In Press, Pre-Proof Version

The Effects of Fertigation on Plant Growth, Fruit and Photosynthesis Attributes of Strawberries (Fragaria×ananassa Duch.) under Deficit Irrigation

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Abstract

This study investigated the effects of irrigation strategies including sustained deficit irrigation (SDI) and partial root-zone drying (PRD) on the growth, physiology, and photosynthesis of strawberry plants in order to maximize crop productivity while maintaining water resources. This experiment has four irrigation strategies (FI: control (full irrigation volume), PRD1 (full irrigation volume), PRD2 (50% of FI), and SDI (50% of FI) and two fertilizer strengths (EC1 and EC2) with four replicates per treatment. Gas exchange, leaf chlorophyll index, stomatal conductance (gs), and maximum quantum efficiency of PSII photochemistry (F'v/F'm) were assessed on three occasions throughout the experimental duration in order to monitor the impact of different irrigation strategies on photosynthesis. Yield water use efficiency, as well as TSS (total soluble solids) and TA (total titratable acidity), two fruit quality-related parameters, were also measured. In the final stage, PRD2-EC2 photosystem II efficiency was 9% higher than SDI-EC2. Also, the PRD strategy effectively influenced and regulated the adjustment of stomatal conductance (gs). In diluted fertilizer (EC2), yield WUE of PRD1 and SDI performed 15% and 30.7% lower than FI-EC2. However, PRD2-EC2 treatment increased 72.5% more than the control. Our observations of leaf and fruit deficiencies showed that the PRD strategy had long-term benefits for the plant and reduced water consumption. However, to establish a sustainable irrigation strategy, the nutrient solution must be adjusted to control growth and photosynthesis attributes.

Keywords: Chlorophyll Fluorescence, Deficit Irrigation, PSII Photochemistry Efficiency, Stomatal Conductance (gs).

1. Introduction

Water regulates physiological processes and plant productivity and is essential for plant growth and development. Water relations affect growth, physiology, and photosynthesis, therefore comprehending them is important. In agricultural systems, deficit irrigation can improve water use efficiency and reduce water management by applying water below plant needs (Arief *et al*., 2023; Martínez-Ferri *et al.*, 2016). Sustained deficit irrigation (SDI) and partial root-zone drying (PRD) have been used in various crops for decades due to their physical and secondary physiological benefits to plants and root settings (Sepaskhah and Ahmadi, 2012). Their research indicates in water-scarce areas, PRD boosts water productivity and maintains yield, prioritizing water value over just economic yield.

According to FAO statistics, in twenty years (2000-2020), the strawberry-cultivated area has increased from 783713 to 384668. Iran has expanded its strawberry cultivation by over a thousand hectares in this period, showing increased farmer interest in this product (Crops and livestock products, 2022).

Strawberry (*Fragaria* × *ananassa* Duch.) is a highly valued crop due to its tasty and nutritious fruits. Strawberry plants are sensitive to water availability, so irrigation is crucial. Research has examined the effects of deficit irrigation on strawberry plant growth, physiology, photosynthetic properties, water uptake, transport, and transpiration. Water availability, soil moisture, and drought stress affect plant physiological and biochemical processes. Strawberry plants, like other crops, need optimal water balance for cellular composition, nutrient absorption, and metabolism. Researching strawberry plant responses to irrigation can aid in developing sustainable irrigation strategies that maximize crop productivity and conserve water resources (Ghaderi and Siosemardeh, 2011; Martínez-Ferri *et al.*, 2016; Weber *et al.*, 2017; Wu *et al.*, 2020). Understanding the response of strawberry plants to irrigation can provide valuable insight into their adaptation mechanisms and help develop sustainable irrigation strategies to maximize crop productivity while maintaining water resources.

Strawberry plants are sensitive to drought stress, which can affect nutrient transport, cell expansion, and growth (Weber *et al.*, 2017; Zhang *et al.*, 2019). Previous research shows that the physiological responses of strawberry plants, including stomata behavior, osmotic regulation, transpiration, and hormonal regulations, which play an important role in their ability to tolerate water stress, are influenced by PRD strategy (Jensen *et al.*, 2009; Yenni *et al.*, 2022). Opening and closing stomata adjust transpiration, which is affected by water availability, especially in PRD (Na *et al.*, 2014; Zhang *et al.*, 2019). However, heavy irrigation or poor drainage can prevent nutrient absorption, reducing growth and productivity. (Wu *et al.*, 2020).

