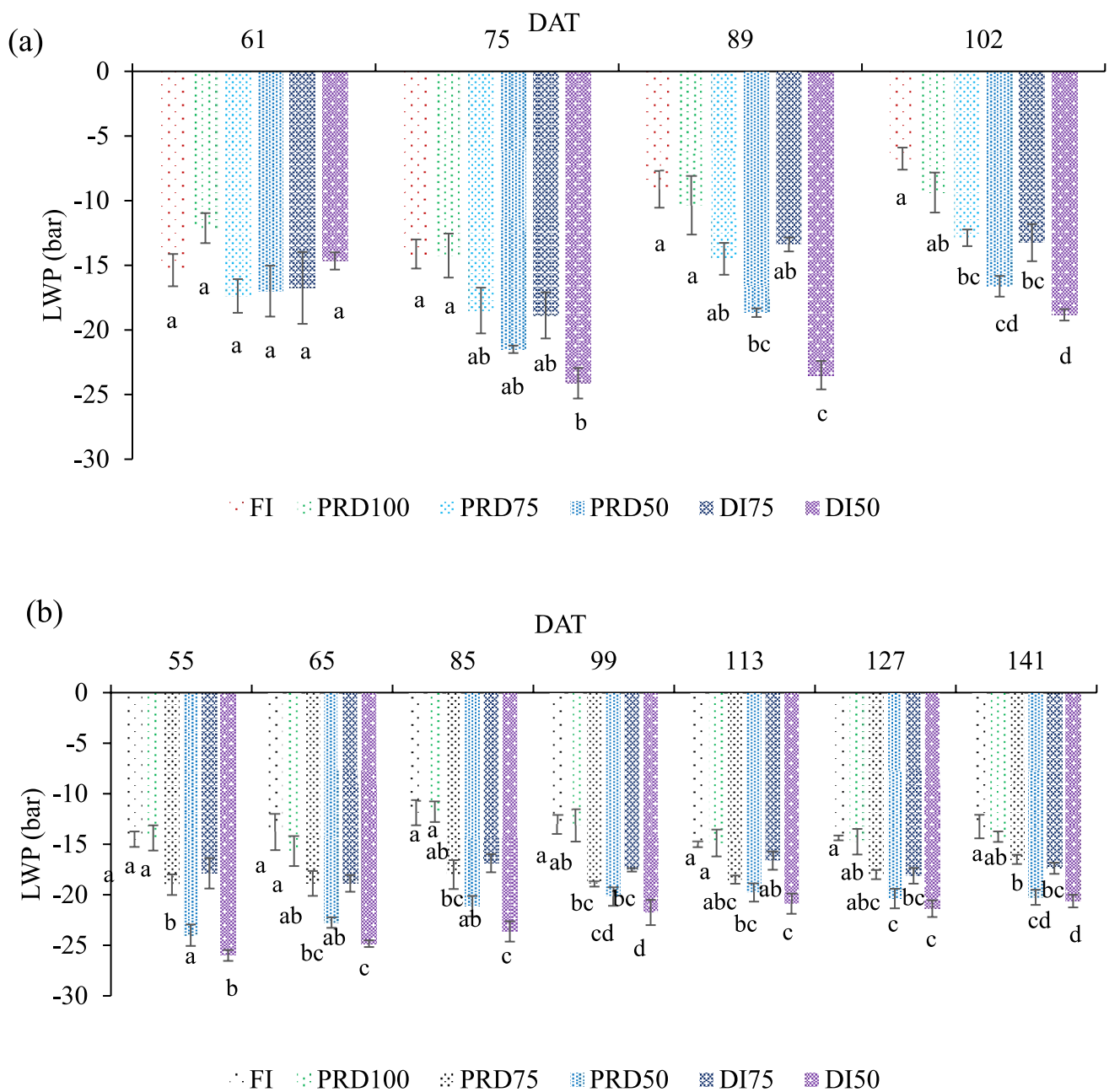


Fig. 5 The effect of six irrigation treatments on leaf water potential (LWP) of jalapeno pepper planted during the growing season (a) 2022 and (b) 2023. The data points represent mean $\pm$ SE ($n=3$).

