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Effects of Drip Irrigation Emitter Density with Various Irrigation Levels on Physiological Parameters, Root, Yield, and Quality of Cherry Tomato

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Abstract: Root morphology and its components' behavior could show a considerable response under multiple water application points per plant to help the ultimate effect of fruit yield and fruit quality. In this study, a comparison of a single emitter per plant was made with two, three, and four emitters per plant under drip irrigation and two irrigation levels (full irrigation 100% and deficit irrigation 75% of crop evapotranspiration) to investigate their effects on physiological parameters, root, yield, and their associated components for potted cherry tomato under greenhouse conditions in Jiangsu-China. The experimental results showed that the plants cultivated in the spring-summer planting season showed significantly higher results than the fall-winter planting season due to low temperatures in the fall-winter planting season. However, the response root length, root average diameter, root dry mass, leaf area index, photosynthetic rate, transpiration rate, fruit unit fresh weight, the number of fruits, and pH were increased by multiple emitters per plant over a single emitter per plant, but total soluble solids decreased. Besides, a decreasing trend was observed by deficit irrigation for both planting seasons, and vice versa for the case for tomato total soluble solids. Due to an increase in measured parameters for multiple emitters per plant over a single emitter per plant, the yield, water use efficiency, and water use efficiency biomass significantly increased by 18.1%, 17.6%, and 15.1%, respectively. The deficit irrigation caused a decrease in the yield of 5% and an increase in water use efficiency and water use efficiency biomass of 21.4% and 22.9%, respectively. Two, three, and four emitters per plant had no significant effects, and the obtained results were similar. Considering the root morphology, yield, water use efficiency, water use efficiency biomass, and fruit geometry and quality, two emitters per plant with deficit irrigation are recommended for potted cherry tomato under greenhouse conditions. The explanation for the increased biomass production of the plant, yield, and water use efficiency is that two emitters per plant (increased emitter density) reduced drought stress to the roots, causing increased root morphology and leaf area index and finally promoting the plant's photosynthetic activity.

Keywords: root components; yield components; fruit quality; deficit irrigation; leaf area index; harvest index; photosynthetic rate; transpiration rate; water use efficiency; greenhouse

1. Introduction

Tomato (*Solanum Lycopersicum* L.) is one of the most produced, popular, and nutritious crops worldwide [1,2]. It provides a nutrient needed for human health [3] and contains antioxidants like lycopene that play a crucial role in preventing cancer and cardiovascular diseases [4–6]. Due to tomato fruit's nutritional and health benefits, tomato producers are much more interested in enhancing its quality and production [7,8].

The fast increasing population has forced an increase in agricultural production that may be attained by consuming more water, thus making water resources run out [9]. Water is one of the main factors influencing crop yield under water-scarce conditions. The crop yield depends on water consumption during the reproductive stage [10,11]. Reducing the quantity of water used for irrigation can increase urban and industrial water use [12]. Thus, the primary research objective concerning sustainable agricultural development and agricultural-ecological balance is to enhance water use efficiency (WUE) [13,14].

In comparison to other gravity-driven and pressure-operated irrigation systems, the drip irrigation system has been accepted as the highest water-saving method for the cultivation of tomato [15] and many other horticultural crops. However, attempts to look for different and more efficient approaches are still ongoing. Water pillow irrigation had been compared with drip irrigation and resulted in improved yield, fruit quality, and WUE than drip irrigation [16]. Water deficit irrigation, mainly for horticultural crops, has been studied worldwide for saving water and, hence, improving WUE [17–22].

Soil water has been found to improve nutrient accessibility, and nutrients have been found to improve root growth and the productivity of crops [23]. Soil water and nutrient uptake are greatly affected by the root morphology and distribution [24]. Root diameter, root surface area, root length density, and root weight density are the primary root morphological features that directly affect the entire root system and, indirectly, the above-ground plant components [25,26].

The quantity of soil water consumed by plant roots depends primarily on soil water availability, the morphological and physiological characteristics of the roots, etc. [27,28]. The plants uptake water from a wetting zone produced by drip irrigation, but the drip irrigation activates only a side of the root zone. The shape and size of the wetting zone produced by an emitter is a function of soil hydraulic conductivity, soil texture, soil structure, and emitter flow rate [29,30]. Despite these factors, the number of irrigation spots (emitter density) on the soil surface may also impact soil moisture distribution and, in turn, root growth, root distribution, and root water uptake. The morphology of roots is affected by the soil water supply [31]. Due to reduced soil moisture stress, moisture is more readily available to roots under multiple irrigation points. An expanded root system supports crops by reducing moisture stress [28]. A study showed that emitters' location could significantly affect the distribution of moisture and salt in the substrate [32]. The use of multiple emitters per plant reduced the leaching fraction compared with that resulting from one emitter, resulting in enhancing the amount and uniformity of substrate moisture in gerbera cultivated within pots [33].

