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1 **In Press, Pre-Proof Version**

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

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13 **Abstract**

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

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

33  
34 **1. Introduction**

35 Water regulates physiological processes and plant productivity and is essential for plant growth and  
36 development. Water relations affect growth, physiology, and photosynthesis, therefore comprehending

37 them is important. In agricultural systems, deficit irrigation can improve water use efficiency and  
38 reduce water management by applying water below plant needs (Arief *et al.*, 2023; Martínez-Ferri *et*  
39 *al.*, 2016). Sustained deficit irrigation (SDI) and partial root-zone drying (PRD) have been used in  
40 various crops for decades due to their physical and secondary physiological benefits to plants and root  
41 settings (Sepaskhah and Ahmadi, 2012). Their research indicates in water-scarce areas, PRD boosts  
42 water productivity and maintains yield, prioritizing water value over just economic yield.  
43 According to FAO statistics, in twenty years (2000-2020), the strawberry-cultivated area has increased  
44 from 783713 to 384668. Iran has expanded its strawberry cultivation by over a thousand hectares in  
45 this period, showing increased farmer interest in this product (Crops and livestock products, 2022).  
46 Strawberry (*Fragaria × ananassa* Duch.) is a highly valued crop due to its tasty and nutritious fruits.  
47 Strawberry plants are sensitive to water availability, so irrigation is crucial. Research has examined  
48 the effects of deficit irrigation on strawberry plant growth, physiology, photosynthetic properties,  
49 water uptake, transport, and transpiration. Water availability, soil moisture, and drought stress affect  
50 plant physiological and biochemical processes. Strawberry plants, like other crops, need optimal water  
51 balance for cellular composition, nutrient absorption, and metabolism. Researching strawberry plant  
52 responses to irrigation can aid in developing sustainable irrigation strategies that maximize crop  
53 productivity and conserve water resources (Ghaderi and Siosemardeh, 2011; Martínez-Ferri *et al.*,  
54 2016; Weber *et al.*, 2017; Wu *et al.*, 2020). Understanding the response of strawberry plants to  
55 irrigation can provide valuable insight into their adaptation mechanisms and help develop sustainable  
56 irrigation strategies to maximize crop productivity while maintaining water resources.  
57 Strawberry plants are sensitive to drought stress, which can affect nutrient transport, cell expansion,  
58 and growth (Weber *et al.*, 2017; Zhang *et al.*, 2019). Previous research shows that the physiological  
59 responses of strawberry plants, including stomata behavior, osmotic regulation, transpiration, and  
60 hormonal regulations, which play an important role in their ability to tolerate water stress, are  
61 influenced by PRD strategy (Jensen *et al.*, 2009; Yenni *et al.*, 2022). Opening and closing stomata  
62 adjust transpiration, which is affected by water availability, especially in PRD (Na *et al.*, 2014; Zhang  
63 *et al.*, 2019). However, heavy irrigation or poor drainage can prevent nutrient absorption, reducing  
64 growth and productivity. (Wu *et al.*, 2020).  
65 The ability to accurately evaluate drought stress and its effects on plants is crucial to understanding  
66 plant responses and formulating effective strategies for production management. In recent years, non-  
67 destructive methods, such as the amount of photosynthesis and fluorescence chlorophyll, have  
68 appeared to evaluate drought stress in strawberry plants. One of the most commonly used chlorophyll  
69 fluorescence parameters is the maximum quantum yield of photosystem II (FV/FM). This is an  
70 indicator of the overall health and performance of the photosynthetic system (Murchie and Lawson,

71 2013; Na *et al.*, 2014). Drought stress typically results in a decrease in Fv/Fm and reflects  
72 photosynthetic function (Murchie and Lawson, 2013; Zebrowska and Michalek, 2014). Strawberry  
73 growth and fruit production depend on photosynthesis. Water status affects leaf carbon dioxide  
74 emission and water availability for photosynthetic reactions, regulating photosynthetic levels. For  
75 example, drought stress can close the stomata, limit carbon dioxide availability, reduce photosynthetic  
76 efficiency, and increase chlorophyll fluorescence. In addition, drought can lead to dehydration and  
77 damage to the photosynthetic system, ultimately affecting the productivity of strawberry plants.  
78 Understanding the complex relation between water and growth, physiology, and photosynthesis of  
79 strawberry plants is very important to optimize cultivation methods, enhance crop productivity, and  
80 formulate solutions to reduce the effects of water stress (Na *et al.*, 2014; Iqbal *et al.*, 2020; Alavi *et*  
81 *al.*, 2023).