According to the Tukey pairwise comparison test, bars with different lowercase letters represent a statistical difference at ($p \leq 0.05$)

et al. 2008; Mohawesh 2016; Farah et al. 2021). Davies et al. (2000) reported that chemical signals that restrict vegetative growth are thought not to reach the fruit because of a restricted xylem connection between the shoot and the fruit, which helps to explain the negligible impact on yield in contrast to the substantial impacts on vegetative growth. The primary means of regulating transpirational losses in plants during PRD and increasing total yield is the

production of ABA during the dry portion of PRD, which causes a reduction in stomatal closure or partial opening of stomata and a reduction in the creation of foliage in plants (Davies et al. 2002). Therefore, PRD75 was not significantly different in yield from FI in both seasons. However, the high level of ABA produced during the dry portion of PRD50 causes a significant reduction in yield. The variation in WUE between treatments among the two seasons

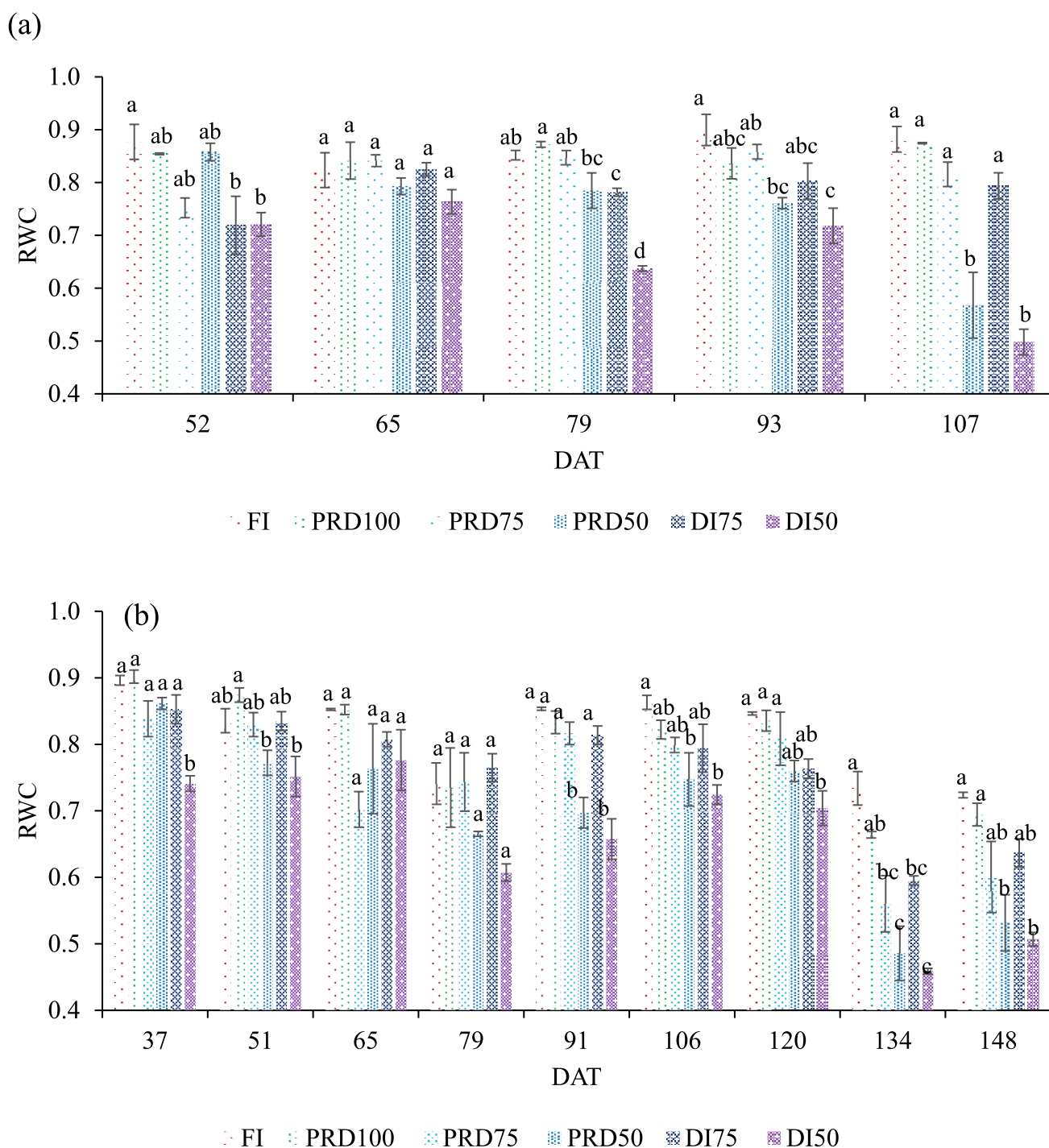


Fig. 6 The effect of six irrigation treatments on relative water content (RWC) of jalapeño pepper planted during the growing season (a) 2022 and (b) 2023. The data points represent mean $\pm$ SE ($n=3$).

According to the Tukey pairwise comparison test, bars with different lowercase letters represent a statistical difference at ($p \leq 0.05$)

reflects the yield of the jalapeño pepper and the applied water. Meidanshahi et al. (2013) concluded that the tomato plant produced fewer fruits when the irrigation water was reduced. Also, Hooshmand et al. (2019) stated that there

is a substantial relationship between the quantity of tomato fruit and irrigation levels.

Our data revealed that PRD75 sustained a high yield while saving 25% of irrigation water compared to FI,