The ability to accurately evaluate drought stress and its effects on plants is crucial to understanding plant responses and formulating effective strategies for production management. In recent years, non-destructive methods, such as the amount of photosynthesis and fluorescence chlorophyll, have appeared to evaluate drought stress in strawberry plants. One of the most commonly used chlorophyll fluorescence parameters is the maximum quantum yield of photosystem II (FV/FM). This is an indicator of the overall health and performance of the photosynthetic system (Murchie and Lawson, 2013; Na *et al.,* 2014). Drought stress typically results in a decrease in Fv/Fm and reflects photosynthetic function(Murchie and Lawson, 2013; Zebrowska and Michalek, 2014). Strawberry growth and fruit production depend on photosynthesis. Water status affects leaf carbon dioxide emission and water availability for photosynthetic reactions, regulating photosynthetic levels. For example, drought stress can close the stomata, limit carbon dioxide availability, reduce photosynthetic efficiency, and increase chlorophyll fluorescence. In addition, drought can lead to dehydration and damage to the photosynthetic system, ultimately affecting the productivity of strawberry plants. Understanding the complex relation between water and growth, physiology, and photosynthesis of strawberry plants is very important to optimize cultivation methods, enhance crop productivity, and formulate solutions to reduce the effects of water stress (Na *et al.*, 2014; Iqbal *et al.*, 2020; Alavi *et al.*, 2023).

Considerable research has been undertaken in this particular field of study. Nevertheless, there exists a shortage of research related to the effects of irrigation strategies on gas exchange and the overall performance of strawberry plants throughout a full cultivation period. The objective of this study was to examine the effects of deficit irrigation strategies on the growth, physiological, and photosynthetic characteristics of hydroponic strawberry plants.

2.Materials and Methods

2.1. Greenhouse Condition

The study was conducted in a research greenhouse on strawberry plants (*Fragaria× ananassa Duch.* var. Camarosa). at the University of Ferdowsi, located in Mashhad, Iran (36.29° N, 59.60° E), during 2021-2022. The humidity and temperature were kept at an average of 63% relative humidity and 26/18°C Day/Night, respectively. To maintain a 14-hour day and 10-hour night schedule, 400-watt sodium vapor lamps were used.

The experiment commenced in November 2021 and finished on April 10th 2022. For the PRD treatment, plant roots were split up and transplanted into pots with artificial substrates made of a mixture of 70% perlite and 30% coco peat. The treatment pots had 25cm heights and 15cm diameters. The PRD were split by polycarbonate plastic sheets and securely sealed with insulating adhesive to block inter-part water transfer (Figure 1). All pots were subjected to a three-week establishment period and received fertilizer applications without experiencing any water deficit. The supply of nutrition solutions followed the Morgan method (Morgan, 2006). Fertigation was delivered to the strawberry plants by a drip irrigation system with two emitters for each pot.

Figure 1. (**a)** Strawberry plant with cleaned and separated roots prepared for planting. (**b)** Strawberry plant grown in PRD pots at the initiation of the experiment with polycarbonate separator.

2.2. Experimental Treatments

The experimental treatments were derived from the interaction of four irrigation strategies, namely Control, PRD1, SDI, and PRD2, with two fertilizer levels, EC1 and EC2. The PRD1 treatment was provided with an equivalent amount of fertigation as the control treatments (FI). The other two treatments, sustained deficit irrigation (SDI) and partial root-zone drying (PRD2) received 50% of FI with half-strength fertilizer in each pot. The experimental design consisted of four replications for each treatment, with each replication comprising three plants. This arrangement yielded a total of 96 pots each pot contains one plant.

Table 1. Composition of nutrient solution used in fertigation (Morgan, 2006).

Chemical Element (ppm)	Transplanting	Vegetative Growth	Flowering Stage	Fruiting Stage
Nitrogen (N)	120.7	118.5	118.5	117.5
Potassium (K)	143.6	157.7	179.51	177
Calcium (Ca)	77.1	40	70.2	70
Phosphorus (P)	40.1	42.5	42.355	42.5
Magnesium (Mg)	28.6	29.5	29.46	27
Sulfur (S)	32.6	38	47.795	37.5
Iron (Fe)	3	3	3.51	3
Zinc (Zn)	1.275	1.275	1.2	0.9
Boron (B)	1.65	1.65	1.485	1.65
Manganese (Mn)	1.755	1.755	1.755	1.49
Molybdenum (Mo)	0.11	0.11	0.12	0.09
Copper (Cu)	0.12	0.12	0.129	0.09

2.3. Irrigation Management

An open hydroponic system that was automated and operated three times per day based on a digital timer was used in this project. Pressurized drippers and diaphragm pumps were used to ensure precise irrigation. The water quality was kept at a level that is suitable for strawberries, with a pH range of 5.5 to 6.0 and an EC (d/Sm) of 1.8 to 2.2 (Maluin *et al.*, 2021). The water holding capacity in the artificial substrate is different from the soil; based on a previous study, available water (AW) was considered in a potential matrix range between -1 and -10 kPa, and water in a potential matrix range between -1 and -5 kPa was considered as easily available water (EAW) (Marcelis and Heuvelink, 2019). The amount of water in the substrates is experimentally dependent on the type of substrates, water intake, and plant resistance (Maluin *et al.*, 2021); In this experiment, a simplified water balance method calculated averaged potential evapotranspiration (ETp). Using plastic bottle lysimeters beneath each pot, water losses from irrigation drainage were collected. The experiment calculated each cultivar's total evapotranspiration for both treatment conditions. The volume of water (V) in milliliters for fertigation was determined and subsequently modified on a weekly basis utilizing Equation 1.