There have been few studies on root–yield relationships for tomato under variable water and nitrogen rates [34–37]. However, there have been scarce studies on the influences of root–yield relationships under variable drip irrigation emitter densities (number of emitters per plant) under water deficit conditions for cherry tomato crop. Therefore, the study was conducted to compare the effects of drip irrigation emitter density with deficit irrigation on root and root components, plant physiological parameters, yield and yield components, fruit quality, and water use efficiency for potted cherry tomato grown under greenhouse conditions.

2. Materials and Methods

2.1. Experimental Site and Materials

The current study was conducted at a Venlo-Type greenhouse located in the School of Agricultural Engineering, Jiangsu University, Zhenjiang, Jiangsu-China (31°56′ N, 119°10′ E) from 13 March to 14 July 2019 (124 days) as the spring-summer planting season (SS) and from 2 September to 31 December 2019 (121 days) as the fall-winter planting season (FW). The greenhouse is situated in a humid sub-tropical monsoon climatic zone with an average annual rainfall of 1058.8 mm, a relative humidity of 76%, and a mean annual air temperature of 15.5 °C [38]. Firm rooted seedlings, 30 days old, of cherry tomato ("fenxiaoke xt–12020") were transplanted on 13 March and 2 September 2019 for the SS and FW, respectively, with plant density equal to 3.84 per m^2. The experimental soil was clay loam with the physical properties shown in Table 1.

Table 1. Soil physical properties.

Soil Property	Particle Size Distribution (%)			Bulk Density (g cm^{-3})	Field Capacity (cm^3 cm^{-3})	Organic Matter (g kg^{-1})
	Sand	Silt	Clay			
Range	34%	23%	43%	1.31	0.36	31.23

2.2. Experimental Design

The experimental design involved 2 factors factorial under a randomized complete block design (RCBD) with 4 replications for both seasons. Each replication consisted of five plants, of which three representative plants were used for data collection and then their averaged values were used for data analysis. The test influencing parameters were a single emitter (N1) and multiple emitters per plant (N2, N3, and N4: 2, 3, and 4 emitters per plant, respectively) under the drip irrigation system with two irrigation levels (full irrigation, W1; 100% of crop evapotranspiration (ETc); and deficit irrigation, W2; 75% of ETc). The treatment details are given in Table 2. Moreover, a single emitter (as in the case of N1) was placed in the north-west quadrant of the pot, 2 emitters (as in the case of N2) were placed in opposite quadrants as north-west and south-east quadrants, 3 emitters (as in case of N3) were placed as, one emitter was placed in the north-west quadrant, and the other 2 emitters were placed at an angle of 120° from each other. In the case of N4, 4 emitters, they were placed in all 4 quadrants of the pot, i.e., north-east, north-west, south-east, and south-west. The placement of the emitters was arbitrary and not dependent on sun orientation. All the emitters were equally spaced from each other in the case of multiple emitters per plant (N2, N3, and N4) and were placed at a 9 cm radius from the plant, approximately midway between the plant and pot boundary. For the growing practice, the plastic pots (40 cm in diameter and 40 cm in height) were filled with approximately 53 kg of air-dried soil, sieved through a 5 mm mesh sieve, up to a height of 35 cm so that these may contain the roots for tomato plants; as [36] found, for the surface drip irrigation system, the surface soil layer with 0 to 15 cm depth contained a tomato root length density up to 70%–75% of the total. The pots were placed alternatively with a plant-to-plant spacing of 80 cm and row-to-row spacing of 25 cm. All the pots were placed on 3 to 5 cm gravels mixed with sand to avoid waterlogging in the bottom soil.

Table 2. Treatment details.

Treatments	Emitter Density (Number of Emitters Per Plant), N	Irrigation Level (% of Crop Evapotranspiration), W
N1W1 (control)	1	100
N2W1	2	100
N3W1	3	100
N4W1	4	100
N1W2	1	75
N2W2	2	75
N3W2	3	75
N4W2	4	75

The control treatment (NIW1) pots were used to find the quantity of water being applied by the weighing method. To avoid soil evaporation, initially, the pots were covered with a plastic sheet after saturation. When the drainage stopped, the pots were reweighed and considered to be at field capacity by weight. The mass increase was ignored because of the minimal increment between two successive waterings. The irrigation was applied when the accumulative pan (20 cm in diameter) evaporation (Ep) reached 20 mm [39]. The Ep was calculated by accumulating the values determined by counting the cup every morning at eight o'clock. Adjustable flow rate emitters were used to attain the same flow rate per plant (emitter flow rate decreased as the emitter density increased, keeping the time of irrigation the same). The emitters were tested for flow uniformity before the experiment. The water delivered to all plants under each treatment was controlled by a water flow meter mounted at the control unit.