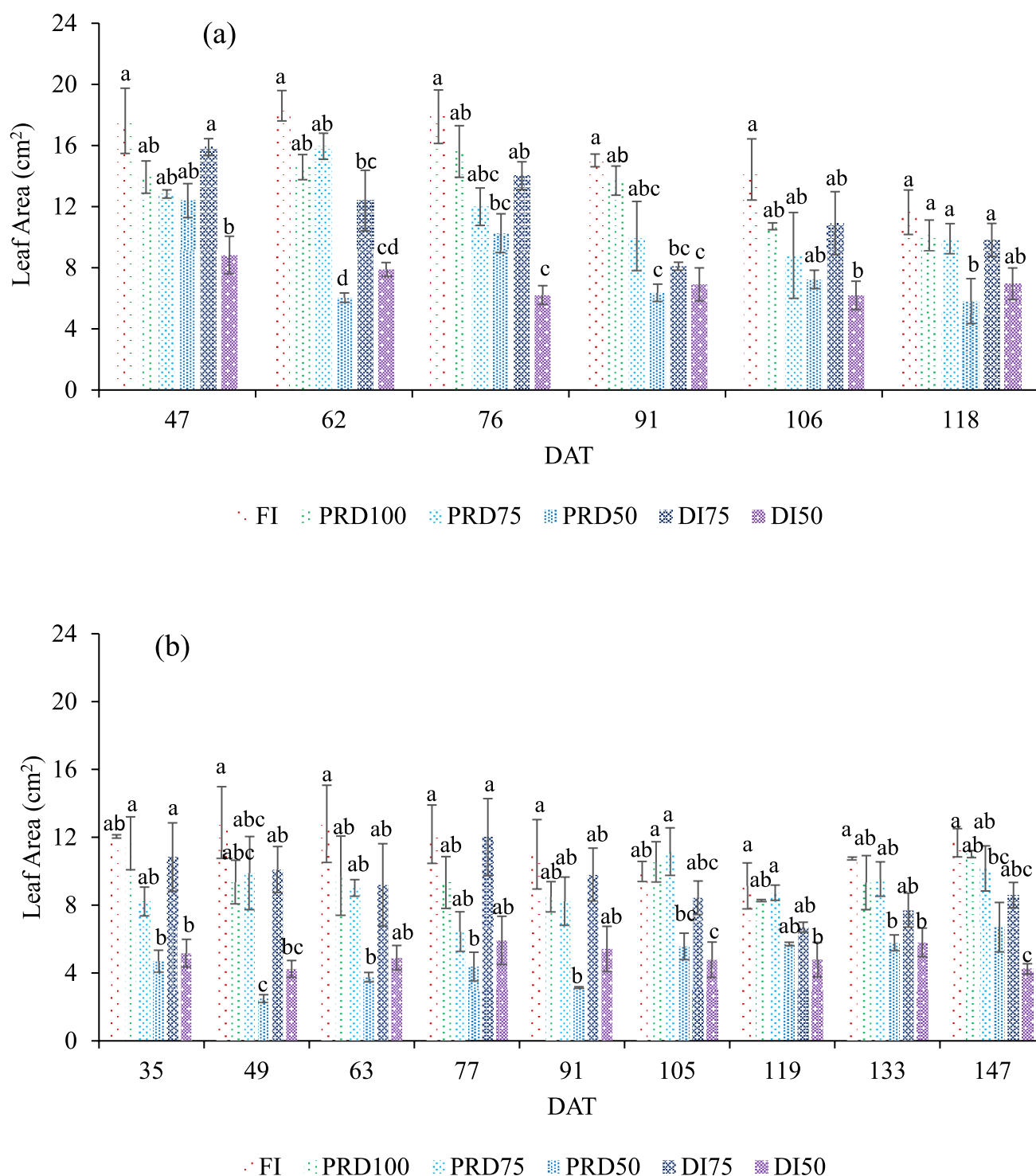


Fig. 7 The effect of six irrigation treatments on leaf area (LA) of jalapeno pepper planted during the growing season (a) 2022 and (b) 2023. The data points represent mean $\pm$ SE ($n=3$). According to the

Tukey pairwise comparison test, bars with different lowercase letters represent a statistical difference at ($p \leq 0.05$)

indicating a superior WUE. This is consistent with previous findings by Mohawesh et al. (2022), who demonstrated that strategic irrigation reduction can enhance productivity per unit of water applied. Notably, DI50 and PRD50 caused

significant yield declines due to extreme water stress, adversely affecting vegetative growth and fruit development. Thus, PRD75 is optimal for arid regions targeting water conservation without compromising yield.