Equ. 1: $V = (\mathrm{ETp})(1 + LF)$

ETp is the averaged potential evapotranspiration (mm) and LF is the leaching fraction percentage in Equation 1. Considering standard irrigation practices used in commercial greenhouses, the LF was 20% during the experiment. Bi-daily irrigation rotation was used in PRD treatments. EC and pH in fertigation were kept at 1.8 (dS m-1) and 6–6.5, respectively. During the experiment, each pot received 15.7 liters of fertigation water for the FI treatment. In PRD treatments, irrigation was rotated on a bi-daily basis, and only one part of the container was irrigated with fertigation in each irrigation. In full fertigation, the EC and pH levels of fertigation were kept at 1.8 (d/Sm) and between 6 and 6.5, respectively.

2.4. Measurements

2.4.1. The morphological attributes

The ripe fruits (at full maturity and fruits ready to be consumed) were daily selected before the first irrigation, between 7:00 and 8:00 a.m., and their weight was recorded using a digital scale (GF 300) with an accuracy of 0.001 kg. At the end of the experiment, all plants were harvested, and the roots were precisely dug out of the substrate. The roots were sent to the lab to determine their volume and dry weight after being thoroughly washed in distilled water. The aerial parts and roots were placed in paper envelopes and dried for 48 hours at 85 ^{o}C to determine their dry weight (DW). A leaf area meter (Li-Cor 1300, USA) calculates the total leaf area. Specific leaf area (SLA) was calculated by dividing leaf area (m^2) by plant leaf biomass (dry weight) in grams (Fernandez *et al.*, 2001).

2.4.2. Gas exchange measurement and photosynthetic attributes

Photosynthesis rate (A), transpiration rate (E), and stomatal conductance (gs)were recorded using the LCA4 device made in England. Four measurements were taken from each plant, with a fully expanded leaf chosen from the young leaves in the middle of the plant canopy and placed in the probe chamber of the device. A young fully expanded leaf was placed in the probe chamber of the device, and the readings were recorded and averaged after four measurements from each plant.

Maximum operating efficiency of photosystem II(PSII) was measured in leaves that were in a light-adapted condition using an OS1-FL Modulated Fluorometer (Opti-Sciences, Inc., USA)(Equ. 1)(Murchie and Lawson, 2013); this measurement was performed on the same leaves used to measure the photosynthetic rate.

Equ. 2: PSII maximum efficiency (φPSII) or $(F_v'/F_m') = (F_m'–F_o')/F_m'$

F_v'/F_m': Maximum efficiency of PSII photochemistry in a light-adapted state.

F_m': A saturating pulse under actinic illumination transiently closes all reaction centers and yields maximal fluorescence in the light-adapted state.

F_o': The chlorophyll fluorescence minimum value.

Finally, the total chlorophyll index of the leaves was measured using the SPAD 502 Chlorophyll Meter. Six replicates per plant were measured at 7:00 a.m. from fully expanded mature leaves. Gas exchange parameters, photosynthetic attributes, and SPAD index were measured non-destructively three times, one month apart.

2.4.3. Determination of TSS, TA and pH

The methodology outlined by Savic *et al.* (2008) (Savić *et al.*, 2008) was used to calculate total titratable acidity (TA). Using a pH meter (Elmetron CP-501) and a digital refractometer (DR 101-60), the pH value and total soluble solids (TSS) concentration were calculated.

2.4.4. Water Use Efficiency

Yield water use efficiency (WUE) was determined by employing Equation 3.

Equ. 3: *WUE = FruitDry Weight (g) / Total Water Consumption (l)*

In this equation, WUE is yield water use efficiency (g lit^{-1}).

2.5. Statistical Analysis and Experimental Design

Data for each variable were subjected to the analysis of variance (ANOVA) with a split-plot design using generalized linear model procedures (JMP®, Version 16, for Mac. SAS Institute Inc., Cary, NC, 1989–2023). This study experimental split-plot with four replications used strawberry (*Fragaria × ananassa* Duch.). Each replication comprised three plants, resulting in a total of 96 pots utilized in the study. Irrigation strategies were the main plot, and the fertilizer levels were the subplot. For the statistical analysis, the LSD test at $p<0.05$ significance level was used.

3. Results

3.1. Morphological characteristics

Several strawberry plant characteristics were significantly affected by irrigation strategies and fertilizer levels ($P \leq 0.01$), as shown in Table 2. PRD1-EC1 and Controls (EC1 and EC2) had the most plant dry weight, but there was no statistical difference. According to Table 2, the Control (FI-EC2) reduced plant dry weight by 15.56%, while the PRD2 and SDI diluted fertilizer treatments reduced it by 47.62%. In this study, PRD2 treatments outperformed SDI treatments.

Table 2 shows that irrigation and fertilizer treatments had statistically significant effects on fruit weight and number. The parameter increased statistically in both the control and PRD1 treatments, as expected. The PRD2-EC2 treatment decreased 5% more than the control, which was not significant. The SDI-EC2 strategy reduced fruit fresh weight by 22.3% compared to the control group, as shown in Table 2. The experiments showed that full fertilizer worked slightly better than diluted fertilizer, but the difference wasn't statistically significant.