The fertigation was done as per local practices. Nitrogen fertilizer was delivered as urea (46% nitrogen). Triple superphosphate (46% P_2O_5) and muriate of potash (60% K_2O) were used as phosphorus and potassium sources, respectively. In addition, 40% of nitrogen and all phosphorus and potassium were applied and mixed into the soil in powdered forms at the start of the experiment. The remaining nitrogen was supplied as 30% in the first week of fruit emergence and 30% in the first week of fruit maturing. The transplanted seedlings were immediately irrigated with the same water volume (1 L) for better establishment and to ensure seedling growth. Besides, the plants were pruned once a week.

2.3. Sampling and Measurements

For each replication of the control (N1W1), the crop evapotranspiration between two consecutive irrigations was calculated using the water balance equation (weight-based, using a ±1 g weighing indicator) reported by [40] using $ET_{c(CR)} = I + (W_n - W_{n+1})$, where $ET_{c(CR)}$ is the crop evapotranspiration of the control, I is the amount of applied irrigation water (L), W_n and W_{n+1} are the pot weights before the nth and n + 1th irrigation (kg), respectively, and $ETc_{\ (CR)}$ is considered the standard amount of water (W_s) to be applied in control treatment for the next irrigation. The low irrigation treatment was irrigated according to the assigned percentage of the ETc of the control ($ET_{c(CR)} \approx W_s$). A data logger (Hobo; Onset Computer, Pocasset, MA, USA) was used to measure the greenhouse air temperature and relative humidity at intervals of 30 s at 1.5 m above ground level, located in the center of the greenhouse.

The crop physiological parameters like the photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (gs), and leaf intercellular CO_2 concentration (Ci) of fifteen leaves, chosen randomly per treatment, were measured with a portable photosynthesis system (LI-6400. Li-Cor, Lincoln, Nebraska, USA) on the 50th, 70th, and 100th days after transplanting at 9:00–11:00 h of local time on sunny days during the SS and FW. Finally, the instantaneous water use efficiency (WUE_{leaf}) was calculated as the ratio of photosynthetic rates and transpiration rates [41].

Fruit morphological parameters were determined upon each fruit harvest. A digital vernier caliper was used to measure the fruit diameter and fruit height, and fresh fruit weight was measured by a precision electronic scale (0.0001 g). To investigate the quality parameters, three fruits per plant with similar size, maturity, and no external defects were picked from each treatment. The fruits were peeled and mixed thoroughly. The blended paste was then squeezed with a muslin cloth to collect juice as a homogenized representative sample for each treatment. A refractometer (ABBE, WYA-2S, Lakeland, FL, USA) was used to measure total soluble solids (TSS, ° Brix), and pH was measured by a pH meter (WTW-InolabLevel 3 Terminal, Weilheim, Almanya, Germany) at 25 °C.

At the end of the planting seasons, three leaves per plant, 7th, 8th, and 9th from the top, were taken for leaf area determination. For root morphology, the roots with soil were dipped into water for 30 min to soften them, and the soil and roots were then poured onto a 100 mm mesh sieve. The roots were washed very gently with tap water and picked up by using tweezers. The roots and leaves were scanned (Figure 1) using an Epson Perfection V700 photo flatbed scanner (Seiko Epson Corp, Nagano, Japan). Later on, the scanned roots and leaves were then analyzed using WinRhizo software (Regent Instruments Inc., Ste-Foy, QC, Canada). The root length, root average diameter, root surface area, root volume, and leaf area were attained from the software.