Table 2 Effect of irrigation treatments on shoot fresh weight (SFW), shoot dry weight (SDW), root fresh weight (RFW), and root dry weight (RDW) of jalapeno pepper plants during the 2022 and 2023 growing seasons

Year	Trts	SFW (g)	RFW (g)	SDW (g)	RDW (g)
2022	FI	91.6 ± 6.4a*	46.5 ± 1.1a	23.91 ± 2.10a	15.71 ± 0.83a
	PRD100	80.8 ± 3.0ab	45.3 ± 2.1a	18.81 ± 0.23ab	17.22 ± 0.96a
	PRD75	66.2 ± 1.6b	36.1 ± 2.5b	18.32 ± 0.98ab	14.83 ± 1.12a
	PRD50	52.7 ± 0.4c	28.6 ± 0.3b	14.90 ± 0.12c	13.17 ± 1.61a
	DI75	73.5 ± 3.1b	36.5 ± 1.4b	19.05 ± 1.14ab	13.70 ± 0.58a
	DI50	58.2 ± 1.8c	30.9 ± 1.7b	15.20 ± 0.67c	15.51 ± 1.38a
2023	FI	137.9 ± 9.3a	26.9 ± 2.9a	40.87 ± 2.64a	19.66 ± 2.48a
	PRD100	119.8 ± 6.5a	26.8 ± 4.9a	32.00 ± 0.98ab	17.66 ± 2.89a
	PRD75	106.2 ± 10.7a	14.9 ± 4.6a	26.17 ± 3.29b	9.95 ± 2.87a
	PRD50	76.6 ± 0.5b	20.0 ± 2.9a	17.39 ± 0.55d	12.04 ± 2.81a
	DI75	134.9 ± 4.5a	32.1 ± 5.1a	34.82 ± 0.99ab	20.31 ± 4.12a
	DI50	68.4 ± 11.8b	16.8 ± 3.2a	15.74 ± 2.77d	8.35 ± 1.81a