Table 2. The interaction effect of deficit irrigation × fertilizer levels on physiological parameters of the strawberry plants.

Deficit Irrigation	Fertilizer	Plant DryWeight (g)	Fruits Num	Average Fruits-FW (g)	Specific Leaf Area ($cm^2 g^{-1}$)
FI	**EC1**	35.06^{a*}	13.75^{bc}	7.96^{a}	65.08^{a}
	EC2	33.68^{ab}	18.75^{a}	7.13^{ab}	57.10^{bc}
PRD1	**EC1**	33.68^{ab}	17.75^{a}	7.15^{ab}	58.27^{bc}
	EC2	30.17^{bc}	14.50^{b}	6.85^{ab}	65.23^{a}
SDI	**EC1**	23.36^{d}	13.75^{bc}	4.68^{c}	57.16^{bc}
	EC2	17.64^{e}	8.00^{d}	5.54^{bc}	53.41^{c}
PRD2	**EC1**	22.67^{d}	11.75^{c}	6.01^{bc}	54.70^{c}
	EC2	28.44^{c}	16.25^{ab}	6.77^{ab}	62.01^{ab}

*Means followed by similar letters in each trait do not have a significant difference based on the LSD test ($P\leq 0.01$).

3.3. The Chlorophyll Index (SPAD)

Table 3 shows leaf chlorophyll index changes during the experiment. No statistically significant difference was found between the initial and subsequent leaf chlorophyll measurements. The final phase of treatment impact measurement changed significantly. The PRD2-EC2 treatment had the highest SPAD index at 72.32, significantly higher than PRD2-EC1 at 61.45 (Table 3). The PRD2-EC2 treatment did not significantly differ from the control or PRD2 treatments in SPAD rates. SDI treatments had the lowest SPAD, 55.5 (Table 3). All treatments showed an upward chlorophyll index trend.

Table 3. The interaction effect of deficit irrigation × fertigation levels on Strawberry plants SPAD index in days after treatment (DAT).

Deficit Irrigation	Fertigation	15 DAT	45 DAT	75 DAT
FI	**EC1**	49.4^{a}	46.32^{b}	70.7^{ab}
(100% FC)	**EC2**	50.15^{a}	48.85^{ab}	55.25^{c}
PRD1	**EC1**	49.82^{a}	48.05^{ab}	61.45^{bc}
	EC2	48.1^{a}	49.65^{ab}	72.32^{a}
SDI	**EC1**	52.35^{a}	50.55^{a}	55.9^{c}
	EC2	49.92^{a}	48.6^{ba}	63.72^{abc}
PRD2	**EC1**	50.15^{a}	50.8^{a}	71.82^{ab}
	EC2	49.92^{a}	50.75^{a}	62.07^{abc}

[*] Means followed by similar letters in each trait do not have a significant difference based on the LSD test ($P \leq 0.01$).

3.4. Analysis of photosynthetic parameters and their performance

FI-EC1 and PRD1-EC1 had higher leaf photosynthesis (A) rates than most treatments, as shown in Figure 2a. Except for PRD1, complete fertilizer yielded better second measurements than the other treatments. The final photosynthesis rate measurement centered around water availability. The amounts of fertilizers did not significantly differ, but the irrigation techniques did. First-phase measurements showed the highest gs for FI-EC1 (Figure 2b). PRD1-EC1 had the highest gs in stages 2 and 3. In the second and third stages, PRD2 had a higher gs than SDI. Strawberry leaf transpiration (E) changes in FI and PRD1-EC2 were the only treatments to decrease in the final stage (Figure 2c). Other than those two, most treatments rose gradually.