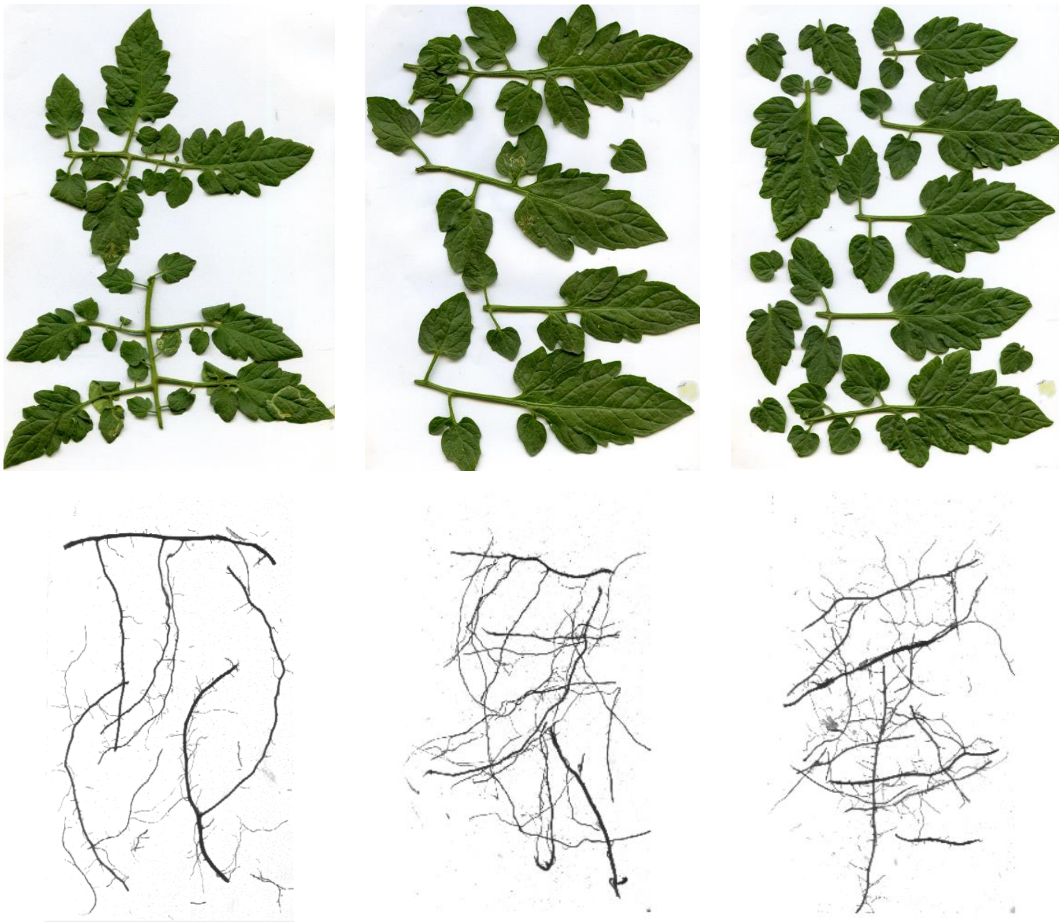

Figure 1. Samples of scanned images for leaves and roots at the end of fall-winter planting season.

At the end of the experiment, the total water applied and fruit yield were recorded for all treatments. To attain dry mass, the samples for each plant component (the roots, stem, leaves, and fruits) were oven-dried separately at a temperature of 70 °C till a constant weight was obtained, and finally, a precision electronic scale (0.0001 g) was used to obtain the weight of the dry mass.

Based on the above measurements, specific root length (root length/root dry mass, m g^{-1}) [42], root fineness (root length/root volume, cm cm^{-3}), root tissue density (root dry mass/root volume, g cm^{-3}) [43], leaf area (0.348(leaf length x leaf width) + 33.85, cm^2, $R^2 = 0.99$, $P < 0.001$), leaf area index (leaf area/surface area occupied by a plant, -) [44], specific leaf area (leaf area/leaf dry mass, cm^2 g^{-1}), leaf area ratio (leaf area/leaf and stem dry mass, cm^2 g^{-1}), harvest index (yield/yield and biomass, -) [45], water use efficiency (yield/irrigation water, kg m^{-3}), and water use efficiency biomass (yield and biomass/irrigation water, kg m^{-3}) were calculated.

2.4. Statistical Analyses

The general linear model (GLM) in SPSS 16.0 software (SPSS Inc., Chicago, USA) was used for the analysis of variance (ANOVA) between seasons (S), emitter density (N), and irrigation level (W). All factors were considered as fixed effects. To compare means, the least significant difference (LSD) test was employed at a probability level of 0.05 when F-values were significant.

3. Results

3.1. Greenhouse Climate

The observed greenhouse climatic data during the spring-summer planting season (SS) and fall-winter planting season (FW) in 2019 are shown in Figure 2. The air temperature (T) and relative humidity (RH) during the SS ranged from 14.4 to 31.0 °C and 51.1 to 89.5%, respectively, with average values equal to 23.7 °C and 70.1%, respectively, while during the FW, T, and RH, they ranged from 6.5 to 28.8 °C and 53.3 to 91.1%, respectively, with average values equal to 18.7 °C and 73.5%, respectively. It is worth noting that T decreased gradually while the RH showed an upward trend in the FW and similar SS trends. A similar phenomenon was described in the same greenhouse in 2018 [38].