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

87

## 88 **2. Materials and Methods**

### 89 **2.1. Greenhouse Condition**

90 The study was conducted in a research greenhouse on strawberry plants (*Fragaria × ananassa* Duch.  
91 var. Camarosa) at the University of Ferdowsi, located in Mashhad, Iran (36.29° N, 59.60° E), during  
92 2021-2022. The humidity and temperature were kept at an average of 63% relative humidity and  
93 26/18°C Day/Night, respectively. To maintain a 14-hour day and 10-hour night schedule, 400-watt  
94 sodium vapor lamps were used.

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

103



104

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

107

## 108 2.2. Experimental Treatments

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

115

**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

116

## 117 **2.3. Irrigation Management**

118 An open hydroponic system that was automated and operated three times per day based on a digital  
119 timer was used in this project. Pressurized drippers and diaphragm pumps were used to ensure precise  
120 irrigation. The water quality was kept at a level that is suitable for strawberries, with a pH range of 5.5  
121 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  
122 substrate is different from the soil; based on a previous study, available water (AW) was considered  
123 in a potential matrix range between -1 and -10 kPa, and water in a potential matrix range between -1  
124 and -5 kPa was considered as easily available water (EAW) (Marcelis and Heuvelink, 2019). The  
125 amount of water in the substrates is experimentally dependent on the type of substrates, water intake,  
126 and plant resistance (Maluin *et al.*, 2021); In this experiment, a simplified water balance method  
127 calculated averaged potential evapotranspiration (ETp). Using plastic bottle lysimeters beneath each  
128 pot, water losses from irrigation drainage were collected. The experiment calculated each cultivar's  
129 total evapotranspiration for both treatment conditions. The volume of water (V) in milliliters for  
130 fertigation was determined and subsequently modified on a weekly basis utilizing Equation 1.

131 *Equ. 1:* 
$$V = (ETp)(1 + LF)$$

132 ETp is the averaged potential evapotranspiration (mm) and LF is the leaching fraction percentage in  
133 Equation 1. Considering standard irrigation practices used in commercial greenhouses, the LF was  
134 20% during the experiment. Bi-daily irrigation rotation was used in PRD treatments. EC and pH in  
135 fertigation were kept at 1.8 (dS m<sup>-1</sup>) and 6–6.5, respectively. During the experiment, each pot received  
136 15.7 liters of fertigation water for the FI treatment. In PRD treatments, irrigation was rotated on a bi-  
137 daily basis, and only one part of the container was irrigated with fertigation in each irrigation. In full  
138 fertigation, the EC and pH levels of fertigation were kept at 1.8 (d/Sm) and between 6 and 6.5,  
139 respectively.

## 140 **2.4. Measurements**

### 142 **2.4.1. The morphological attributes**

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

#### 151 **2.4.2. Gas exchange measurement and photosynthetic attributes**

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

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

161 *Equ. 2:* PSII maximum efficiency ( $\phi$ PSII) or  $(F_v'/F_m') = (F_m' - F_o')/F_m'$

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

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

165  $F_o'$ : The chlorophyll fluorescence minimum value.

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

#### 170 171 **2.4.3. Determination of TSS, TA and pH**

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

#### 175 176 **2.4.4. Water Use Efficiency**

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

178 *Equ. 3:*  $WUE = \text{Fruit Dry Weight (g)} / \text{Total Water Consumption (l)}$

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

#### 180 181 **2.5. Statistical Analysis and Experimental Design**

182 Data for each variable were subjected to the analysis of variance (ANOVA) with a split-plot design  
183 using generalized linear model procedures (JMP®, Version 16, for Mac. SAS Institute Inc., Cary, NC,  
184 1989–2023). This study experimental split-plot with four replications used strawberry (*Fragaria ×*  
185 *ananassa* Duch.). Each replication comprised three plants, resulting in a total of 96 pots utilized in the



186 study. Irrigation strategies were the main plot, and the fertilizer levels were the subplot. For the  
 187 statistical analysis, the LSD test at  $p < 0.05$  significance level was used.