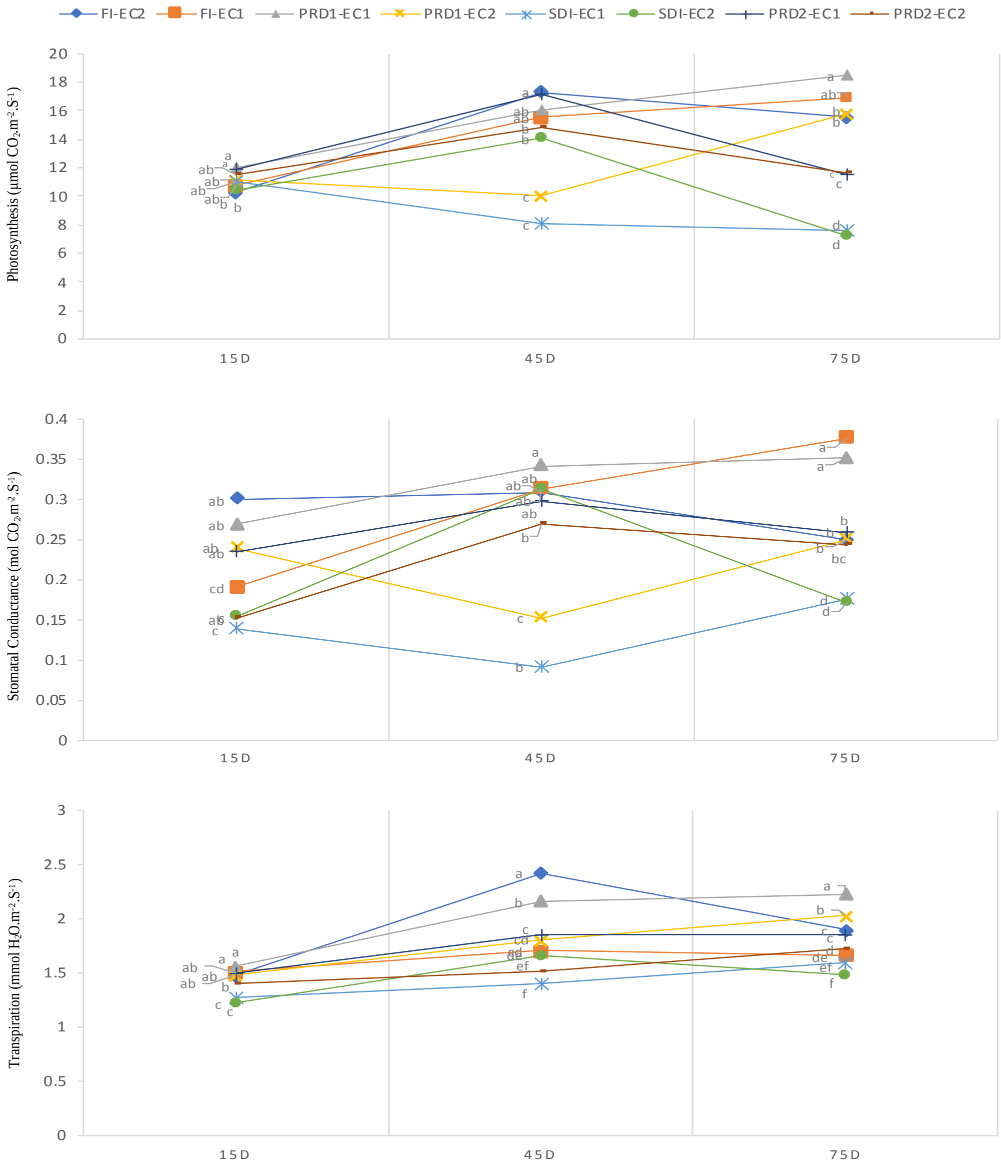

Figure 2. Effects of different treatments on photosynthetic rate (a), stomatal conductance (b), and transpiration (c) in three different data collecting stages.

The PSII photochemistry efficiency (F'v/F'm) results started similarly, with little variation (Figure 3). In stage two, the treatments show similar results to stage one, except for SDI, which decreased significantly. The peak level was recorded in FI-EC1 during the second time assessment. The differences become apparent in the final stage of this measurement. The lowest performance is observed in PRD1-EC2, SDI-EC2, and FI-EC2 treatments. PRD2-EC1 outperformed the other three treatments (Figure 3). Except for PRD2, other treatments have reduced photochemistry efficiency in diluted fertilizer (Figure 3).

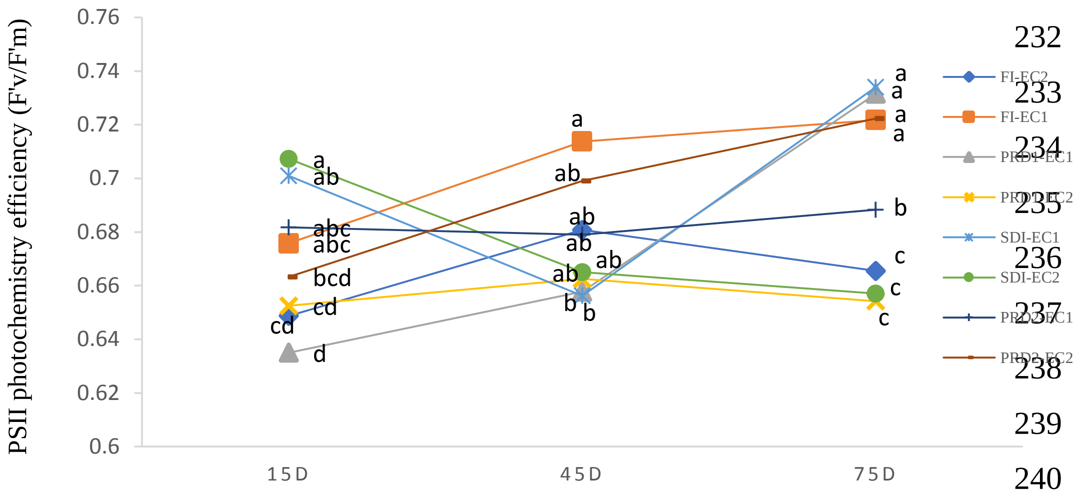

Figure 3. Effects of different treatments on PSII photochemistry efficiency (Fv/Fm) in three different data collecting stages.