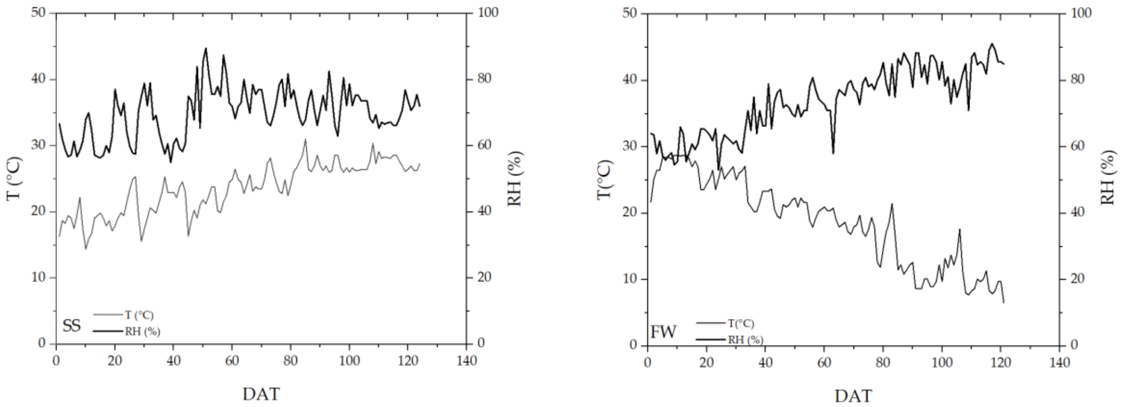

Figure 2. Variations in air temperature (T) and relative humidity (RH) observed for SS and FW. DAT, days after transplanting.

3.2. Root Morphology

Table 3 shows the root morphology and its associated components as affected by the emitter density, irrigation level, and planting season. The SS resulted in enhanced root length (21.7%), root average diameter (5.4%), root dry mass (15%), root surface area (28.2%), root volume (35.4%), and specific root length (6%), and reduced root fineness (6.3%) and root tissue density (15%) than the FW. All the factors had significant individual effects on all the roots measured and parameters calculated except for root average diameter (seasonal effect was significant only), root dry mass, and root fineness (seasonal effect was significant only). Overall, the effects of the emitter density and season were more significant than for irrigation level. All the root parameters increase with emitter density and decrease with deficit irrigation (W2) except for root fineness and root tissue density for which the effects were opposite.

3.3. Leaf Morphology and Yield

The effects of the emitter density, irrigation level, and planting season on leaf morphology, yield, and associated components are shown in Table 4. The SS performed better in terms of tomato plant leaf area (24.4%), leaf area index (24.4%), specific leaf area (13.2%), leaf area ratio (14%), yield (25.2%), harvest index (3.1%), and reduced (due to more irrigation water requirements in the SS than for FW) water use efficiency (WUE) (12.6%) and water use efficiency biomass (WUEB) (15.2%) than the FW. Harvest index was least affected by the treatments. All parameters increased with emitter density and decreased by W2 except WUE and WUEB, which increased with emitter density and W2 for both seasons. Compared to a single emitter per plant (N1), the increase in yield, harvest index, WUE (due to increased yield), and WUEB (due to increased total biomass) were 15.6%, 2.1%, 15%, and 12.7%, respectively, by two emitters per plant (N2). Multiple emitters per plant (N2, N3, and N4) resulted in similar values (with a nonsignificant difference) over N1. Compared to full irrigation (W1), the decrease in yield and harvest index were 5% and 2%, respectively, by W2. The increase in WUE and WUEB was 21.4% and 22.9%, respectively, for W2 over W1.

Table 3. Root morphology and its components as affected by the emitter density, irrigation level, and planting season.

Factors	Root Length	Root Average Diameter	Root Dry Mass	Root Surface Area	Root Volume	Specific Root Length	Root Fineness	Root Tissue Density
	(m)	(mm)	(g)	(m^2)	(cm^3)	(mg^{-1})	(cm cm^{-3})	(g cm^{-3})
Emitter density (N)								
N1	482.49 d	0.351 a	4.78 c	0.536 c	47.64 c	100.58 d	1048.6 a	0.105 a
N2	558.41 c	0.358 a	5.17 c	0.633 b	57.40 b	107.91 c	1008.0 a	0.094 b
N3	617.14 b	0.362 a	5.33 b	0.708 a	64.71 ab	115.54 b	991.3 a	0.086 bc
N4	667.83 a	0.362 a	5.39 a	0.766 a	70.31 a	123.47 a	987.7 a	0.081 c
Water Level (W)								
W1	617.13 a	0.361 a	5.27 a	0.707 a	64.58 a	116.51 a	992.9 a	0.086 b
W2	545.81 b	0.356 a	5.07 a	0.615 b	55.54 b	107.24 b	1024.9 a	0.096 a
Season (S)								
SS	638.41 a	0.368 a	5.53 a	0.743 a	69.05 a	115.11 a	955.6 b	0.086 b
FW	524.52 b	0.349 b	4.81 b	0.579 b	50.98 b	108.64 b	1062.2 a	0.097 a
ANOVA								
N	***	ns	***	***	***	***	ns	***
W	***	ns	*	***	**	***	ns	**
S	***	**	***	***	***	***	**	***
N * W	ns	ns	ns	ns	ns	ns	ns	ns
N * S	ns	ns	ns	ns	*	ns	ns	ns
W*S	ns	ns	ns	ns	ns	ns	ns	ns
N * W * S	ns	ns	ns	ns	ns	ns	ns	ns

N1, N2, N3, and N4; 1, 2, 3, and 4 emitters per plant, W1; full irrigation; W2; deficit irrigation, SS; spring-summer planting season, FW; fall-winter planting season. *; significant at $P < 0.05$, **; significant at $P < 0.01$, ***; significant at $P < 0.001$, ns; nonsignificant at $P > 0.05$. Values within the same columns that are accompanied by different letters vary significantly at $P < 0.05$.