188  
 189 **3. Results**

190 **3.1. Morphological characteristics**

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

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

**Table 2.** The interaction effect of deficit irrigation  $\times$  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 <sup>2</sup> g <sup>-1</sup> )
FI	EC1	35.06 <sup>a*</sup>	13.75 <sup>bc</sup>	7.96 <sup>a</sup>	65.08 <sup>a</sup>
	EC2	33.68 <sup>ab</sup>	18.75 <sup>a</sup>	7.13 <sup>ab</sup>	57.10 <sup>bc</sup>
PRD1	EC1	33.68 <sup>ab</sup>	17.75 <sup>a</sup>	7.15 <sup>ab</sup>	58.27 <sup>bc</sup>
	EC2	30.17 <sup>bc</sup>	14.50 <sup>b</sup>	6.85 <sup>ab</sup>	65.23 <sup>a</sup>
SDI	EC1	23.36 <sup>d</sup>	13.75 <sup>bc</sup>	4.68 <sup>c</sup>	57.16 <sup>bc</sup>
	EC2	17.64 <sup>e</sup>	8.00 <sup>d</sup>	5.54 <sup>bc</sup>	53.41 <sup>c</sup>
PRD2	EC1	22.67 <sup>d</sup>	11.75 <sup>c</sup>	6.01 <sup>bc</sup>	54.70 <sup>c</sup>
	EC2	28.44 <sup>c</sup>	16.25 <sup>ab</sup>	6.77 <sup>ab</sup>	62.01 <sup>ab</sup>

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

202 **3.3. The Chlorophyll Index (SPAD)**

203 Table 3 shows leaf chlorophyll index changes during the experiment. No statistically significant  
 204 difference was found between the initial and subsequent leaf chlorophyll measurements. The final  
 205 phase of treatment impact measurement changed significantly. The PRD2-EC2 treatment had the  
 206 highest SPAD index at 72.32, significantly higher than PRD2-EC1 at 61.45 (Table 3). The PRD2-EC2

207 treatment did not significantly differ from the control or PRD2 treatments in SPAD rates. SDI  
 208 treatments had the lowest SPAD, 55.5 (Table 3). All treatments showed an upward chlorophyll index  
 209 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
<b>FI</b> (100% FC)	<b>EC1</b>	49.4 <sup>a</sup>	46.32 <sup>b</sup>	70.7 <sup>ab</sup>
	<b>EC2</b>	50.15 <sup>a</sup>	48.85 <sup>ab</sup>	55.25 <sup>c</sup>
<b>PRD1</b>	<b>EC1</b>	49.82 <sup>a</sup>	48.05 <sup>ab</sup>	61.45 <sup>bc</sup>
	<b>EC2</b>	48.1 <sup>a</sup>	49.65 <sup>ab</sup>	72.32 <sup>a</sup>
<b>SDI</b>	<b>EC1</b>	52.35 <sup>a</sup>	50.55 <sup>a</sup>	55.9 <sup>c</sup>
	<b>EC2</b>	49.92 <sup>a</sup>	48.6 <sup>ba</sup>	63.72 <sup>abc</sup>
<b>PRD2</b>	<b>EC1</b>	50.15 <sup>a</sup>	50.8 <sup>a</sup>	71.82 <sup>ab</sup>
	<b>EC2</b>	49.92 <sup>a</sup>	50.75 <sup>a</sup>	62.07 <sup>abc</sup>