*Values represent means ± SE ($n=3$). According to the Tukey pairwise comparison test, mean values not sharing lowercase letters are significantly different ($p \leq 0.05$)

Table 3 Effect of six irrigation treatments on yield, water use efficiency (WUE), and yield relative reduction in the 2022 and 2023 growing seasons

Year	Trts	Yield (g)	Yield Relative reduction (%)	WUE (kg/m ³)
2022	FI	193.5 ± 7.9a		6.86 ± 0.69b*
	PRD100	206.8 ± 11.9a	−6.9%	7.32 ± 0.78b
	PRD75	186.8 ± 9.4a	3.5%	7.65 ± 0.89b
	PRD50	73.3 ± 7.6c	62.1%	8.86 ± 0.47a
	DI75	174.1 ± 13.0b	10.0%	6.85 ± 0.92b
	DI50	87.8 ± 12.0c	54.6%	8.80 ± 0.39a
2023	FI	156.7 ± 13.1a		5.77 ± 0.23b
	PRD100	158.6 ± 17.3a	−1.2%	5.81 ± 0.31b
	PRD75	141.7 ± 24.9a	9.6%	5.12 ± 0.57b
	PRD50	88.4 ± 6.9c	43.6%	6.57 ± 0.23a
	DI75	135.7 ± 14.7b	13.4%	5.86 ± 0.34b
	DI50	71.5 ± 5.5c	54.4%	6.71 ± 0.18a

*Values represent means ± SE ($n=3$). According to the Tukey pairwise comparison test, mean values not sharing lowercase letters are significantly different ($p \leq 0.05$)

Table 4 Effect of six irrigation treatments on leaf nutrient contents of the jalapeno pepper plant in the 2022 and 2023 growing seasons

		2022			
		Leaf Nutrient			
Trts	% N	P (mg/g)	K (mg/g)	Ca (mg/g)	
FI	2.53 ± 0.39b*	0.11 ± 0.022a	42.8 ± 1.1a	12.4 ± 2.6a	
PRD100	2.36 ± 0.24c	0.12 ± 0.020a	40.7 ± 0.1a	13.1 ± 2.2a	
PRD75	2.75 ± 0.14b	0.11 ± 0.032a	39.2 ± 1.6a	11.9 ± 2.3b	
PRD50	3.08 ± 0.24a	0.07 ± 0.001c	32.6 ± 2.9b	12.5 ± 1.9a	
DI75	2.70 ± 0.31b	0.08 ± 0.018b	35.0 ± 2.3b	9.2 ± 1.1c	
DI50	2.94 ± 0.17a	0.06 ± 0.003c	30.4 ± 0.9b	8.1 ± 0.4c	
		2023			
		Leaf Nutrient			
Trts	% N	P (mg/g)	K (mg/g)	Ca (mg/g)	
FI	2.34 ± 0.09c	0.12 ± 0.012a	34.6 ± 0.3a	7.9 ± 0.2a	
PRD100	2.72 ± 0.25bc	0.12 ± 0.004a	33.8 ± 0.5a	8.6 ± 0.9a	
PRD75	3.96 ± 0.47ab	0.11 ± 0.010a	32.2 ± 1.5a	7.6 ± 0.4a	
PRD50	4.21 ± 0.06a	0.07 ± 0.013b	34.7 ± 1.3a	7.8 ± 0.1a	
DI75	3.76 ± 0.14ab	0.01 ± 0.007a	29.4 ± 1.3b	5.8 ± 0.4b	
DI50	3.58 ± 0.31ab	0.06 ± 0.003b	27.3 ± 0.6b	5.9 ± 0.1b	

*Values represent means ± SE ($n=3$). According to the Tukey pairwise comparison test, mean values not sharing lowercase letters are significantly different ($p \leq 0.05$)

4.1 Plant and fruit nutrient content analysis

Significant differences in leaf mineral content of the jalapeño pepper plant were observed among irrigation treatments (Table 4). Leaf nitrogen increases with a decreased amount of irrigation water. PRD50 (3.08%) and DI50 (4.21%) had the highest nitrogen content in the 2022 and 2023 growing seasons. Moreover, the lowest nitrogen content in the 2022 and 2023 growing seasons was observed under the PRD100 (2.36%) and FI (2.34%), respectively. Generally, most results of the leaf nitrogen content of the jalapeño pepper were highest under PRD than DI treatments; these results may be explained by Wang et al.