3.5. Fruit quality characteristics

Our study found that irrigation and fertilizer levels affected fruit quality parameters notably total soluble solids (TSS) and titratable acidity (TA), as well as fruit pH (Table 4). The SDI-EC2 has nearly twice the TSS of the control. Compared to FI-EC2, PRD2-EC2 increased TSS by 35.7%. Table 4 shows that PRD1 treatments did not differ significantly from control. Moreover, Table 4 reveals that no significant difference in TA between SDI, PRD2, and the control group. However, PRD1-EC2 displayed the highest TA level of 1.61 g/100 ml, while SDI-EC2 exhibited the lowest TA amount of 0.64 g/100 ml. Except for PRD1, which had a statistically significant 10% pH reduction compared to the control, strawberry juice pH did not vary significantly across treatments. Compared to complete fertilizer, diluted fertilizer lowers pH by 5.7% (Table 4).

Table 4. The interaction effect of deficit irrigation×fertilizer levels (A) and their simple effect (B) on fruits chemical characteristics of strawberry plants

(A)

Deficit Irrigation	Fertilizer	Fruit-TSS (°Brix)	Fruit-TA (g/100 ml)
FI	**EC1**	10.35[b*]	1.09[bc]
	EC2	8.22[d]	0.81[cd]
PRD1	**EC1**	10.14[bc]	1.05[bc]
	EC2	8.71[cd]	1.61[a]
PRD2	**EC1**	7.9[d]	0.92[bcd]
	EC2	16.37[a]	0.67[d]
SDI	**EC1**	8.51[d]	1.15[b]
	EC2	11.16[b]	0.64[d]

(B)

		Fruit-pH
Deficit irrigation	**FI**	3.69[a]
	PRD1	3.31[b]
	SDI	3.6[a]
	PRD2	3.63[a]
Fertigation	**EC1**	3.66[a]
	EC2	3.45[b]

*Means followed by similar letters in each trait do not have a significant difference based on the LSD test ($P\leq 0.01$).

3.6. Yield Water Use Efficiency

The findings of our study indicate that yield WUE in full irrigation treatments (FI and PRD1) did not have a significant difference from each other. Also, in the diluted fertilizer (EC2), the performance of PRD1 and SDI compared to FI-EC2 decreased by 15% and 30.7%, respectively. However, the PRD2-EC2 treatment increased significantly by 72.5% compared to the control (Figure 4). Furthermore, the SDI-EC2 had the lowest outcome among other treatments.

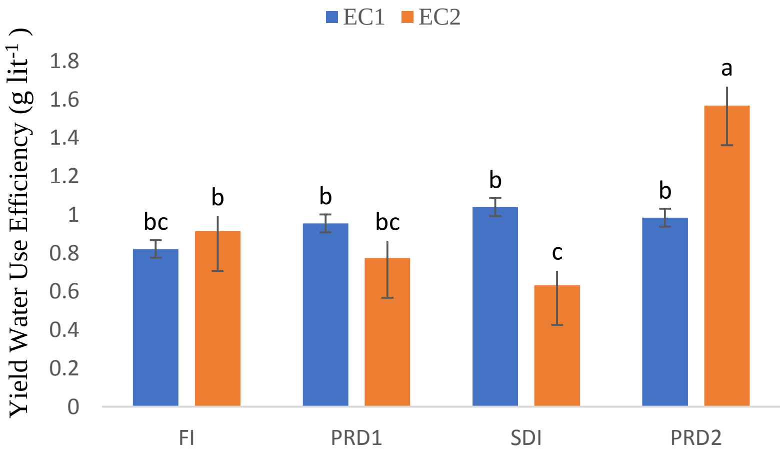

Figure 4. Effects of different treatments on yield water use efficiency in strawberry plants.

4. Discussion

The strawberry variety, stress duration, and implementation conditions are factors that have been found to impact the use of water, photosynthetic activity, and the application of deficit irrigation techniques (Jensen *et al.*, 2009; Ghaderi and Siosemarde, 2013; Shahnazari and Rezaiyan, 2015; Weber *et al.*, 2017). Although the objective of deficit irrigation strategies is not to induce severe drought stress and reduce yield, these occurrences are unavoidable due to the reduction in the amount of water applied (Ghaderi and Siosemarde, 2013). Different irrigation techniques, through modifications in the physical and chemical mechanisms of plants, can induce alterations in the plants internal and external reactions, thereby enhancing their water use efficiency (Jensen *et al.*, 2009; Shi *et al.*, 2019).