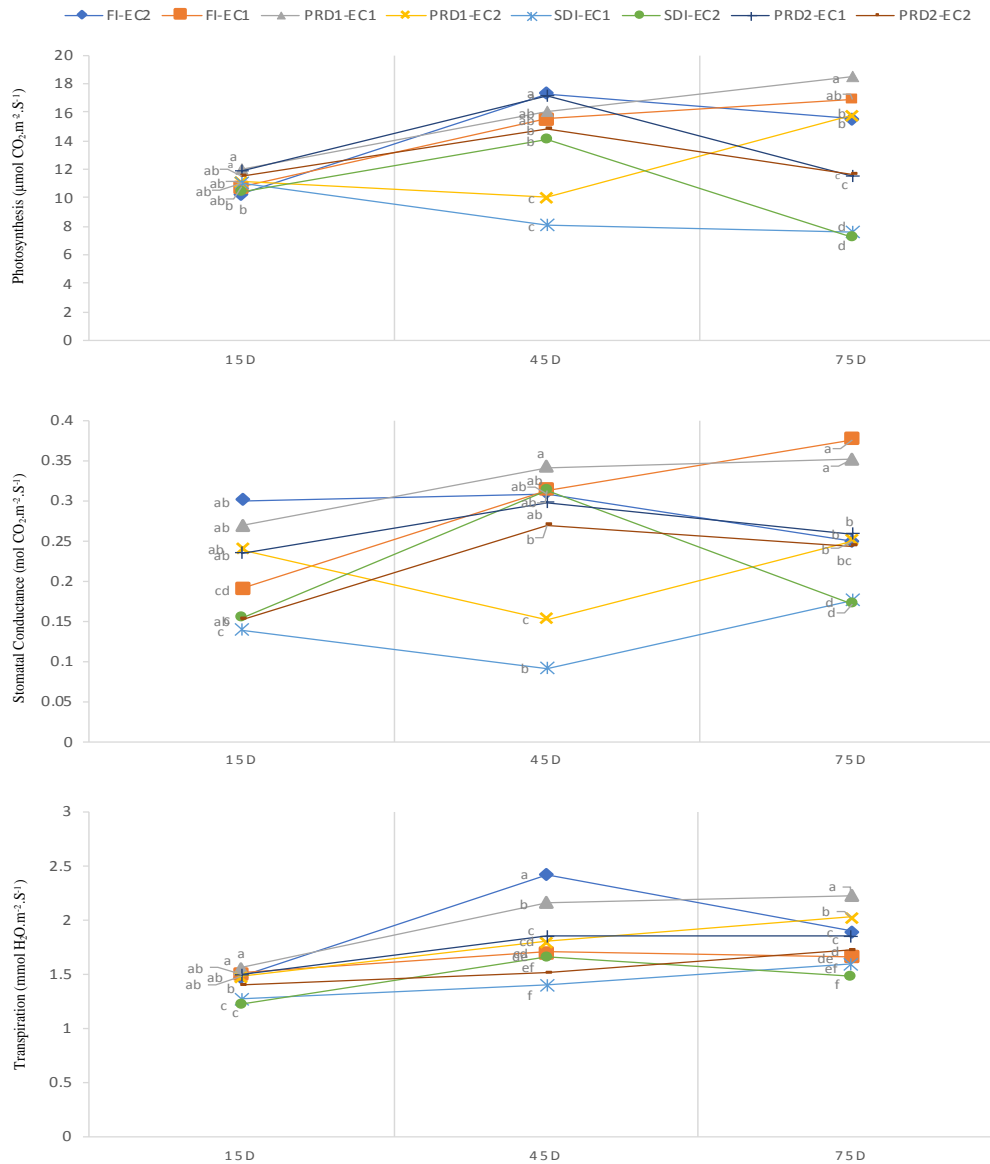
\* Means followed by similar letters in each trait do not have a significant difference based on the LSD test ( $P \leq 0.01$ ).

210

### 211 3.4. Analysis of photosynthetic parameters and their performance

212 FI-EC1 and PRD1-EC1 had higher leaf photosynthesis (A) rates than most treatments, as shown in  
 213 Figure 2a. Except for PRD1, complete fertilizer yielded better second measurements than the other  
 214 treatments. The final photosynthesis rate measurement centered around water availability. The  
 215 amounts of fertilizers did not significantly differ, but the irrigation techniques did. First-phase  
 216 measurements showed the highest  $g_s$  for FI-EC1 (Figure 2b). PRD1-EC1 had the highest  $g_s$  in stages  
 217 2 and 3. In the second and third stages, PRD2 had a higher  $g_s$  than SDI. Strawberry leaf transpiration  
 218 (E) changes in FI and PRD1-EC2 were the only treatments to decrease in the final stage (Figure 2c).  
 219 Other than those two, most treatments rose gradually.