(2012a), who reported that in PRD treatments, the combination of wet and dry soil increases the roots' ability to absorb nitrogen, which helps move minerals from the soil's volume to their surface. Based on these findings and our results, it is hypothesized that the PRD irrigation increased the soil's microbial activity, improved the N availability, and made more mineral N available for the plants. Irrigation treatment application impacted the leaf phosphorus content of the jalapeño pepper plant (Table 4). Compared to DI treatments, reduced PRD treatments had higher leaf

phosphorus content. Wang et al. (2012b) showed that, in PRD conditions, the dry and wet cycle increases phosphorus absorption and enhance phosphorus diffusion to the root surface.

Applying DI and PRD treatments influenced the leaf potassium content of the jalapeño pepper plant (Table 4). PRD treatments had higher potassium content than DI treatments. Wang et al. (2008, 2009) reported that PRD increased the amount of essential plant nutrients absorbed. Our results showed that PRD had higher leaf calcium content DI treatments at the same irrigation level. Similar effects were observed in lettuce plants grown under PRD compared to DI at the same irrigation levels (Demir et al. 2022). As discussed earlier, we attribute similar mechanisms to those that affected the availability of other nutrients. The dry portion of PRD produces ABA, which reduces stomatal closure or partial stomatal opening and reduces foliage production in plants; these are the primary mechanisms for regulating transpiration losses in plants under PRD and improving crop quality. Also, the soil's bio-physicochemical processes and solute transportation may be impacted by the PRD treatment's drying and wetting cycles, which could affect the soil's nutrient availability and crop uptake.

Water deficit treatments caused an increase in the nitrogen content of jalapeño pepper fruit compared to full-watered treatments (Table 5). Jalapeño pepper fruit is characterized by high fruit nitrogen content under PRD treatments compared to FI and DI treatments. Previous research has demonstrated that PRD irrigation stimulates the formation of roots, especially secondary roots, which

may increase the area that can absorb nutrients and water (Mingo et al. 2004). Moreover, PRD is characterized by frequent wetting and drying of the root zone's soil surface, which may promote soil organic N mineralization and increase the amount of mineral N available to the plants (Valé et al. 2007). DI and PRD treatments affected the fruit phosphorus content of jalapeño pepper (Table 5). Sánchez-Rodríguez et al. (2014) reported that increased potassium concentrations under water stress were seen in several grafted and non-grafted tomatoes, supporting the theory that increased potassium content enhances stomatal resistance, which enhances drought tolerance. Sun et al. (2014) summarized that the fruit potassium content of tomato dry matter was higher under FI. Also, in comparison of FI to DI treatments, the fruit phosphorus content of the jalapeño pepper was decreased when water stress increased. Our results agree with the results of Mohawesh (2016), who reported that tomato fruit phosphorus content decreased with water deficit. The fruit calcium content of FI was significantly higher than that of water-stressed treatments (Table 5). The jalapeño pepper's fruit calcium content under PRD was higher than DI at 50% and 75% FI irrigation levels.