3.4. Plant Physiological Parameters

The physiological parameters like photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (gs), leaf intercellular CO_2 concentration (Ci), and instantaneous water use efficiency (WUE_{leaf}) under different treatments are given in Table 5. The SS had higher physiological parameter values (7%, 7.6%, 11.4%, 12.3%, and 25.4% higher Pn, Tr, gs, Ci, and WUE_{leaf}, respectively) than the FW due to higher temperatures in the SS. All parameters increased with emitter density and decreased with W2 except WUE_{leaf} that increased with emitter density and also W2 for both seasons. The increase in Pn, Tr, gs, Ci, and WUE_{leaf} for N2 over N1 was 6.2%, 6.4%, 10.8%, 12.9% and 17.6%, respectively. Multiple emitters per plant produced similar values with a nonsignificant difference over N1. The W2 caused a decrease in Pn, Tr, gs, and Ci by 7.2%, 10%, 13%, and 15.4%, respectively, and an increase in WUE_{leaf} by 7.2%.

Table 4. Leaf morphology and tomato fruit yield as affected by the emitter density, irrigation level, and planting season.

Factors	Leaf Area	Leaf Area Index	Specific Leaf Area	Leaf Area Ratio	Yield	Harvest Index	WUE	WUEB
	(cm^2)	(-)	(cm^2 g^{-1})	(cm^2 g^{-1})	(kg $plant^{-1}$)	(-)	(kg m^{-3})	(kg m^{-3})
Emitter density (N)								
N1	3672.7 b	2.92 b	151.52 c	79.01 c	1.86 b	0.661	41.04 b	62.23 b
N2	4541.9 a	3.62 a	176.15 b	92.16 b	2.15 a	0.675	47.20 a	70.11 a
N3	4844.0 a	3.86 a	184.20 ab	96.47 ab	2.20 a	0.676	48.46 a	71.87 a
N4	5104.7 a	4.06 a	192.94 a	100.75 a	2.24 a	0.676	49.17 a	72.89 a
Water Level (W)								
W1	4837.7 a	3.85 a	182.89 a	96.03 a	2.16 a	0.679	40.91 b	60.33 b
W2	4243.9 b	3.38 b	169.52 b	88.17 b	2.06 b	0.665	52.02 a	78.22 a
Season (S)								
SS	5034.7 a	4.01 a	187.08 a	98.10 a	2.35 a	0.682	43.33 b	63.56 b
FW	4047.0 b	3.22 b	165.33 b	86.10 b	1.88 b	0.662	49.60 a	74.99 a
ANOVA								
N	***	***	***	***	***	ns	***	***
W	**	**	**	**	**	ns	***	***
S	***	***	***	***	***	ns	***	***
N * W	ns	ns	ns	ns	ns	ns	ns	ns
N * S	ns	ns	ns	ns	ns	ns	ns	ns
W * S	ns	ns	ns	ns	ns	ns	ns	ns
N * W*S	ns	ns	ns	ns	ns	ns	ns	ns

N1, N2, N3, and N4; 1, 2, 3, and 4 emitters per plant, W1; full irrigation; W2; deficit irrigation, SS; spring-summer planting season, FW; fall-winter planting season, WUE; water use efficiency, WUEB; water use efficiency biomass. *; significant at $P < 0.05$, **; significant at $P < 0.01$, ***; significant at $P < 0.001$, ns; nonsignificant at $P > 0.05$. Values within the same columns that are accompanied by different letters vary significantly at $P < 0.05$.

Table 5. Physiological parameters as affected by the emitter density, irrigation level, and planting season.

Factors	Photosynthetic rate (Pn)	Transpiration Rate (Tr)	Stomatal Conductance (gs)	Leaf Intercellular CO_2 Concentration (Ci)	Instantaneous Water Use Efficiency (WUE_{leaf} = Pn/Tr)
	(μmol (CO_2) m^2 s^{-1})	(mmol m^2 s^{-1})	(mol (H_2O) m^{-2} s^{-1})	(μmol mol^{-1})	(μmol mol^{-1})
Emitter density (N)					
N1	13.35 c	11.38 b	0.42 c	270.27 c	1.17 b
N2	15.07 b	12.11 a	0.49 b	299.34 b	1.25 a
N3	15.47 ab	12.34 a	0.52 a	310.49 ab	1.25 a
N4	15.81 a	12.44 a	0.53 a	320.63 a	1.27 a
Water Level (W)					
W1	15.44 a	12.93 a	0.51 a	318.44 a	1.19 b
W2	14.41 b	11.20 b	0.47 b	281.93 b	1.28 a
Season (S)					
SS	16.61 a	12.76 a	0.51 a	311.19 a	1.30 a
FW	13.24 b	11.37 b	0.47 b	289.17 b	1.17 b
ANOVA					
N	***	**	***	***	**
W	***	***	***	***	***
S	***	***	***	***	***
N * W	ns	ns	ns	ns	ns
N * S	ns	ns	ns	ns	ns
W * S	ns	ns	ns	ns	ns
N * W * S	ns	ns	ns	ns	ns