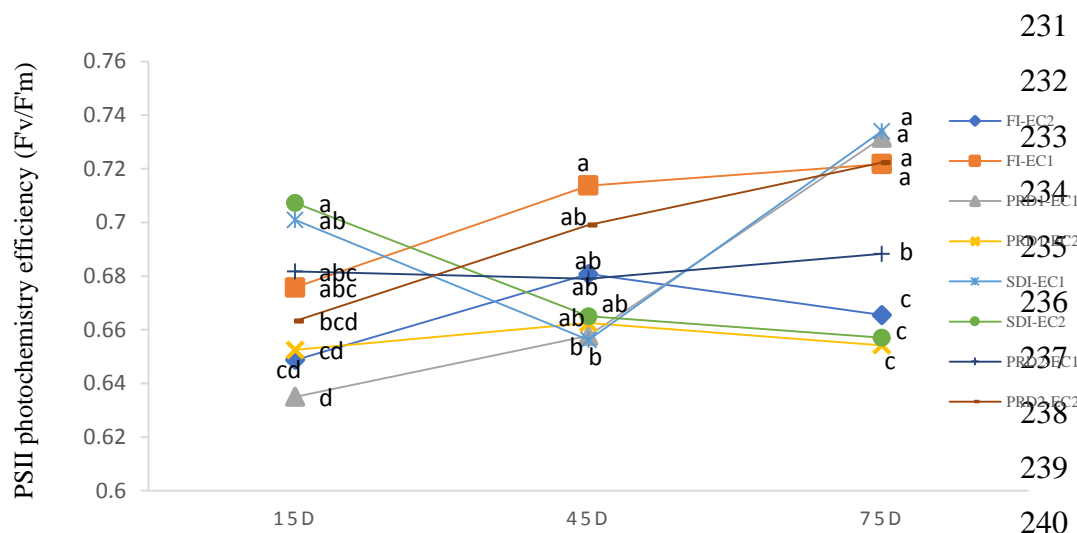


220

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

223

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



241 **Figure 3.** Effects of different treatments on PSII photochemistry efficiency (Fv/Fm) in three different  
 242 data collecting stages.  
 243

### 244 3.5. Fruit quality characteristics

245 Our study found that irrigation and fertilizer levels affected fruit quality parameters notably total  
 246 soluble solids (TSS) and titratable acidity (TA), as well as fruit pH (Table 4). The SDI-EC2 has nearly  
 247 twice the TSS of the control. Compared to FI-EC2, PRD2-EC2 increased TSS by 35.7%. Table 4  
 248 shows that PRD1 treatments did not differ significantly from control. Moreover, Table 4 reveals that  
 249 no significant difference in TA between SDI, PRD2, and the control group. However, PRD1-EC2  
 250 displayed the highest TA level of 1.61 g/100 ml, while SDI-EC2 exhibited the lowest TA amount of  
 251 0.64 g/100 ml. Except for PRD1, which had a statistically significant 10% pH reduction compared to  
 252 the control, strawberry juice pH did not vary significantly across treatments. Compared to complete  
 253 fertilizer, diluted fertilizer lowers pH by 5.7% (Table 4).

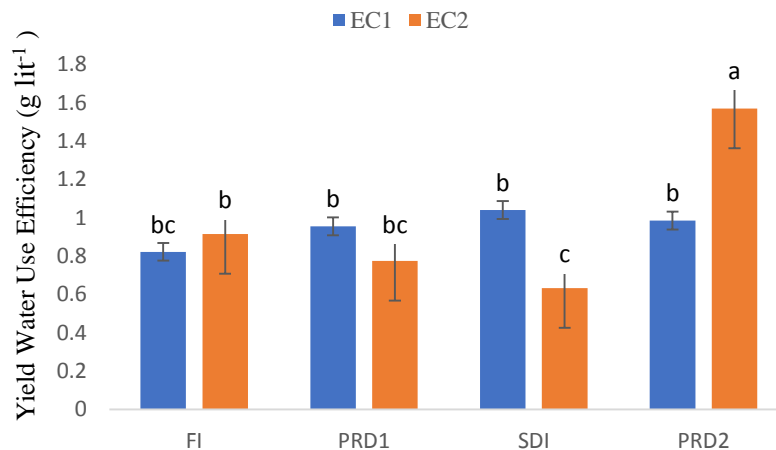
**Table 4.** The interaction effect of deficit irrigation×fertilizer levels (A) and their simple effect (B) on fruits chemical characteristics of strawberry plants