One of the initial responses of plants to drought stress is the reduction of gs and gas exchange in leaves. In SDI, the reaction reduces biomass production and water use efficiency, as previously reported(Ghaderi and Siosemarde, 2013). In previous studies, the PRD approach, which boosts root signaling in response to drought stress, modulated leaf stomatal conductance (Tabata *et al.*, 2014). Prolonged dryness in a root zone causes a chain of physiological responses in the plant. Chemical processes in the root release plant hormones like abscisic acid. They protect plant tissues from stress and stabilize the cell wall membrane (MSI) in water-scarce conditions along with osmotic and plastic adjustments in branches and leaves. By preserving cellular water and lowering leaf WSD, this adaptation maintains leaf turgor (Ghaderi and Siosemarde, 2013; Weber *et al.*, 2017; Rokosa and

Mikiciuk, 2020). According to previous studies and our findings in Table 3, PRD preserved leaf chlorophyll better than SDI. This observation is of particular significance due to the established correlation between chlorophyll content and leaf photosynthesis rate(Shi *et al.,* 2019).

Yield is greatly influenced by photosynthesis (A) and leaf transpiration (E) in the second and third stages, especially during fruiting stage. Moreover, water stress and gs reduction are positively correlated with decreased transpiration rate (Ghaderi and Siosemardeh, 2011; Ghaderi and Siosemarde, 2013). PRD decreases plants gs compared to FI but increases it compared to SDI (Figure 2). These arrangements increased CO2 assimilation (photosynthesis) over SDI. Strawberries and other plants have shown this mechanism of action. However, gs regulation and yield were unaffected by short-term PRD implementation in strawberry plants (Jensen *et al.,* 2009); as shown in Figures 2 and 3, initial assessments of gs, A, E, and SPAD index showed no significant differences. During drought-induced stress, the PRD strategy has shown better outcomes over time. Previous studies, similar to SDI treatments, reports that drought stress decreases strawberry chlorophyll, A, gs, and E (Ghaderi and Siosemardeh, 2011; Ghaderi and Siosemarde, 2013).

A key characteristic of stress is photosystem II quantum efficiency (F_v'/F_m'), which indicates its efficiency of photosystem II. Drought reduces photosynthesis and increases ROS production by decreasing F_v'/F_m'. The decline in F_v'/F_m' can accurately measure plant drought tolerance in greenhouse cultivation. According to other studies, photosynthetic rates decreased as plant growth and productivity decreased. CO2 assimilation decreased mostly due to diffusional limitations (Murchie and Lawson, 2013; Shi *et al.,* 2019). Gs reduction and yield are related, and F_v'/F_m' changes support this significant decrease (Figure 3).

Physical mechanisms in the substrate environment and plant tissues make PRD more effective. PRD improves water and nutrient absorption by increasing root hydraulic conductivity (Kang *et al.,* 2002; Shao *et al.,* 2008). Compared to SDI methods, applying an equivalent amount of water in a smaller substrate volume creates a deeper moisture front. Therefore, the plant will be more resilient to drought (Kang *et al.,* 2002; Wang *et al.,* 2017). SDI plants exhibited severe deficiency in our experiment. Insufficient nutrients reduce yield and quality in hydroponic cultivation (Wu *et al.,* 2020). The aforementioned inadequacy is noted in SDI treatments. Fertilizer toxicity reduces flower and fruit yield (Massa *et al.,* 2020). In Table 2, FI-EC1 and PRD2-EC1 plants show this phenomenon. FI-EC2 and PRD2-EC2 were more effective due to lower root salt concentrations (Table 2).

Fruit taste parameters affect marketability and economics (Wu *et al.,* 2020). Previous research linked sugar/acid ratio to sensory preference. Analysis has also shown that low TSS or high TA content causes low sweetness in sensory evaluation (Ran, 2014; Wu *et al.,* 2020). Similar to our findings in Table 4, previous research has also shown deficit irrigation increases TSS and decreases TA in strawberry cultivars (Weber *et al.*, 2017; Ariza *et al.*, 2021).

Water availability mainly affected the plant's dry weight. The experiment linked water scarcity to number reduction. Water availability dominated the plant's dry-weight growth. Water scarcity was linked to leaf number reduction in the experiment. A decrease in foliage during periods of drought was reported in a previous report on C3 plants due to chlorophyll degradation (Shi *et al.*, 2019) in strawberries (Yenni *et al.*, 2022). In comparison to diluted fertilizer, complete fertilizer improved SLA performance in control and SDI pots compared to diluted fertilizer. PRD pots improved the plant's SLA by increasing water accessibility. The analysis of growth parameters in split and unsplit pots, utilizing equal volumes of diluted fertigation, effectively illustrates the effects of prolonged root dryness (Table 2).

According to empirical data (Table 2), water stress (SDI) reduces fruit weight and quantity which ultimately leads to a reduction in the plant's overall yield (Martínez-Ferri *et al.*, 2016; Adak *et al.*, 2018; Rugienius *et al.*, 2021). The PRD2 treatment did not significantly reduce fruit quantity or weight compared to control (Table 2). The deficit irrigation didn't affect 'Flamenco' strawberry yield or size, according to Weber *et al.* (2017). Shahnazari and Rezaiyan (2015) reported that PRD performed best and was closest to full irrigation treatment in quantitative and qualitative terms. The quantity of fertilizer applied also made a difference. For instance, Due to over-irrigation and nutrient deficiency, PRD1-EC1 performed better than PRD1-EC2(Table 2).