N1, N2, N3, and N4; 1, 2, 3, and 4 emitters per plant, W1; full irrigation; W2; deficit irrigation, SS; spring-summer planting season, FW; fall-winter planting season. The values are at 70 DAT (days after transplant). *; significant at $P < 0.05$, **; significant at $P < 0.01$, ***; significant at $P < 0.001$, ns; nonsignificant at $P > 0.05$. Values within the same columns that are accompanied by different letters vary significantly at $P < 0.05$.

3.5. Fruit Morphology and Fruit Quality

Table 6 shows the effects of the emitter density, irrigation level, and planting season on fruit morphology like unit fresh weight, number of fruits per plant, fruit diameter, fruit height, and fruit quality like total soluble solids (TSS) and pH for both the SS and FW. The SS produced increased fruit morphology (1%, 4.2%, 7.8%, and 16.1%, increase in unit fresh weight, number of fruits, fruit diameter, and fruit height, respectively) and decreased TSS (0.6%, nonsignificant) and pH (2.6% nonsignificant) over the FW. All the parameters increased with emitter density and decreased with W2, but the fruit TSS was vice versa. Compared to N1, N2 resulted in enhanced fruit morphology (unit fresh weight, number of fruits, fruit diameter, and fruit height by 1.5%, 3.5%, 4.3%, and 10.7%, respectively) and reduced TSS (3%) and increased pH (0.2%). Similar values were observed for multiple emitters per plant with no significant difference over N1. The W2 resulted in reduced fruit morphology (unit fresh weight, number of fruits, fruit diameter, and fruit height by 2.3%, 2.4%, 2.6%, and 3%, respectively). W2 increased TSS (11.7%) and reduced pH (1.3%).

Table 6. Fruit morphology and fruit quality as affected by the emitter density, irrigation level, and planting season.

Factors	Unit Fresh Weight	Number of Fruits Per Plant	Fruit Diameter	Fruit Height	Total Soluble Solids	pH
	(g)	(-)	(mm)	(mm)	(^{0}Brix)	(-)
	Emitter density (N)					
N1	29.72 b	62.44 b	28.31 b	30.56	4.22 a	4.13
N2	30.99 ab	69.14 a	29.29 ab	31.00	4.10 ab	4.14
N3	31.62 a	69.50 a	29.96 a	31.72	4.05 ab	4.14
N4	31.92 a	69.88 a	30.31 a	31.91	4.02 b	4.15
	Water Level (W)					
W1	31.45 a	68.51 a	29.90 a	31.66	3.84 b	4.16
W2	30.67 a	66.97 a	29.03 a	30.94	4.35 a	4.11
	Season (S)					
SS	32.23 a	72.79 a	30.08 a	31.45	4.08 a	4.08
FW	29.90 b	62.69 b	28.86 b	31.15	4.11 a	4.19
ANOVA						
N	*	***	*	ns	ns	ns
W	ns	*	ns	ns	***	ns
S	***	***	**	ns	ns	ns
N * W	ns	ns	ns	ns	ns	ns
N * S	ns	ns	ns	ns	ns	ns
W * S	ns	ns	ns	ns	ns	ns
N * W * S	ns	ns	ns	ns	ns	ns

N1, N2, N3, and N4; 1, 2, 3, and 4 emitters per plant, W1; full irrigation; W2; deficit irrigation, SS; spring-summer planting season, FW; fall-winter planting season. *; significant at $P < 0.05$, **; significant at $P < 0.01$, ***; significant at $P < 0.001$, ns; nonsignificant at $P > 0.05$. Values within the same columns that are accompanied by different letters vary significantly at $P < 0.05$.

4. Discussion

The spring-summer planting season (SS) performed better than the fall-winter planting season (FW). Due to very low temperatures in the FW, 6.5 °C at the later stage in the month of December, it had a negative impact on the maximum fruit growth rate [46]. Several studies have shown that the tomato crop's optimum temperatures ranged between 20 and 24 °C to ensure further growth, flowering, and fruit maturation, and 12 and 36 °C were the temperature limits for growth [47]. Further, there were no significant effects on response parameters for two, three, and four emitters per plant, and the findings obtained were identical for both seasons.