Nitrogen content in the leaf increased under water stress. Conversely, fruit nitrogen nutrient contents under water stress showed a lower value than FI. A plausible explanation for the observed results may be the formation of induced inhibition, which occurs when minerals translocated from the leaf (source) struggle to transfer to the growing fruits (sink) under drought conditions (Soussani

Table 5 Effect of six irrigation treatments on fruit nutrient contents of the jalapeno pepper plant in the 2022 and 2023 growing seasons

		2022		
		Fruit Nutrient		
Trts	% N	P (mg/g)	K (mg/g)	Ca (mg/g)
FI	2.72 ± 0.07a*	0.36 ± 0.022a	27.0 ± 0.1a	0.50 ± 0.021a
PRD100	2.43 ± 0.10a	0.36 ± 0.013a	25.9 ± 0.9a	0.40 ± 0.009a
PRD75	2.93 ± 0.17a	0.35 ± 0.018a	25.2 ± 1.0a	0.47 ± 0.007ab
PRD50	2.62 ± 0.15a	0.30 ± 0.016ab	23.9 ± 1.1ab	0.48 ± 0.011ab
DI75	2.61 ± 0.06a	0.31 ± 0.020ab	24.7 ± 1.0ab	0.46 ± 0.010ab
DI50	2.59 ± 0.06a	0.26 ± 0.010b	20.5 ± 0.1b	0.43 ± 0.010b
		2023		
		Fruit Nutrient		
Trts	% N	P (mg/g)	K (mg/g)	Ca (mg/g)
FI	2.52 ± 0.15a	0.29 ± 0.001a	23.1 ± 0.7a	0.59 ± 0.011a
PRD100	2.69 ± 0.15a	0.31 ± 0.007a	22.6 ± 0.6a	0.58 ± 0.007a
PRD75	2.84 ± 0.13a	0.33 ± 0.025a	24.5 ± 0.8a	0.57 ± 0.017b
PRD50	2.93 ± 0.16a	0.33 ± 0.024a	24.5 ± 1.3a	0.52 ± 0.014c
DI75	2.71 ± 0.27a	0.32 ± 0.007a	24.5 ± 0.3a	0.57 ± 0.021b
DI50	2.44 ± 0.14a	0.28 ± 0.041a	24.5 ± 0.2a	0.52 ± 0.063c

*Values represent means ± SE ($n=3$). According to the Tukey pairwise comparison test, mean values not sharing lowercase letters are significantly different ($p \leq 0.05$)

et al. 2023). The statistical analysis showed that leaf and fruit phosphorus content in DI50 was significantly lower than that of other treatments, implying that drought inhibited plant growth by reducing the uptake of nutrients more than water uptake, which reduced plant phosphorus uptake (Kareem et al. 2020). Fruit calcium content was significantly lower under water deficit; such a decrease in calcium concentration under low water availability may be caused by changes in root activity and the movement of calcium through the xylem and phloem (Kabir et al. 2021). By alternating wet and dry zones, PRD improves ABA signaling, maintains root–shoot communication, and enhances nutrient mobilization. However, the results are from pot experiments, conducted in two seasons, under controlled greenhouse conditions, which limit field-scale generalization. Therefore, we suggest the need for multi-season field validation.

5 Conclusion

This study showed that applying DI50, DI75, PRD50, and PRD75 led to a decrease in jalapeño pepper plants' LA, RWC, and LWP during the two experimental seasons. Moreover, DI and PRD treatments adversely affected the fresh and dry shoot weights of jalapeño pepper plants. The highest yield was obtained under FI and PRD100 in both growing seasons. Although the DI75 and PRD75 treatments received approximately 25% less irrigation water than FI, the yields of DI75 and PRD75 did not significantly differ from FI. Under water-limited conditions, PRD75 emerges as the most suitable strategy, enabling approximately 25% water savings while maintaining over 80% of maximum yields. Moreover, PRD improved nutrient availability (N, P, K, Ca) and WUE compared to DI without causing a significant yield loss. Furthermore, when water resources are limited, the PRD75 is recommended as an alternative irrigation practice to FI and an applicable water-saving irrigation strategy to increase WUE and achieve maximum yield while maintaining statistically similar yields to FI in both years under PRD75 and DI75. Our results also support PRD75 as a viable water-saving irrigation strategy in commercial pepper production under arid conditions, suggesting future field-scale trials or long-term assessments of PRD on soil and yield quality.

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Data availability Data supporting the results of this study are not accessible and can be provided by the author if requested.

Declarations

Competing interest The authors declare no competing interests.

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