Research has shown that drought stress reduces leaf numbers (Razavi *et al.*, 2008; Shi *et al.*, 2019). Water use efficiency can be improved by using drought-resistant cultivars (Martínez-Ferri *et al.*, 2016), as reducing leaf area and SLA reduces transpiration. Furthermore, previous research indicates that the weight of a single strawberry fruit is correlated with the amount of water given to plants (Rokosa and Mikiciuk, 2020); because of PRD's superiority, this parameter did not differ significantly between control and PRD, but SDI did (Table 2).

Water use efficiency (WUE) is an important practical parameter and a stress indicator for this experiment. Strawberry berry size and yield decrease with water deficit (Giné Bordonaba and Terry, 2010; Weber *et al.*, 2017; Rugienius *et al.*, 2021). Water consumption efficiency (WUE) was superior in PRD treatments than SDI treatments which was achieved by reducing water consumption by 50%, ensuring adequate nutrient supply, maintaining the health of the substrates, and irrigating with a deep moisture level. The functions were detailed above. Previous studies on strawberries found similar results (Giné Bordonaba and Terry, 2010; Zhang *et al.*, 2019; Rokosa and Mikiciuk, 2020). Insufficient water and essential elements caused plant and fruit quality issues, regardless of PRD treatment's superior performance. Despite the lack of statistical significance, the decrease in mean fruit weight may have adverse effects on the marketability of the crop (Giné Bordonaba and Terry, 2010; Rokosa and Mikiciuk, 2020), thereby posing a significant challenge to the efficacy of the irrigation approach.

5. Conclusions

Deficit irrigation can improve yield water use efficiency, according to this study. We found that FI-EC2 treatment significantly increased second-stage evaporation from leaves. When FI-EC1 and PRD1-EC1 treatments were used, the rate of leaf photosynthesis increased, and the rate of leaf photosynthesis for these treatments showed an upward trend. The PRD2 treatment had higher gs than SDI in the second and third stages. Using an appropriate approach for the plant can maintain strawberry productivity and quality and increase water use efficiency. We found a clear difference between deficit irrigation strategies. The PRD2-EC2 had the best performance in the terms of saving water and fertilizers. However, diluted fertilizer levels may have quality issues despite maintaining yield water use efficiency. Thus, future research can address nutrient deficiencies and improve sustainable production with appropriate fertilizer. It was shown that using a PRD strategy in hydroponic greenhouses to grow strawberries in water-scarce conditions can balance environmental sustainability and economic benefit.

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بررسی اثر کودآبیاری بر برخی صفات رویشی، زایشی و فتوسنتزی گیاه توت فرنگی تحت شرایط کم آبیاری (Fragaria× ananassa Duch var. Camarosa)

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چکیده

در این مطالعه با هدف به حداکثر رساندن عملکرد محصول در عین حفظ منابع آب، اثرات برخی استراتژی‌های آبیاری از جمله بر صفات رشدی، فیزیولوژیکی و فتوسنتزی گیاه توت‌فرنگی مورد (PRD) و خشکی موضعی ریشه (SDI) کم آبیاری پایا (حجم PRD1))، (FIبررسی قرار گرفت. آزمایش فوق دارای چهار استراتژی آبیاری شامل تیمار شاهد (حجم آبیاری کامل و چهار تکرار در هر)EC2 و EC1) به همراه دو سطح کودی (FI (50 درصد SDI) و FI (50 درصد PRD2آبیاری کامل)، در سه نوبت در (F'v/F'm) وII کارایی فتوسیستم (gs) تیمار بود. تبادلات گازی، شاخص کلروفیل برگ، هدایت روزنه ای طول مدت آزمایش ارزیابی گردید. شاخص برداشت، کارایی مصرف آب، عملکرد، مواد جامد محلول، اسیدیته کل از دیگر صفات (MSI و WSD اندازه گیری شده بود. نتایج نشان داد کمبود آبیاری و کوددهی به‌طور معنی‌داری بر شاخص‌های تنش در گیاه (

به میزان ۹ درصد بیشتر II کارایی فتوسیستمPRD2-EC2و کیفیت میوه تأثیر گذار است. در نوبت سوم اندازه گیری، در تیمار ، (EC2)تأثیر گذاشت. در کود رقیق شده   به طور موثر بر هدایت روزنه ای PRD بود. همچنین، استراتژی SDI-EC از تیمار بود و در F1-EC2   15٪ و 30/7٪ کمتر از به ترتیب به میزان SDI و PRD1 راندمان تولید به ازای آب مصرفی در تیمار دارای مزایای PRD به میزان 72/5 درصد بیشتر از شاهد افزایش یافت. مشاهدات نشان داد که استراتژی PRD2-EC2 تیمار بلندمدت برای گیاه و موثر در کاهش مصرف آب است. با این حال، برای ایجاد یک استراتژی آبیاری پایدار، هدایت الکتریکی محلول غذایی باید برای کنترل رشد و ویژگی‌های فتوسنتز گیاه تنظیم شود.