Plant roots are the primary organ that absorbs water and nutrients, so their size and distribution in the soil are closely linked to their capacity for water and nutrient absorption [48]. Few earlier studies have found that water conditions in excess or deficit can change maize root zones' size and distribution, thus inhibiting root development [49]. The primary parameters that affect water and nutrient absorption are root diameter and length [50]. The present study indicated that root length, root average diameter, and root dry mass (Table 3) increased with emitter density and decreased with deficit irrigation (W2). The increase was attributed to the more uniform moisture distribution under increased emitter density that facilitated the root absorbing water easily (as the distance between water source and roots decreased) and reduced the drought stress to roots. This agrees with the previous study, which stated that root and shoot growth in weeping fig was significantly affected by both the irrigation water and several emitters per plant [51]. Furthermore, drought stress can prevent root growth and plays a vital role in the morphology of the maize crop root [52]. The increased root length with increased emitter density (Table 3) is attributed to the increased specific root length [42], increased root dry mass, and decreased root tissue density [43]. The effect of W2 is the opposite, which is in agreement with [53]. Besides, low-density tissues allow a fast relative growth rate and quick resource acquisition, as the plant can rapidly expand the leaf, stem, or root system with low investment in the dry matter [54–56]. In this study, in line with [57], the root fineness decreased due to the increased root dry mass with emitter density, and vice versa for W2.

The main physiological mechanism of plants is photosynthesis, which can provide 90% of plant biomass [58]. The primary explanation for most biomass and crop production differences is leaf photosynthesis [59]. In this study, the physiological parameters (Table 5) increased, due to an increase in leaf area index (Table 4), with emitter density and irrigation levels for both seasons (Table 5). A drop in intercellular carbon dioxide concentration can be attributed partly to metabolic elements due to the decline in photosynthesis [60] and partly due to the stomata's closure. The study results are in accordance with [22,61].

The leaf components, yield, and yield components (Table 4) increase with emitter density and decrease with W2. Previous studies have shown that, in line with the present findings, deficit irrigation reduces vegetative growth and fruit yield [62–65]. The explanation for this was that considerably decreased plant photosynthesis reduced the volume and energy of metabolites needed under water-stressed conditions for proper plant growth [62,66]. In a typical subtropical climate, the 80% crop evapotranspiration (ETc) irrigation regime induced a slight decrease in plant growth [67]. In the present study, in accordance with the above, the 75% ETc irrigation regime reduced yield by 4.6% only. The increase in yield (18.1% higher for multiple emitters per plant over a single emitter per plant (N1), Table 4) is due to an increase in mean unit fresh fruit weight and the number of fruits per plant (6% and 11.3%, respectively, higher for multiple emitters per plant over N1, Table 6). The increase in fruit unit fresh weight is due to increased fruit size (fruit diameter and fruit height, Table 6). As is known, plant vigor has been closely connected to the root system that supplies the shoot with water and nutrients. The reason is that the pattern of root growth and shoot development is strongly correlated [68], and both increase with emitter density in this study, which may be considered the key factor promoting increased yield (Table 4). The harvest index is increasing because the increase in fruit weight is higher as compared to the biomass weight with an increasing emitter density and vice versa for irrigation levels for both seasons. The harvest index decreases due to stress [69], which is consistent with these research results. The reported harvest index for cherry tomato is slightly more than [70], due to different growing conditions. The most critical indicator used to measure agricultural output is water use efficiency (WUE) [71,72]. The WUE and water use efficiency biomass (WUEB) (Table 4) increased with W2 because the numerator increased more than the denominator's reduction. According to [73], initially reducing irrigation water levels in tomatoes increases the water use efficiency, and reducing water level reduces water use efficiency.

Under deficit conditions, tomatoes' fruit quality can be increased [74]. The total soluble solids decreased with emitter density and irrigation level, and pH response was vice versa (Table 6). This is due to increased moisture availability to plant roots under increasing emitter density and irrigation level, ultimately decreasing water stress in soil. The fact that the accumulation of water in the fruit allows the dilution of fruit ingredients may explain this effect [75]. The results are in accordance with [65,76,77].

5. Conclusions

The spring-summer planting season performed better than the fall-winter planting season because of low temperatures in the fall-winter planting season. All the root and root components, leaf and leaf components, yield and yield components, plant physiology, and fruits morphology and pH showed an increasing trend with an increasing emitter density and decreasing trend with deficit irrigation except water use efficiency, water use efficiency biomass, instantaneous water use efficiency (increase with emitter density and deficit irrigation), root fineness, root tissue density, and total soluble solids (decrease with emitter density and increase with deficit irrigation). Overall, it was seen that two, three, and four emitters per plant had no significant effects, and the obtained results were similar under full and deficit irrigation. Bearing in mind the trade-off among plant fruit quality, fruit yield, and water use efficiency, the two emitters per plant with deficit irrigation was found as the best combination for the emitter density and irrigation level management approach for cherry tomato grown under greenhouse conditions within pots. It is recommended that the emitter placement around the plant (in this study at 9 cm radius) should be varied to study its effects on root development that will ultimately affect plant yield and water use efficiency.

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