(A)			(B)				
Deficit Irrigation	Fertilizer	Fruit-TSS (°Brix)	Fruit-TA (g/100 ml)		Fruit-pH		
FI	EC1	10.35 <sup>b*</sup>	1.09 <sup>bc</sup>	<hr/> <b>Deficit irrigation</b> <hr/>	FI	3.69 <sup>a</sup>	
	EC2	8.22 <sup>d</sup>	0.81 <sup>cd</sup>		PRD1	3.31 <sup>b</sup>	
PRD1	EC1	10.14 <sup>bc</sup>	1.05 <sup>bc</sup>		SDI	3.6 <sup>a</sup>	
	EC2	8.71 <sup>cd</sup>	1.61 <sup>a</sup>		PRD2	3.63 <sup>a</sup>	
PRD2	EC1	7.9 <sup>d</sup>	0.92 <sup>bcd</sup>		<hr/> <b>Fertigation</b> <hr/>	EC1	3.66 <sup>a</sup>
	EC2	16.37 <sup>a</sup>	0.67 <sup>d</sup>			EC2	3.45 <sup>b</sup>
SDI	EC1	8.51 <sup>d</sup>	1.15 <sup>b</sup>				
	EC2	11.16 <sup>b</sup>	0.64 <sup>d</sup>				

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

### 254 3.6. Yield Water Use Efficiency

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



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

## 262 4. Discussion

263 The strawberry variety, stress duration, and implementation conditions are factors that have been found  
264 to impact the use of water, photosynthetic activity, and the application of deficit irrigation techniques  
265 (Jensen *et al.*, 2009; Ghaderi and Siosemarde, 2013; Shahnazari and Rezaiyan, 2015; Weber *et al.*,  
266 2017). Although the objective of deficit irrigation strategies is not to induce severe drought stress and  
267 reduce yield, these occurrences are unavoidable due to the reduction in the amount of water applied  
268 (Ghaderi and Siosemarde, 2013). Different irrigation techniques, through modifications in the physical  
269 and chemical mechanisms of plants, can induce alterations in the plants internal and external reactions,  
270 thereby enhancing their water use efficiency (Jensen *et al.*, 2009; Shi *et al.*, 2019).

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

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

283 Yield is greatly influenced by photosynthesis (A) and leaf transpiration (E) in the second and third  
284 stages, especially during **fruiting** stage. Moreover, water stress and gs reduction are positively  
285 correlated with decreased transpiration rate (Ghaderi and Siosemardeh, 2011; Ghaderi and  
286 Siosemardeh, 2013). PRD decreases plants gs compared to FI but increases it compared to SDI (Figure  
287 2). These arrangements increased CO<sub>2</sub> assimilation (photosynthesis) over SDI. **Strawberries** and other  
288 plants have shown this mechanism of action. However, gs regulation and yield were unaffected by  
289 short-term PRD implementation in strawberry plants (Jensen *et al.*, 2009); as shown in Figures 2 and  
290 3, initial assessments of gs, A, E, and SPAD index showed no significant differences. During drought-  
291 induced stress, the PRD strategy has shown better outcomes over time. Previous **studies**, similar to  
292 SDI treatments, reports that drought stress decreases strawberry chlorophyll, A, gs, and E (Ghaderi  
293 and Siosemardeh, 2011; Ghaderi and Siosemardeh, 2013).

294 A key characteristic of stress is photosystem II quantum efficiency ( $F_v'/F_m'$ ), which indicates its  
295 efficiency of photosystem II. Drought reduces photosynthesis and increases ROS production by  
296 decreasing  $F_v'/F_m'$ . The decline in  $F_v'/F_m'$  can accurately measure plant drought tolerance in greenhouse  
297 cultivation. According to **other studies**, photosynthetic rates decreased as plant growth and productivity  
298 decreased. CO<sub>2</sub> assimilation decreased mostly due to diffusional limitations (Murchie and Lawson,  
299 2013; Shi *et al.*, 2019). Gs reduction and yield are related, and  $F_v'/F_m'$  changes support this significant  
300 decrease (Figure 3).

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

310 Fruit taste parameters affect marketability and economics (Wu *et al.*, 2020). Previous research linked  
311 sugar/acid ratio to sensory preference. Analysis has also shown that low TSS or high TA content causes  
312 low sweetness in sensory evaluation (Ran, 2014; Wu *et al.*, 2020). Similar to our findings in Table 4,

313 previous research has also shown deficit irrigation increases TSS and decreases TA in strawberry  
314 cultivars (Weber *et al.*, 2017; Ariza *et al.*, 2021).

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

324 According to empirical data (Table 2), water stress (SDI) reduces fruit weight and quantity which  
325 ultimately leads to a reduction in the plant's overall yield (Martínez-Ferri *et al.*, 2016; Adak *et al.*,  
326 2018; Rugienius *et al.*, 2021). The PRD2 treatment did not significantly reduce fruit quantity or weight  
327 compared to control (Table 2). The deficit irrigation didn't affect 'Flamenco' strawberry yield or size,  
328 according to Weber *et al.* (2017). Shahnazari and Rezaian (2015) reported that PRD performed best  
329 and was closest to full irrigation treatment in quantitative and qualitative terms. The quantity  
330 of fertilizer applied also made a difference. For instance, Due to over-irrigation and nutrient deficiency,  
331 PRD1-EC1 performed better than PRD1-EC2 (Table 2).

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

338 Water use efficiency (WUE) is an important practical parameter and a stress indicator for this  
339 experiment. Strawberry berry size and yield decrease with water deficit (Giné Bordonaba and Terry,  
340 2010; Weber *et al.*, 2017; Rugienius *et al.*, 2021). Water consumption efficiency (WUE) was superior  
341 in PRD treatments than SDI treatments which was achieved by reducing water consumption by 50%,  
342 ensuring adequate nutrient supply, maintaining the health of the substrates, and irrigating with a deep  
343 moisture level. The functions were detailed above. Previous studies on strawberries found similar  
344 results (Giné Bordonaba and Terry, 2010; Zhang *et al.*, 2019; Rokosa and Mikiciuk, 2020). Insufficient  
345 water and essential elements caused plant and fruit quality issues, regardless of PRD treatment's  
346 superior performance. Despite the lack of statistical significance, the decrease in mean fruit weight

347 may have adverse effects on the marketability of the crop (Giné Bordonaba and Terry, 2010; Rokosa  
348 and Mikiciuk, 2020), thereby posing a significant challenge to the efficacy of the irrigation approach.

## 349 **5. Conclusions**

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

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

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#### 473 چکیده

474 در این مطالعه با هدف به حداکثر رساندن عملکرد محصول در عین حفظ منابع آب، اثرات برخی استراتژی‌های آبیاری از جمله  
475 بر صفات رشدی، فیزیولوژیکی و فتوسنتزی گیاه توت‌فرنگی مورد (PRD) و خشکی موضعی ریشه (SDI) کم آبیاری پایا  
476 (حجم PRD1)، (FI بررسی قرار گرفت. آزمایش فوق دارای چهار استراتژی آبیاری شامل تیمار شاهد (حجم آبیاری کامل  
477 و چهار تکرار در هر (EC1 و EC2) به همراه دو سطح کودی (FI (50 درصد SDI) و (FI (50 درصد PRD2 آبیاری کامل)،  
478 در سه نوبت در (F'v/F'm) II و کارایی فتوسیستم (gs) تیمار بود. تبادلات گازی، شاخص کلروفیل برگ، هدایت روزنه ای  
479 طول مدت آزمایش ارزیابی گردید. شاخص برداشت، کارایی مصرف آب، عملکرد، مواد جامد محلول، اسیدیته کل از دیگر صفات  
480 WSD و MSI اندازه گیری شده بود. نتایج نشان داد کمبود آبیاری و کوددهی به‌طور معنی‌داری بر شاخص‌های تنش در گیاه )

481 به میزان ۹ درصد بیشتر II کارایی فتوسیستم PRD2-EC2 و کیفیت میوه تأثیر گذار است. در نوبت سوم اندازه گیری، در تیمار  
482 (EC2) تأثیر گذاشت. در کود رقیق شده به طور موثر بر هدایت روزنه ای PRD بود. همچنین، استراتژی SDI-EC از تیمار  
483 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  
484 دارای مزایای PRD به میزان 72/5 درصد بیشتر از شاهد افزایش یافت. مشاهدات نشان داد که استراتژی PRD2-EC2 تیمار  
485 بلندمدت برای گیاه و موثر در کاهش مصرف آب است. با این حال، برای ایجاد یک استراتژی آبیاری پایدار، هدایت الکتریکی  
486 محلول غذایی باید برای کنترل رشد و ویژگی‌های فتوسنتز گیاه تنظیم شود.  
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